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VIRTUAL BALKAN POWER CENTRE FOR ADVANCE OF RENEWABLE ENERGY SOURCES IN WESTERN BALKANS

WORKSHOP 1.3. (WS1.3): OPERATION AND CONTROL OF RES IN ISOLATED REGIONS

AGENDA

Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia and Montenegro
07 – 08 November 2005

Monday, 7th November

$9^{30} – 10^{00}$	**Registration**	
$10^{00} – 10^{15}$	**Welcome and Introduction**	
$10^{15} – 10^{45}$	**Integrated system of DMS analytical functions**	**DMSG & University of Novi Sad**
$10^{45} – 11^{15}$	**Load flow and optimal PF**	**ETF**
$11^{15} – 11^{30}$	**Coffee break**	
$11^{15} – 11^{45}$	**Optimal configuration of power system**	**UPB**
$11^{45} – 12^{15}$	**RESY-PAN tool: Overview**	**CMU**
$12^{15} – 12^{30}$	**Discussion**	
$12^{30} – 14^{30}$	**Lunch Break**	
$14^{30} – 15^{00}$	**Generators Impact on Protection in Distribution Networks**	**DMSG**
$15^{00} – 15^{30}$	**State Estimation on Distribution Level**	**DMSG**
$15^{30} – 16^{00}$	**Short circuit currents**	**UNI-ZG**
$16^{00} – 16^{30}$	**Optimal power flow**	**ETF (local presentation)**
$16^{30} – 17^{00}$	**Discussion**	
20^{00}	**Official dinner**	

Tuesday, 08th of November

$09^{00} – 09^{20}$	**Security**	**ICCS/NTUA**
$09^{20} – 09^{45}$	**Wind Forecasting**	**ICCS/NTUA**
$09^{45} – 10^{15}$	**Control aspects: SCADA**	**INTRADE**
$10^{15} – 10^{30}$	**DMS Tool: Overview**	**ICCS/NTUA & CRES**
$10^{30} – 10^{45}$	**Coffee break**	
$10^{45} – 11^{00}$	**Technical aspects of connecting RES to distribution network in Serbia**	**Electric Industry of Serbia**
$11^{00} – 11^{30}$	**Power Quality of RES**	**UNI-MB**
$11^{30} – 12^{00}$	**Discussion**	
$12^{00} – 13^{30}$	**Lunch**	
	End of workshop	
	(Extended Steering Committee Meeting)	

Sixt Framework Programme, Priority 6
Sustainable Development, Global Change and Ecosystems
Contract: INCO-CT-2004-509205

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Renewable Energy Sources in Western Balkans

Balkan Power Center Report

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Workshop T.1.3, WP 1

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INDEX

Summary

The two days workshop “Operation and control of RES of isolated power system” was held at the University of Belgrade, Faculty of Electrical Engineering (ETF), between November 7 – 8, 2005. The Workshop belongs to the project “Virtual Balkan Power Centre for Advance of Renewable Energy Sources in Western Balkans”, project acronym: VBPC-RES, Contract INCO-CT-2004-509205, under the Sixth Framework Program, International Cooperation (INCO). The Workshop WS 1.3 is a part of the Work Package 1 (WP1) of the VBPC-RES project, entitled “Regulatory and organizational framework: barriers and incentives for renewable energy sources penetration”.

At the beginning of the workshop, Mrs. Elena Boškov of DMSG, as the the organizer of this workshop greeted the participants. His presentation comprised a short review of the WP1 goals, and the introduction of the topic of the Workshop WS 1.3. The program of the WS comprised 11 contributions from Project Partners and one from the outside expert, Mr. Cicović, from Electric Power Industry of Serbia. The main points of their contributions are presented below.

Nikola Rajaković, Nemanja Milojčić, Faculty of Electrical Engineering, University of Belgrade, Serbia and Montenegro: “Load flow and Optimal Power Flow in Distribution Networks with Dispersed Generation”

Dispersed generation becomes more and more important part of the generation capacities in some existing power system. The operation and planning of the small generating units within the distribution networks is connected with many theoretical and practical problems. Generally, motives for optimization are related to minimization of expenses and maximization of profit. Methods used in distribution networks are derived from the methods which have been used in transmission networks and main idea is to make distribution network much more controllable and flexible in comparison with the conventional ones. It is very important to consider all the specifics of the distribution networks with embedded generation when it is needed to solve some optimization problem. Some of the generating units may be renewable energy sources which would have commitment priority in the future. Sometimes, in the optimization procedures in distribution networks with distributed generation conflicting goals should be considered.

Ion Tristiu, Mircea Eremia, Constantin Bulac, Lucian Toma, University “Politehnica” of Bucharest, Romania: “Optimal Configuration of Power System”

The major changes the power industry undergone in the last years set up a favourable framework for development of small and average size production units, connected to the electric networks in a dispersed manner. Usually, the distributed generators are used to produce locally, in consumption areas, relatively reduced amounts of power. The main differences with respect to the classical power plants (thermal, nuclear, and hydro) are related to the location and the installed capacity. Dispersed generators of small size are generally connected in medium and low voltage distribution networks. They are embedded in the distribution networks. Thus, this kind of electricity generation is considered as: *embedded generation* or *distributed generation* or *dispersed generation*.

Introduction of distributed generation can have notable impacts on operating of distribution electric networks. The first step in any study consists in power flow calculation. Information obtained at this step are used for establish the means to optimise operating of electric networks, in order to obtain *Optimal Power Flow*.

The distribution electric networks of medium and low voltage, especially the urban ones, can be strongly meshed, but, for technical and economical reasons, under normal conditions they operate radially. During short periods of time, these networks can operate in meshed configuration, especially when usual manoeuvres are done for configuration changes.

Based on the particularities of distribution networks generated by the arborescent constraint, the load flow calculation can be performed using a specific method, known in literature as the *backward/forward sweep*. Dispersed generation alters unidirectional power flow in distributed networks. In this situation, backward/forward sweep can be applied for load flow calculation, only with some specifications and adaptations.

Other consequence of the arborescent constraint of meshed distribution networks consists in the existence of several operating configurations. In this situation there is the possibility of achieving the most suitable configuration in order to improve or optimise the operating state, in terms of the strategy of network configuration and of the electricity demand. The presence of dispersed generation can significantly change the power weight centre of consumption zones and implicitly operating regime of distribution networks. Reconfiguration process can be also applied to optimise the operating regime.

In this paper two aspects are studied: load flow calculation and reconfiguration of distribution electric network with embedded generation

V. Glamocanin, S. Velickovic, Ss. Cyril And Methodius University in Skopje, FYROM: “RESY PAN Tool: An Overview”

PAN software is used for analysis and planning of power transfer and distribution grids. It is a modular program and functionality could be increased by adding additional modules.

The program consists multiple tools such as:

- Database
- Graphic editor

- Graphic display
- Project manager
- Analyzer

Also, this program can connect with an on-line system for gathering information.

PAN gives possibility for working with more than one project. In each project several cases could be defined, each with several variants.

There are two types of databases. First one is general database and contains information about any element used in the power system. Second type is local type database and each project generates one just for the elements used in the same project (example: The basic database contains data about certain type of cable and the projects' database contains information such as length, intermediate loads, etc. about power line using that same type of cable). Moreover projects' database contains information about connections between used elements.

Graphic editor is used for creating a scheme of the system.

There are different methods of analysis but the best way is trough the graphic display. Besides analysis it can be used to modify data or there actual states, witch could be gathered on-line.

One part of the analysis that can be performed:

- load flows
- voltage regulations
- three phase short circuit
- harmonics
- protection coordination
- asymmetrical faults

This program also can generate reports about the project and the performed analysis.

Bekut Dusko, Saša Mandić, Izabela Berić, DMS Power Engineering Group ltd, Serbia and Montenegro: "Generators Impact on Protection in Distribution Network"

The modern trend in the world is usage of renewable (clear) power sources. In this paper authors consider influence of renewable distribution generators usage on short circuit currents and functionality of existing over current protections in distribution networks. The main goal of this paper is to analyze effect of installing such generators in distribution networks with regards to effects that are not yet specified in actual technical regulative. One of those is effect on existing protection on feeders in distribution networks. The generator in radial distribution networks causes increasing of short circuit current value on fault location and sometimes changing direction of short circuit current in comparison with situation before insertion of generator. For this reason, installation of the generator can cause non–selective relay tripping. Goal of this paper is to point out those problems and also to offer possible solutions. Final considerations try to find answer on dilemma where to install distribution generator without degradation of feeder relay functionality. Possible solution is offered as an idea in environment of Distribution Management System (DMS). All considerations are supported by examples.

Goran S. Švenda, Vladimir C. Strezoski, University of Novi Sad, Faculty of Technical Sciences, Serbia and Montenegro: "The Real-Time Distribution State Estimation"

The State Estimation represents the basic function in both Energy Management System (EMS) and Distribution Management System (DMS), since a lot of power applications in both systems (load flow, fault calculation, relay protection, voltage control, security and loss analysis, etc.) are based on the estimated actual (or studied) state. The state estimation of transmission networks has been established several years ago [1]. The corresponding estimation procedures are founded on the high level of network remote monitoring provided by usual Supervisory Control and Data Acquisition (SCADA) systems. The redundancy of real-time telemetered data about both the network state and topology is usually higher than 2.0. Such a redundancy provides not only a high quality estimation of the network state, but also a high quality dealing with wrong measurements, validation of network parameters and topology.

New factors introduced by connection of renewable sources generators to MVDN bring one more factor into this equation. State estimation represents the basic DMS function, because practically all other DMS power functions are based on its results (under-load switching, fault calculation, relay protection, supply restoration, etc.).

A simple, fast and robust State Estimation algorithm for MVDNs is described and verified in this paper. It can be applied in any distribution utility and encounters influence of measurements in distribution generators originating from renewables – with or without installed SCADA system. Proposed algorithm was developed with regards to the fact that experience with (real-time) state estimation application in standard MVDNs is modest at best, i.e. there is no reference that could offer a standard for realization of this function. Thus, the proposed solution represents a compromise between complex methods proposed in the literature and usually available data in distribution utilities. This state estimation algorithm can be applied in distribution utility with motors, capacitor banks and dispersed (renewables) generation.

Finally, an experience with the application of the DMS state estimation is presented in this paper. A software package for DMS state estimation was developed for the State Electric Power Company of Serbia and EPS Elektrovojvodina – Distribution Power Company. It is applied in several other distribution utilities in Yugoslavia. Thus, the developed algorithm and the corresponding software package are verified in practice of distribution utilities.

Maja Božičević Vrhovčak, Vesna Bukarica, Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia:

“Short – Circuit Currents Analysis for Isolated Systems with Renewable Energy Sources”

Growing environmental concerns as well as the security of energy supply issues are providing opportunity for increased penetration of renewable energy sources into power systems. Especially attractive are small generation units that are placed near consumers and that can satisfy their power demand. Systems with renewable energy sources can be successfully implemented in isolated regions, like mountain areas or islands, which do not have connection to the main distribution grid or where such connection will be technically and/or economically unjustified. However, there are number of technical challenges associated with operation of isolated systems, especially once with renewable energy sources. Varying loads and climate conditions can cause disturbances in the system, like frequency and voltage variances. It is thus important to develop adequate control and operational procedures of such systems.

Important step in definition of control and operational procedures for any power system is short circuit current calculation. It should be performed in order to obtain the magnitude of fault currents, which is used for grid elements dimensioning and protection adjustments. Results depend, of course, on grid topology, location of the fault and the type of the fault. However, the first and the most important step in short-circuit current calculation is to develop grid equivalent model and to determine overall impedance of the fault circuit. That means that every grid element should be presented with equivalent model, i.e. equivalent scheme. Equivalent models for power sources (generators), transformers, power lines and loads should be developed. Every element is represented by its reactance.

In systems with renewable energy sources it is interesting to consider and analyse different types of power sources and to develop their equivalent models. Power source in the most of power plants is rotating machine, i.e. electric generator. In conventional power plants the most commonly used are synchronous generators. However, power plants using renewable energy sources usually have smaller power output and synchronous generators are not always the best choice. Especially interesting are wind power plants, since their operation is quite different then conventional power plant with gas, steam or hydro turbine. There are two types of wind turbines: constant-speed and variable speed-wind turbines. Constant-speed turbines are based on a directly grid-coupled squirrel-cage induction generator. Variable-speed wind turbines can be coupled with double fed (wound rotor) induction generator or with direct drive synchronous generator. In case of variable-speed turbine, there is always a need for power electronics as an interface between the generator and the grid. The contribution of wind turbines to the fault current differs between these three main wind aggregates types.

Photovoltaic cells are another interesting example. They are semiconductor elements that produce direct current, which has to be alternated to the grid frequency current using power electronics elements.

This paper will try to explain how to model different types of power sources, i.e. how to determine their reactance. The influence of different power sources to short-circuit currents will be analysed. Short circuit currents for different type of faults and power sources will be calculated.

Nikos Hatziargyriou, Pavlos Georgilakis, Institute of Communication and Computer Systems, National Technical University of Athens, Greece: "Dynamic Security Assessment and Monitoring of Isolated Networks with Increased Wind Power Penetration"

This paper describes the security assessment functions of an advanced control system for secure operation of isolated networks with increased renewable penetration. One of the key features of this system is related with the capability of assessing on-line dynamic security and providing preventive control measures that can assure a robust operation for the system regarding some disturbances. The paper describes with some detail the general approach followed to derive these evaluation functions, which are based in functional knowledge generated off-line through computational simulation. The development and use of security assessment applications is of crucial importance in helping defining the operation policies of isolated power systems where non-controllable power sources (like wind power) have important share of the production. In this paper the application of tools that exploit functional knowledge of the system (gathered off-line) was the key for the success of the dynamic security assessment and monitoring.

George Sideratos, Nikos Hatziargyriou, Pavlos Georgilakis, Institute of Communication and Computer Systems, National Technical University of Athens, Greece: "State-of-the-art in Wind Power Forecasting"

Wind power is a necessary addition to traditional power market. Wind power prediction therefore is necessary because of the low utilization factor of wind farms and the intermittence nature of wind. A lot of studies have been performed to accurately predict wind power and local wind speed. This paper reviews the state-of-the-art in short-term prediction of wind power. It also investigates the performance of a hybrid method for wind speed forecasting. The hybrid approach utilizes a nonlinear filter in conjunction with artificial neural networks. Experiments are performed with the data from Crete. The experimental results of the hybrid algorithm are compared with those of linear regression approaches.

Short-term forecasting has come a long way since the first attempts at it. Often, running the grid would not be possible without wind power forecasting, especially in situations with high wind power penetration. The current crop of models, typically combining physical and statistical reasoning, are fairly good, although the accuracy is limited by the employed numerical weather prediction (NWP) model.

Short-term prediction consists of many steps. For a forecasting horizon of more than 6 hours ahead, it starts with a NWP model. Further steps are the downscaling of the NWP model results to the site, the conversion of the local wind speed to power, and the upscaling from the single wind farms power to a whole region. On all these fronts, improvements have happened since the first models. Typical numbers in accuracy are an RMSE of about 10-15% of the installed wind power capacity for a 36 hour horizon.

Artificial neural networks (ANN) are now the tool of choice for wind speed forecasting. ANNs are independent to any mathematical models and adapt themselves to training data. In this paper, a nonlinear filter is utilized in conjunction with ANNs. The ANNs summarize short-term pattern in the wind speed data and the nonlinear filter takes the long-term pattern into consideration. Experiments are performed with the data from the largest island of Greece. The results show that ANNs outperform persistence model just a little. Considering the long-term pattern, the results further improved by 15% on average. Although this algorithm handles short-term prediction very well, multiple hours ahead prediction show that meteorological and geographical information must be included if longer term prediction is needed. It is also necessary to study more advanced ANN tools to improve the short-term prediction.

A. Ajanovic, INTRADE Energija, Sarajevo, Bosnia and Herzegovina: "Control Aspects: SCADA"

SCADA is an acronym of **S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition (data acquisition, supervision, monitoring and control) and means the entire spectrum of equipment, systems and solutions enabling data acquisition about some process – remote system, data processing, supervision and in some cases reaction in adequate way.

Due to its flexibility it is applied in different fields:

- Electricity generation (conventional and nuclear),
- Oil industry,
- Metal industry,
- Water management services,
- Communications,
- Safety systems,
- Chemical industry, etc.

The simplest example of SCADA system is an ordinary PS, which through acquisition-control card receives data, creates data about the process, processes them and thus makes supervision, but also performs control if foreseen at that level. Basically it is centralized system of acquisition and control.

More complex example of SCADA system is network supported by computers and through radio connection controlled terminals TU (Terminal Unit) which communicate with computer center. It is a distributed control system DCS (Distributed Control System).

The most complex example of SCADA system is network of the SCADA systems that functions by principal server–server, server–client. Those are WASCAD (Wide Area SCADA) systems.

Input physical values could be: force, temperature, relative humidity, length, revolutions, speed, light intensity, etc.

The electrical equivalent of input value can be: voltage, current, capacitance, inductivity, power, energy.

Nikos Hatziargyriou, Pavlos Georgilakis, Institute of Communication and Computer Systems, National Technical University of Athens, Kostis Karras, Centre for Renewable Energy Sources, Greece: “Distribution Management System Software for Isolated Power Systems: An Overview”

This paper presents an overview of a distribution management system (DMS) software that aims at optimizing the overall performance of isolated and weakly interconnected systems in liberalized market environments by increasing the share of wind and other renewable energy sources, taking into account pumped hydro storage facilities and providing advanced on-line security functions, both in preventive and corrective mode.

The main features of the control system comprise advanced software modules for load and wind power forecasting, unit commitment and economic dispatch of the conventional and renewable units and on-line security assessment capabilities integrated in a friendly Man-Machine environment. Pilot installations of advanced control functions have been implemented on the islands of Crete, Ireland and Madeira.

Andrej Hanžič, Boris Čižmešija, Viljem Muzek, Jože Voršič, University of Maribor, Slovenia: “Power Quality of RES – EMC of Micro Generations Unit”

Electromagnetic compatibility (EMC) is the capability of electric and electronic devices or systems to function in coordination with their purpose in their electromagnetic environment without any negative effects on other equipment and people's health by means of conduction or radiation electromagnetic emission. Producers of dc/ac inverters are convinced that their products are immune or resistant to external electromagnetic occurrences; at the same time emissions, disturbing to other devices or living beings, shall not be produced. Industrialized countries have a regulative that establishes the limits of the maximum value of electromagnetic emissions. The comparison of standards in the field of electromagnetic compatibility (EMC) for Australia, Europe, Japan and the United States indicates differences in evaluation of the electromagnetic emission parameter. The acquired results are welcome when planning a dispersed generation of electricity from small and micro cogeneration systems, which operate or will operate in the Slovenian public system.

Dragoslav B. Cicović, EPS:
"Technical recommendation no. 16.- Base technical requirements for connection small - scale power at distribution network in Serbia"

In the presentation, Mr. Cicovic presented the technical requirements as well as the scope and the implementation guidelines for distributed connection of small-scale power distribution in Republic of Serbia.

For connection of small-scale distributed generation, the category that comprises most of the RES generation, the criteria include standards for connection, metering, protection, reactive power compensation, regulations for connection and conditions for operation and management of small scale power facilities.

1 Load Flow and Optimal Power Flow in Distribution Networks with Dispersed Generation

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1.1 Introduction

The story about the future of energy sector development in general, and especially of electric power subsector, begins mainly with the facts that reserves of the conventional energy sources (oil, gas, coil) are being more and more exhausted and that their use is a large ecological problem. Besides, the global trend of the demand growth (for electric power) is very evident and expected in future. Reasons for that are the growth of the population and also the lifestyle. Future solutions include many aspects that should be dealt with: technical, economical, ecological, social, legal, organizational etc. The concept of dispersed generation is one of them.

Dispersed generation is a concept that describes a great number of small generation units within an electric power system. These units use renewable and non-renewable sources for electric power production and they are connected to medium voltage or low voltage networks. Wind generators, small hydro plants, solar plants, thermal power plants fuelled by biomass, geothermal plants, burning cells, small gas turbines, tidal energy and other units. Installed capacities range from a few kW to MW range, and according to that there are: micro, small, medium and large ones. It doesn't mean that large generating units that participate dominantly in electric power generation at the moment are of lesser importance. They are still essential from the aspect of secure operation of the entire electric power system.

The introduction of distributed sources primarily has impact on the active and reactive power flows in the system. Therefore, distribution network is not more passive as it is in the centralized electric power system concept. It can decrease power losses, because of the fact that a part of energy production is much closer to the consumers. It happens that dispersed generation has been developing side by side with the global development of electric power market, and this leads to the larger number of market transaction members. But, the use of these dispersed generating sources is connected with many problems which appear during their integration and exploitation. Some of them are: integration into the unique control system, complexity of top-quality and selective relay protection for the system elements, the influence on the level of short circuit currents, impossibility to plan generation production in some cases, the influence on some aspects of electric energy quality etc. Also, the large capital investments are needed for introduction of these sources. The great part in dispersed generation should be overtaken by the facilities for combined production of electrical energy and technical warm water (CHP - Combined Heat and Power) which are mostly close to the larger consumer areas and which demand installation of additional infrastructure.

Biomass, wind energy, hydro energy of small river flows, solar and geothermal energy should be mentioned as promising renewable energy sources in Serbia & Montenegro. It is necessary to complete qualitative and extensive researches in order to examine economical justification of introducing these distributed sources into the electric power system. The prerequisite of the broader introduction of the dispersed generation is the electric energy market deregulation that will lead to the open and nondiscriminatory access of all the members according to the appropriate rules and legal standards. Future of dispersed generation brings new challenges in this area and needs the involvement of a large number of experts from different scientific areas.

1.2 Importance of load flow and optimal power flow in distribution networks with dispersed generation

The introduction of dispersed generation into distribution networks has significant impact on the different aspects of their modeling, analysis, control, planning, economic exploitation etc. These distribution networks are no more passive systems and they are much more complicated in comparison with the systems without dispersed generation. For successful operation, they need some new and modified algorithms and methods for accurate and fast power flow and optimal power flow analyses. The aim of OPF applications is to achieve the most favourable technical conditions, minimization of costs and maximization of profit. It is important to determine priority objectives, which should be achieved by adjusting of different power system control variables, while satisfying all physical and operating constraints. All that can be achieved by the use of different techniques and methods for OPF.

1.3 Overview of the methods for load flow calculations in distribution networks

There are different methods for power flow calculations in distribution networks. Due to some specifics of distribution networks (radial network configuration or network with small number of loops, large ratio R/X and a uncertainty about the consumer's nodes load), it was needed to modify existing methods or to develop some new methods. Some of them are:

Iterative method for power flow calculations in radial networks

This method is based on the direct use of the both Kirchoff's laws. Starting information are network parameters, active and reactive power loads in consumer's nodes and the voltage in the source node. The network has to be radial (without loops). It is important to mark each node and branch in the specific way to gain better efficiency in calculations. Iterative procedure moves in two directions: upstream (calculation of branch currents), and downstream (calculation of node voltages) in the network.

Compensation method for networks with small number of loops

When some loops within the distribution network are present previous method cannot be used. The existing loops must be cut, and two new nodes will be created with two new current injections. In such a way the network becomes radial. This method is also iterative by its nature.

Modified Newton-Raphson method

This method is developed for solving power flow problems without the dimension reduction and it is very robust and effective. Advantages of this method are:

- Method is of Newton's type and it should be developed for other applications, as for state estimation procedures for example,
- Jacoby matrix is in the form UDU^T and shouldn't be formed explicitly.

Node voltage method

This is the modification of the iterative method for radial networks calculations. Main difference between them is in direct calculation of the voltage magnitudes and second one is that only powers are used in calculation, not currents. Method is based on the ordinary voltage drop equations when the voltage at the beginning and the power at the end of the line are known.

Fuzzy methods

These methods start with the fact that consumption loads are not exactly known, and that they can be considered as fuzzy numbers.

1.4 Formulation of the optimal power flow problem

The main features of all OPF problems are: huge dimensions (especially in distribution networks with thousands of variables), large number of non-linear equality constraints (power flow equations), the fact that relatively few inequality constraints are binding at the optimal solution and the objective function may be highly non-linear and non-separable.

There is a large number of different optimization methods for solving OPF problems, each with its own mathematical algorithm. Some of them employ linear programming techniques and other non-linear programming methods. The necessary conditions for the existence of optimal solution **x*** are that all partial derivatives of objective function with respect to control variables are equal to zero in that point. Then we call **x*** stationary point and it is point of minimum, maximum or bend point.

The problem of optimal power flow can be generally defined as a non-linear optimization problem. Common form of an optimization problem is to minimize the objective function:

$$\mathbf{F}(\mathbf{x}, \mathbf{u})$$

subject to the equality constraints:

$$\mathbf{g}(\mathbf{x}, \mathbf{u}) = 0$$

and subject to the inequality constraints:

$$\mathbf{h}(\mathbf{x}, \mathbf{u}) \geq 0$$

where **x** is a vector of dependent variables (state variables) and **u** is a vector of independent variables (control variables).

There are four intrinsic parts which define an OPF problem in general:

1. An objective function related to the analyzed problem that have to be minimized (total cost of generation for example),
2. A set of equality and inequality constraints which represent physical and operational constraints that have to be satisfied,
3. A set of independent (control) variables which may be adjusted in order to minimize the objective function and to enforce constraints,
4. A set of dependent (state) variables which may be determined from a network solution, when the control variables are known.

Generally, starting assumption for application of nonlinear method for the OPF calculations is that the objective function and constraints are non-linear. There is a series of methods based on the non-linear programming and the most frequently used are:

- *Kuhn-Tucker's technique of optimization,*
- *Techniques of optimization with penalty functions,*
- *Gradient methods,*
- *Newton's type method,*
- *Lagrange multipliers methods, ...*

Methods based on the linear programming enable to find solution very rapidly and reliably without a lot demand for computer time. Although OPF is non-linear problem in general, it can be solved very successfully with the methods of linear programming. It is especially obvious by use of the successive linear programming techniques. Method of linear programming is very effective in calculations of OPF in the P-δ contour, but in Q-U contour there is a problem of successful linearization, because of the sensitivity of reactive variables and methods are limited. The Linear Programming and the Newton method have emerged as the dominant optimization methods for solving OPF problems.

1.4.1 Objective functions

The objective function is a scalar function of the variables of the specified problem. The choice of the appropriate objective function mainly depends on what is a problem which have to be solved. Some criteria for creating an objective function and some general objectives in the optimization calculations are:

- minimization of the active & reactive power losses,
- optimization of the voltage profiles,
- minimization of the generation fuel costs,
- minimization of the system energy costs,
- maximization of the profit,
- maximization of the system performance,
- optimization of the power exchange with other systems,
- maximization of the voltage & flow security indices,
- control generator's MW & MVAR settings within the specified limits,
- control voltage regulators (transformer tap positions) etc.

1.4.2 Equality and inequality constraints

Generally, equality constraints in an OPF calculation include all the real and reactive power flow equations which have to be satisfied in any power flow analysis. There are the other equality constraints that may be also important. If a feasible OPF solution is achieved then every equality constraint must be satisfied exactly.

Inequality constraint is upper or lower bound on the value of an OPF variable or function. All the control variables and many of the state variables have lower and upper bounds. For example, typical inequality constraints are:

- bus voltages,
- branch flow (amps or MVA),
- voltage phase angle difference between two buses,
- transformer tap position,
- generating unit injections (MW and MVAr) ...

1.4.3 Control and state variables

Control variables can be directly adjusted by different physical devices which can change the operating state of the power system. Their settings may be changed independently and this is in contrast to the state variables which are determined by solving the power flow equations when the control variables are already known. The main set of state variables are the bus voltage magnitudes and phase angles. The performance of the entire power system network is completely determined by the control and state variables.

1.5 Illustrative example

This is an example of the small distribution medium voltage (10kV) network configuration with the dispersed generating units. OPF computer calculation has been done by the use of

MATLAB software package. Algorithm is based on the non-linear Newton's method for OPF calculation. This is a simple calculation intended mainly to show benefits of the OPF calculations in systems with dispersed generation. The method and algorithm of the calculations will be presented shortly.

The goal of optimization: MINIMIZATION OF REAL POWER LOSSES

Objective function: $\sum_{k=1}^{N} P_{Gk} - \sum_{k=1}^{N} P_{Pk}$

Subject to: - power flow equations as equality constraints

$$P_k = U_k \sum_{m=1}^{N} U_m [G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m)] - P_{Gk} + P_{Pk} = 0$$

$$Q_k = U_k \sum_{m=1}^{N} U_m [G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m)] - Q_{Gk} + Q_{Pk} = 0$$

- node voltage limits as inequality constraints

$$U_i - U_{i\max} \le 0$$
$$U_{i\min} - U_i \le 0$$

Lagrange function L(z) is defined as the sum of the next terms:

$\sum_{k=1}^{N} P_{Gk} - \sum_{k=1}^{N} P_{Pk}$ - objective function which should be optimized,

$\lambda_{Pk} P_k$
$\lambda_{Qk} Q_k$ } equality constraints,

$k(U_i - U_{i\max})^2$
$k(U_{i\min} - U_i)^2$ } penalty functions (included only if the appropriate constraint is active),

$\lambda_{Uih}(U_i - U_{i\max})$
$\lambda_{Uil}(U_{i\min} - U_i)$ } inequality constraints (included only if the appropriate constraint is active).

Algorithm of the calculations is shown in the Figure 5.1:

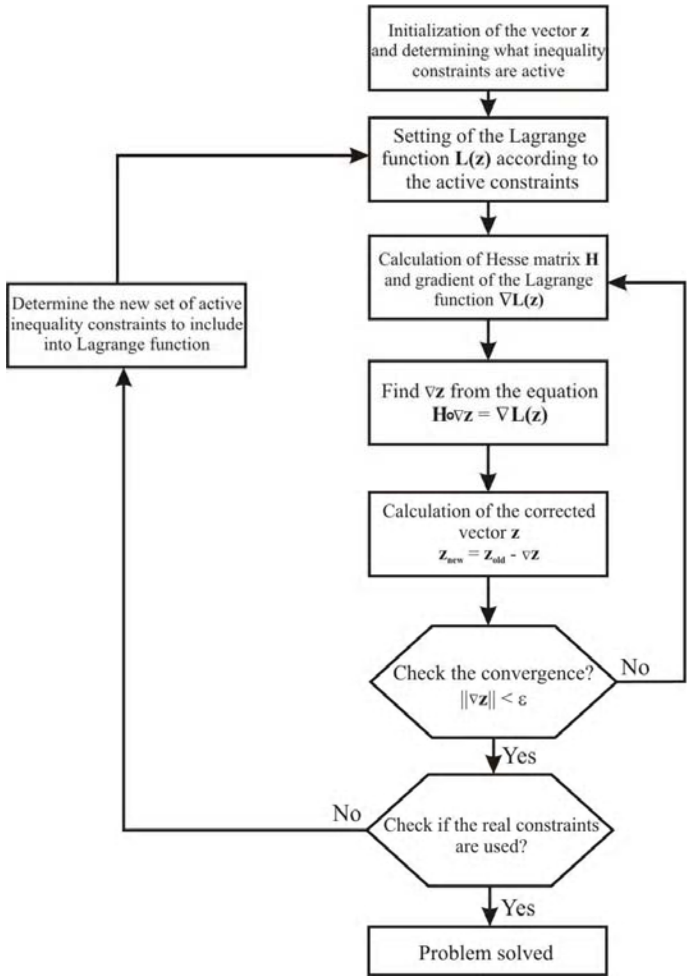

Figure 5.1. Illustration of the algorithm for Newton OPF calculation

Network parameters are taken from practical distribution network example and values of the node consumption powers (marked with green arrows on the figure bellow) are taken arbitrarily. There is a possibility to model each node consumption as self-regulatory with the change in voltage magnitudes (factors K_{PU} and K_{QU} in the input file). Every branch is modeled by the line impedances which have to be put in the input file. If some part of network has different voltage level then every parameter has to be presented at its own voltage level and program has the procedure for recalculations of all the data at the same voltage level (generally it is the rated voltage of the source node).

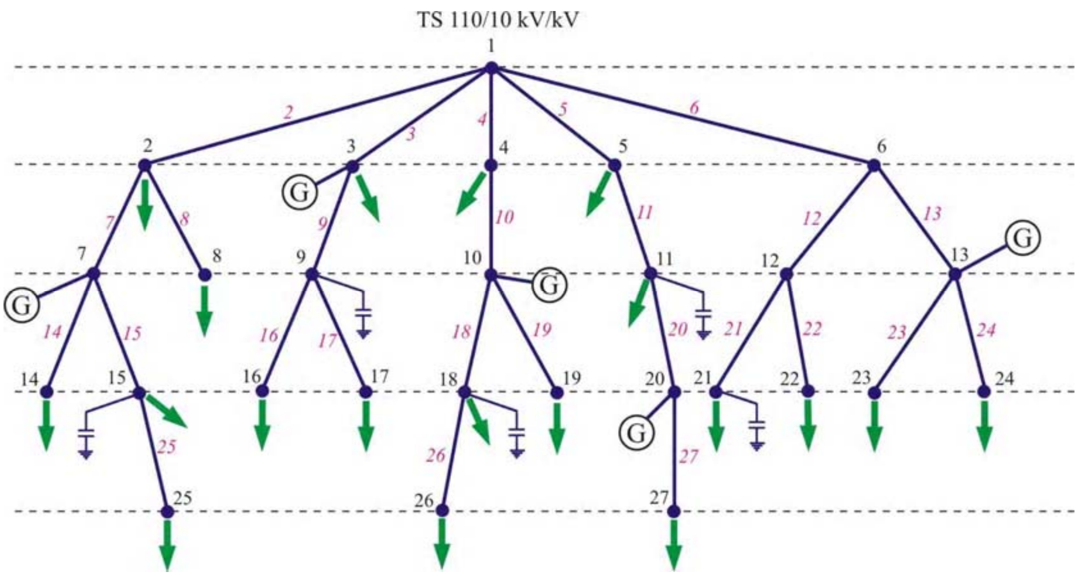

Figure 5.2. Example of the distribution network with dispersed generation

As the result of calculations in this example the reduction of real power losses and improved voltage profile will be achieved. The assumption is the worst case scenario from the point of view of total losses, when all loads are maximal (and because of that power losses are maximal also). Another possibility is to create different load schedules and to apply them in calculations. It is important to mention that results achieved in this example are not of general value. Very different results would be achieved in some other examples with different scenarios and sometimes it is not possible to get the optimal solution so easy. It is a challenging problem for the further work.

- Case 1: Distribution network without dispersed generation (General LF calculation)

Total real power losses: 0.424 MW

Real and reactive power generations and voltage profiles:

Node	Real power generation (MW)	Reactive power generation (MVAr)	Node voltage (p.u.)
1	8.564	3.3384	1.05
2	0	0	1.0234
3	0	0	0.9408
4	0	0	1.0009

5	0	0	1.0287
6	0	0	1.0453
7	0	0	1.0193
8	0	0	1.0213
9	0	0	0.91946
10	0	0	0.99752
11	0	0	1.0155
12	0	0	1.0442
13	0	0	1.0434
14	0	0	1.0174
15	0	0	1.0175
16	0	0	0.90897
17	0	0	0.90891
18	0	0	0.98918
19	0	0	0.99002
20	0	0	1.0063
21	0	0	1.0439
22	0	0	1.0434
23	0	0	1.0424
24	0	0	1.0425
25	0	0	1.0168
26	0	0	0.98469
27	0	0	0.99867

Table 5.1. Results of the calculation in case 1

Minimal voltage: 0.90891 p.u.

- Case 2: Distribution network with dispersed generation (all generators are included in optimization) (Optimal power flow calculation)

Total real power losses: 0.055024 MW

Real and reactive power generations and voltage profiles:

Node	Real power generation (MW)	Reactive power generation (MVAr)	Node voltage (p.u.)
1	1.6925	0.65694	1.05
2	0	0	1.0424
3	2.1669	0.79204	1.05
4	0	0	1.0469
5	0	0	1.0386
6	0	0	1.0493
7	1.9605	0.80086	1.05
8	0	0	1.0404
9	0	0	1.0323
10	1.1639	0.37056	1.05
11	0	0	1.0396
12	0	0	1.0482
13	0.58099	0.19541	1.05
14	0	0	1.0481
15	0	0	1.0483
16	0	0	1.023
17	0	0	1.0229
18	0	0	1.0425
19	0	0	1.0429
20	0.63031	0.13809	1.05
21	0	0	1.0479
22	0	0	1.0475
23	0	0	1.0491
24	0	0	1.0491
25	0	0	1.0476
26	0	0	1.0382
27	0	0	1.0427

Table 5.2. Results of the calculation in case 2

Minimal voltage: 1.0229 p.u.

- Case 3: Distribution network with dispersed generation (generator at the node 10 and the main injection in source node 1 are included in optimization and other generators have predefined (constant) real and reactive injections)

Total real power losses: 0.0759 MW

Real and reactive power generations and voltage profile:

Node	Real power generation (MW)	Reactive power generation (MVAr)	Node voltage (p.u.)
1	3.052	1.0659	1.05
2	0	0	1.0336
3	1.8	0.6	1.0316
4	0	0	1.0469
5	0	0	1.037
6	0	0	1.0504
7	1	0.5	1.0358
8	0	0	1.0315
9	0	0	1.0134
10	1.1639	0.37056	1.05
11	0	0	1.0356
12	0	0	1.0493
13	0.7	0.3	1.051
14	0	0	1.0339
15	0	0	1.0341
16	0	0	1.0039
17	0	0	1.0038
18	0	0	1.0425
19	0	0	1.0429
20	0.5	0.15	1.0428
21	0	0	1.049
22	0	0	1.0485
23	0	0	1.0504
24	0	0	1.0506
25	0	0	1.0334
26	0	0	1.0382

27	0	0	1.0354

Table 5.3. Results of the calculation in case 3

Minimal voltage: 1.0038 p.u.

It is obvious that differences between these three cases are enormous. Power losses in case 2, with the optimal dispersed generation are only about 13% of the losses in case 1 without dispersed generator included. There are also differences between cases 2 and 3. They are presented to show the contribution of generating units to optimization. In case 3 injected generation powers are not fully optimized and the losses are greater by 38%. Voltage profiles are also improved in the system with optimally dispersed generating capacities. This fact is more obvious from the practical experience, because the generating units are much closer to the consumption nodes.

1.5.1 Further work

Further work has to include some additional aspects for the optimal planning and operation of the dispersed generation and general improvement of applied optimization methods and algorithms. For instance, it is important to have in mind installation of generating units with production stochastic nature of energy and specifics of their operation (errors of prediction...). Also, optimal reactive power compensation could be implemented into the integrated OPF calculations. One of the assumptions in the presented example has been the location of the dispersed generating units. The provided calculation doesn’t include possibility to optimize location for installing future generating capacities and this could be one of the future research challenges. The main operational aspect is the implementation and control of the relay protection system (general fault analysis) and security analysis in such optimized networks.

1.6 Conclusion

There are many promising results in the OPF applications presented in this contribution.. The next question is how to practically implement them into some existing or new distribution networks with distributed generation. Significant reductions of losses and costs could be achieved by the optimal operation of the dispersed generating capacities. The reduction of losses is indirectly achieved in the transmission network also. These are some of the benefits due to the introduction of the dispersed generation into the existing power system.

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2 Optimal configuration of power system

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2.1 Introduction

Reorganization of the electricity sector, as well as deregulation and opening of the energy market created favourable conditions for development of small and average size production units, connected to the electric networks in a dispersed manner.

Usually, the distributed generators are used to produce locally, in consumption areas, relatively reduced amounts of power. The main differences with respect to the classical power plants (thermal, nuclear, and hydro) are related to the location and the installed capacity. Distributed generators of small size are generally connected in medium and low voltage distribution networks. They are embedded in the distribution networks. Thus, this kind of electricity generation is considered as: *embedded generation* or *distributed generation* or *dispersed generation*.

Distributed generation doesn't only constitute a reserve for electricity supply from transmission networks, but can be an alternative for this.

Introduction of distributed generation can have notable impacts on operating of distribution electric networks. The first step in any study consists in power flow calculation. Information obtained at this step are used for establish the means to optimise operating of electric networks, in order to obtain *Optimal Power Flow*. Objectives of optimisation process can follow:

- power losses minimization;
- coordination of regulating devices to optimise the voltage level;
- reduction of charge on electric lines and transformers;
- improvement of reliability supply of consumers.

Possibilities available to obtain Optimal Power Flow in a distribution electric network, with dispersed generators, are:

- regulating in charges of electric transformers;
- introduction of FACTS devices;
- modification of specified voltage of distributed generators;
- use of condenser;
- reconfiguration of distribution electric network;
- optimal location of distributed generators.

In the next, we study two aspects: load flow calculation and reconfiguration of distribution electric network with embedded generation.

2.2 Load flow calculation of radial electric networks

The radial configurations are specific to the distribution electric networks of medium and low voltage. These networks, especially the urban ones, can be strongly meshed, but, for technical and economical reasons, under normal conditions they operate radially. During short periods of time, these networks can operate in meshed configuration, especially when usual manoeuvres are done for configuration changes.

2.2.1 Particularities of the radial electric networks

The radial electric networks have some particularities, which make possible the use of some appropriate analysing methods of their operation, among which the load flow calculation can be mentioned.

The main particularity of the radial electric networks is related to the power (current) flow through branches. Assuming that within a radial network there are no local generators (distributed generation), the network is supplied from only one power injection point, called *source node*. Under these conditions, the power flow through network branches has a well-determined character, the flow being unidirectional in any natural operating state. In conclusion, in a radial network, any node *k* called *derivation* (*parent*) *node*, except the source node, receives electrical energy from only one node, called *up stream node*, through only one branch called *ingoing branch* and can transmit electrical energy to one or more *next nodes*, or to none of them, case in which the node *k* is called *end node* (Fig. 1).

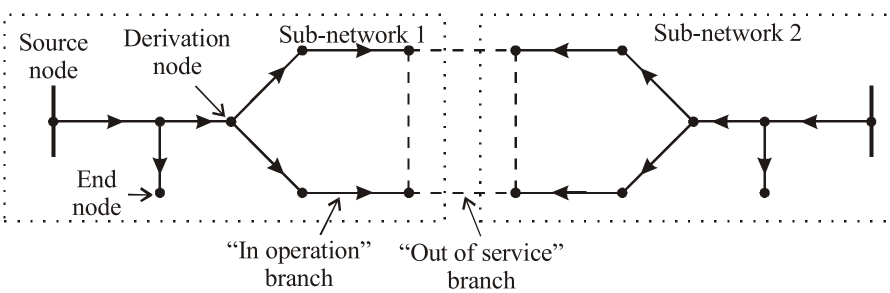

Figure 1: Notations used for distribution networks with meshed topology.

When a meshed network is subjected to radial operation (the case of distribution networks), the network opening is done in a well-determined number of points, obtaining one or more distinct radial sub-networks. Every sub-network consists of a source node and one or more load nodes, including also the derivation nodes, which may have no consumption.

The following assumptions are considered for the modelling of the electric networks elements [Ere00]:

- the three phase voltages form a positive-sequence symmetrical system;
- the currents form a balanced three-phase system;
- the network parameters are homogeneous, constant in time and independent of the supply voltage or currents;
- the network operates under steady state conditions.

Under these conditions, the positive-sequence one-line diagram is used for the load flow calculation. The electric lines (overhead and underground cables) can be represented by equivalent Π circuits with lumped parameters. Taking into account the unidirectional character of the power flows, the transformers can be represented by equivalent Γ circuit with transformer operator.

In the absence of distributed generation, for the load flow calculation of radial electric networks, only two of the three types of nodes existing in complex meshed networks are considered:

- *load nodes*, modelled through complex powers, obtained by combining three components [Ber74]:

  $$\underline{S} = \left(P_c + jQ_c\right) + \sqrt{3}\left(I_{ac} + jI_{rc}\right)U + \left(G_c + jB_c\right)U^2 \qquad (1)$$

  where: P_c and Q_c represents the components of a constant complex power, I_{ac} and I_{rc} are the components of a constant complex current, G_c and B_c are the components of a constant admittance, and *U* is the phase-to-phase voltage magnitude of the node;
- *the slack node*, representing the point of power injection into the radial network (the source node), where the specified quantities are the voltage magnitude and phase angle.

2.3 Backward/forward method

In the case of a radial (arborescent) electric network, with *n* nodes and *l* branches and only one injection node, the number of closed loops (independent cycles) is equal to zero, all branches being of tree type. Under these conditions $l - n + 1 = 0$, which leads to $l = n - 1$. The unknown steady state quantities of this network are: the voltages of the $n-1$ load nodes and the currents (powers) flowing through the $l = n - 1$ branches. Therefore, there are $2\left(n-1\right)$ unknown quantities, whose determination requires an equal number of equations. By applying the Kirchhoff's current law in the $n-1$ load nodes, considered as being independent, the currents flowing through branches can be obtained. The Kirchhoff's voltage law cannot be applied because $l - n + 1 = 0$. Instead, by applying Ohm's law on the $l = n - 1$ tree branches, the voltage drops at their ends can be obtained. Considering the voltage at the source node as reference, and using the voltage drop on network branches, the voltages at the load nodes can be calculated.

Based on the previous issues, the load flow calculation in radial electric networks can be performed using a specific method, known in literature as the *backward/forward sweep* [Chi90]. Basically, this method consists of two steps:

- Backward sweep, where, starting from the end nodes and going toward the source node S, using the Kirchhoff's current law, the current at each load node as well as the current flowing through its ingoing branch are calculated (Fig. 2,a);
- Forward sweep, where, starting in the opposite direction, from the source node S (whose constant voltage is taken as reference) and going toward the end nodes, using the Ohm's law, the voltage drop on each branch as well as the voltage at each load node are calculated (Fig. 2,b).

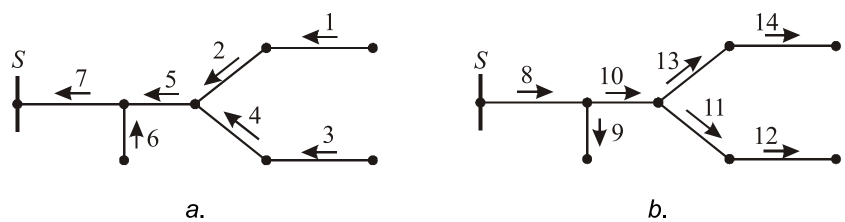

Figure 2: The steps of the load flow calculation by means of the backward/forward sweep: *a*. calculation of the currents through branches; *b*. calculation of the nodal voltages.

To understand this method the following specifications are to be mentioned:

1. When the electric network consists of more arborescent sub-networks, the backward/forward algorithm is independently applied for each sub-network, considering its source node as reference;
2. The load flow calculation in radial electric networks can be also performed by means of the nodal voltages method. Solving the equations, having the form $[\underline{Y}_{nn}][\underline{U}_n]=[\underline{I}_n]$, for the linear model, or $[\underline{Y}_{nn}][\underline{U}_n]=\left[\underline{S}_n^*/\underline{U}_n^*\right]$ for the non-linear model, the voltages of the independent nodes are obtained, and finally the powers (currents) flowing through branches are calculated. Using the backward/forward sweep, the unknown quantities are simultaneous obtained after performing the two steps.

The load flow solution, by the backward/forward sweep, for the linear network model (the loads represented through constant currents, the lines and transformers modelled through series impedances) is obtained processing only once the two steps. In the case of the non-linear model of the network (the loads represented in the form given in (1), the electric lines modelled by equivalent Π circuits, and the power transformers by Γ circuits), the load flow solution is obtained by iterative calculations. The convergence criterion consists in comparing the modulus of the complex power at the source node or the voltage magnitude at the load nodes between two successive iterations.

2.3.1 Backward/forward sweep adaptation for the case of distributed generation

Distributed generators (*DGs*) can generate active power and sometimes can generate or consume reactive power. They can have the possibility to maintain the nodal voltage at a set value by means of an automatic voltage regulator, controlling reactive power. The *DGs* capable to vary their output active power can contribute to the frequency control into the power system. Taking into account these considerations, the nodes to which *DGs* are connected can be classified in:

- PQ nodes, to which the specified quantities are the generated active P_g^{sp} and reactive Q_g^{sp} (capacitive or inductive) powers, and the unknown quantities are the components of the complex voltage $\underline{U}$;
- PU nodes, to which the specified quantities are the generated active power P_g^{sp} and voltage magnitude U^{sp}, and the unknown quantities are the generated reactive power Q_g and the voltage phase θ;
- Uθ nodes, to which the specified quantities are the components of the complex voltage $\underline{U}^{sp}$ (magnitude U^{sp} and phase θ^{sp}), and the unknown quantities are the generated active P_g and reactive Q_g powers.

DGs alter unidirectional power flow in distributed networks. In this situation, backward/forward sweep cannot be applied for load flow calculation, without some specifications and adaptations. In the case where *PQ* nodes are used to model *DGs*, the specified quantities P_g^{sp} and Q_g^{sp} are considered as being components of a constant complex power with negative sign $\underline{S} = -\left(P_g^{sp} + jQ_g^{sp}\right)$. For the *PU* and *U*$\theta$ model nodes the backward/forward sweep, presented above, cannot be applied. This inconvenience is due to the fact that for these types of nodes, one or both components of the voltage are specified, which is not appropriate to the backward/forward sweep algorithm where the voltage components are specified only at the source node. Starting from the voltage of this node, chosen as reference, the voltages of the others nodes are calculated in terms of the voltage drops on the line sections. However, in order to apply the backward/forward sweep algorithm for the *PU* and *U*θ nodes, some adaptations are required, which are based on the decoupling of the four state quantities, i.e. the interdependences *P* – θ and *Q* – *U*, respectively. These adaptations are presented below.

2.3.1.1 Modelling of PU type nodes

As previously explained, the *PU* nodes are characterized by the specification of the generated active power P_g^{sp} and the voltage magnitude U^{sp}. In the load flow calculation process, by backward/forward sweep, these nodes are assimilated with *PQ* type nodes. The specified active generated power P_g^{sp} and reactive generated power Q_g are considered with negative sign. To maintain the nodal voltage at the specified value U^{sp}, the interdependence relationship between the voltage and the reactive power is used, i.e. appropriate change of the reactive power Q_g, between the limits Q_g^{min} and Q_g^{max}, is adopted. Depending on the model used for the nodes, two situations could be encountered:

- in the case of modelling by constant currents, the reactive component of the complex current I_{gr} is determined based on the condition that the nodal voltage should be equal to the specified value U^{sp} [Aug04]; for the backward/forward sweep algorithm, the nodal current is considered as $\underline{I} = -\left(I_{ga}^{sp} + jI_{gr}\right)$, where I_{ga}^{sp} represents the specified value of the generated active current;
- in the case of modelling by constant powers, the generated reactive power Q_g is determined based on the condition that the nodal voltage should be equal to the specified value U^{sp}; in the backward/forward sweep algorithm, the nodal power is considered as $\underline{S} = -\left(P_g^{sp} + jQ_g\right)$.

The use of the second model for the load modelling requires a non-linear mathematical model for load flow calculation. Like the global load flow calculation methods, for the backward/forward sweep algorithm, the calculation of the generated reactive power and its comparison with the capability limits at every step is performed.

For better understanding of the *modified backward/forward method* applied when *PU* nodes are present within the network, a radial electric network with only one *DG* located at the node *k* is considered. The calculation steps are presented in the following:

1. Initialise the iterative step $p = 0$ and establish the initial value of the reactive power $Q_{g,k}^{(0)} = 0$, so that $\underline{S}_k^{(0)} = P_{c,k} + jQ_{c,k} - \left(P_{g,k}^{sp} + jQ_{g,k}^{(0)}\right)$, where $P_{c,k}$ and $Q_{c,k}$ are the components of a complex constant power consumed at the node *k*, and $P_{g,k}^{sp}$ is the specified active power generated at the node *k*;
2. Update the iterative step $p = p + 1$;
3. Perform load flow calculation by backward/forward sweep;
4. If $\left|U_k^{(p)} - U_k^{sp}\right| < \varepsilon_U$ the iterative process stops;
5. Calculate the generated reactive power $Q_{g,k}^{calc}$ necessary to achieve the specified voltage U_k^{sp} at the node *k*. Establish the new value of the generated reactive power $Q_{g,k}^{(p)}$ in terms of its value with respect to the capability limits $Q_{g,k}^{\min}$ and $Q_{g,k}^{\max}$:

$$\begin{cases} Q_{g,k}^{(p)} = Q_{g,k}^{calc} \text{ if } Q_{g,k}^{\min} \le Q_{g,k}^{calc} \le Q_{g,k}^{\max} \\ Q_{g,k}^{(p)} = Q_{g,k}^{\min} \text{ if } Q_{g,k}^{calc} < Q_{g,k}^{\min} \\ Q_{g,k}^{(p)} = Q_{g,k}^{\max} \text{ if } Q_{g,k}^{calc} > Q_{g,k}^{\max} \end{cases} \quad (2)$$

6. Calculate the new value of the complex power at the node *k* by formula

$\underline{S}_k^{(p)} = P_{c,k} + jQ_{c,k} - \left(P_{g,k}^{sp} + jQ_{g,k}^{(p)}\right)$ and go to step 2.

There are several possibilities to calculate the value of the generated reactive power $Q_{g,k}^{calc}$ necessary to achieve the specified voltage U_k^{sp} at the node *k*, i.e.:

(i) using the voltage sensitivity to the reactive power variation $\partial U_k / \partial Q_k$, obtained from the sensitivity matrix:

$$Q_{g,k}^{calc} = Q_{g,k}^{(p-1)} + \frac{\left(U_k^{(p)} - U_k^{sp}\right)}{\left(\frac{\partial U_k}{\partial Q_k}\right)^{(p)}} \tag{3}$$

(ii) using the secant method [Shi88]:

$$Q_{g,k}^{calc} = Q_{g,k}^{(p-1)} + \frac{Q_{g,k}^{(p-1)} - Q_{g,k}^{(p-2)}}{U_k^{(p-1)} - U_k^{(p-2)}} \left(U_k^{(p)} - U_k^{sp}\right) \tag{4}$$

(iii) using a calculation formula based on the generated reactive current $I_{gr,k}$, calculated by considering the constant currents model for the load:

$$Q_{g,k}^{nec} = \sqrt{3} U_k^{(p-1)} I_{gr,k} \tag{5}$$

2.3.1.2 Modelling of $U\theta$ type nodes

The $U\theta$ nodes are characterized by the specification of the components of the complex voltage $\underline{U}^{sp}$ (magnitude U^{sp} and phase θ^{sp}). In the load flow calculation process, by backward/forward sweep, these nodes are assimilated with *PQ* type nodes. The active and reactive generated powers are equal to the specified values P_g and Q_g, considered with negative sign. To maintain the complex nodal voltage at the specified value $\underline{U}^{sp}$, the interdependence relationship between the voltage magnitude *U* and the reactive power *Q* and respective between voltage phase θ and the active power *P* are used. Appropriate changes of the generated active power P_g and reactive power Q_g are adopted. Depending on the model used for the nodes, two situations could be encountered:

- in the case of *modelling by constant currents*, the components of the complex current $\underline{I}_g = I_{ga} + jI_{gr}$ are determined based on the condition that the nodal voltage should be equal to the specified value $\underline{U}^{sp}$ [Aug04a]; for the backward/forward sweep algorithm, the nodal current is considered as $\underline{I} = -\left(I_{ga} + jI_{gr}\right)$;
- in the case of *modelling by constant powers*, the generated active power P_g and reactive power Q_g are determined based on the condition that the complex nodal

voltage should be equal to the specified value $\underline{U}^{sp}$; in the backward/forward sweep algorithm, the nodal power is considered as $\underline{S} = -\left(P_g + jQ_g\right)$.

The use of the second model for the load modelling requires, like for *PU* model, a non-linear mathematical model for load flow calculation. The difference relative to the *PU* model is that for *U*θ nodes there are no limits for generated powers. The calculation steps for the *modified backward/forward method*, applied when a *U*θ node is located at the *k* node of a radial electric network, are presented in the following:

1. Initialise the iterative step $p = 0$ and establish the initial value of the active and reactive power $P_{g,k}^{(0)} = Q_{g,k}^{(0)} = 0$, so that $\underline{S}_k^{(0)} = P_{c,k} + jQ_{c,k} - \left(P_{g,k}^{(0)} + jQ_{g,k}^{(0)}\right)$, where $P_{c,k}$ and $Q_{c,k}$ are the components of a complex constant power consumed at the node *k*;
2. Update the iterative step $p = p + 1$;
3. Perform load flow calculation by backward/forward sweep;
4. If $\left|U_k^{(p)} - U_k^{sp}\right| < \varepsilon_U$ and $\left|\theta_k^{(p)} - \theta_k^{sp}\right| < \varepsilon_\theta$ the iterative process stops;
5. Calculate the generated active power $P_{g,k}^{(p)}$ and reactive power $Q_{g,k}^{(p)}$ necessary to achieve the specified voltage $\underline{U}_k^{sp}$ at the node *k*.
6. Calculate the new value of the complex power at the node *k* by formula $\underline{S}_k^{(p)} = P_{c,k} + jQ_{c,k} - \left(P_{g,k}^{(p)} + jQ_{g,k}^{(p)}\right)$ and go to step 2.

There are several possibilities to calculate the value of the generated active power $P_{g,k}^{(p)}$ and reactive power $Q_{g,k}^{(p)}$ necessary to achieve the specified voltage $\underline{U}_k^{sp}$ at the node *k*, i.e.:

(i) using the sensitivity of magnitude and phase of voltage to the active and reactive power variation, to calculate the correction values for the components of complex power [Luo90]:

$$\begin{bmatrix} \dfrac{\partial U_k}{\partial P_k} & \dfrac{\partial U_k}{\partial Q_k} \\ \dfrac{\partial \theta_k}{\partial P_k} & \dfrac{\partial \theta_k}{\partial Q_k} \end{bmatrix} \begin{bmatrix} \Delta P_{k,g}^{(p)} \\ \Delta Q_{k,g}^{(p)} \end{bmatrix} = \begin{bmatrix} U_k^{(p-1)} - U_k^{imp} \\ \theta_k^{(p-1)} - \theta_k^{imp} \end{bmatrix} \tag{6}$$

and the new values for active and reactive generated power:

$$\begin{cases} P_{k,g}^{(p)} = P_{k,g}^{(p-1)} + \Delta P_{k,g}^{(p)} \\ Q_{k,g}^{(p)} = Q_{k,g}^{(p-1)} + \Delta Q_{k,g}^{(p)} \end{cases} \tag{7}$$

(ii) using a calculation formula based on the generated complex current $\underline{I}_{k,g} = I_{k,ga} + jI_{k,gr}$, calculated by considering the constant currents model for the load:

$$\begin{cases} P_{k,g}^{(p)} = \sqrt{3} U_k^{(p-1)} I_{k,ga} \\ Q_{k,g}^{(p)} = \sqrt{3} U_k^{(p-1)} I_{k,gr} \end{cases} \tag{8}$$

2.3.2 Advantages over the using of the backward/forward method

The backward/forward method used for steady-state calculation has some advantages comparing with the global methods based on using the nodal voltages method:

- For the linear model of electrical network, the number of the iterations is smaller than the number of the Seidel-Gauss and Newton-Raphson methods, and the volume of the calculations for every iteration is smaller too;
- It isn't necessary that we calculate the nodal admittances matrix;
- The introducing of reduced impedance elements (shunts) doesn't pose any problem over the method convergence.

2.3.3 Case study

The testing of the backward/forward method has been made on the rural distribution network from figure 3. This is a radial network composed by 47 nodes, having a main axis and some derivations. The network operates at nominal voltage of 20 kV and includes four *DGs* ($DG_1 \div DG_4$), which cover totally the power of all consumption nodes. The surplus of the locally generated power is injected in transmission network through the SOURCE node.

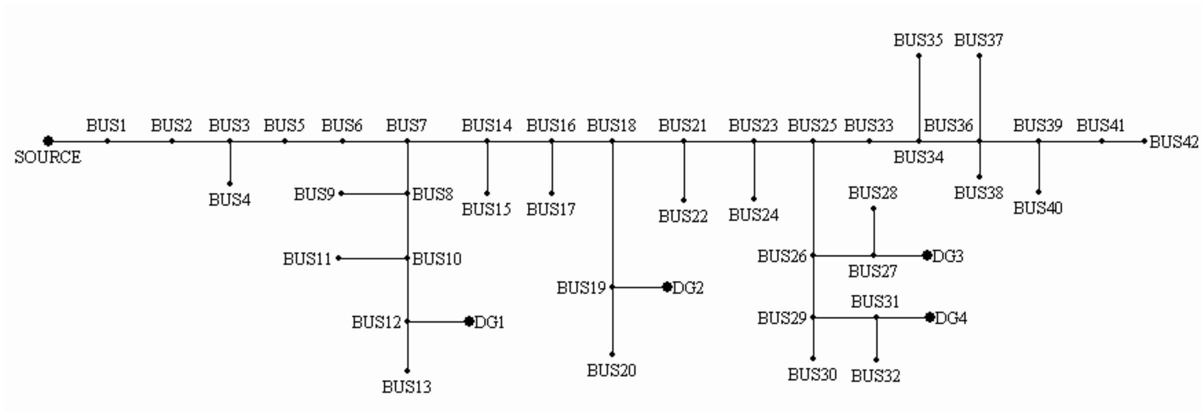

Figure 3: Rural distribution network.

For this network three operating regimes were considered:

- "Without DGs" in which DGs are considered in the state "out of service";
- "Asyn" in which DGs are equipped with asynchronous machines. PQ type nodes model DGs. The specified active power generated P_g^{sp} is equal to the rated active power. The specified reactive power generated Q_g^{sp} corresponds to the operating in inductive regime without compensation reactive power;
- "Syn" in which DGs are equipped with synchronous machines. PU type nodes model DGs. The specified active power generated P_g^{sp} is equal to the rated active power. The specified value for voltage magnitude was 5% greater than nominal voltage of electric network.

In Figure 4 is shown the voltage level for nodes situated on main axis of the network. The loads of line sections of the main axis are shown in Figure 5.

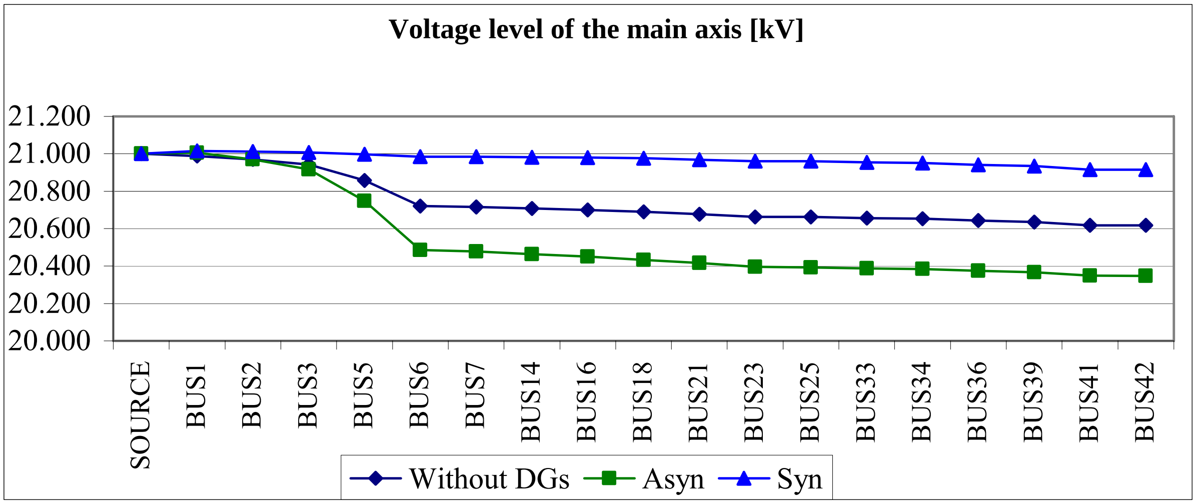

Figure 4: Voltage level at nodes of the main axis.

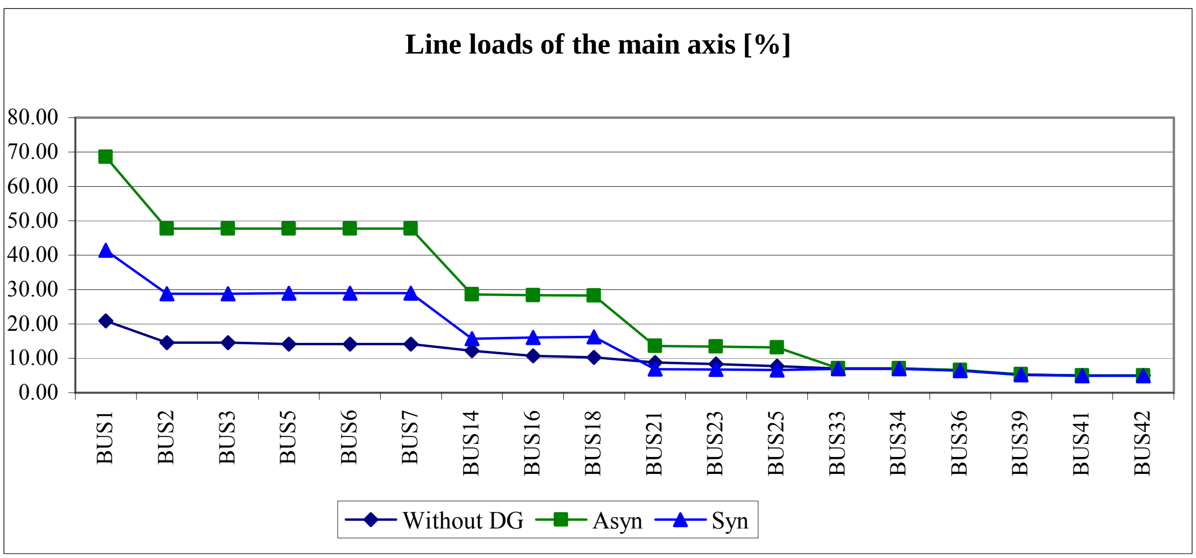

Figure 5: Loads on line sections of the main axis.

2.4 Reconfiguration of the distribution electric networks

Usually, the urban distribution electric networks consist of underground cables. These cables rise some problems concerning the repairing of insulation damages or braking of conductors. The time necessary to detect and repair the damages can be important, time in which many loads can remain not supplied. In order to cope with this inconvenient, a back-up supply is recommended, which implies the existence of at least two supply paths for each consumption point, from the same source or from different sources. In order to limit the number of loads affected by a short circuit emerging into the electric networks with such configurations, the networks are operated in radial configuration.

The rural distribution electric networks mainly consist of overhead electric lines. This type of lines doesn't present special problems in detecting and repairing the damages. In addition, the density of the loads supplied by these networks is much smaller than the one in urban networks. A reserve in the power supply of these loads is not economically justified, the structure of the rural distribution electric network being usually arborescent or radial. Although these networks have a meshed structure they are operated in radial configuration.

In practice, for short periods of time, the distribution electric networks can de operated in a meshed configuration, especially when reconfiguration manoeuvres are performed within the network.

2.4.1 Operating issues

Generally, by reconfiguration of a physical system is understood the modification of the operational connections that exist among its components, in order to improve the system operation as a whole or just a part of it, without modifying the characteristic parameters of the system components.

In the particular case of distribution electric networks, the reconfiguration aims at improving and optimising the operating state by changing only the topological state "*in operation*" / "*out of service*" of some electric lines. The network reconfiguration is possible only for meshed networks, for which the arborescent operation is recommended. For such configuration, the set of electric lines "in operation" and "out of service" have a well determined number of elements, the number of the electric lines "in operation" being equal to the number of load nodes. The elements of these two sets can be exchanged subject to the arborescent operation of the network. The advantage is the possibility of achieving the most suitable configuration in order to improve or optimise the operating state, in terms of the strategy of network configuration and of the electricity demand. For example, consider a simple meshed electric network, which supplies *n* loads (Fig. 6). The arborescent configuration allows us to achieve $n+1$ possible arborescent configurations in operation.

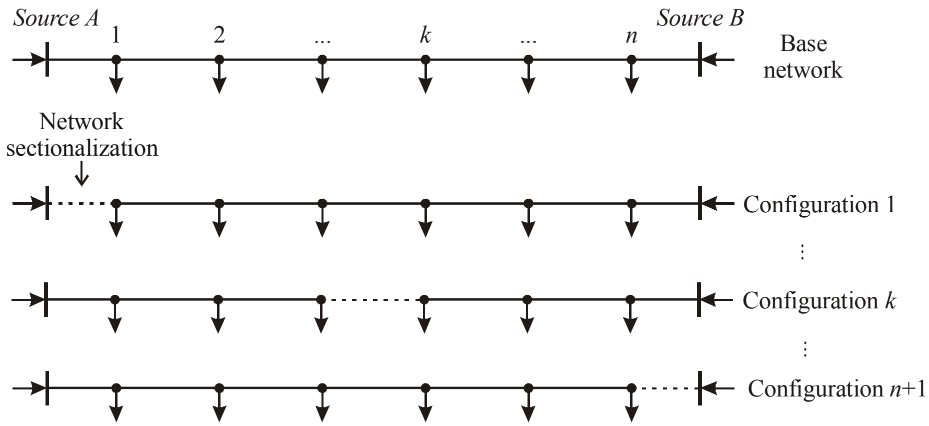

Figure 6: Possible arborescent configurations for a simple meshed electric network.

The reconfiguration process can be applied for all the possible operating conditions of a distribution electric network:

- *normal conditions*, characterized by the availability of all the network elements, the state quantities being within the admissible operating limits;
- *critical conditions*, characterized by the availability of all the network elements, with some of the state quantities being at the limit of normal operation (the thermal limit, the voltage stability limit, etc.);
- *emergency operation*, characterized by the unavailability of one or more elements of the network, due to operation under critical conditions on expanded period of time or to some accidental damages emerged from outside the network.

For the normal and critical conditions, finding the optimal configuration of an electric network actually implies network reconfiguration, but for the emergency operation the process becomes one of reconstruction. Usually, under normal conditions, the purpose is to reach an optimum in operation in order to minimize the active power losses and energy losses and to improve the security in supplying the loads. For the critical conditions the goal of the reconfiguration process is to restore the network normal operating state, by load reducing and balancing the lines load as well as by reducing the voltage drops and also by obtaining uniformity of the voltage level at the loads. For the emergency operation the goal is to supply as many as possible loads after the detection and isolation of the fault. In this case, the optimisation is of lower interest, more important being the restoration of the power supply of all loads in a time as short as possible and the reducing of the financial penalties for the electricity not supplied.

At least two arguments are supporting of the reconfiguration process:

- the operating state of the network can be improved by a reduced coordination effort, achieving considerable results. The advantages mainly consist in decreasing the active power losses and, in most cases, in decreasing the reactive power losses as well as the decreasing of the line load, the decreasing of the voltage drops and the improvement of the voltage level at loads. The effort done for network reconfiguration is related to the cost of the manoeuvres necessary to change the present configuration and, eventually, the cost of the electricity not supplied during these manoeuvres;

- a second aspect refers to the dynamics of the power energy demanded by the loads. The load curve can be significantly changed either for long or for shorter periods of time, causing the change of the load gravity centre and thus of the operating state of the network. Therefore, specific (normal) operating configurations can be defined for each period of time in terms of the season and the characteristics of the consumer activity during the week-days.

In addition of these arguments is the case of distribution networks with *DGs*. The presence of *DGs* can significantly change the power weight centre of consumption zones and implicitly operating regime of distribution networks. Applying reconfiguration process the operating regime can be optimised.

2.4.2 Mathematical model of the reconfiguration process

The reconfiguration process of a distribution electric network can be seen as an optimisation problem. To define the mathematic model, we start from the observation that to any electrical network, consisting of *n* nodes and *l* branches, a graph $G(\mathbf{X},\mathbf{A})$ can be assigned, where $\mathbf{X}$ is the set of nodes and $\mathbf{A}$ is the set of branches. To these sets, state or operational quantities can be also assigned, which characterize the operating state of the network.

Therefore, to the set $\mathbf{A}$ of the branches it can be assigned:

- the set $\mathbf{I}$ of state quantities, representing the branches currents;
- the set $\mathbf{C}$ of decision quantities, representing the topological states of the branches; for any branch *l* from the set $\mathbf{A}$, the topological state can be:
  - $c_l = 1$, if the branch *l* is "in operation";
  - $c_l = 0$, if the branch *l* is "out of service".

To the set $\mathbf{X}$ of the nodes, it can be assigned:

- the set $\mathbf{U}$ of state quantities representing the nodal voltages;
- the set $\mathbf{R}$ of quantities representing the reliability indices of the nodes.

Based on these notations, the mathematical model of the reconfiguration optimisation problem has the general form [Che92], [Tri01]:

$$\mathrm{OPTIM}\left[f\left(\mathbf{U},\mathbf{I},\mathbf{R},\mathbf{C}\right)\right] \tag{9}$$

subject to equality and inequality constraints:

$$\begin{gathered} g\left(\mathbf{U},\mathbf{I},\mathbf{R},\mathbf{C}\right)=0 \\ h\left(\mathbf{U},\mathbf{I},\mathbf{R},\mathbf{C}\right)>0 \end{gathered} \tag{10}$$

The criteria that can be used in the objective function for the electric distribution network reconfiguration problem are:

- real power losses decrease;
- decrease and balancing the branch load;
- voltage drops decrease;
- improve the safety in power supply of the loads;
- decrease the manoeuvres cost.

Analysing the criteria shown above, it can be seen that, in most of the cases, for the mathematic model solution, the main goal is the minimization of the objective function. There can be also situations when the goal is to find the maximum of the objective function.

In terms of the number of criteria taken into account, the objective function is of single-criterion type, when only one criterion is considered, or multi-criterion type, when two or more criteria are considered.

The constraints can be related to the network exploitation or operation:

- the network connectivity or the supply of all loads, constraint checked by applying the Kirchhoff's current law in all load nodes;
- the arborescent configuration of the network;
- the security in operation, which refers to branch load, voltage drops as well as nodal voltage level;
- the reliability level in the power supply of the loads;
- the possibility of the network branches to be subjected to manoeuvres;
- the maximum number admitted for manoeuvres to change the network operating configuration.

In order to identify the theoretical and practical possibilities for reconfiguration problem solution we start from some remarks regarding the mathematical model. In the case when the problem solution does not involve the voltage change at the source node, the size of the sets $\mathbf{U}$, $\mathbf{I}$ and $\mathbf{R}$ implicitly depend on the quantities of the set $\mathbf{C}$, so that the objective function can be written as:

$$\text{OPTIM}\left[f\left(\mathbf{U}(\mathbf{C}),\mathbf{I}(\mathbf{C}),\mathbf{R}(\mathbf{C})\right)\right] \tag{11}$$

Therefore, in solving the optimisation reconfiguration problem, the final goal is to explicitly determine the decision variables $c_l, l \in \mathbf{A}$. These are discrete binary variables, which can be equal to 1 or 0. Under these conditions, the mathematical model has the form of a general mathematical programming problem with discrete variables. Furthermore, for the previously discussed issues, the functions assigned to each criterion, as well as the ones that describe the constraints, have a convex character. Hereby, the mathematical model takes the form of a convex programming problem with discrete variables.

Out of the previous remarks, the conclusion that comes out is that a theoretical possibility to solve the mathematical model consists in the use of tools specific to the mathematical programming: linear programming, convex programming, dynamic programming, etc.

A modern and relatively new possibility in solving the reconfiguration optimisation problem is based on artificial intelligence techniques, such as decision trees, genetic algorithms, fuzzy logic, expert systems, Petri nets, etc.

A practical possibility to obtain the solution to the reconfiguration process consists in searching within the solutions' space, which is the set of all arborescent configurations that can be generated for an electric network with a meshed structure. The number of elements of the solutions space is directly influenced by the complexity and the geographical spread of the electric network.

Only a small part of the possible arborescent configurations of an electric network, that form the solutions' space, fulfil the inequality constraints, and they form what is called the set of allowed operating configurations. Because the optimum is related to various issues, the final configurations obtained after the reconfiguration process can be different. The goal of reconfiguration is to identify those optimal configurations, which fulfil all the technical and operational constraints.

The methods based on searching within the solutions' space, used for reconfiguration problem solution, can be systematic or heuristic.

In the frame of the *systematic methods* (*uninformed searching methods*) all the possible arborescent configurations of a distribution electric network are individually generated and analysed. The configuration corresponding to the optimal operation subjected to the main objective is further considered. As far as this principle is concerned, the systematic search methods are optimal methods, which ensure finding the global optimal solution. This is the main advantage of the systematic searching methods. Although there are only two possible values for each variable, it is rather difficult to apply this kind of methods for most of the distribution networks because of the very large number of arborescent configurations which have to be generated and analysed. This is the main disadvantage on the systematic methods.

The *heuristic methods* (*informed searching methods*) are used in order to decrease the number of configurations that should be analysed to achieve the reconfiguration solution. These methods use a number of observations that allow filtering for analysing only the intermediary configurations that lead to a final solution close to or even identical to the optimal global solution. The advantage consists in a considerable reduced computation time and effort to the detriment of the fact that they are not optimal.

The theoretical and practical possibilities of solving the reconfiguration optimisation problem are synthetically presented in Figure 7.

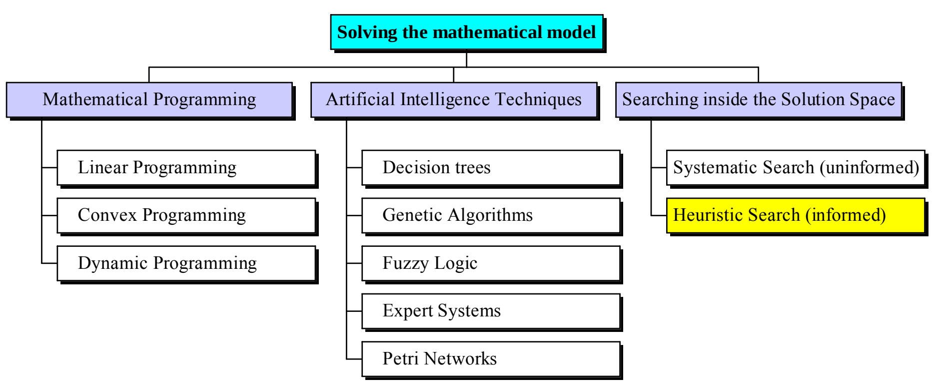

Figure 7: Possibilities of solving the reconfiguration problem.

2.4.3 Reconfiguration heuristic methods

The heuristic methods starts from an initial configuration, chosen based on specific requirements, and scan for improved configurations. If there is at least one improved configuration, the selection criterion replaces the actual configuration with the improved one. The procedure ends when no improved configuration can be found by applying the searching mechanism for the actual configuration. An improved configuration of the actual one is defined as being that configuration which leads to the evolution of the objective function value in the desired direction.

2.4.3.1 Reconfiguration strategies

The heuristic reconfiguration methods of the distribution electric networks are based on three strategies [Che92]:

- "*Constructive*" *strategy*, in which all the branches of the initial configuration are in "out of service" state. By successively transitions to the "in operation" state of some branches, the desired arborescent configuration is achieved (Fig. 8). Because each load node can be supplied by just one branch, the number of intermediary steps necessary to achieve the final configuration is equal to the number of the load nodes.

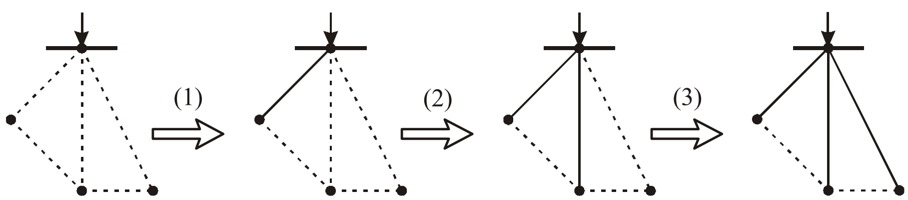

Figure 8: Principle of the "constructive" strategy.

- "*Destructive*" *strategy*, in which all branches of the initial configuration are "in operation" state. By successive transition to the "out of service" state of some branches the desired arborescent configuration is achieved (Fig. 9). The number of intermediary steps necessary to achieve the final configuration is equal to difference between the total number of branches and the number of the load nodes.

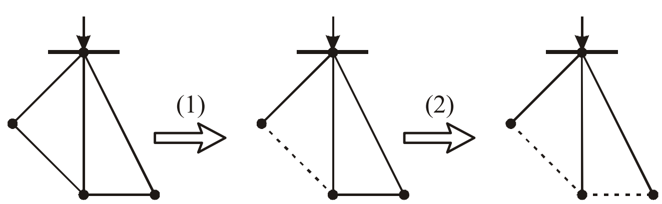

Figure 9: Principle of the "destructive" strategy.

- "*Branch exchange*" *strategy* starts from an initial arborescent configuration and preserves the arborescent character during the process. For the transition from one configuration to another, a branch is switched "in operation" and than another one, from the loop resulted from this manoeuvre, is switched "out of service" (Fig. 10). While for the previous strategies the number of intermediary steps necessary for achieving the final configuration is well defined, for this strategy the number of steps depends on many factors, out of which the most important are the searching manner of the substituting configuration and its selection criterion.

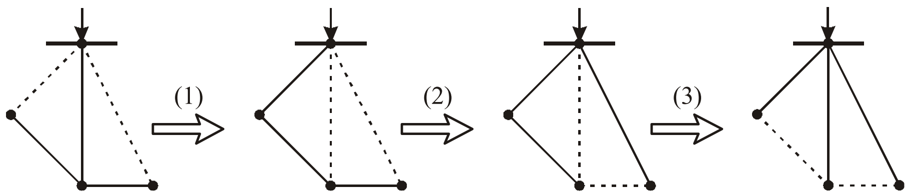

Figure 10: Principle of the "branch exchange" strategy.

2.4.3.2 Heuristic methods for active power losses reducing

Reducing the active power losses is the main objective of the reconfiguration process of the distribution electric networks operated under normal conditions. The improved configurations are strictly subjected to the inequality constraints, especially to those referring to line load, nodal voltage level and voltage drops.

"Power losses" include three components, namely:

- own technologic consumption;
- technical losses;
- commercial losses.

The reduction that can be achieved by reconfiguration is aimed at Joule losses that belong to own technologic consumption, the objective function of this criterion having the form:

$$MIN\left[\Delta P\right] = MIN\left[\sum_{l \in \mathbf{A}} R_l I_l^2 c_l\right] \tag{12}$$

where R_l is the impedance, I_l is the current and c_l the topological state of the branch l .

Minimization of the active power losses by reconfiguration requires, irrespective of the strategy employed, to start from an initial configuration and adopting some intermediary configurations to reach the final configuration. Theoretically, the analysis of the objective function while passing from one configuration to another is performed by load flow calculation and evaluating the total active power losses of the network. For the linear model of the network, the evaluation of the active power losses variation can be performed without load flow calculation. For this, we consider a radial electric network that supplies n loads, whose one-line diagram is illustrated in Figure 11. The loads are modelled by constant currents and the lines sections by series impedances.

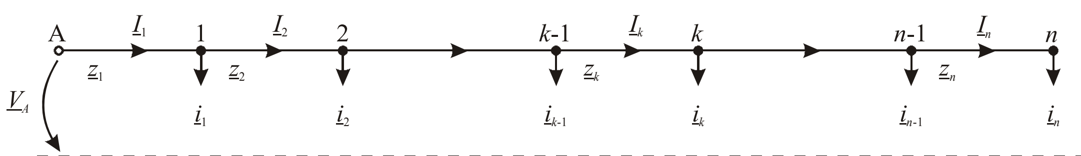

Figure 11: Radial electric network supplying *n* loads.

The latter equation expresses the active power losses variation in the network due to the change of current in node *k*, of the form $\Delta \underline{i}_k = \Delta i_{ka} + j\Delta i_{kr}$ [Cin88], [Tri98]:

$$\Delta(\Delta P) \overset{Not}{=} \delta P = 3\left[\left(\Delta i_{ka}^2 + \Delta i_{kr}^2\right)\sum_{i=1}^{k} r_i + 2\Delta i_{ka}\sum_{i=1}^{k} r_i I_{ia} + 2\Delta i_{kr}\sum_{i=1}^{k} r_i I_{ir}\right] \quad (13)$$

2.4.3.2.1 Branch exchange strategy

Consider a simple meshed electric network supplying *n* loads (Fig. 12,*a*). The initial radial configuration from which the "branch exchange" strategy starts is the one in which the splitting is done between the nodes *k* and $k+1$ (Fig. 12,*b*).

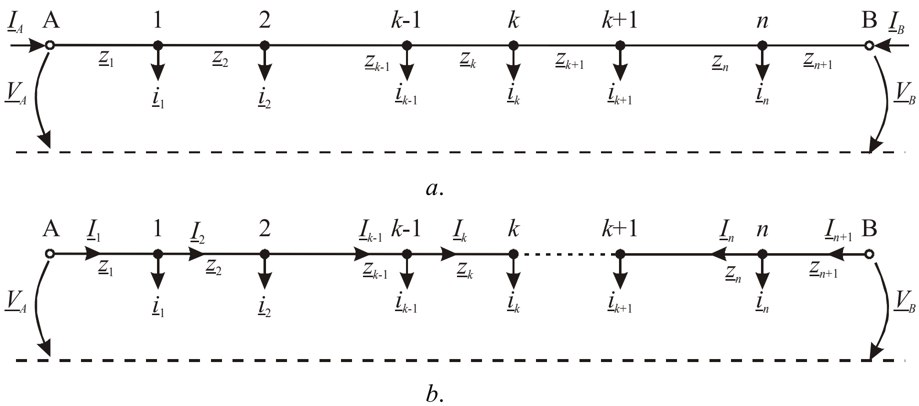

Figure 12: Simple distribution electric network:
a. meshed network; *b*. meshed electric network with radial operation.

- The *local load transfer* of one load or of a group of loads between two neighbouring feeders is performed by doing an elementary exchange for an "out of service" branch. The selection of this branch exchange is based on using the equation (13) to estimate the active power losses variation δP generated by the load transfer from one feeder to another. The condition for the load transfer is $\delta P < 0$. For the network shown in Figure 12,*b*, consider the transfer of the load from the node *k* located on the feeder supplied from node A to the feeder supplied from node B (Fig. 13).

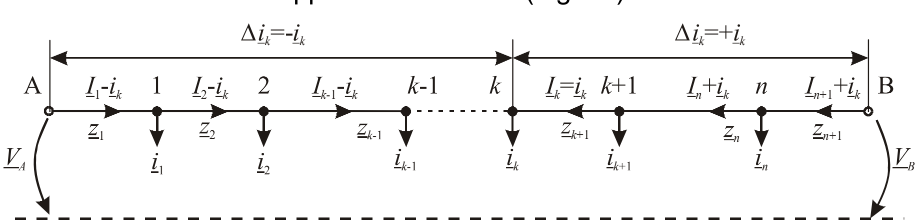

Figure 13: Simple meshed electric network after the transfer
of the node *k* from the feeder A to the feeder B.

After the load transfer the currents through the line sections between the nodes A and *k* will decrease with the value of $\underline{i}_k$, and the currents through the line sections between the nodes B and *k* will increase with the same value. By applying equation (13) for the mentioned line sections, for the current flows corresponding to the situation previous to the load transfer, and considering that $\Delta \underline{i}_k = \pm \underline{i}_k$, one obtains:

$$\begin{aligned} \delta P_{A,k} &= 3\left[i_k^2 \sum_{i=1}^{k} r_i - 2 i_{ka} \sum_{i=1}^{k} r_i I_{ia} - 2 i_{kr} \sum_{i=1}^{k} r_i I_{ir} \right] \\ \delta P_{B,k} &= 3\left[i_k^2 \sum_{i=k+1}^{n} r_i + 2 i_{ka} \sum_{i=k+1}^{n+1} r_i I_{ia} + 2 i_{kr} \sum_{i=k+1}^{n+1} r_i I_{ir} \right] \end{aligned} \tag{14}$$

By summing up the above relations, the active power losses variation, as a result of the transfer of the node *k* from the feeder A to the feeder B, is [Cin88]:

$$\delta P = 3\left[i_k^2 R_{AB} + 2 i_{ka} \left(\sum_{i=k+1}^{n+1} r_i I_{ia} - \sum_{i=1}^{k} r_i I_{ia} \right) + 2 i_{kr} \left(\sum_{i=k+1}^{n+1} r_i I_{ir} - \sum_{i=1}^{k} r_i I_{ir} \right) \right] \tag{15}$$

where R_{AB} is the resistance between nodes A and B.

- The *optimal currents pattern* represents the current flows through the branches of a simple meshed electric network for which the active power losses are minimised, in comparison with any other operating state. For a simple meshed electric network, the optimal currents' pattern corresponds to the natural repartition of currents through the line sections, considering only their resistances, given that the voltages at the two ends are equal [Ber74], [Gos92], [Shi89].

Consider that the meshed electric network in Figure 12,*a* has equal voltages at both ends. The current flows through the network branches is determined starting from the current $\underline{I}_A$ or $\underline{I}_B$ and subsequently applying Kirkhoff's current law in nodes $1, 2, \ldots, n$, or in the nodes $n, \ldots, 2, 1$, respectively. The currents injected by the two supplying nodes are calculated with the relations for simple meshed electric networks adapted for the situation in which only the branches resistances are considered:

$$\begin{aligned} \underline{I}_A &= \frac{\sum_{k=1}^{n} R_k^{'} \underline{i}_k}{R_{AB}}; \; R_k^{'} = \sum_{i=k+1}^{n+1} r_i \\ \underline{I}_B &= \frac{\sum_{k=1}^{n} R_k \underline{i}_k}{R_{AB}}; \; R_k = \sum_{i=1}^{k} r_i \end{aligned} \tag{16}$$

To obtain the radial configuration from Figure 13, the line section between nodes $k-1$ and k from the meshed network is switched "out of service" state. The currents through the line sections between nodes A and k decrease with the value of $\underline{I}_k$, and the currents through the line sections between nodes B and k increase with the same value. By applying the relation (13) for the mentioned line sections, corresponding to the current flows in meshed operation and considering that $\Delta \underline{i}_k = \pm \underline{I}_k$, the active power losses variation, after transforming the simple meshed networks into two radial sub-networks, is:

$$\delta P = 3\left[I_k^2 R_{AB} + 2I_{ka}\left(\sum_{i=k+1}^{n+1} r_i I_{ia} - \sum_{i=1}^{k} r_i I_{ia} \right) + 2I_{kr}\left(\sum_{i=k+1}^{n+1} r_i I_{ir} - \sum_{i=1}^{k} r_i I_{ir} \right) \right] \tag{17}$$

Taking into account that the current flows for the line sections of the simple meshed network has been calculated considering only the branch resistances, the voltage drops of the nodes A and B with respect to the node *k* can be written as:

$$\begin{aligned} \Delta \underline{V}_{Ak} &= \sum_{i=1}^{k} r_i \left(I_{ia} + jI_{ir} \right) = \sum_{i=1}^{k} r_i I_{ia} + j\sum_{i=1}^{k} r_i I_{ir} \\ \Delta \underline{V}_{Bk} &= \sum_{i=k+1}^{n+1} r_i \left(I_{ia} + jI_{ir} \right) = \sum_{i=k+1}^{n+1} r_i I_{ia} + j\sum_{i=k+1}^{n+1} r_i I_{ir} \end{aligned} \tag{18}$$

Assuming equal voltages at both ends $\underline{V}_A = \underline{V}_B$, the voltage drops of the nodes A and B with respect to the node *k* are identical $\Delta \underline{V}_{Ak} = \Delta \underline{V}_{Bk}$, and subtracting the first row of equation (18) from the second one, one obtains:

$$\left(\sum_{i=k+1}^{n+1} r_i I_{ia} - \sum_{i=1}^{k} r_i I_{ia} \right) + j\left(\sum_{i=k+1}^{n+1} r_i I_{ir} - \sum_{i=1}^{k} r_i I_{ir} \right) = 0 \tag{19}$$

which leads to:

$$\begin{aligned} \sum_{i=k+1}^{n+1} r_i I_{ia} - \sum_{i=1}^{k} r_i I_{ia} &= 0 \\ \sum_{i=k+1}^{n+1} r_i I_{ir} - \sum_{i=1}^{k} r_i I_{ir} &= 0 \end{aligned} \tag{20}$$

Based on the previous results, relation (17) becomes:

$$\delta P = 3 I_k^2 R_{AB} \tag{21}$$

The previous equation shows that by transforming a simple homogeneous meshed network, which operates with equal voltages at both ends, into two radial sub-networks, the active power losses increase. The smallest increase is recorded on the line section with the smallest current. Consequently, applying the optimal current pattern method, in order to reduce the active power losses, three steps are necessary:

- Closing a loop by switching a line section from the “out of service” state to the “in operation” state;
- Calculating the optimal currents pattern in the closed loop achieved previously;
- Identifying the line section from the loop whose current magnitude is minimal and switching it in the “out of service” state.

2.4.3.2.2 Destructive strategy

Employment of the destructive type strategy for active power losses reduction is based on the notion of optimal currents pattern in a loop. As presented in section 3.3.1, the destructive strategy consists in subsequent openings of the loops within a complex meshed network, until the final radial configuration is achieved. The selection criterion at each computation step of the branch of a loop that should be switched “out of service” is based on the conclusions provided by equation (21). The following steps are required:

- Load flow calculation, considering only the branch resistances;
- All closed loops are individually analysed, by identifying the “origin” nodes and calculating the cumulative resistance of the line sections between them;
- Identifying for each loop, the branch with the minimal current and calculating the power losses variation after switching the branch “out of service”;
- Selecting the branch for which the variation of the power losses δP has the lowest value and switching it “out of service”.

2.4.3.2.3 Constructive strategy

This strategy consists in subsequently switching “in operation” some network branches, until the final arborescent configuration is achieved. The selection of the branch that should be switched “in operation” among the candidate branches at each computation step, is based on the active power losses increase minimization criterion [Che92].

Consider the electric network in Figure 12, for which, at a certain computation step, a choice between introducing either the line section between the nodes $k-1$ and *k* or the line section between the nodes *q* and $q+1$ is necessary (Fig. 14).

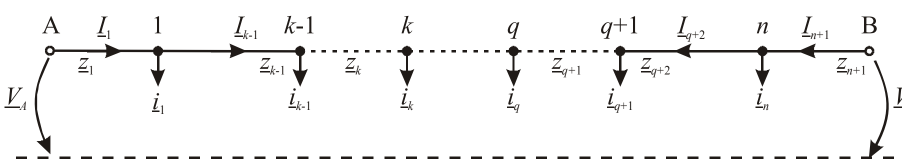

Figure 14: Selecting the branch that has to be added to the network.

By applying the expression (13) to the current flows corresponding to Figure 14, the active power losses variation for both cases becomes:

$$\begin{aligned}\delta P_{A,k} &= 3\left[i_k^2\sum_{i=1}^{k} r_i + 2i_{ka}\sum_{i=1}^{k-1} r_i I_{ia} + 2i_{kr}\sum_{i=1}^{k-1} r_i I_{ir}\right]\\ \delta P_{B,q} &= 3\left[i_q^2\sum_{i=q+1}^{n+1} r_i + 2i_{qa}\sum_{i=k+2}^{n+1} r_i I_{ia} + 2i_{qr}\sum_{i=k+2}^{n+1} r_i I_{ir}\right]\end{aligned} \quad (22)$$

The choice is done based on the criterion $\min\left\{\delta P_{A,k}, \delta P_{B,q}\right\}$.

2.4.4 Reconfiguration of distribution networks with DGs

Usually the installation node and capacity of *DGs* are not optimum from point of view of power losses. The reason is that owners of *DGs* determine the installation location and capacity of it to improve their economic benefits [Cho00].

In the situation of distribution networks with *DGs*, the reconfiguration process can be used to reduce power losses. With *DGs*, the power distribution systems have locally looped network and bidirectional power flow. The looped are formed between sources nodes and *DGs* nodes. If these looped are sectionalised, *DGs* have to operate islanding. In conclusion, in reconfiguration problem, the looped between sources and *DGs* are ignored and heuristic methods can be applied.

2.4.5 Case study

The testing of the reconfiguration method has been made on the urban distribution network from figure 15. The network operates at nominal voltage of 16 kV and is composed by 120 nodes, of which 4 supplying nodes and 137 electric lines.

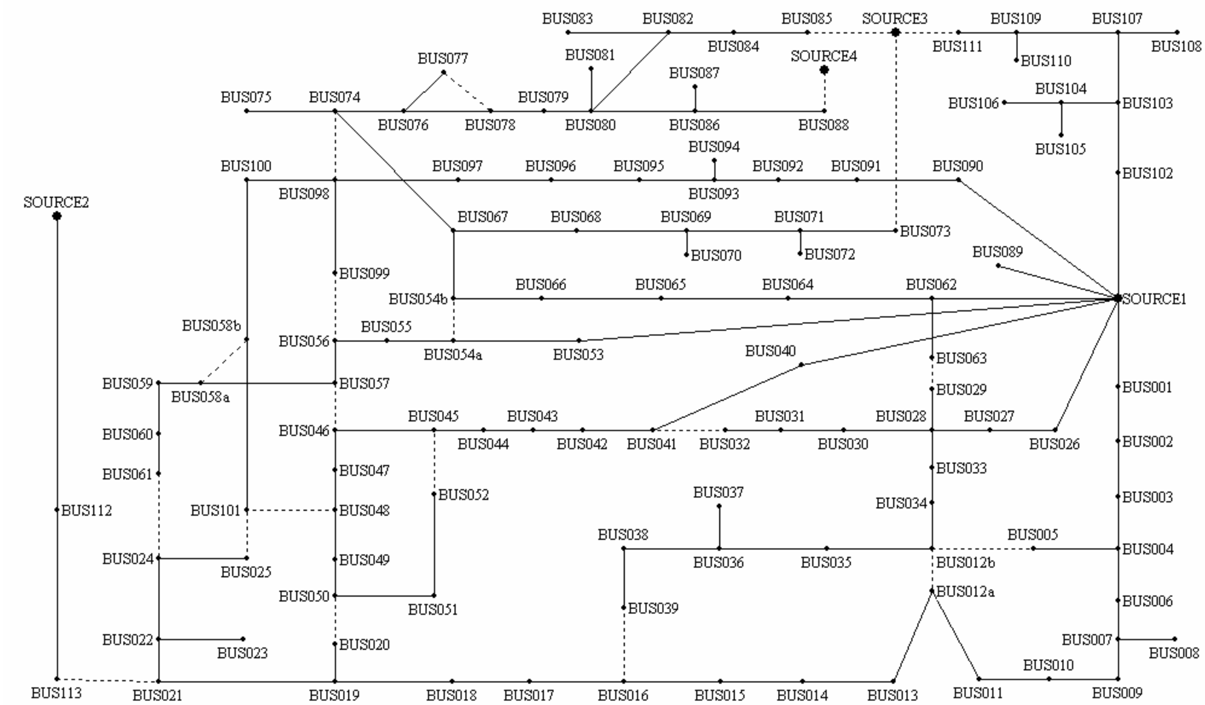

Figure 15: Urban distribution network.

The first study made on urban network was the reconfiguration, without consider *DGs*. The results are presented in Table 1 for the objective of minimization of active power losses. The quantities of this table are:

- ΔP active power losses;
- ΔQ reactive power losses;
- I/I_{adm} maximum load of line sections;
- $\Delta U_{\max}$ maximum value of drop voltage of the network.

Table 1. *Reconfiguration results without* DGs

No.	Switch on	Switch off	ΔP [kW]	ΔQ [kVAr]	I/I_{adm} [%]	$\Delta U_{\max}$ [%]
1	Initial configuration		86.4	53.9	63.2	1.27
2	BUS058a - BUS058b	BUS058b - BUS100	74.6	46.6	59.8	0.98
3	BUS016 - BUS039	BUS015 - BUS016	72.2	45.1	74.2	0.77

4	BUS029 - BUS063	BUS028 - BUS029	70.8	44.2	60.6	0.77
5	BUS052 - BUS045	BUS048 - BUS049	70.0	43.7	60.6	0.74

After the best configuration has been obtained by reconfiguration process, three *DGs* was considered in the network, to nodes: "BUS042", "BUS045" and "BUS048". Every *DGs* can cover only the consumption from connection node. Then the reconfiguration process was again applied. The results are shown in Table 2.

Table 2. Reconfiguration results with *DGs*

No.	Switch on	Switch off	ΔP [kW]	ΔQ [kVAr]	I/I_{adm} [%]	$\Delta U_{\max}$ [%]
1	Initial configuration		56.9	35.4	60.6	0.74
2	BUS020 - BUS050	BUS019 - BUS020	55.8	34.7	56.4	0.74
3	BUS048 - BUS049	BUS050 - BUS049	55.5	34.6	56.4	0.74
4	BUS061 - BUS024	BUS061 - BUS060	55.4	34.5	55.2	0.73

By introducing *DGs* active power losses decrease from 70 kW to 56.9 kW. The reconfiguration process applied for this situation reduces power losses to the value 55.4 kW. The variation of active power losses is shown in Figure 16.

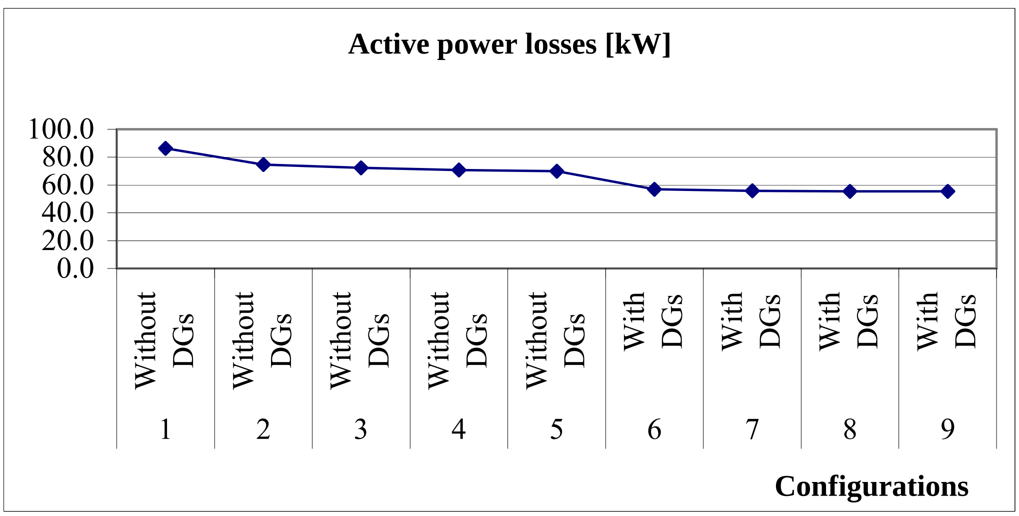

Figure 16: Variation of active power losses in urban network.

2.5 Conclusions

Backward/forward is a simple and efficient method for load flow calculation. In comparison with classical methods (e.g. Newton-Raphson, Seidel-Gauss) is faster and the calculating volume is smaller.

Backward/forward method is specified for radial electric networks. With some adaptations the method can be used to calculation load flow of distribution networks, which include *DGs*.

Introduction of *DGs* in distribution networks modifies power flow. In combination with application of reconfiguration methods, the introduction of *DGs* can improve (optimise) power flow. The objective of power losses minimisation leads habitually to decreasing of voltage drops and lines load, as well as to equilibration of lines load and voltage level to nodes. The application of reconfiguration process using heuristic methods in distribution networks with *DGs* is simple.

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3 Modelling and Fault Analysis of Different Wind Generator Technologies

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3.1 Introduction

Growing environmental concerns as well as the security of energy supply issues are providing opportunity for increased penetration of renewable energy sources into power systems. Especially attractive are small generation units that are placed near consumers and that can satisfy their power demand. Systems with renewable energy sources can be successfully implemented in isolated regions, like mountain areas or islands, which do not have connection to the main distribution grid or where such connection will be technically and/or economically unjustified. However, there are a number of technical challenges associated with operation of isolated systems, especially once with renewable energy sources. Varying loads and climate conditions can cause disturbances in the system, like frequency and voltage variances. It is thus important to develop adequate control and operational procedures of such systems.

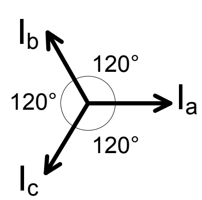
An important step in definition of control and operational procedures for any power system is short circuit analysis. It should be performed in order to obtain the magnitude of fault currents, which is used for grid elements dimensioning and protection adjustments. Results depend, of course, on grid topology, location of the fault and the type of the fault. However, the first and the most important step in short-circuit analysis is to develop a grid equivalent model and to determine overall impedance of the fault circuit. That means that every grid element should be presented with an equivalent model, i.e. equivalent circuit. Equivalent models for power sources (generators), transformers, power lines and loads should be developed. Another issue is behaviour of the generating units in case of disturbances on the grid. Both, contribution of different generation units to the fault currents and behaviour of generating units during disturbances will be discussed in this paper.

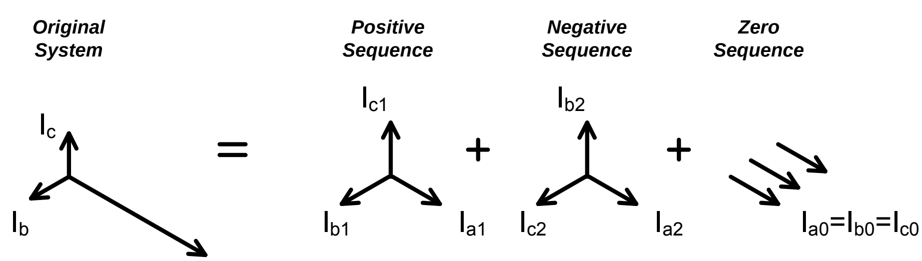
In systems with renewable energy sources it is interesting to consider and analyse different types of power sources and to develop their equivalent models. Power source in the most of power plants is rotating machine, i.e. electric generator. In conventional power plants the most commonly used are synchronous generators. However, power plants using renewable energy sources usually have smaller power output and synchronous generators are not always the best choice. Especially interesting are wind power plants, since their operation is quite different then conventional power plant with gas, steam or hydro turbine. There are two types of wind turbines: constant-speed and variable speed-wind turbines. Constant-speed turbines are based on a directly grid-coupled squirrel-cage induction generator. Variable-speed wind turbines can be coupled with doubly fed (wound rotor) induction generator or with direct drive synchronous generator. In case of variable-speed turbine, there is always a need for power electronics as an interface between the generator and the grid. The contribution of wind turbines to the fault current and behaviour under fault conditions differ between these three main wind aggregates types.

3.2 General about short circuit analysis

When designing electrical grids it is necessary to be familiar with nominal currents but also with fault currents, since both of them are crucial for equipment dimensioning. Nominal current is the current that equipment must be able to permanently endure in normal operational conditions. Short-circuit currents are important in determination of mechanical tensions during the fault (surge current), breaking capacity of circuit breakers and other switchgear (breaking current) and temperature rising during the fault that equipment must endure. Short-circuit currents are also crucial for adjustments of protective relays.

Short-circuit currents are calculated using symmetrical components method. Method of symmetrical components is a modelling technique that converts a three phase unbalanced network to a set of three balanced networks that each can be represented by a single phase equivalent circuit. These circuits are then connected in a way that simulates the conditions on the actual unbalanced system and allows calculation of the currents and voltages during a fault. Any unbalanced set of three related vectors can be resolved into three sets of balanced vectors, which are called symmetrical components. We distinguish between positive, negative and zero sequence components. The positive sequence retains the concept of three balanced vectors having the same phase sequence as the original vectors while the negative sequence component retains the concept of three balanced vectors but rotating in opposite direction of rotation. The zero sequence component is balanced set of three coincident vectors rotating in the same direction as the original unbalanced vectors. The basic principal of symmetric components method is given in figure 2.1.





Balanced 3 Phase System

Unbalanced 3 Phase System modelled with 3 Balanced 3 Phase Systems

Figure 2.1 Symmetrical components modelling of unbalanced 3 phase system

The concept can be mathematically described with set of equations:

$$I_a = I_{a1} + I_{a2} + I_{a0}$$
$$I_b = I_{b1} + I_{b2} + I_{b0} \ldots(2.1)$$
$$I_c = I_{c1} + I_{c2} + I_{c0}$$

If vector operator "a" is defined as $a = 1\angle 120°$ system (1) can be reformulated →

$$I_a = I_{a1} + I_{a2} + I_{a0}$$
$$I_b = a^2 I_{a1} + aI_{a2} + I_{a0} \ldots(2.2)$$
$$I_c = aI_{a1} + a^2 I_{a2} + I_{a0}$$

Sequence components can be then solved from the equation system (2.2):

$$I_1 = \frac{1}{3}(I_a + aI_b + a^2 I_c)$$
$$I_2 = \frac{1}{3}(I_a + a^2 I_b + aI_c) \quad \ldots (2.3)$$
$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$

The same set of equations can be obtained for system voltages.

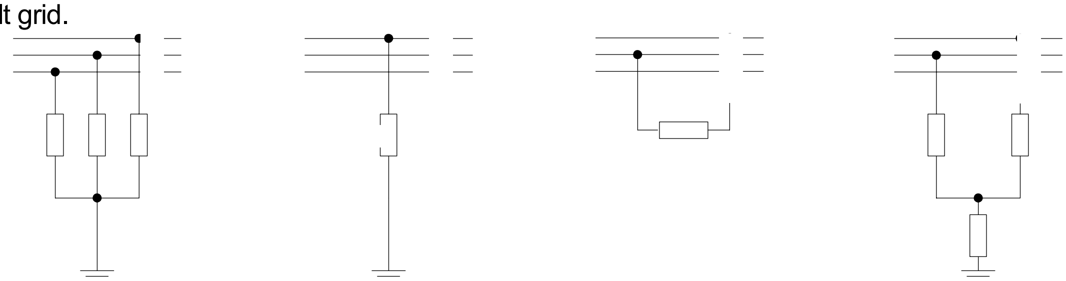
Since in general, current consists of positive, negative, and zero sequence components, every grid element will present impedance to each of the current components. Thus, every grid element will be represented with positive sequence impedance, negative sequence impedance and zero sequence impedance. These impedances can be different. Positive sequence impedance is the normal impedance of three phase circuits to the flow of balanced three phase current that is given in the equipment specifications. Negative sequence impedance is the impedance of three phase circuits to the flow of currents whose phasors rotate in the opposite direction. For most equipment the negative sequence impedance is the same as the positive sequence impedance. The exception may be some rotating machines. If the negative sequence impedance differs from the positive sequence impedance, it must be given in the equipment specifications. Zero sequence impedance is different from positive and negative sequence impedances because the zero sequence currents must return to the source through the ground and/or the neutral wire. The exact path of zero sequence current depends on the connection of the equipment and on the current path through the ground. For calculation of the fault circuit conditions it is important to know sequence impedances for every grid element. So, the first step in short-circuit analysis is to develop three sequence impedance networks, that will afterwards be connected in a way that represents voltage and current conditions during the fault. With development of advanced computation softwares, calculation of short circuit currents becomes less and less difficult. Sequence impedances of the faulted circuit are easily calculated from equipment data on resistances and reactances, so no further detailed explanations will be provided in this paper.

Currents produced during faults depend on the impedance of the fault circuit and on the type of the fault. There are four types of the fault that can occur:

1. **Three phase fault** (either three line or three line to ground). Three phase fault is a connection between all three phases and between the phases and the ground. Only during this type of fault voltages and currents are balanced.

2. **Single line to ground fault** is a connection between one of the phases and the ground.
3. **Line to line fault** is a connection between any two phases.
4. **Double line to ground fault** is a connection between any two of the phases and the ground.

The basic configuration of every fault type is given in Figure 2. Every fault type has its own boundary conditions that are given in table 2.1. These are very useful when modelling the grid with sequence impedance networks. Boundary conditions are applied to the set of sequence equations for currents and voltages. According to the new set of equations, sequence impedance networks will be connected in proper way to represent the equivalent model of the fault grid.



Three phase fault with fault impedance Z — **Single line to phase fault with fault impedance Z** — **Line to line fault with fault impedance Z** — **Double line to ground fault with fault impedance Z**

Figure 2.2 Types of the short-circuit fault

Table 2.1 Boundary conditions for different types of the short-circuit fault

Type of fault	Boundary conditions
3 Phase	$I_a + I_b + I_c = 0$ and $V_a = V_b = V_c$
Single Phase	$I_b = I_c = 0$ and $V_a = 0$
2 Phase	$I_a = -I_b$, $I_c = 0$ and $V_a = V_b$
2 Phase to ground	$I_c = 0$ and $V_a = V_b = 0$

3.3 Power sources modeling

It is obvious that for short circuit currents calculations the overall impedance of faulted circuit should be determined. This actually means that every grid element should be represented by its own impedance (resistance and reactance). It is thus necessary to develop equivalent models of the grid elements. This paper will address how to model different power sources that are used in renewable energy sources power plants. Special attention will be given to different types of “wind turbine –electric generator – grid” connections.

As already stated, there are two types of wind turbines: constant-speed and variable-speed wind turbines.

Constant-speed turbines are usually coupled with squirrel-cage induction generator.

There are two ways of connecting variable-speed wind turbines to the electrical grid: double fed (wound rotor) induction generator and direct drive synchronous generator.

Generators used in wind power plants differ from traditionally used synchronous generators used in conventional power plants. Most commonly used are induction generators coupled with constant-speed wind turbine. Variable-speed wind turbines always require power electronics as an interface between generator and the grid.

This paper will address how to model induction generator, synchronous generator and power electronics elements in different wind power plants types.

Electromagnetic processes in rotating machine's windings are, in general, determined with voltage equations that can be presented in matrix form:

$$[v] = [R] \cdot [i] + \frac{d[\Psi]}{dt}$$

When transformation and rotation voltage are decoupled, the equation can be restated as follows:

$$[v] = [R] \cdot [i] + [L] \cdot \frac{d[i]}{dt} + \omega \cdot \frac{d[L]}{d\gamma}[i]$$

where [R] is resistance and [L] is inductance matrix of the machine, and γ is the angle between stator's a phase axis and rotor's longitudinal axis. [R] and [L] are dependant on γ, i.e. they are dependant on mutual position of stator and rotor. This equation system is thus very difficult to access. Simplification is made by very well known Park's transformation that transforms above equation system from stator (abc) to rotor (dq0) reference frame. In this paper d-q reference frame will be used when modelling rotating machines.

Rotating machines have time-varying impedances when subjected to disturbances. However, for simplification purposes, their impedances are usually divided into three zones:

- sub-transient (first few cycles) (X"),
- transient (5 cycles - 60 cycles) (X'),
- steady-state (longer than 60 cycles) (X).

When performing fault studies, the time period of interest is usually a few cycles, so that machines are represented by their sub-transient impedances when forming the impedance matrices. These impedances are determined from machine's equivalent circuit by applying fault conditions. For synchronous generators three above reactances differ from each other. It is due to specific construction of the synchronous machine. Modelling of induction generators is somewhat easier since these machines do not have excitation and damper windings. Hence, only sub-transient and steady-state currents are of interest. Important is to say that values of machine's reactance are obtained by the measurements and should be provided by equipment manufacturer. They are input data for short-circuit calculations.

3.3.1 Squirrel cage induction generator modelling

A squirrel cage induction generator is an asynchronous machine, composed by a squirrel cage rotor and a stator with three distributed windings which are directly coupled to the grid. The wind turbine rotor is coupled to the generator through a gearbox. Substantially this is a constant speed wind turbine because the power converted from the wind is limited by designing the turbine rotor in such a way that its efficiency decreases in high wind speed. This kind of generators always consumes reactive power and is not able to control and regulate the voltage level. Hence capacitors close to these generators are necessary to avoid a voltage decrease.

The system with constant speed wind turbine coupled with squirrel cage induction generator is shown in figure 3.1.

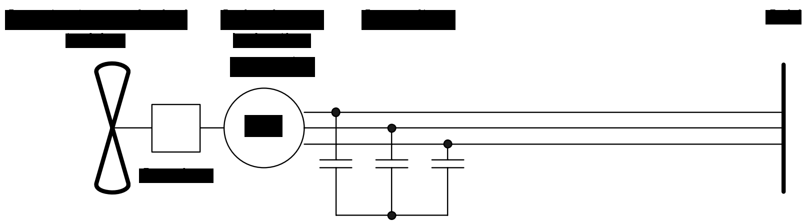


***Figure 3.1** Constant-speed wind turbine coupled with squirrel-cage induction generator system*

Squirrel-cage induction machines are not widely used in power production. The exceptions are wind power plants and some small hydropower units. However, induction machines are extremely widely used as electric motors and their operation characteristics are thus very well known. The most important advantages of induction machines are in very high reliability and low expenses.

3.3.1.1 Squirrel cage induction generator model

The induction generator model is very well known and it is shown in figure 3.2.

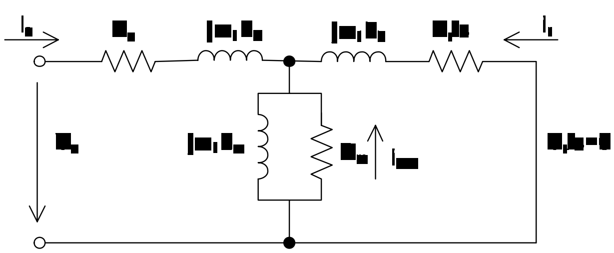


***Figure 3.2** Equivalent circuit of squirrel cage induction generator*

After applying Kirchhoff's voltage law to the circuit in figure 6 set of equations are obtained that represent the model of the generator:

$$v_s = R_s i_s + j\omega_1 \Psi_s$$

$$\frac{v_r}{s} = 0 = \frac{R_r}{s} i_r + j\omega_1 \Psi_r$$

$$0 = R_m i_{rm} + j\omega_1 \Psi_m$$

Parameters and variable used in above equations have meaning as follows:

v_s	– stator voltage	R_s	– stator resistance
v_r	– rotor voltage	R_r	– rotor resistance
i_s	– stator current	R_m	– magnetizing resistance
i_r	– rotor current	L_{ls}	– stator leakage inductance
i_{Rm}	– magnetizing resistance current	L_{lr}	– rotor leakage inductance
ω_1	– stator frequency	L_m	– magnetizing (mutual) inductance
s	– slip		

The flux linkage (air-gap flux, stator flux and rotor flux) are expressed by following equations:

$$\Psi_s = L_{ls} I_s + L_m (I_s + I_r + I_{Rm}) = L_{ls} I_s + \Psi_m$$

$$\Psi_r = L_{lr} I_r + L_m (I_s + I_r + I_{Rm}) = L_{lr} I_r + \Psi_m$$

The slip s equals:

$s = \frac{\omega_1 - \omega_r}{\omega_1} = \frac{\omega_2}{\omega_1}$, where ω_r is the rotor speed and ω_2 is the slip frequency.

If well-known *Park transformation* is used, equivalent model of induction generator in d-q reference frame that is fixed to the rotor is obtained:

$$v_{sd} = -R_s \cdot i_{sd} - \omega_s \cdot \Psi_{sq} + \frac{d\Psi_{sd}}{dt}$$

$$v_{sq} = -R_s \cdot i_{sq} + \omega_s \cdot \Psi_{sd} + \frac{d\Psi_{sq}}{dt}$$

$$v_{rd} = 0 = -R_r \cdot i_{rd} - \omega_r \cdot \Psi_{rq} + \frac{d\Psi_{rd}}{dt}$$

$$v_{rq} = 0 = -R_r \cdot i_{rq} + \omega_r \cdot \Psi_{rd} + \frac{d\Psi_{rq}}{dt}$$

The stator and rotor fluxes are related to the currents with equations:

$$\Psi_{sd} = -(L_{ls} + L_m) \cdot i_{sd} - L_m \cdot i_{rd}$$

$$\Psi_{sq} = -(L_{ls} + L_m) \cdot i_{sq} - L_m \cdot i_{rq}$$

$$\Psi_{rd} = -(L_{lr} + L_m)_m \cdot i_{rd} - L_m \cdot i_{sd}$$

$$\Psi_{rq} = -(L_{lr} + L_m) \cdot i_{rq} - L_m \cdot i_{sq}$$

Squirrel-cage induction generator equivalent model in d-axis and q-axis is given in figures 3.3 and 3.4.

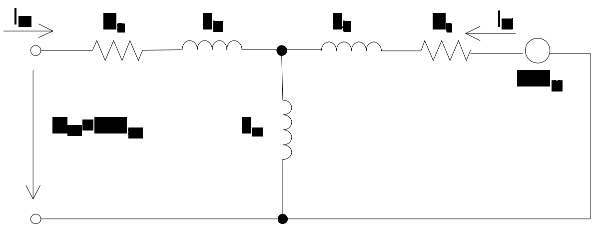


Figure 3.3 *d-axis squirrel-cage induction generator equivalent circuit*

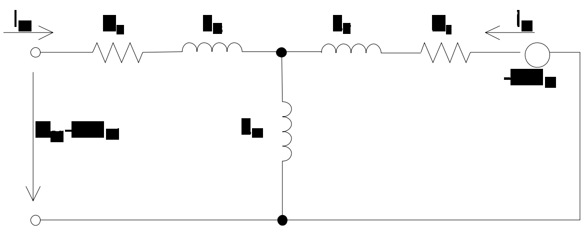


Figure 3.4 *q-axis squirrel-cage induction generator equivalent circuit*

3.3.2 Doubly fed induction generator

Doubly fed induction generators are the most widely used for units above 1 MW. Wind turbine coupled with doubly fed induction generator system is shown in figure 3.5. A doubly fed induction generator has a wound rotor, with the windings being externally accessible via slip rings. The wind turbine rotor is coupled to the generator through a gearbox in the same way of the constant speed generator. The rotor current is regulated using power electronics, allowing the generator to operate over a relatively large speed range. A doubly fed induction generator's rotor is connected to the grid through a back-to-back voltage source converter. This converter controls the excitation system in order to decouple the mechanical and electrical rotor frequency and to match the grid and rotor frequency.

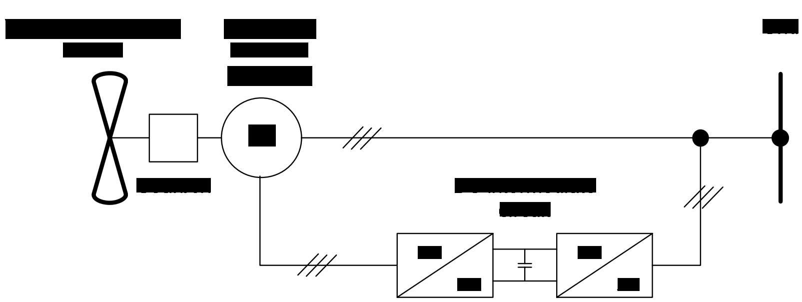


__Figure 3.5__ Doubly fed induction generator (DFIG) system

Electrical power is fed into the main grid through the stator and rotor windings. Stator winding is directly connected to the grid while rotor winding is connected to the grid by AC/DC/AC converters that are able to control the slip ring voltage in magnitude and phase angle. What is very important in this model is that electrical power is independent from the speed. It is thus possible to use variable speed wind turbine and to adjust its mechanical speed to the wind speed, which allows turbine operation at the aerodynamically optimal point for a certain wind speed range. Variable speed operation allows higher efficiency in generating system.

This concept has become very popular since power electronic converter only has to handle a fraction (20–30%) of the total power, which means that the losses in the power electronic converter can be reduced compared to a system where the converter has to handle the total power. As it can be seen in figure 3.5, rotor-side and grid-side converters are connected “back-to-back” and in between is placed DC-link capacitor as energy storage, purposed for keeping DC voltage variations low.

Doubly fed induction generator model is taken from [6].

3.3.2.1 Wound rotor induction generator model

Equivalent circuit diagram of the doubly-fed induction generator is given in Figure 3.6. It could be seen that if rotor windings are short circuited, this equivalent scheme becomes equivalent scheme for squirrel-cage induction machine. Note that equivalent scheme is given in stator reference frame. Set of equations obtained from this model is later used for developing models in d-q reference frame.

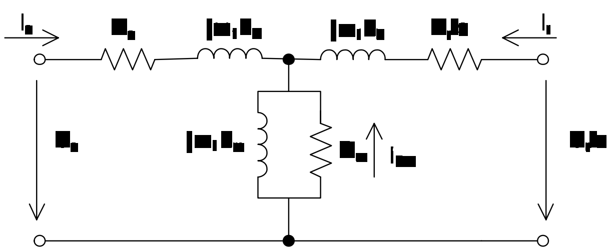


__Figure 3.6__ Equivalent circuit of doubly fed induction generator

After applying Kirchhoff’s voltage law to the circuit in figure 3.6. a set of equations is obtained that represent the model of the generator:

$$v_s = R_s i_s + j\omega_1 \Psi_s$$

$$\frac{v_r}{s} = \frac{R_r}{s} i_r + j\omega_1 \Psi_r$$

$$0 = R_m i_{rm} + j\omega_1 \Psi_m$$

Parameters and variable used in above equations have meaning as follows:

v_s	– stator voltage	R_s	– stator resistance
v_r	– rotor voltage	R_r	– rotor resistance
i_s	– stator current	R_m	– magnetizing resistance
i_r	– rotor current	L_{ls}	– stator leakage inductance
i_{Rm}	– magnetizing resistance current	L_{lr}	– rotor leakage inductance
ω_1	– stator frequency	L_m	– magnetizing (mutual) inductance
s	– slip		

The flux linkage (air-gap flux, stator flux and rotor flux) are expressed by following equations:

$$\Psi_s = L_{ls} I_s + L_m (I_s + I_r + I_{Rm}) = L_{ls} I_s + \Psi_m$$

$$\Psi_r = L_{lr} I_r + L_m (I_s + I_r + I_{Rm}) = L_{lr} I_r + \Psi_m$$

The slip *s* equals:

$s = \frac{\omega_1 - \omega_r}{\omega_1} = \frac{\omega_2}{\omega_1}$, where ω_r is the rotor speed and ω_2 is the slip frequency.

If well-known Park transformation is used, equivalent model of induction generator in d-q reference frame that is fixed to the rotor is obtained:

$$v_{sd} = -R_s \cdot i_{sd} - \omega_s \cdot \Psi_{sq} + \frac{d\Psi_{sd}}{dt}$$

$$v_{sq} = -R_s \cdot i_{sq} + \omega_s \cdot \Psi_{sd} + \frac{d\Psi_{sq}}{dt}$$

$$v_{rd} = -R_r \cdot i_{rd} - \omega_r \cdot \Psi_{rq} + \frac{d\Psi_{rd}}{dt}$$

$$v_{rq} = -R_r \cdot i_{rq} + \omega_r \cdot \Psi_{rd} + \frac{d\Psi_{rq}}{dt}$$

The stator and rotor fluxes are related to the currents with equations:

$$\Psi_{sd} = -(L_{ls} + L_m) \cdot i_{sd} - L_m \cdot i_{rd}$$

$$\Psi_{sq} = -(L_{ls} + L_m) \cdot i_{sq} - L_m \cdot i_{rq}$$

$$\Psi_{rd} = -(L_{lr} + L_m)_m \cdot i_{rd} - L_m \cdot i_{sd}$$

$$\Psi_{rq} = -(L_{lr} + L_m) \cdot i_{rq} - L_m \cdot i_{sq}$$

Doubly fed induction generator equivalent model in d-axis and q-axis is given in figures 3.7 and 3.8.

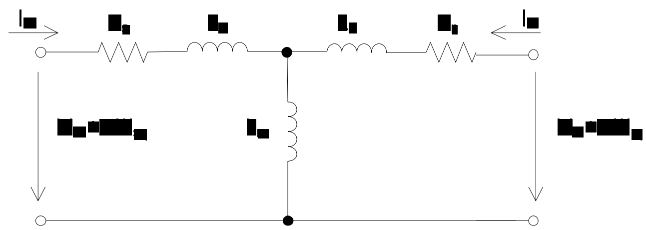


Figure 3.7 *d-axis induction generator equivalent circuit*

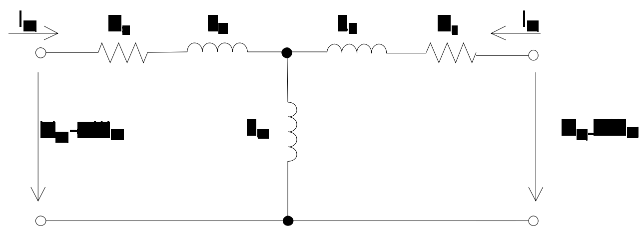


Figure 3.8 *q-axis induction generator equivalent circuit*

3.3.2.2 PWM converter model (DC intermediate circuit model)

In order to model whole doubly-fed induction generator system, DC intermediate circuit should also be modelled. The circuit consists of rotor-side and grid-side converters. They are self-commutated converters consisting of six-pulse bridges, as shown in figure 3.9.

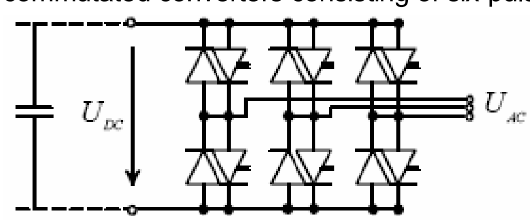


Figure 3.9 *DC-link model*

If ideal DC voltage and ideal PWM modulation is assumed, AC and DC voltages can be related to each other with following equation:

$$\left|V_{AC}\right| = \frac{\sqrt{3}}{2\sqrt{2}} P_m V_{DC}$$

The pulse-width modulation factor P_m is the control variable of the PWM converter. The above equation is only valid for $0 \le P_m < 1$. If P_m is above 1, converter starts saturating and the level of low order harmonics starts increasing.

The converter model is completed by power conservation equation:

$$V_{DC} I_{DC} + \sqrt{3}\,\mathrm{Re}(\underline{V}_{AC} \underline{I}^{*}_{AC}) = 0$$

This equation disregards converter losses. This is of course not valid, especially since PWM converters usually have very high switching frequency, hence predominant type of losses are switching losses. They are proportional to U_{DC}^2, and thus can be represented by a resistance between two DC poles.

3.3.2.3 Control concept

Typical control concept consists of d-q regulators for the generator control.

The rotor-side converter operates in a stator-flux d-q reference frame. Rotor current is decomposed into and active (q-axis) and reactive (d-axis) component. Inner loop is very fast and it regulates rotor current. The concept is shown in figure 3.10. Outer loop is slower and it regulates active and reactive power (by defining current-set point).

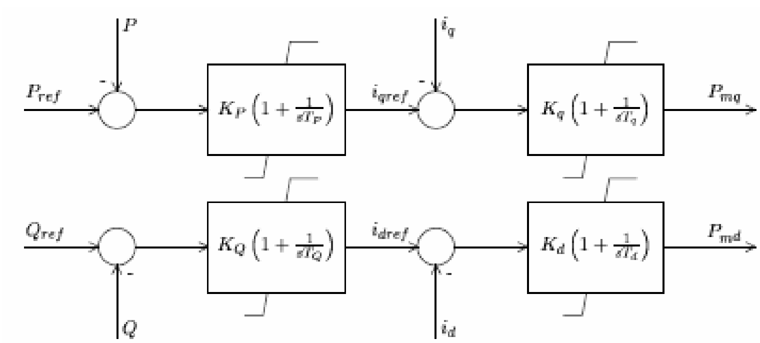


Figure 3.10 *Rotor-side converter controller*

The grid-side converter controller operates in AC d-q reference frame. Inner loop is faster and it is used for active and reactive components regulation. Outer loop is slower and it is used for regulating DC voltage to a predefined value (by q-current set point). The set point of d-axis component can be used for optimal reactive power sharing between the generator and the grid side converter. Another possibility is to keep it at constant value.

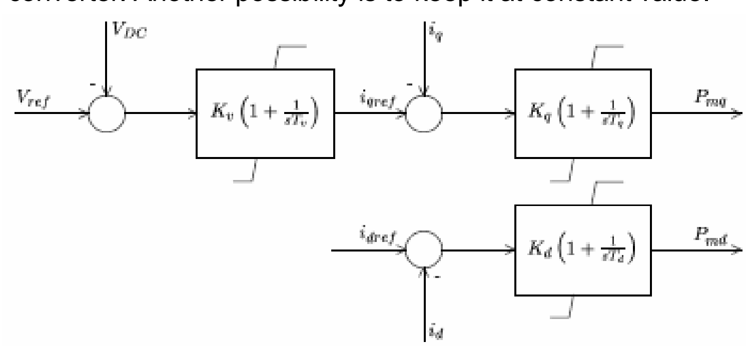


Figure 3.11 *Grid-side converter controller*

3.3.3 Direct drive synchronous generator

Direct drive synchronous generator is completely decoupled from the grid by a power electronics converter connected to the stator winding. The converter is composed by a voltage source converter on the grid side and a diode rectifier (or a voltage source converter) on the generator side. The direct drive generator is excited by an excitation winding or permanent magnets. Wind turbine and generator are directly coupled, without gearbox. This allows variable speed operation over a wide range.

Although for wind turbines above 1 MW doubly fed induction generators are he most widely used concept, direct drive wind generators based on converter-driven synchronous generator are present in large number of wind power plants. In direct drive synchronous generator system, turbine and generator shafts are coupled directly, without gearbox. Generator used in such systems is high-pole synchronous generator designed for low speed. Due to high number of poles this generators are quite large. The solution is found in direct drive concept but with single stage gear box with low ratio. Hence, the required number of poles is lower and generator is smaller. However, these two concepts are electrically the same. Figure 3.12 shows direct drive synchronous generator system.

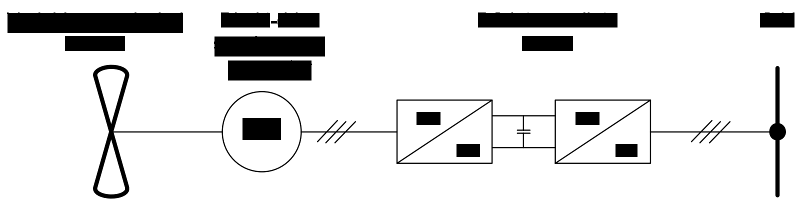


Figure 3.12 *Direct-drive synchronous generator system*

In order to allow variable speed operation of the wind turbine, synchronous generator has to be connected to the grid through a frequency converter. Frequency converter is actually very similar as in case of doubly fed induction generator. The generator is connected to intermediate DC circuit by diode rectifier or by self commutated pulse-width modulated (PWM) converter (machine-side converter). The grid-side converter is always self commutated pulse-width modulated converter. Filter is set between grid-side converter and the grid.

Direct drive synchronous generator model is taken from [7].

3.3.3.1 Synchronous generator model

The theory of the synchronous machine is well known, so only the basic model characteristics will be described here.

Synchronous machine is a machine with three identical armature windings, symmetrically distributed around the air-gap, and one field winding. One or more damper windings can also be present. For modelling purposes usually one damper winding is assumed in each machine axis. Mathematical model is based on set of electrical equations that are obtained by writing Kirchhoff's voltage law for every winding. This means that voltage at the winding's terminal is equal to the sum of resistive and inductive voltage drops across the winding. The damper winding is always short circuited and therefore its terminal voltage equals zero. In order to set these equations, total magnetic flux linked with the winding needs to be evaluated. This is done by inductance matrix that relates all windings' flux linkages to all windings' currents. Inductance matrix is dependant on the rotor position due to magnetic asymmetry of the rotor: because of the rotor construction there is preferable magnetic direction. This direction coincides with the direction of the flux produced by the field winding and it is defined as machine's d-axis. Q-axis is placed at 90 electrical degrees with the respect to d-axis. In that way, generator equations can be set in different reference frame. D-q coordinate system rotates with rotor speed ω_r, so time dependant inductances are replaced with fictive inductances that rotate together with rotor. In the stationary or stator reference system (*abc*) the machine parameters are time dependant (since magnetic flux is a function of time). In rotor, *d-q* reference frame, machine parameters are constant.

Figures 3.13 and 3.14 show d-axis and q-axis equivalent circuits

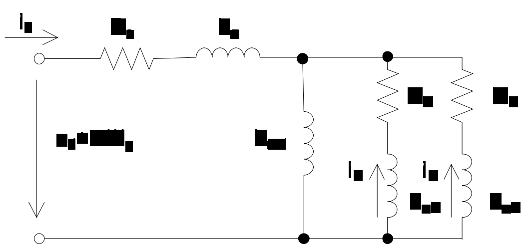


***Figure 3.13** d-axis synchronous generator equivalent circuit*

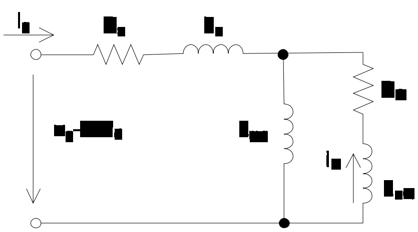


***Figure 3.14** q-axis synchronous generator equivalent circuit*

Final set of electrical equations in *d-q* reference frame for synchronous generator are:

Stator windings equations

$$v_d = R_s \cdot i_d - \omega \cdot \Psi_q + \frac{d\Psi_d}{dt}$$

$$v_q = R_s \cdot i_q + \omega \cdot \Psi_d + \frac{d\Psi_q}{dt}$$

where stator flux is equal to:

$$\Psi_d = (L_\sigma + L_{md}) \cdot i_d + L_{md} \cdot i_E + L_{md} \cdot i_D$$

$$\Psi_q = (L_\sigma + L_{mq}) \cdot i_q + L_{mq} \cdot i_Q$$

Excitation winding equations

$$v_E = R_E \cdot i_E + \frac{d\Psi_E}{dt}$$

where

$$\Psi_E = L_{md} \cdot i_d + (L_{\sigma E} + L_{md}) i_E + L_{md} i_D$$

Damper winding equations

$$v_D = 0 = R_D \cdot i_D + \frac{d\Psi_D}{dt}$$

$$v_Q = 0 = R_Q \cdot i_Q + \frac{d\Psi_Q}{dt}$$

where

$$\Psi_D = L_{md} \cdot i_d + L_{md} i_E + (L_{md} + L_{\sigma D}) i_D$$

$$\Psi_Q = L_{mq} \cdot i_q + (L_{mq} + L_{\sigma Q}) i_Q$$

Above equations represent mathematical model of synchronous generator. Variables and parameters in these equations have the following meaning:

ω	– rotor speed	R_s	– stator phase resistance
v_d	– stator d-axis terminal voltage	L_σ	– stator phase leakage inductance
v_q	– stator q-axis terminal voltage	L_{md}	– d-axis coupling inductance
i_d	– stator d-axis terminal current	L_{mq}	– q-axis coupling inductance
i_q	– stator q-axis terminal current	R_E	– excitation winding resistance
v_E	– excitation winding terminal voltage	$L_{\sigma E}$	– excitation winding leakage inductance
i_E	– excitation winding terminal current	R_D	– d-axis damper winding resistance
i_D	– damper winding d-axis current	$L_{\sigma D}$	– d-axis damper winding leakage inductance
i_Q	– damper winding q-axis current	R_Q	– q-axis damper winding resistance
		$L_{\sigma Q}$	– q-axis damper winding leakage inductance

This model is the basis for analysis of the synchronous generator behaviour during the short circuit-fault. By using this model, generator reactances (sub-transient, transient and steady- state) can be obtained for both axis as well as equivalent schemes in symmetrical components representation.

3.3.3.2 PWM converter model

The rotor-side and grid-side converters are usually self commutated pulse-width modulated circuits, as shown in figure 3.15. It is the same type of converter used in DFIG systems. The circuit consists of six valves and six antiparallel diodes. Valves have turn-off capability and are usually realized by bipolar transistors or IGBTs, since these elements allow higher switching frequencies than classical GTOs.

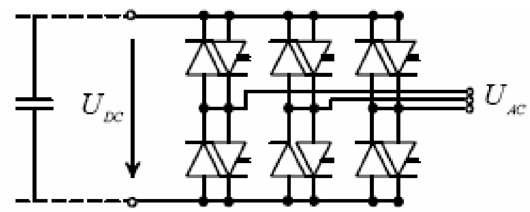


Figure 3.15 *PWM-converter circuit*

AC and DC voltage can be related to each other with- equation:

$$|V_{AC}| = \frac{\sqrt{3}}{2\sqrt{2}} P_m V_{DC}$$

where P_m is a control variable of the PWM-converter. This equation assumes ideal converter without losses. To complete the converter model, power conservation equation is needed:

$$V_{DC} I_{DC} + \sqrt{3}\,\mathrm{Re}(\underline{V}_{AC} \underline{I}^{*}_{Ac}) = 0$$

Besides PWM converters, for rotor-side converters diode rectifier with DC-booster can be used.

3.3.3.3 Control concept

The grid-side converter operates in stator oriented reference frame in which d-axis represents the active and q-axis the reactive current component. Inner loop is very fast and it controls d- and q-axis current components. Slower outer loop regulates active and reactive power (by defining current references). MPT characteristic defines the active power reference which is important to drive generator into the optimum speed-power operation point. The grid-side converter controller is shown in figure 3.16.

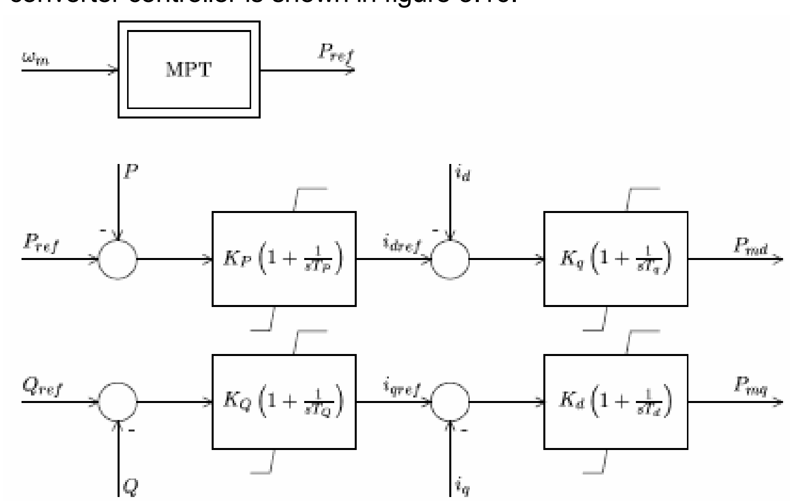


Figure 3.16 Grid-side converter controller

The generator-side converter regulates AC voltage and DC voltage of intermediate DC circuit. The controller is equipped with fast current controllers. The current reference values are defined by voltage regulators. The generator-side converter controller is shown in figure 3.17.

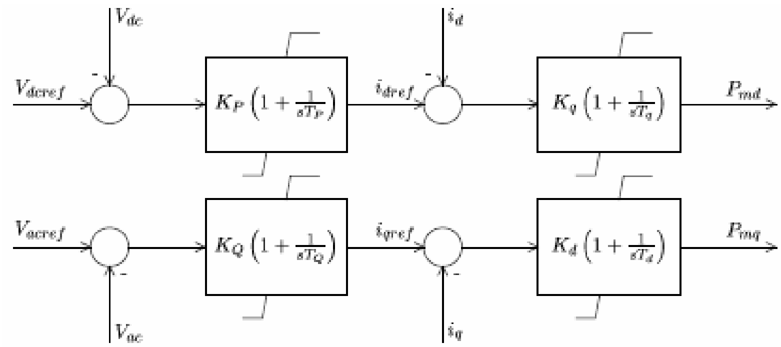


Figure 3.15 *Generator-side converter controller*

3.4 Short circuit analysis

Wind energy is the fastest growing renewable energy source for electricity production. Integration of wind power into weak systems raises several questions that must be clarified. Typical, this will include system operation and control issues to ensure system stability. Stricter requirements demanding accurate reactive power control and voltage regulation capability has led to the integration of power electronic converters in many of wind generator designs. Important is to notice that different wind power technologies have different characteristics and control possibilities. Different wind power technologies and modelling issues have already been discussed in previous sections. Here, we can summarise findings about different wind generator technologies.

Behaviour of different wind generator types in fault conditions will be analysed. How different types of generators influence and contribute to the fault currents will be presented. For that purpose, example grid will be examined just to draw some general conclusions. Behaviour of asynchronous and synchronous generators will be compared.

Another issue that will be addressed in this paper is behaviour of different wind generator types in case of disturbance in the grid (*fault ride through*). This is especially important issue since new grid codes for wind power plants are introduced in some countries due to large penetration of wind power into power grids.

3.4.1 Short circuit contributions from wind generators

When calculating short-circuit contributions from wind generation facilities, calculations may become quite complicated and difficult due to fallowing reasons [1]:

- Most often in wind generation facilities induction machines (generators) are used, which differs from standard procedures and assumptions used in calculation of short-circuit contributions on the grid.
- Power electronics employed with wind generator can substantially modify the behaviour of the generator in response to a sudden drop in terminal voltage due to short circuit fault, which additionally complicates calculations

To show differences between asynchronous (induction) and synchronous generator contribution to the fault currents, following grid was assumed. It is just a test grid, and it has to be emphasised that situation will vary depending on grid characteristics. The example is used for impact analysis of distributed generation on distribution grid. However, the example is beneficial to confirm theoretical knowledge. Calculation has been done by program package *Neplan*. Power electronic elements were not included in the calculation due to some performance problems. However, the discussion on power electronic influences on fault currents will be performed.

Analysed grid is shown in figure 4.1. Example grid as well as result calculations are taken from [2].

As it can be seen, this is an example of distribution network. However, the system can be disconnected from the grid and operate as an isolated system. For 3 phase short circuit only direct component (impedances) of network elements are important. For 2 phase and 1 phase short circuit, apart from direct system indirect and zero system (impedances) should be obtained. They depend on types of transformers and type of earthing.

Two cases of power sources were analysed: asynchronous (induction) generator and synchronous generator.

Induction generator in first few periods is acting as active source. After few periods and due to lack of own excitation system, generator loses characteristics of active source and starts to act as a passive element. This is only valid in case of 3 phase short circuit. In case of 2 phase or 1 phase short circuit, induction generator can be excited through sound phase(s) (due to earthed neutral point).

The behaviour of synchronous generator in fault conditions is very well known – it does not lose it excitation and is feeding the fault.

Calculations are made for sub-transient, transient and steady-state short circuit current on Pe bus-bars. Calculations are made without generation unit, with induction generator and with synchronous generator. Generator unit of 400 kV was considered. Results are given in following tables.

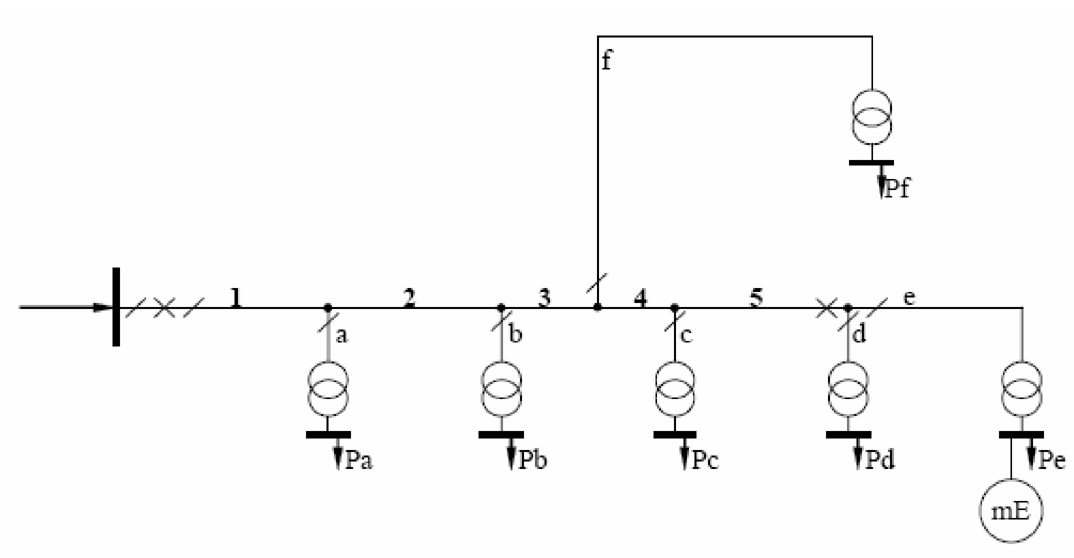


Figure 4.1 Example grid for short circuit currents calculation

Table 4.1 Short circuit current in case of 3 phase short circuit

	Sub-transient	Transient	Steady-state
SC current without generator	$0{,}34\angle-70{,}8°$	$0{,}34\angle-70{,}8°$	$0{,}34\angle-70{,}8°$
SC current with induction generator	$0{,}46\angle-76{,}0°$	$0{,}34\angle-70{,}8°$	$0{,}34\angle-70{,}8°$
SC current with synchronous generator	$0{,}43\angle-74{,}7°$	$0{,}40\angle-73{,}5°$	$0{,}36\angle-71{,}8°$

Table 4.2 Short circuit current in case of 2 phase short circuit

	Sub-transient	Transient	Steady-state
SC current without generator	$0{,}30\angle-19{,}2°$	$0{,}30\angle-19{,}2°$	$0{,}30\angle-19{,}2°$
SC current with induction generator	$0{,}45\angle-8{,}4°$	$0{,}30\angle-19{,}2°$	$0{,}30\angle-19{,}2°$
SC current with synchronous generator	$0{,}37\angle-15{,}3°$	$0{,}46\angle-15{,}9°$	$0{,}34\angle-16{,}9°$

Table 4.3 Short circuit current in case of 1 phase short circuit

	Sub-transient	Transient	Steady-state
SC current without generator	$0{,}39\angle-75{,}5°$	$0{,}39\angle-75{,}5°$	$0{,}39\angle-75{,}5°$
SC current with induction generator	$0{,}56\angle-84{,}0°$	$0{,}39\angle-75{,}5°$	$0{,}39\angle-75{,}5°$
SC current with synchronous generator	$0{,}48\angle-78{,}5°$	$0{,}47\angle-77{,}9°$	$0{,}45\angle-77{,}1°$

Theoretical findings are confirmed by these calculations. During the short circuit it can be clearly seen that synchronous generator constantly contributes to the short circuit current, while induction generator gives only sub-transient component. In this calculation power electronic influences were not included. However, brief discussion will be conducted in order to explain differences between conventional induction generator (direct drive) and doubly-fed induction generator used in wind power plants, since these are the most usual generator configurations used in wind power plants.

Induction generator requires magnetic excitation from the external source for torque production and power flow. In case of short circuit, excitation source is removed and main flux field in induction machine collapses in certain time period. This is just what calculations have confirmed – induction generator only gives sub-transient component of short circuit current. In first few cycles there are both sinusoidal and dc current components. Sinusoidal current component is approximately equal to pre-fault terminal voltage divided by the sum of the sub-transient reactance of the generator and the reactance of the equivalent network to the point of fault. DC component depends on the reactance to resistance (X/R) ratio of the equivalent system impedance and the precise point on the terminal voltage wave where the fault is initiated. After few cycles, dc component vanish and sinusoidal component decrease in value.

In case of doubly fed induction generator, rotor current is controlled by static converter coupled with algorithms in turbine and converter controller. Converter controls can limit the stator currents during the fault. When fault occurs, power converter in rotor circuit suddenly loses control which results in high increase of stator current. Control is regained quickly and stator currents are brought to near their pre-fault value for the duration of the fault event. After the fault is cleared, the phase and magnitude of terminal voltage again change suddenly, inducing another short duration transient in the stator current. However, the control is ones again regained and stator current is set to the level desired by turbine control. However, if the rotor power converter is bypassed, such as might be done to protect it from high rotor circuit voltage, the behaviour of the turbine during the fault would be better characterized as a conventional induction machine.

3.4.2 Wind generator behaviour during the fault (fault ride through)

As wind energy more and more penetrates into power systems, utilities are creating interconnection requirements which wind generators must satisfy. Since the majority of wind generators are induction machines, the reactive power is of a major concern. Apart from compensation requirements, reactive power is important in supporting the system voltage. Important requirement that is imposed to wind generators is the ability to maintain stability during normally occurring power system disturbances. Premature tripping of numerous wind generators due to local disturbances can be a risk for stability of whole system. It is especially the case for systems where there is a high concentration of wind generating facilities, e.g. isolated systems of remote areas like large islands.

Different wind power technologies have different characteristics. Example for this analysis was taken from [3]. Example network is rural regional grid with weak connection to the main system. In order to illustrate different wind generator technologies' dynamic response to fault conditions, a three phase fault is considered as the heaviest fault. Fault has been applied for 150 ms with a following 300 ms line outage. The same fault conditions are applied at same grid topology just using different wind generator technologies. Interesting is to mention that in early stages of wind power developments, only small scale power was produced from wind turbines. Usually, when fault in the system occurred (voltage at the wind turbine drop), wind turbine was simply disconnected from the grid and reconnected when the fault was cleared and the voltage returned to the normal. However, with higher wind power penetration, disconnection of large wind power plant may have significant even dramatic impact on the grid, especially if it has a great share in power production and if the system is weak. Therefore, wind turbines should be able to “ride through” during disturbances and faults to avoid total disconnection from the grid.

Case of *induction generator* is given in figure 4.2. When fault occurs the active power drops and the generator supplies reactive power to the grid. Reactive power supply is decreasing in accordance to rotor circuit time constant. After fault has been cleared, the active power production increases again, but not sufficiently to reach the balance between the mechanical and electrical power. The power surplus leads to acceleration, which also leads to increased reactive power production. It leads to further voltage decrease and less active power supply from generator to the grid. The generator can not recover after the fault without tripping.

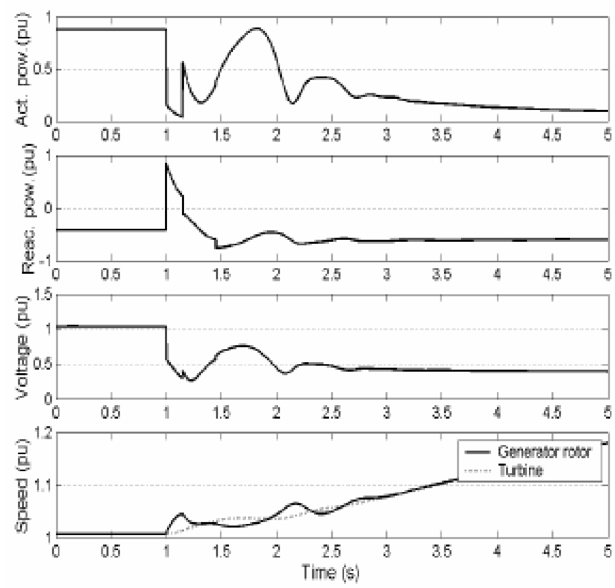
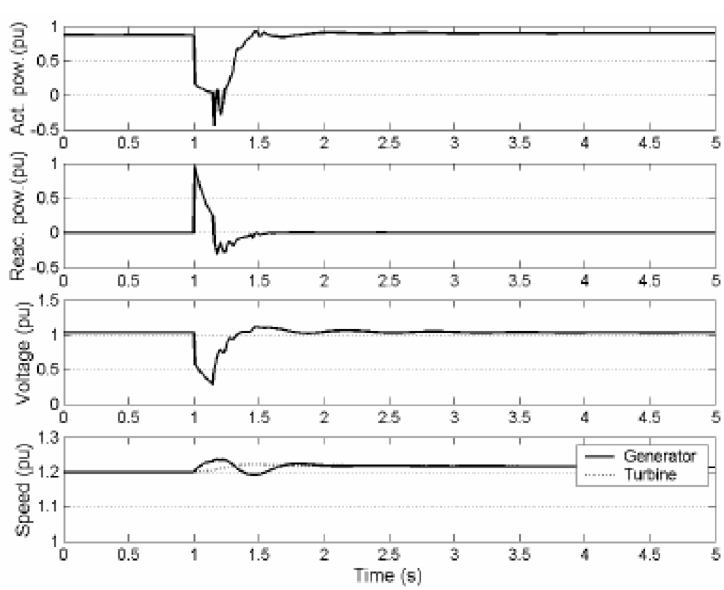


Figure 4.2 Induction generator responses to three phase fault

Doubly fed induction generator has good control capabilities of active and reactive power. When the fault is applied, the behaviour of DFIG is the same as for traditional induction generator – the generator feeds reactive power into the grid and active power is considerably reduced. When the fault is cleared the rotor controller tries to achieve the active and reactive settings. The generator is able to reach a stable position after the fault has been cleared. Thus, DFIG has a better performances compared to the traditional induction generator



solution.

Figure 4.3 DFIG responses to three phase fault

Direct drive synchronous generator response to the same fault conditions is shown in figure 4.4. When the fault occurs the voltage is reduced and active and reactive power production is set to zero. After the fault is cleared the converter starts operating again. The active power is controlled so that reference speed can be achieved. The reactive power reference is set to zero, but is reduced in a short period after the fault has been cleared. This is due to the voltage control, which tries to reduce the voltage at the generator terminal when its value exceeds a certain limit. The curves shown indicates that a stable position can be reached after the fault has been cleared, and that it is acceptable to keep the generators connected during such a fault transient.

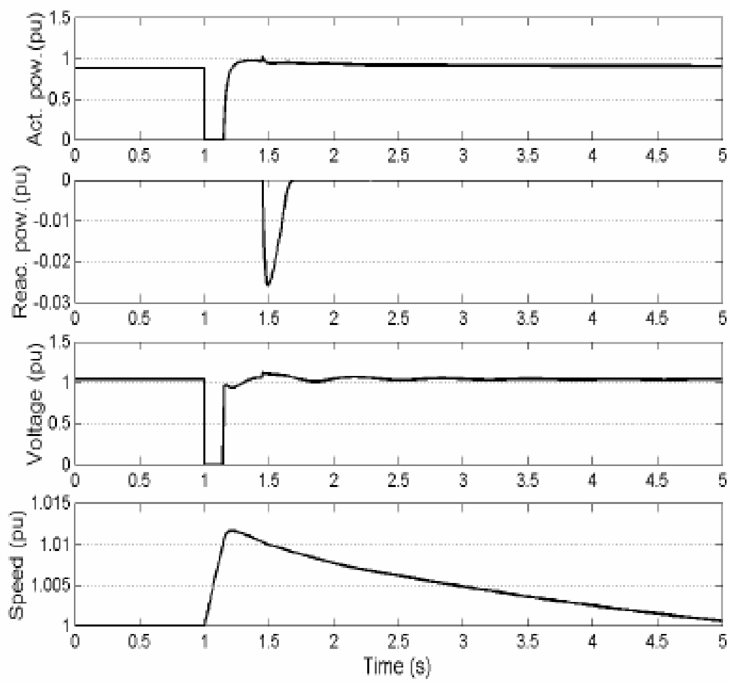


Figure 4.3 Synchronous generator responses to three phase fault

3.5 Final remarks

The aim of this paper was to present three main wind generator technologies. Only machine modelling was presented. However, modelling of whole wind systems has to also include power electronics and sophisticated control procedures. It is very complex task and it has to be done in order to assess influence of wind generation facilities on whole power system operation. It is especially important to examine the influence of large scale wind power integration into weak systems. Problems are usually related to connection and integration to the network, system stability and system control and operation procedures. As it was shown in this paper, different wind power technologies have different characteristics and control possibilities. The contribution form different wind generators to the fault currents was analysed as well as their behaviour during the fault. No general recommendation which technology is the best could be given. It strongly depends on number of factors like site conditions, grid strength and topology, technology and production costs, etc. However, in order to find the best solution detailed analysis with simulation models for every specific system should be carried out.

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4 Generators Influence on Protection in Distribution Network

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4.1 Introduction

Increasing efficiency of distribution network operation is one of important directions where development of contemporary distribution networks (DM) is going. Distribution generators are a very important link in the chain. Usage of such distribution generators (especially if they are green – clear and renewable) are stimulated by most governments. These sources provide direct production of energy close to final consumers and in such way make more efficient energy transport. Finally, installation of more capacity results in stability and reliability increasing [1,2].

It is a fact that most distribution generators are renewable. The main task of this paper is to estimate impact of such generators on distribution network. Large number of papers deals with this task [2–6]. The main concerns of this paper are distribution networks in Serbia and Montenegro where installation of distribution generator is in the beginning.

Taking into account necessity of installation of such generators, appropriate technical recommendations have been issued [4]. This technical recommendation has been made with regards to similar world known recommendation in this area. The following aspects are comprised in the recommendation:

- Defining part of electric network where the recommendation is valid – voltage levels up to 35 kV and rated power of generator up to 16 MVA.
- Basic technical data about network: rated voltages, radial structure, grounding of supply transformer neutral point, maximal short circuit current (power of short circuit), and automatic reclosing.
- Basic technical data about generator: standard voltages and power, frequency, allowed voltage drops on generator connection point, types of generator that can be used.
- Requirements for connecting generator in DM (equipment for parallel operation with network or for island operation); requests for power factor, flickers, harmonic spectrum and short circuit power.
- Requests for realization of connecting line between connecting network point and generator; necessary equipment.
- Measurements; location and equipment; energy meter.

- Protection; minimal required protection (voltage, frequency, overcurrent (over current I>, instantaneous I>>, zero Io>); testing periods of protection.
- Reactive energy compensation (VAR); requirements for synchronous and asynchronous generators; capacitor usage.
- Technical documentation and compliance for append to network.
- The first append of generator; technical examination; checking equipment, synchronization check.
- Operation; maintenance.
- Single line diagrams for appending on different voltage levels.

This technical recommendation makes good basis for operation of distribution generators but some issues are still open. Some of these issues are:

- Impact of distribution generators on existing feeder protections in DM in Serbia/Montenegro; practical question is: when do we have to consider impact of distribution generators (to do some activity about setting and maybe reconstruction/improvement of protection) or what are situations when we have not to do with existing protection.
- If generators are appended on low voltage busbars in substations medium/low voltage (MV/LV), whether MV fuse in such substations burn out for faults on MV supply line.
- How we can identify parts of network which are more suitable to append generator in comparisons with other parts.

Above mentioned issues are the main goals of this paper. In addition, the issues are considered and appropriate solutions are suggested. In the next part, impact of generators on existing feeder protection are considered, then impact of LV generator on MV fuse and finally design of software solution for selection of append point for generator. Conclusion and literature comprises last two parts of the paper.

4.2 Impact of generators on existing 10 kV feeder protection

In this part one important aspect of distribution generator operation is considered. This is impact of generator on feeder protection.

State in distribution network is changed after generator appending. Changes are evident in both – normal and faulted state. Fault state is of particular interest for consideration that follows. Presence of generator changes value of fault current. If generator rating is not so significant (e.g. up to a few MVA and standard size of conductors[1]) increasing of fault current on fault location is not significant. However it is necessary to point out that generator introduce

[1] Standard size of conductors means ACSR 95/15 mm^2 for overhead and Cu 95 mm^2, for cable feeder; Typical feeder length is up to 2 or 3 km.

additional current flow as it is shown on figure 1. Figure shows configuration of one typical 10 kV feeder with 2 MV/LV substations.

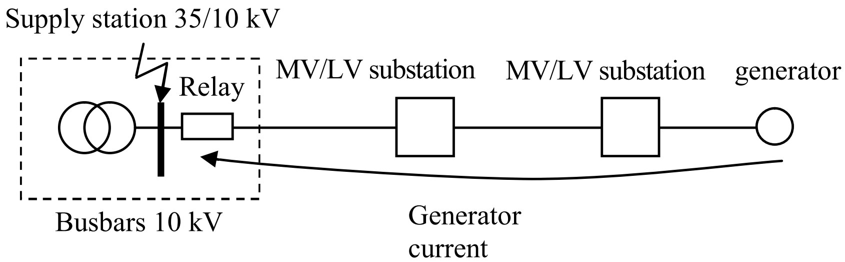

Figure 1 – Fault on 10 kV busbars and direction of generator current

This current is usually of smaller value then current that flow from supply station but direction of this current is opposite. Typical feeder protection is not directional (not directional because radial operation is usual and loops are allowed for short time only).

General problem is that time selectivity of distribution network is provided regarding supply direction. Relays that are physically very far from supply substation have to trip faster then closer relays. But distribution generators can inject currents exactly in opposite direction and it is obvious that existing setting of relays can cause non-selective tripping.

There two moments those are investigated in addition. In previous paragraphs have been mentioned that generator current value is relatively small. So natural question is: when will the generator current have such a magnitude to initiate relay tripping? And if such problem exists, how to solve it.

Answers are given in the following chapters.

4.2.1 Brief description of existing 10 kV feeder protection

In this paper is considered 10 kV distribution network of one real town. This network is mostly of cable type and only small part is of mixed cable/overhead type. This network operates with isolated neutral.

Protection of feeders in such networks is very simple. The main protection is low stage over current time defined protection J> with typical current setting in range 300 – 480 A (for standard size of conductors) while time delay is about 0.3 – 0.5 seconds. This protection is placed on feeder head only. Back-up protection is provided via over current time defined protection J> on supply transformers. Setting of the protection is typically on 1.6 transformer rated current and time delay is 0.8 – 1 second. This protection is intended for line to line faults while line to ground faults are signaled only (operation with line to ground fault is limited on 2 hours after fault occurrence).

Design of distribution network protection is carried out with preposition of radial supply and radial operation. Installation of distribution generators along feeders introduces additional supply source and additional supplying of fault. Generally speaking, currents caused by distribution generators can initiate unselective relay tripping or even unnecessary relay tripping (so called hidden fault). Having in mind request for reliable and save operation of network and protection inside, it is necessary to check if installation of distribution generators initiate selectivity problems on feeder relay (feeder relay are scope of this paper) [5,8]. In addition are elaborated situation when such unexpected relay tripping can occur.

4.2.2 Selectivity problems caused by distribution generators

Let consider the feeder given in figure X.2. One 10 kV generator has been connected on MV busbar inside the first MV/LV substation.

On these two feeders have been simulated the following faults (three phase faults – transient state, no load condition):

A. fault on the first section of left feeder (fault location is approximately 450m from feeder head); before adding generator, feeder protections have the same time delay; this means that current from generator will flow trough 2 feeder relays (from generator can cause
B. fault on feeder heads (supply busbar),
C. fault on the first section of right feeder (fault location is approximately 220m from feeder head).

Results of fault current calculation are given in table 1. Fault current are given for right feeder head. Calculation made by software [11–15].

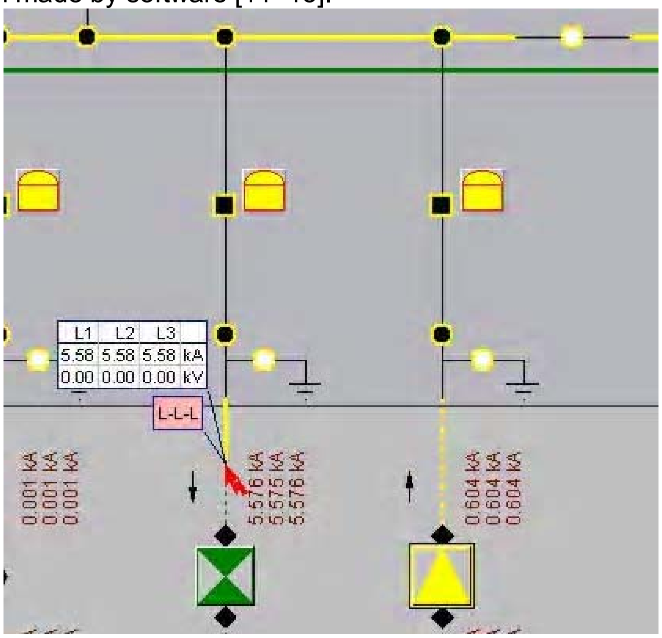

Figure 2 – Fault on left feeder; Power of generator in yellow colored substation is 2500 kVA, current trough right feeder head is 0.604 kA

Table 1 – Currents trough right feeder head

Fault current on feeder head [kA] for:	**Rated generator power Sng [kVA]**					
	630	**1000**	**1600**	**2500**	**4000**	**6300**
A type fault	0.255	0.397	0.402	0.604	0.976	1.519
B type fault	0.265	0.419	0.408	0.635	1.01	1.584
C type fault	5.140 (0.263)	5.145 (0.417)	5.150 (0.405)	5.161 (0.633)	5.165 (1.012)	5.168 (1.586)

Setting of relay on right feeder head is 480A with 0.5 seconds time delay.

From table 1 can be noticed following facts:

For A type fault and rated power of generator 2500 KVA and more, current on right feeder are 0.604 KA and more and such current initiate tripping of relay on that feeder nevertheless the fault is on left feeder! For these cases generator current injection is higher then setting of relay and expected but not necessary relay tripping will occur. This problem can be easily solved by directional relay application. For powers of generators up to 1600 KVA such action is not required. Time delay of generator J> protection has to be greater then delay of relays on feeder head.

If directional protection is applied on right side feeder head, some other problems can occur during B type fault. In this case generator supply fault location, relay on right feeder is blocked and fault will be eliminated by generator protection. Formal problem in this case is that fault on busbar will not be eliminated by closest relay (because this relay is blocked) and duration of fault supply is determined by generator protection that has higher time delay (because this protection has higher time delay then feeder head relay). If distribution generator is of asynchronous type fault will cause losing excitation and this problem will spontaneously disappear.

Then C type fault result analysis follows. Purpose of this analysis to estimate impact of generator on fault current. Two values are given in this row: the first one is current from supply station while value in brackets denote generator current. Conclusion is obvious: impact of generator on fault is relatively small even for high rated power (for 6300 kVA generator current is less then 1/3 of supply station current).

In order to complete consideration for B type fault, one mixed feeder has been taken into consideration. Length of feeder is about 6000 m. Location of generator installation has been moved along the feeder. Results are given in table 2.

Table 2: – Changing generator location along feeder (generator power is parameter); fault locations on supply busbar

Sng [kVA]	**630**	**1000**	**1600**	**2500**	**4000**	**6300**
distance[m]	**fault current [kA]**					
340	0.137	0.231	0.383	0.611	0.988	1.564
1300	0.137	0.221	0.357	0.591	0.937	1.435
4000	0.133	0.191	0.282	0.530	0.783	1.082
5440	0.132	0.177	0.247	0.501	0.714	0.943

It is not difficult to identify that generator current decrease with moving along the feeder. For small generators (630 KVA) changing of current is of symbolic value 0.132 – 0.137 kA while for 6300 kVA generator this interval is also modest 0.943 – 1.564 kA. This result is expected because smaller generator has greater value of absolute impedance (in comparison with generator with higher rating) and this impedance is greater then feeder impedance. Because changing of generator location will not impact on fault current.

One conclusion is also important. Absolute amount of generator fault current becomes comparable with value of feeder relay setting for rated power of 2500 KVA and more. This means that for generators with power with 2500 KVA and more have to check functionality of relays more carefully.

4.3 Impact of LV generators on feeder protection

Finally, the impact of LV generators on supply feeder protection has been analyzed. Analysis carried out in this part has been devoted on checking if fuse (normally placed in MV bay of MV/LV transformer) burn out for fault on MV supply feeder. Consideration is carried out on one 10/0.4 kV substation where LV generator has been directly connected to LV busbar.

Transformer substation with LV generator is given on figure X.3. Feeder is of cable type. Rated power of LV generator should be less or equal with rated power of MV/LV transformer. In this case, the powers of generator and transformer are equal – 630 kVA. Calculations results of faults along the feeder point that impact of the generator on fault current value is **very modest**. Impact of generator is practically constant for any location between feeder head and substation with generator. Also, position of the substation on feeder is irrelevant for generator impact (the same impact in the first and last substation). This means that impact on feeder protection is negligible.

According to usual technical recommendation, rated fuse current is takes as double transformer rated current. Such selection of rated current will give relatively high fuse burn out time (in this case about 50 sec). This means fuses in MV/LV substations will not burn out for faults on MV feeder (otherwise for every fault will be necessary to change fuse patron). This situation is OK for asynchronous generators (most of renewable distribution generators are of this type) while for synchronous (self exciting) generators it can be potential problem because fault location will be supplied by generator and this situation has to be solved by additional protections.

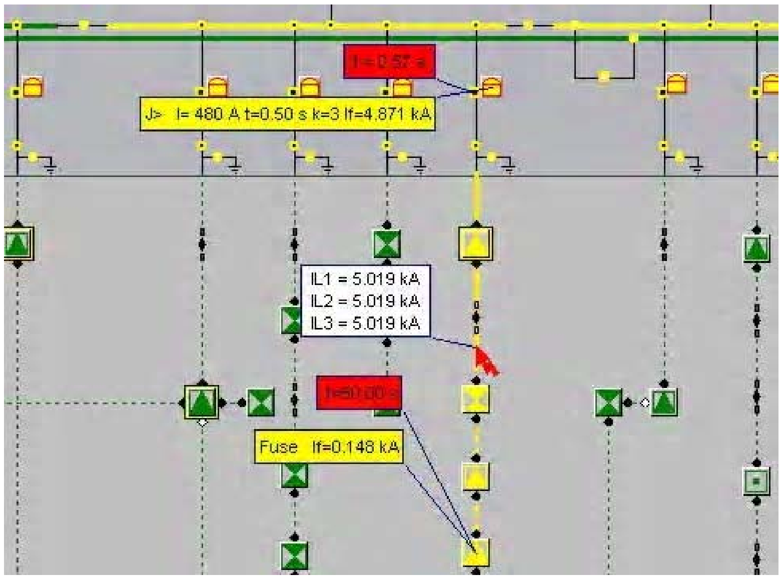

Figure 3 – Fault and protections; Explanation – yellow rectangles contains protection type, setting (current and time normally for relay, not for fuse) and fault current If; red rectangles contains tripping time; fault location is marked by red arrow and in white rectangle is fault current magnitude.

4.4 Design of "Generator location" application

It is obvious from previously carried out analysis that a relatively great set of parameters has to be considered in calculation. Firstly these parameters are generator parameters and then parameters of other distribution network elements. Therefore, it is very difficult to get analytical relations that can describe generator impact on existing feeder protection.

In order to solve this problem, authors suggest one elegant solution that can be carried out through DMS environment. Having in mind this idea following set of data should be required:

1. generators features (set of possible generators which can be potentially installed in the network),
2. set of potential locations (feeders and substations) where generators can be installed and
3. set of constrains that have to be checked:
    a. rated generator current have to be less or equal with rated current of connecting section (connecting section makes link between the generator

and existing feeder; if connection of generator is directly in substation this constrain will be omitted)

b. checking selectivity and functionality of relays (e.g. checking unexpected tripping of non directional relays on feeder head).

Set of constrains can be defined in such a way that additional investment or replacing existing relays is not required. Also can be investigated the case where existing type of relays can be replaced with other one (this can be what/if analysis).

Algorithm of this application should consist of the following steps:

1. defining generators features (defining set of generators that can be installed),
2. set of potential locations (feeders and substations) where generators can be installed; normally possible locations for installation of generators are known in advance; dilemma that appears in which point of the network is the most appropriate to connect this generator; so all feeders that are physically in neighborhood of generator location have to be taken into consideration as possible connecting points; generator can be connected in existing or brand new transformer substation (joint, switching station) directly or via connecting line.
3. defining set of constrains,
4. connecting generator in the first of possible points, calculations and checking constrains
5. repeating of step 4 for other possible connecting points,
6. identification of solutions where constrains are not violated and identification of possible solutions.

The "Generator Location" application would be used previously established calculation engine for other DMS functions [11–15]: network planning, fault calculation, state estimation and relay protection.

For practical realization in steps 4 and 5 it is necessary to create projects/scenarios that take in consideration all events connected to generator installation in the distribution network (e.g. this means creation new substation and reconstruction of existing sections, …). Planning tool provide also cost analysis, so this very important factor can be taken in consideration, so identification of possible solutions in step 6 can be partially or completely directed to costs.

4.5 Conclusion

In this paper the impact of distribution generators on existing relay protection on feeders has been considered. Analyzed cases and appropriate calculated results point out, that the impact of generators is evident and has to be carefully taken into consideration. In the paper are given some numerical values that can be used during estimation of generator impact. Finally, the idea is promoted, that the problem of distribution generator installation should be considered trough special DMS application "Generator location" that can be powerful and useful for comprehensive analysis of generator impact. This application is elaborated on design level in the paper.

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5 In-field verification of the real-time distribution state estimation

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5.1 Introduction

The State Estimation represents the basic function in both Energy Management System (EMS) and Distribution Management System (DMS), since a lot of power applications in both systems (load flow, fault calculation, relay protection, voltage control, security and loss analysis, etc.) are based on the estimated actual (or studied) state. The state estimation of transmission networks has been established several years ago [1]. The corresponding estimation procedures are founded on the high level of network remote monitoring provided by usual Supervisory Control and Data Acquisition (SCADA) systems. The redundancy of real-time telemetered data about both the network state and topology is usually higher than 2.0. Such a redundancy provides not only a high quality estimation of the network state, but also a high quality dealing with wrong measurements, validation of network parameters and topology.

Usually modest remote monitoring of distribution networks referring to transmission ones is the key difference in the management of both networks. Distribution SCADA systems usually cover only supply substations and a small number of medium voltage (MV) points. Thus, the redundancy of real-time telemetered data in distribution networks is significantly smaller than 1.0 (it amounts about 0.2 – 0.3 [2]). Nevertheless, there is a large number of attempts to transfer and adopt the estimation algorithms from the transmission into the distribution environment [3-6]. These attempts have not high chance for success for the noted small distribution data redundancy. That is why new specialized algorithms for distribution state estimation have been developing in the last ten years [7-9]. Nevertheless, there is no reference that establishes a standard state estimation procedure and proves it in the distribution network practice.

A simple, fast and robust Real-Time Distribution State Estimator (DSE) is briefly described in Section 2. It represents a compromise between complex methods proposed in the literature and standard available data in distribution utilities. The developed DSE can be applied in any distribution utility – with or without installed SCADA system, in both the on-line (real-time) and off-line mode.

In-field verification of the DSE is presented in Section 3. It is done by comparison of the results obtained by its running and the measurements performed in the field. The sensitivity of the estimation results on both the real-time measurements and historical data is specially accented. Particularly from renewable systems perspective crucial example is presented in Section 4 for test network with dispersed generators. The conclusion derived in Section 5 is that the state estimation in distribution networks is not only possible, but also sufficiently reliable and accurate for the purpose of real-time managing of distribution networks. References used for writing this paper are listed in Section 6.

5.2 State Estimation Methodology

Distribution state estimation consists of calculation of the entire network state for specified voltage phasor of the network root, the network topology, the real-time (telemetered) data about both the state – *measurements* and topology – switchgear statuses, as well as known historical data about loads. The measurements could be current magnitudes and power factors, active and reactive powers and voltage magnitude at any network location. The historical data consist of two groups: (*i*) dimensionless *daily load profiles* for current magnitude – DLP (I) and power factor – DLP (cos φ) and active power – DLP (P) and reactive power – DLP (Q) and (*ii*) *load weights* – peak values (kW, kVAR, A), supplied energies (kWh, kVARh) and rated powers of the equipment (kVA). DLPs (currents or powers) multiplied by corresponding peak values give daily load curves (DLCs) in corresponding units.

The developed DSE algorithm consists of 5 steps:

1. Pre-estimation,
2. Topology Verification,
3. Measurements Verification,
4. Load Calibration and
5. Load Flow Calculation.

5.3 Pre-estimation

The Pre-estimation consists of Load Flow Calculation [10] for specified root voltage and loads taken from DLCs, for the considered time moment. All calculated values in this step are termed *pre-estimated values*. If the network is not remotely monitored (by SCADA system), this step is the last step of the estimation algorithm.

5.4 Topology Verification

Topology Verification means detection and elimination of errors made in updating of changes of switchgear statuses that are performed by SCADA and specially those that are performed manually in the field. This verification is not a simple issue in distribution networks where the redundancy of telemetered data is very modest. However, the following two heuristic rules are used in Topology Verification process: In networks where the load continually varies, and the state estimation is permanently run (e.g. each 10 seconds), each step-change of a telemetered measurement and a high differences between "good" historical data and telemetered measurements means change of the network topology or error in telemetered measurement.

5.4.1 Measurements Verification

Measurements Verification means detection, correction of errors or elimination of telemetered *"bad" measurements*. Because of the small data redundancy, like the Topology Verification, the Measurements Verification is not a simple issue either. It is based on the artificial data redundancy provided using pseudo or virtual measurements taken from the results of the Pre-estimation step. Measurements Verification consists of 5 sub-steps.

5.4.1.1 Preparing of measurements.

This sub-step consists of transformation of all measurements of different nature (powers, currents, power factors) into uniform measurements:

- current magnitude and power factors or
- active and reactive powers.

5.4.1.2 Elimination of obviously bad measurements.

The term *obviously bad measurements* means a measurement: 1 – that is outside of limits imposed by relay protection that has not tripped; 2 – that is zero-valued, but downstream this measurement exists a load and 3 – that exceeds the pre-specified difference from its pre-estimated value. These measurements are discarded from the next steps of the estimation procedure.

5.4.1.3 Network reduction.

In this sub-step the network is reduced by equivalence of all non-observable parts – islands. An island consists of all electrically connected elements (line sections, transformers …) without telemetered measurements of currents and powers. The island is connected to the external network exclusively by branches with telemetered measurements. Thus, islands are not observable in details, but their total load is. In this way, after applying a very simple equivalencing procedure, the predominantly non-observable network with N buses (Fig.1a) is reduced to a fully observable equivalent network with No buses (islands are stressed by dashed lines in Fig.1).

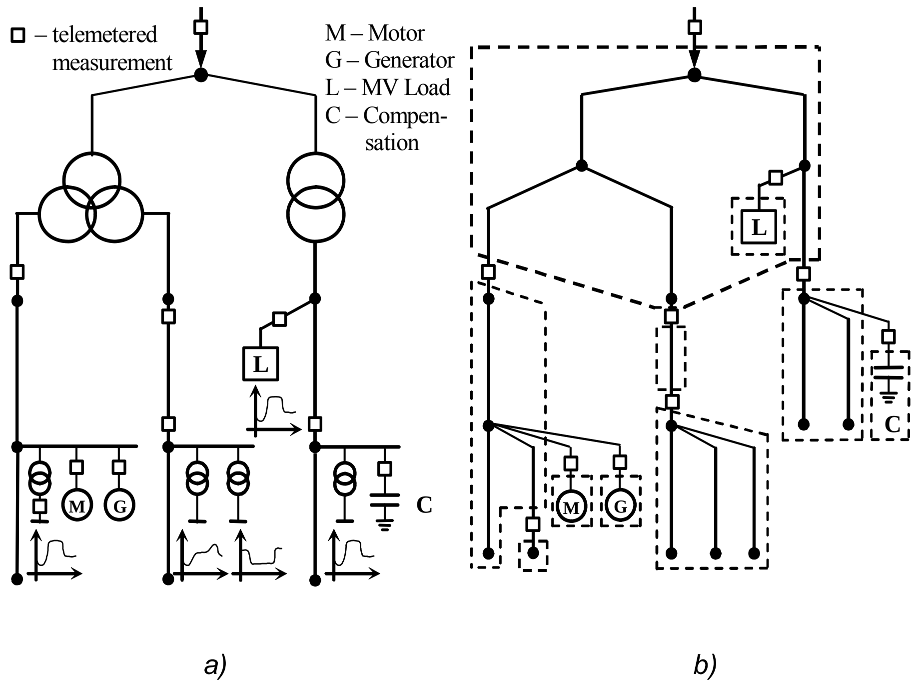


Fig.1 – (a) The network, (b) divided on non-observable islands

5.4.1.4 Verification procedure.

The constrained optimization procedure for verification of measurements, applied on the observable network equivalent model (with reduced number of buses), is radically faster than one applied on the total network model. This procedure consists of minimization of the objective function – the sum of weighted squares of differences between measured (m) and pre-estimated (p) from estimated values (e) of N_m telemetered measurements x_j and N_o total islands loads x_n:

$$\Phi = \sum_{j=1}^{N_m}[w_j^m(x_j^m - x_j^e)^2 + w_j^p(x_j^p - x_j^e)^2]W_j + \sum_{n=1}^{N_o}[w_n^p(x_n^p - x_n^e)^2]W_n \;, \tag{1}$$

with one constraint per each island:

$$f_n = x_n^e + \Delta x_n^p - \sum_{j=1}^{N_m} k_{nj} x_j^e = 0 \;, n=1, \ldots N_o \;. \tag{2}$$

The relative weights of telemetered and pre-estimated values are denoted with w; the relative weights of state variables and islands loads are denoted with W; k represents the sign of the measured value xj (positive when the measured value enters into the island); ∆xn represents the total active and reactive losses when active and reactive powers are the unknown variables xj in (1) and real and imaginary parts of island total shunt current when currents are unknown variables.

The load flow equations are the main constraints of the considered optimization procedure. They are implicitly included in the procedure in both the Pre-estimation step and the fifth sub-step of this step – Load Flow Calculation.

The results of the optimization procedure consist of estimated measurements and total islands loads that will be checked in the following sub-step.

5.4.1.5 Bad data detection and elimination.

The measurement with maximal deviation from its estimation calculated in the previous sub-step, that exceeds the pre-specified threshold, is also termed bad measurement and it is eliminated from the remaining part of the estimation procedure. After elimination of the bad measurements, sub-steps 2.3.3 and 2.3.4 are repeated until no one bad data appears.

5.4.2 Load Calibration

All loads (active and reactive powers or currents magnitudes with power factors) that are directly monitored (telemetered) are already estimated in the previous step. The other ones belong to non-observable islands. The estimation of the load of bus *i*, in the island *n*, with *N* buses, states:

$$x_{ni}^{e} = \frac{x_{n}^{e}}{x_{n}^{p}} x_{i}^{p}, \quad i=1, \dots N, \qquad n=1, \dots N_{o}. \qquad (3)$$

5.4.3 Load Flow Calculation

Finally, the estimation of the state of the original network is performed by running the distribution Load Flow [10], for loads calibrated in the previous step and specified root voltage phasor.

5.5 In-Field Verification Of DSE

DSE is verified with the practical experience collected in the real-life network of Distribution Utility Elektrovojvodina, Division ED Sombor, Serbia, presented in Fig.2. The considered part of the network consists of the area of the supply transformer ST1, 31.5 MVA, in the supply substation SS 110/20 kV/kV "Sombor 2". ST1 supplies 6 MV feeders and 8.975 customers through 135 distribution transformers with total rated power of 40.300 kVA. The considered supply substation is covered by SCADA system. MV (20 kV) network (except the MV feeder heads) is not remotely monitored. The results of DSE real-time running are compared with the measurements provided by both the SCADA (ST1 and MV feeders heads) and specially installed instruments at the low voltage (0.4 kV) sides of distribution transformers 20/0.4 kV/kV. Presented results belong to the experiments performed in autumn 2004.

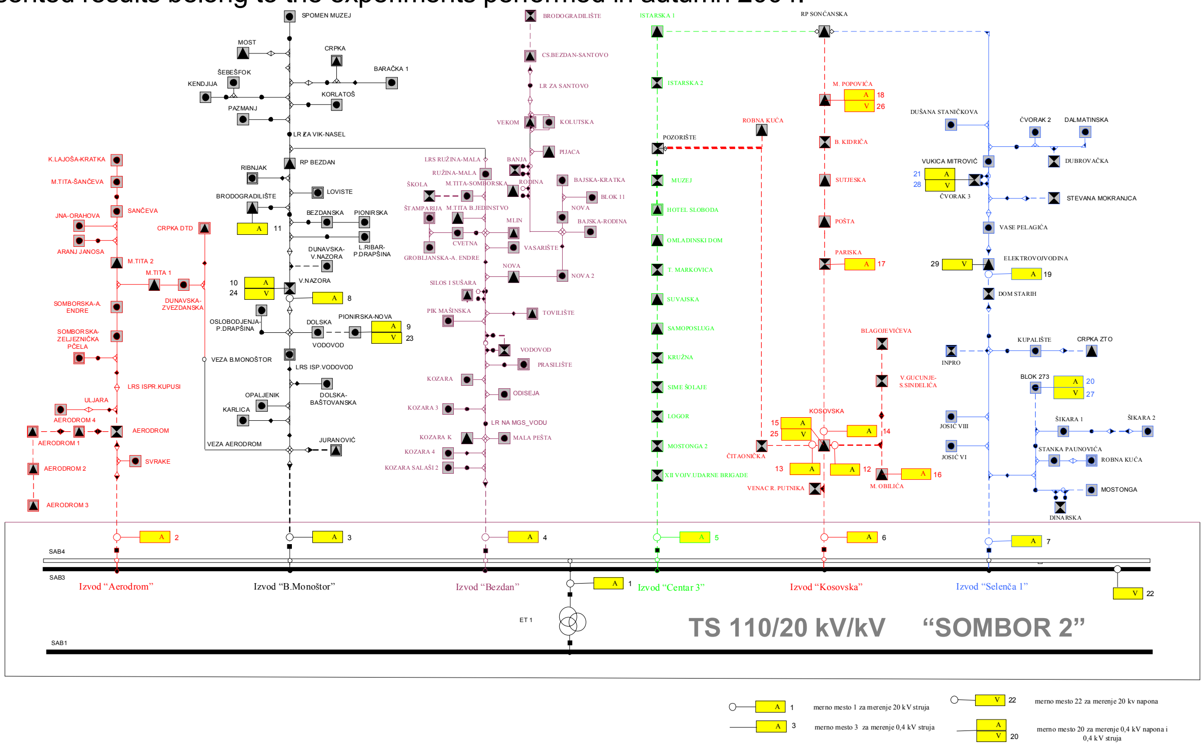


Fig.2 – Considered part of the network of Distribution Utility Elektrovojvodina, Division ED Sombor

Five important aspects of DSE are specially stressed in the presentation that follows: (*i*) the significance of a "good and accurate history", (*ii*) the estimation of voltages is significantly "better" than one of currents (powers), (*iii*) the estimation error decreases as the estimated point supplies higher number of loads, (*iv*) the ratio of weights of the history and measurements in the distribution estimation is quantified and (*v*) the contribution of measurements to the distribution estimation is quantified either.

Three types of lines are used at figures that follow: black dashed for DLCs; dotted blue for measured and thick red for estimated values. Four measures for estimation error are presented in these figures: *A* – averaged absolute deviation of the pre-estimated from the measured value [%]; *B* – maximal absolute deviation of the pre-estimated from the measured value [%]; *C* – averaged deviation of the estimated from the measured value [%]; *D* – maximal absolute deviation of the estimated from the measured value [%].

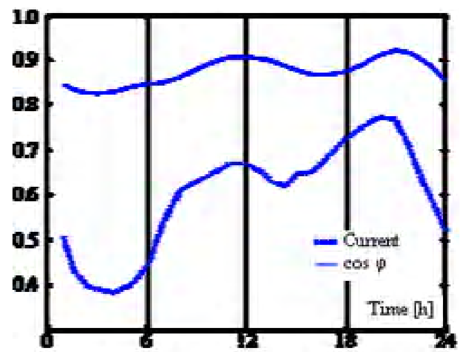


Fig.3 – Daily load profiles of the distribution transformer "Skola".

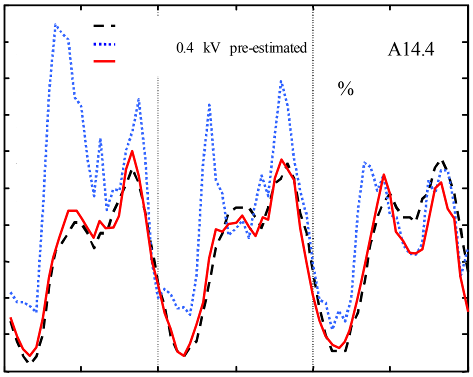
Fig.3 shows samples of DLP(I) and DLP(cos φ) for the "worst case" distribution transformer "Skola" that is considered in the sequel. This transformer is supplied by the feeder "Bezdan". Its estimation results are presented in Fig.4 (a – currents, b – voltages). It is obvious from Fig.4a that this transformer has a "bad history", especially for Friday and Saturday.

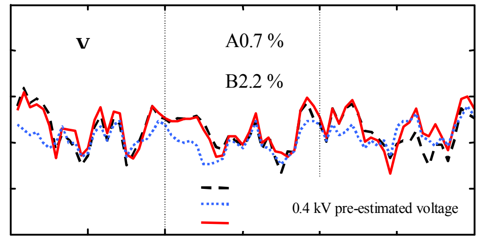
History – Fig.5a and b present the same results as Fig.4a and b, a month later, for significantly "better" historical data. These data were provided in the previous month (since the load of distribution transformer "Skola" was monitored).

Estimation of voltages – It is obvious from both pairs of figures Fig.4 and Fig.5 that the quality of the estimation of voltages is significantly better than one for currents (powers) – measures of estimation errors in Fig.4b and Fig.5b against ones in Fig.4a and Fig.5a. Moreover, the pre-estimated values of voltages are very close to estimated ones. This is a principal consequence of the good root voltage that is used for both pre-estimation and estimation calculations.

Estimation at points which supply large number of loads – Fig.6 and Fig.7a present estimation results for currents of feeder "Bezdan" head and supply transformer ST1 from supply substation "Sombor 2", that supply this feeder. It is obvious from these figures that estimation errors are significantly smaller (the estimation quality is significantly better) than ones for distribution transformer "Skola" in Fig.4a, for the same – "bad" historical data. This is a general conclusion confirmed in all parts of the considered network.

History weight – It is obvious from figures 6 and 7a that the historical data for Sunday afternoon are "bad". To increase the estimation quality with the same quality of the historical data, in the networks with good telemetered real-time data (measurements), one could decrease the weight of the history against the weight of the measurements in the estimation procedure. The results of all estimations that are presented were made with weights of the history and measurements in the proportion of 30%/100%. The results of the estimation of supply transformer ST1 in Sunday, with decreased weight of the history in four steps (from 30% to 1%), are presented in Fig.7b. In addition, all experiments with the DSE confirm that weight of the history in the distribution state estimation shouldn't be smaller than 1% referring to the weight of measurements.

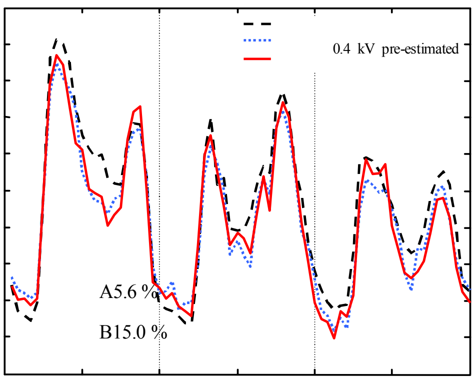


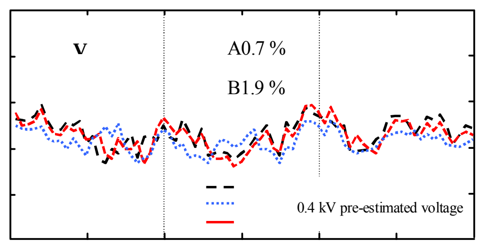


a – 0.4 kV side load current

b – 0.4 kV side load voltage

Fig.4 – Distribution transformer "Skola" – "bad history".





a – 0.4 kV side load current

b – 0.4 kV side load voltage

Fig.5 – Distribution transformer "Skola" – "good history".

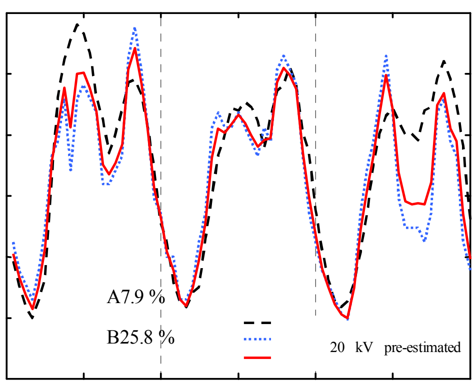
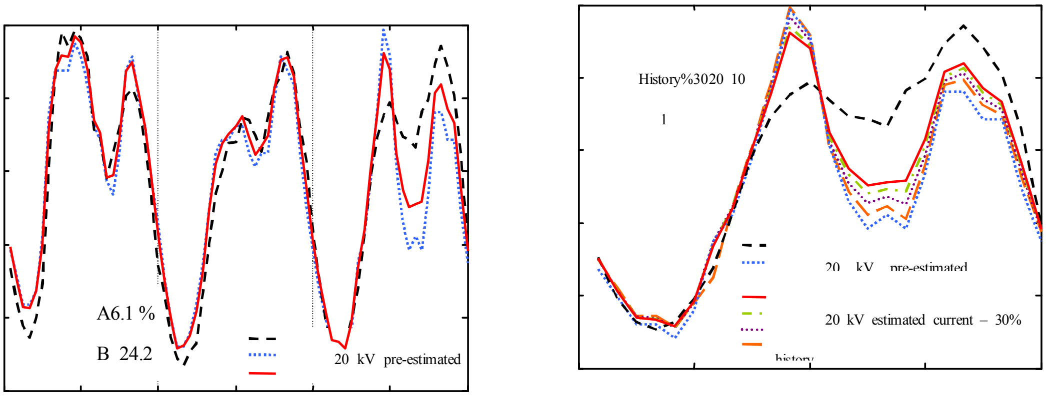


Fig.6 – The current of 20 kV feeder "Bezdan".



a – the history is weighted with 0.3 b – with different weights of the history

Fig.7 – The current of supply transformer ST1 in supply substation "Sombor 2"

Measurements – The quantitative contribution of measurements (real-time telemetered data) to the quality of the distribution state estimation is obvious from all figures on the base of the differences of measures of estimation errors (*A* – *C*) and (*B* – *D*). From the other side, all figures (and all experiments made in the network) confirm that the state estimation in distribution networks without real-time telemetered data (measurements), where only the historical data are at one's disposal, is not useless (see measures of estimation errors *A* and *B*).

5.6 Test System With Generations

Considered part of the network does not have a single generator, so possibilities of a developed mathematical model for state estimation of distribution networks with disperse generators have been shown in example of medium voltage test distribution network, Fig.8.

The network consists of 10 cable sections, 8 distribution substations (TS) – one TS HV/MV$_1$/MV$_2$ (110/20/10 kV/kV/kV) with 2 supply transformers and seven TS MV/LV (20/0.4 kV/kV), with total 13 MV/LV transformers. The following figure also has locations with telemetered values of measured current phasor displayed with mark , and magnitudes of voltage phasor with .

Test network consists of two equal generators: G1 generator placed in the supply substation, and G2 placed deep in the network.

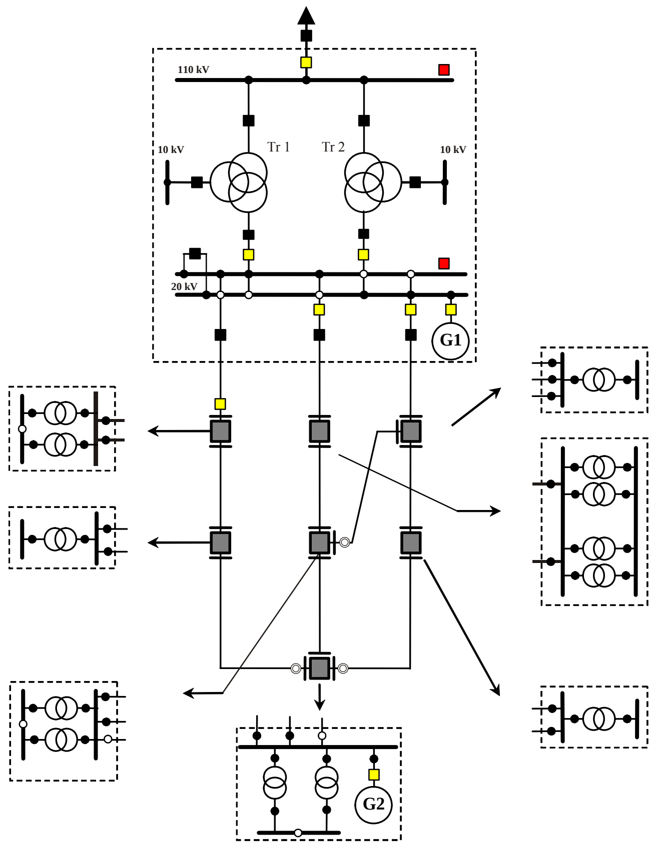


Fig.8 – Test network with dispersed generators.

First is considered the influence of measurements quality of current phasor to generator G1 (generator in the supply substation). In Table 1 are displayed exact values of magnitude of current phasor, active and reactive powers on generators as well as objects with measurements: MV/LV substations and MV feeder heads.

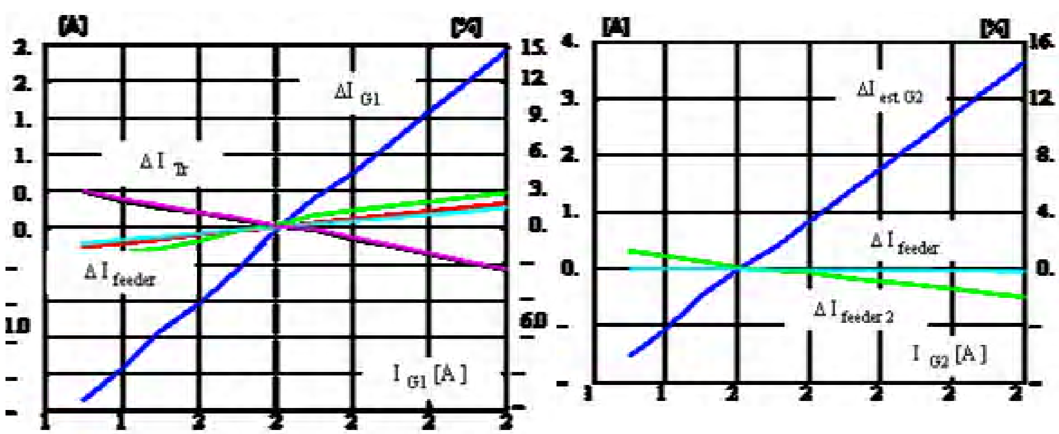
Table 1 – Values of current magnitudes, active and reactive powers of objects with measurements in the network

object	*I* [A]	*P* [W]	*Q* [VA]
Generator in TS VN/SN	22.10	647.70	426.50
Generator in TS SN/NN	19.98	641.60	305.90
Transformer 1	33.70	1186.10	168.29
Transformer 2	33.60	1189.46	131.23
Feeder 1	22.33	781.50	129.67
Feeder 2	47.90	1590.40	606.80
Feeder 3	18.34	650.08	31.92

In examples that follow the value of magnitude of measured current on generators has been varied in interval from 17 to 28 [A]. In figures 9, 10 and 11 are presented values of errors between estimated and exact values of current magnitudes, active and reactive powers in the network. Figures 9a, 10a and 11a are related to examples when value of measured current magnitude is varied on generator G1, and figures 9b, 10b and 11b when value of measured current magnitude is varied on generator G2.

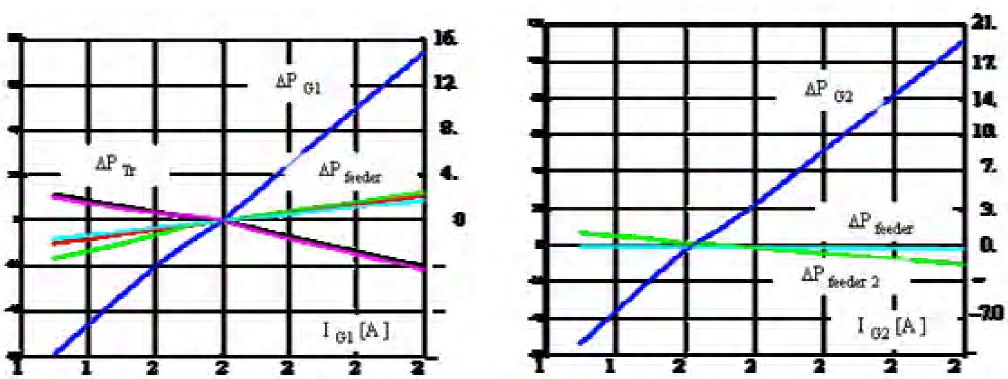
Curves in figures have the following meanings:

- blue line — generator
- red line — feeder 1
- green line — feeder 2
- cyan line — feeder 3
- black line — Transformer Tr1
- magenta line — Transformer Tr2



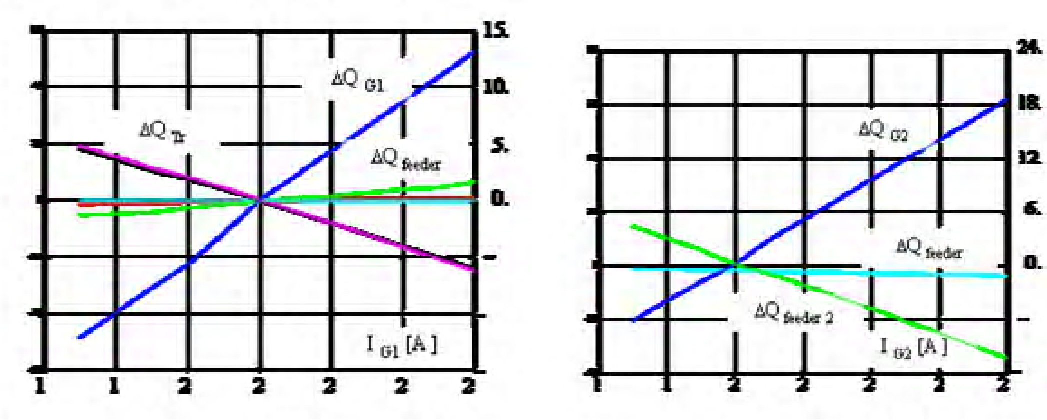
a) b)

Fig.9 – Estimation errors of current values



a) b)

Fig.10 – Estimation errors of active powers



a) b)

Fig.11 – Estimation errors of reactive powers

5.7 Conclusion

This paper briefly describes the idea of DSE – a fast, robust and very efficient distribution real-time state estimator. Its speed is a result of the reduction of all parts of the network which are not observable (remotely monitored) in the network mathematical model. It is robust since it is tailored to be applicable in any distribution network – from one where only historical data are available, until one that is fully remotely controlled. In-field proof of its efficiency was the main aspect of this paper. The presented results are only a small, but representative sample of the large complex of measurements and DSE running, performed in the last few years, especially in autumn 2004. This sample stresses the main conclusions derived from the named large complex of measurements. These are: 1 – The significance of historical and real-time (telemetered) data is not only stressed, but also their relative weights are practically stated; 2 – The estimation results are much better as the estimated network elements supply higher number of loads; therefore, the estimation of losses in these elements is better; 3 – The estimation of voltages is very good; therefore, the centralized voltage control could be performed very efficiently.

Finally, the paper proves that the real-time state estimation in distribution networks is not only possible, but also it is sufficiently reliable and accurate for the purpose of real-time managing of distribution networks with motors, capacitor banks and dispersed (renewable sources) generation. DSE is designed in such a way that its effectiveness is in direct proportion with the size of the observable part of the network and the quality of the historical data.

5.8 Acknowledgments

DSE was developed and put into operation by DMS GROUP Ltd. for Power Engineering Novi Sad, in the Electric Power Distribution Utility Elektrovojvodina, Novi Sad, Serbia, in accordance with the Protocol No. 1.311 – 9153/1, dated November 12, 2002.

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6 Control Aspects: SCADA Systems

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6.1 System of remote Controling

6.1.1 SCADA System

SCADA is an acronym of **S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition (data acquisition, supervision, monitoring and control) and means the entire spectrum of equipment, systems and solutions enabling data acquisition about some process – remote system, data processing, supervision and in some cases reaction in adequate way.

Due to its flexibility it is applied in different fields:

- Electricity generation (conventional and nuclear),
- Oil industry,
- Metal industry,
- Water management services,
- Communications,
- Safety systems,
- Chemical industry, etc.

Depending on user's needs SCADA provides range from few thousands to few 10-thousands input/output (I/O) channels.

The simplest example of SCADA system is an ordinary PS, which through acquisition-control card receives data, creates data about the process, processes them and thus makes supervision, but also performs control if foreseen at that level. Basically it is centralized system of acquisition and control.

More complex example of SCADA system is network supported by computers and through radio connection controlled terminals TU (Terminal Unit) which communicate with computer center. It is a distributed control system DCS (Distributed Control System).

The most complex example of SCADA system is network of the SCADA systems that functions by principal server–server, server–client. Those are WASCAD (Wide Area SCADA) systems.

Classic SCADA system is oriented toward control of the industrial processes or automation of laboratories and distinguished with small dislocation of some SCADA elements, more reliable execution of communication activities and much higher level of automation of the control activities.

More complex SCADA system (WASCAD) is oriented toward control of geographically distributed systems where due to complexity of the process and communication errors the automatic control of process on local as well as supervision level is avoided.

The first SCADA systems had been applied in mid (60's) of the last century.

6.1.2 Basis of data acquisition and control

Sensor is an element, which directly receives physical value, and it is part of measuring transmitter. Measuring transmitter "gives a life" to the sensor because only when measuring transmitter is connected to the sensor it is possible to measure modifications of electrical value proportional to modification of some physical value. Input physical values could be:

- force,
- temperature,
- relative humidity,
- length,
- revolutions,
- speed,
- light intensity, etc.

Of course there are the sensors that immediately give electricity by modification of some physical value (e.g. pressure gauge by mean of crystals which at their ends give voltage proportional to the pressure - piezo effect), but beside that it is necessary to connect measuring transmitter because the electrical signal is most often small and it is necessary to be increased and adjusted for analog – digital converting. The electrical equivalent of input value can be:

- voltage,
- current,
- capacitance,
- inductivity,
- power,
- energy.

However, basic elements composing primary data acquisition – ***primary acquisition,*** work only with the voltage signal. Essentially, modifications of other values could be observed trough the modification of voltage.

Adjustment or preparation of the measuring signal is performed through ***measuring module*** that also performs conditioning of the signal.

Adjustment of measuring signal means:

- filtering,
- amplification,
- linearization,
- buffering – sample/hold,
- damping.

For example if the signal for measuring transmitter is change so quick so that A/D converter can not process it, it is necessary to adjust level which perform sampling and holding of signal while conversion is not finished.

If measuring transmitter at the exit gives the normalized signal then the term measuring converter is in use. Part of the measuring converter providing standard signal into another, considering that they have the same physical nature (electrical) is called the signal converter. Ver often the measuring transmitter and measuring converter in one cabinet are called the probe. Results of measurements taken by probe could be shown through:

- analogue indicator,
- digital indicator,
- PC.

Display through the digital indicator and PC is anticipated by conversion through AD cards. The referred method of displaying presents conventional conversion method of physical to electrical value, which implies hardware conversion of measuring signal.

New approach implies program supported conditioning of the measuring signal, while acceptance itself of measuring signal is of course still left to the analog-digital converter, but with higher resolution.

The feedback influence to measuring-regulation system is realized through the actuating mechanism, ***activator*** to whom is anticipated previous actuating converter. Here as in data acquisition, the converter enables “remote operation”, in this case activation of the actuating mechanism by standard current (4-20 mA) or voltage (10 V, 24 V) signal. The most common activators are: valves, dampers, etc.

The activator is composed of:

- Mechanical device (valve, dampers, etc.),
- Driving device (solenoid, servomotor – electric, pneumatic or hydraulic).

6.1.2.1 SCADA Subsystem

SCADA subsystem is composed of:

- Terminal unit (TU),
- Transmitters,
- Converters,
- Activators.

The terminal units (TU) are electronic equipment installed at places where is performed monitoring of conditions, events, measuring of values through the sensors or monitoring of operation of some other device. The unit converts the measured signal or condition into the form that can be sent through the communication medium toward the supervisory control unit SCU (Supervisory Control Unit). The terminal unit also receives data from supervisory-control unit (SCU) and converts them in form of commands for some actuating device. Programmable logic controllers PLC (Programmable Logic Controller) are most often used as terminal units. Basically, the terminal unit (TU), i.e. the PLC has:

- Application software in memory,
- Microprocessor,
- Components for control of switch on/ switch off of some other device.

But, more sophisticate TU or PLC presents PC that has acquisition-control card or the extended BUS designated for monitoring and control of systems – other devices. In dependence of nature of the application TU (PLC) depends the hardware and program support of:

- Measuring of analogue signals through A/D cards,
- Monitoring of status in real time through DI cards,
- Control of analogue devices through D/A cards,
- ON/OFF control through DO cards, etc.

Processing of measuring data, perceiving of alarm conditions and events, but also executing of control functions of SCADA system, could be entirely performed locally at terminal unit TU (PLC) itself.

6.1.2.2 Topology of the SCADA network

Communication between terminal units TU (PLC) and supervisory-control units SCU as well as communication SCU-SCU is carried out through the communication media in dependence of possibilities and requests of users. Transfer of data is possible to be realized through:

- public phone network,

- hired phone pairs,
- other allocated wire connections,
- two-way radio systems,
- satellite connections,
- fiber – optic connections,
- available LAN networks, etc.

The local networks that enable very well known topologies:

- BUS - open multipoint,
- STAR - point to point,
- RING - closed multipoint.

are ideal for SCADA systems with small dislocation of element of some control process.

Supervisory-control centers are usually equipped with PC or some strong computer system. Those computers are programmable supported by application type MMI (Man Machine Interface) that enables interactive dialog with computer for particular system of supervision and control.

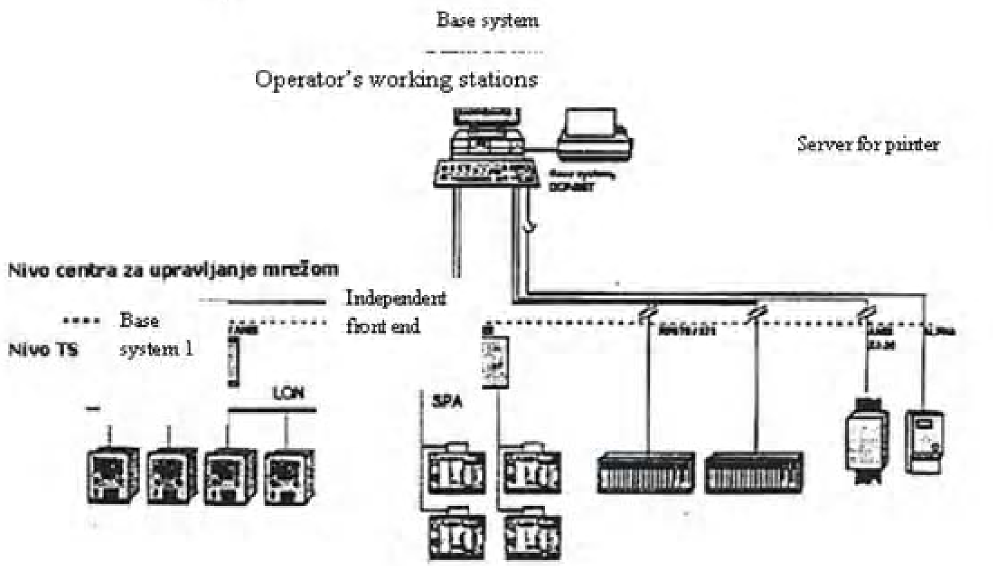
Basis for decision-making and control at this level make data received from terminal units TU (PLC). By forming central database all data are converted in form suitable for presentation and generating of control actions (MMI application – SCADA program support). MMI application is inevitably supported with graphic interface that offers possibility of some parts of reports or displaying of more signals at one diagram, scaling the system, but also possibility of signal processing (digital filtering, spectrum analyze) ***in real time*** (on-line processing). Additional possibilities of MMI interface are:

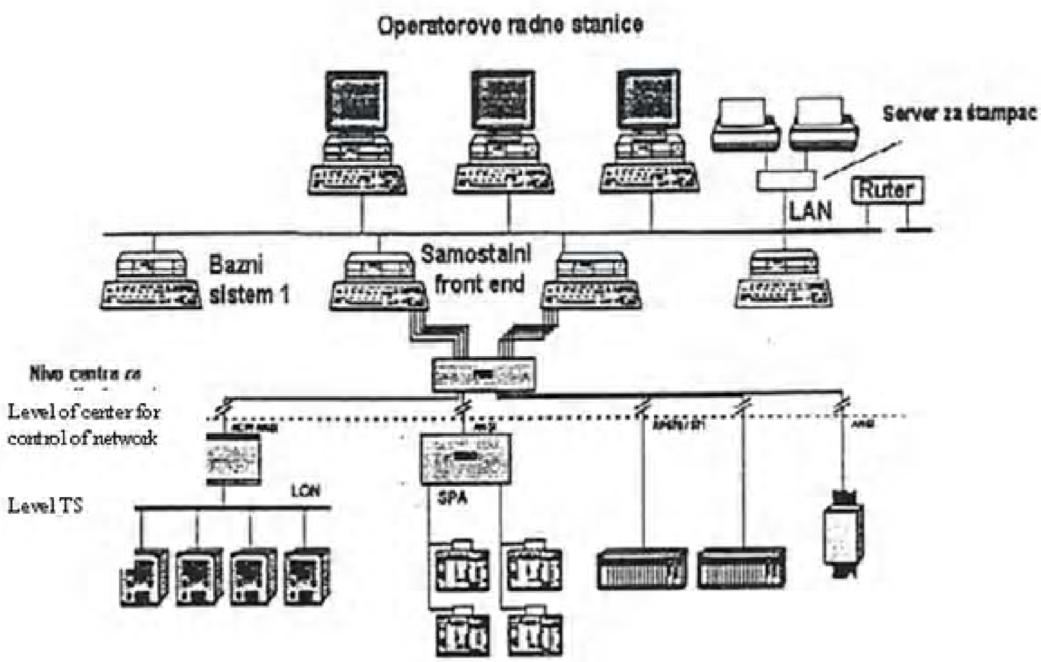
- graphic displaying of objects from different perspective,
- displaying of installations per levels, i.e. mechanical sub-stations in form of mimic diagrams with display of work status,
- display of measuring values, etc.

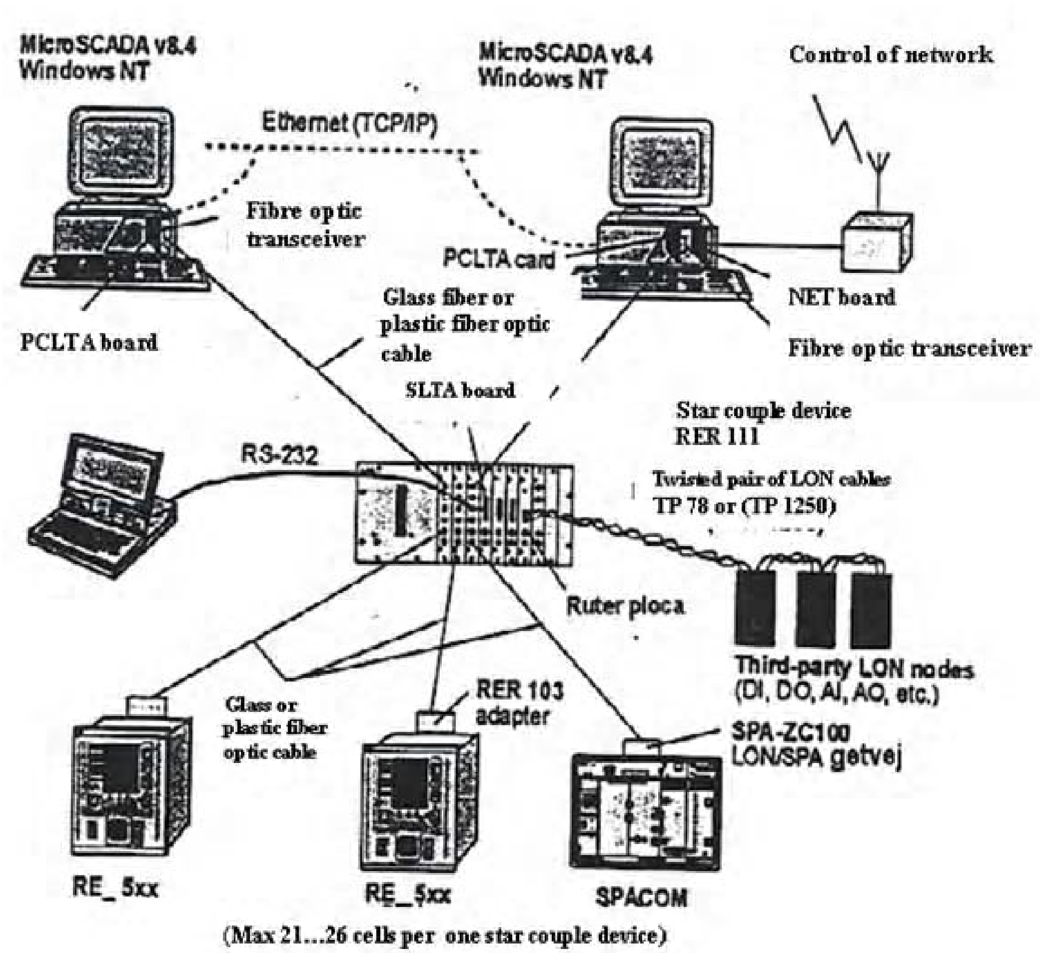
One of main characteristics of the SCADA system is centralization of the most priority functions at control unit SCU. Namely, program support in terminal units TU (PLC) ensures data acquisition and local control of process up to the level which is set from supervisory control unit, but initiating of all control functions and final verification of their execution is performing only at supervisory control unit SCU.

However, it is very important to emphasize the difference between program support that is used for supervision, check and synchronization of other systems during control of the process in real time (SCADA program support) and program support for post analyze (off – line processing) acquired by data acquisition.

Today, can be said that we are far away from own development of program support (MMI applications) for some control process because on the market is offered support already standardized for process control through the computer. Those program supports are generators of SCADA applications for the opened computer systems. Each requirement of a user can be simply realized by choosing of options or adding the segments of program code within application generator. Therefore, today the accent is put on proper designing, and not to development of own (elements) of the SCADA system.







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7 Dynamic security assessment and monitoring of isolated networks with increased wind power penetration

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Abstract: This paper describes the security assessment functions of an advanced control system for secure operation of isolated networks with increased renewable penetration. One of the key features of this system is related with the capability of assessing on-line dynamic security and providing preventive control measures that can assure a robust operation for the system regarding some disturbances. The paper describes with some detail the general approach followed to derive these evaluation functions, which are based in functional knowledge generated off-line through computational simulation.

7.1 Introduction

In autonomous power systems, dynamic security assessment is a key issue in the operation and management of the networks. In fact, sudden changes of system operating conditions must be quickly and efficiently compensated by generators to avoid frequency excursions or high df/dt variations, which may trigger the operation of system frequency relays, like under frequency protection relays of generators, provoking system collapse. This means that expected system frequency excursions and df/dt values, for the most important disturbances, must be assessed in a fast way to help in defining the more robust operating strategies. In addition, under- or over-voltages might disconnect generation and the system should be able to face also these disturbances [1].

On-line dynamic analysis of system behavior for a number of pre-specified disturbances is practically impossible using conventional tools. Therefore “Learning from examples” techniques, e.g. Decision Trees (DT), Hybrid Regression Trees (HRT) or Artificial Neural Networks (ANN), are then used to provide accurate and fast evaluation of system dynamic security by defining security rules and security functions. These structures need to be extracted from a “Data Set” and are used for evaluating the dynamic security of the system and for providing security restrictions in the Unit Commitment (UC) and Economic Dispatch (ED) modules, in order to arrive at the most economic and secure operating strategies.

The main stages followed for the development of these functions within this project were:

1. Identification and analysis of the critical operating conditions and disturbances for the isolated power system;
2. Generation of the functional knowledge (learning set and test set) about the behaviour of the isolated power system, under the selected disturbances;
3. Derivation of security structures and security rules;
4. Evaluation of the quality of the security assessment functions;
5. Development of preventive control approaches.

This paper describes the approach followed in the development of these functions, including some specific results obtained for the systems of Crete and Madeira.

7.2 Architecture Of The Security Assessment Functions

As explained in [1], in order to present to the system operator the operation strategy suggestions for a given time horizon, the MORE CARE system must perform two main execution cycles. This task scheduling is appropriate for relatively larger systems comprising steam and diesel or gas units. The operation suggestions that are presented to the operator should lead to the most economic strategy, assuring at the same time system security relatively to a given set of critical disturbances. This requires therefore security evaluations when solving the UC problem and a security complementary checking after the determination of the ED solution, due to possible changes in the system operating conditions.

In the proposed framework, security assessment functions can be used for two main purposes: security evaluation and preventive control for a given operating point and having in mind the disturbance under consideration.

As frequency behavior is here the matter of concern, when the security degree is not enough so a preventive control strategy can be determined exploiting two main avenues:

1. Rescheduling units;
2. Re-dispatching active powers among generators.

The determination of the appropriate active power re- dispatch may be performed exploiting rules derived from the DTs or through sensitivities of neural networks. However, this re-dispatch can, in some cases, be an insufficient preventive control measure because no solution is available. Therefore, the hypothesis of rescheduling generating units should also be considered.

The security functions were then implemented at two different levels:

1. Dynamic security assessment (DSA), by performing rescheduling of the unit-commitment proposed solutions;
2. Dynamic security monitoring (DSM), by evaluation the dynamic security of the power system for the economic dispatch proposed solution or for the online situation; and by suggesting re-dispatching of these solutions in order to achieve security.

7.2.1 Dynamic Security Assessment

Under operator's request, the dynamic security assessment (DSA) module evaluates the dynamic security of the Unit Commitment (UC) solution proposed for the highest planning horizon.

The implementation of this approach was performed by embedding the fast security assessment evaluation in the Long Term Unit Commitment (UC) module, as an additional restriction. This was modeled trough a Genetic Algorithm approach with insecurity margins to penalize insecure solutions. Since the security evaluation is provided by Artificial Neural Network (ANN) or Decision Trees (DT), each security evaluation is extremely fast.

Including security restrictions in the UC module increased the execution time of the module, however without compromising the proper operation of the system.

7.2.2 Dynamic Security Monitoring

Under operator's request, the dynamic security monitoring (DSM) module has the task to evaluate the dynamic security of the power system, for the solution outputted by the economic dispatch (ED) module or for the current system operating stage. When insecurity is detected, this module may suggest an alternative secure dispatch solution. These measures directly act on the solution to be presented to the operator, which are provided in the form of new produced generators set points, based on a sensitivity analysis of the ANN outputs with respect to the inputs.

7.3 Generation Of Functional Knowledge

The generation of a representative knowledge *Data Set* of frequency dynamic behavior is a key stage for the success of this approach. An innovative data set generation procedure was adopted aiming at building an adequate knowledge base, able to describe implicitly the system dynamic security behavior of power systems with large wind power production.

This phase was based on the Structured Monte Carlo Sampling, considering system oddities and producing different settings for: system load level, non-dispatchable synchronous generation, asynchronous generation including wind power production, unit commitment and dispatch solution for the dispatchable synchronous generators. At the same time, other simplification techniques were used, like grouping similar generation units at the same power plant, in order to decrease the number of necessary patterns to be considered. This approach was able to embrace all the system operating conditions and generate feasible operating scenarios, with a viable number of samples, decreasing computational time without compromising the data set quality.

The automatic procedure developed to generate the DS and consists of the following main steps:

1. Construction of Hypercells

   The DS operating range is previously defined and divided into *hypercells*. This procedure is performed according to the range and resolution assigned for the independent operating conditions to change, namely the total system load (P_{load}) and the non-dispatchable production (P_{nd}).

2. Structured Monte Carlo Sampling
   For each *hypercell*, the *Pload* and all *Pnd* variables are randomly sampled. In this procedure, besides the active generation sampling, the on/off status of the machines may also be sampled with a pre-defined probability.
3. Units Scheduling
   For each *Pload/Pnd* scenario, a scheduling module considers all feasible scheduling combination of the dispatchable units, taking into account: maximum and minimum acceptable production limits of each unit and a spinning reserve criterion.
4. Dispatch
   For each *feasible units scheduling scheme*, a dispatch module randomly distributes the insufficiency of power production by the units that were defined to be in operation by the scheduling module, considering again their production limits.
5. Power Flow
   For each *selected dispatch solution*, the steady-state operating conditions are obtained through a power flow calculation. Before power flow solution, the total active load is splited by system loads and there is a previous definition on power factor for PQ synchronous generators, voltage values for PV synchronous generators and Mvar value for the local capacitor bank (including asynchronous generators).
6. Feasible Steady-State Solution
   Before starting the dynamic simulation, the feasibility of the power flow solution is checked regarding system operating restrictions.
7. Dynamic Simulation
   For each accepted steady-state solution and considered disturbance, a dynamic simulation analysis is performed in order to get the dynamic security indices. Namely, regarding the security problem under analysis for the study system, the considered security index was the maximum value reached by negative frequency deviations Δf (due to the importance of the relay settings of the load shedding frequency protection devices) and the maximum frequency rate of change (df/dt).

After each dynamic simulation analysis, a pattern is added to the DS, being characterized by the set of candidate attributes and the security indices Δf and (df/dt).

Some other requirements can be included in the DS generation procedure in order to increase the number of operating points near the security border, as described in [2].

7.4 Design Of Security Assessment Functions

The design of the security assessment structures involved two main interactive stages: attributes selection and derivation of security structures.

In order to perform accurately security assessment and preventive control, the set of attributes chosen to represent system state should have the following main characteristics:

1. To be related with the dynamic phenomena under study;
2. The number of attributes should be as low as possible without losing relevant information (the concept of “equivalent machine” was used to group similar generators operating in parallel in the same plant);
3. To use independent (or easy related) and dispatchable variables for further control use.

For instance, generated powers and spinning reserves were found to be very interesting variables due to their relation regarding the phenomena under analysis and being also workable for the preventive control algorithms, as described in [2]. Although during an initial stage of this research, a feature selection mathematical approach (based on an F measure of separation ability) was used [5], the selection of relevant variables that feed the SA structures was only based in engineering judgment, according to the variable’s properties described above.

Three approaches have been used in this research to derive different alternative types of SA structures. Decision Trees are able to provide a classification in secure/insecure and ANN and Hybrid Regression Trees do provide an evaluation of the degree of robustness of the system through the emulation of the security indices.

7.4.1 Decision Trees

Decision trees are classification structures able to provide a classification in stable / unstable for each operating point under analysis. The construction of a DT starts at the root node with the whole learning set of pre-classified Operating Points (secure / insecure). The initial classification in secure/ insecure is performed by observing the security indices values, calculated in the DS generation stage, and checking this value relatively to a security threshold that is naturally system dependent and that is related with frequency relay settings installed in the power system.

The construction of the DT is made through successive dichotomy tests that split the remaining data into a number of most “purified” mutually exclusive sub-tests, where the a priori classification is to be reproduced. A detailed description of this method is given in [3]. The DT is made of internal nodes and terminal nodes that can be leafs (where a sufficiently pure amount of data exists) or dead-ends. Each of the terminal nodes receives a classification according to the majority of the LS operating point classification that belong to that node.

7.4.2 Neural Networks

In this work we have used feedforward ANN, which were trained with the Adaptive Backpropagation (ABP) algorithm [4]. The stop training criterion was based in the well known cross validation principle, which fights against overfitting.

The ANN are trained for an architecture where the inputs are the relevant attributes that describe each operating point in the DS and the outputs are the one or two security indices, mentioned before.

ANN was chosen to perform SA functions, not only because they perform consistently better than traditional statistical methodsin the dynamic security classification of power systems [5], but also because they provide evaluation of the system security degree, through the emulation of the security indices values.

7.4.3 Hybrid Regression Trees

The Hybrid Regression Tree (HRT) applied technique, is an automatic learning technique approach based on a Kernel Regression Tree (KRT) method, which integrates the classical Regression Trees (RT) with kernel regression [6]. This applied HRT approach, may provide 2 types of tree structures:

1. a RT security structure, by considering the mean value as the predicting model to use at the tree terminal nodes (i.e. at the leafs);
2. a KRT security structure, by considering a kernel regression as the predicting model to use at the tree terminal nodes. In all the current work, a K=3 was applied for the K-Nearest Neighbour rule, used to set the bandwidth of the regression model.

When applied to perform SA of power systems, the HRT approach may be used mainly to perform two types of functions:

1. fast on-line security evaluation;
2. extraction of interpretable security rules.

In fact, the HRT can approximately reproduce the security indices values and provide in this way an evaluation of the robustness degree of the system. At the same time, since it contains a structure of if then else rules, it is possible to extract interpretable security rules, that can be used for preventive control purposes.

7.5 Evaluation Of Security Assessment Functions

The numerical indices used to evaluate the quality of the SA structures were, for ANN and HRT, the following:

Mean Absolute Error, MAE, defined as:

$$\mathrm{MAE} = \frac{1}{\mathrm{N(TS)}} \sum_{\mathrm{OP_i \in TS}} \left| \mathrm{y_i} - \hat{\mathrm{y}}_\mathrm{i}(\mathrm{OP_i}) \right|$$

Root Mean Squared Error, RMSE, defined as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N(TS)}} \sum_{\mathrm{OP_i \in TS}} \left[\mathrm{y_i} - \hat{\mathrm{y}}_\mathrm{i}(\mathrm{OP_i}) \right]^2}$$

where $N(TS)$ is the number of operating points (OP) in the testing set, y_i is the real value of the security index for the i-th OP (OP_i), and $\hat{y}_i$ is the value estimated by the structure for the security index of OP_i.

The classification accuracy of each obtained structure was estimated by the following misclassifications rates:

$$\text{Global Classification Error} = \frac{\text{Number of OP of the TS incorrectly classified}}{\text{Number of OP of the TS}} \cdot 100\%$$

$$\text{False Alarm Error} = \frac{\text{Number of 'secure' OP of the TS classified as 'insecure'}}{\text{Number of 'secure' OP of the TS}} \cdot 100\%$$

$$\text{False Alarm Error} = \frac{\text{Number of 'insecure' OP of the TS classified as 'secure'}}{\text{Number of 'insecure' OP of the TS}} \cdot 100\%$$

These evaluation tests were performed for each relevant disturbance in each system (Crete and Madeira). From this analysis it was possible to identify that the most performing SA structures, regarding accuracy in predicting or evaluating security and computational time, were DT and ANN. In fact HRT, although showing a comparable accuracy relatively to DT and ANN, were demanding larger computational requests namely in terms of memory (since the LS needs to be stored together with the security rules) and larger computational times, because when used for security prediction purposes a regression procedure needs to be used, which may become more burden.

Therefore, only DT and ANN were installed in the systems running in Madeira and Crete. The exploitation of these structures can then be activated by the operator, for each of the considered relevant disturbances.

7.6 Dynamic Security Monitoring

In the advanced control system, a security monitoring for the selected disturbances is performed continuously, which means that each trained ANN or DT (one for each considered disturbance) will be continuously fed with system attributes and will output the expected negative frequency deviation Δ*f* (if an ANN is used) or will provide a secure / insecure classification if a DT is adopted. The attributes that feed the SA structure can be the output of the proposed dispatch solution or the same variables related with the present system operating conditions.

Two approaches have been developed to deal with the need to identify preventive control measures when insecurity is detected:

1. Heuristic approach based on the combined use of DT and economic dispatch;
2. Systematic approach based on a gradient iterative procedure that exploits the sensitivities of the ANN inputs relatively its output (the security index) to move the system towards a security region.

7.6.1 Heuristic Preventive Control Approach

Crossing the DT requires a simple checking of few rules and leads to a leaf of secure or insecure OPs. If the leaf is secure, the units' set points are displayed to the operator. In case of an insecure leaf or a deadend with a low security index, an alternative dispatch solution in the neighborhood of the previous solution is sought for, as follows: The test of the last splitting node of the DT is recorded and its threshold value Pu is used as equality constraint fixing the power produced by the respective generating unit. This restriction is then added to the Economic Dispatch problem that is then solved again for a total load that is now reduced in the amount of the power that is assigned to the generating that imposed the restriction. This procedure is applied iteratively until crossing the DT leads to a terminal node with a secure index. A complete description of this approach can be found in [7].

7.6.2 Exploiting ANN Sensitivities

This approach aims also in presenting to the system operator an alternative secure dispatch solution after an insecure state is detected. An exchange of power among generators is performed in order to move system towards security. For that purpose, a gradient-based iterative procedure was implemented, where each step is given towards the security domain. Gradient directions are based on ANN sensitivity coefficients considering, at the same time, dependencies among ANN inputs. In this approach, the solution may include re-dispatch of conventional units, but also connection / disconnection of wind generators.

Having in mind that the power system may have several independent producers, the search is constrained, in a first approach, to the utility generators. Although there are some agreements between utility and independent producers in what respect system control in case of insecurity, in this study the generators belonging to independent producers were considered as "non-controllable" – the most restrictive situation. A detailed description of the application of this method to the case of Madeira power system can be obtained in [2].

Both approaches will not necessarily lead to optimal solutions from the economic point of view. However they are able to provide an answer for those situations where insecurity is is detected and an alternative solution needs to be identified to increase operator's confidence regarding the system dynamic behavior. The implementation of these preventive control measures will always be done on operators decision, namely for instance when due to abnormal atmospheric conditions the operator decides to increase robustness of operation.

7.7 Results

The SA structures have been integrated in the MORE CARE software and are presently being exploited in the prototypes running in Madeira and Crete [1].

The quality of the SA structures used can be observed through the performance results obtained for two disturbances, one in the Cretan system (machine outage) and the other in the Madeira system (short circuit in a selected bus at the western side of the island, causing the disconnection of several wind parks and hydro plants). Table 1 describes these results.

Table 1: Evaluation of quality of security assessment functions.

Parameter	Crete	Madeira
Number of secure operating points	1136	6616
Number of insecure operating points	4599	1412
Mean absolute error	-	0.023
Root mean squared error	-	0.037
Total error (%)	3.47	0.33
False alarm error (%)	4.68	0.30
Missed alarm error (%)	3.14	0.48

The classification errors were obtained in a test set that contains around 30% of the total DS operating points. By analyzing these results (which give a good image of the typical performance behavior), we may conclude that, in general, ANN provide better classification performance results and are able to predict the system frequency deviation or df/dt for a specified disturbance. However DT rules can be easily understood and exploited for preventive control as mentioned.

More information on the quality of the preventive control procedures mentioned in this paper can be obtained in [2,7].

Figure 1 displays the frequency deviation assessed by the DSA module based on Neural Networks during October 2001. It is shown that although the disturbance that initiated the system collapse was different than the ones used to train the security modules, the DSA modules have successfully assessed insecure operation. The security modules were evaluated on actual load, wind and economic scheduling data. It is interesting to note that the average frequency of the DSM module during October before the disturbance was 48.85Hz, while it was increased to 49.2 Hz in November. In Figure 2, the frequency deviation assessed by the DSA module during October 2001 based on the proposed scheduling of the UC and ED MORE CARE functions [1]. The improvement in the Dynamic Security performance of the system is remarkable.

Figure 1: October 2001 frequency deviations resulting from three disturbances, as assessed by the MORE CARE Neural Network function based on actual operation.

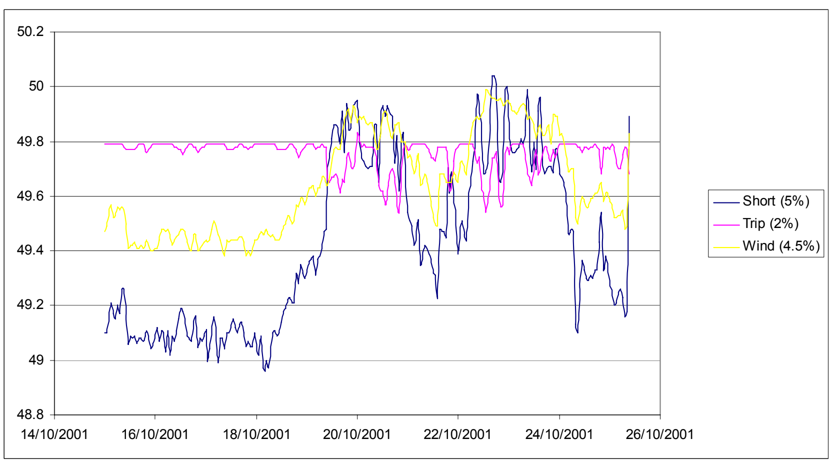

Figure 2: October 2001 frequency deviations resulting from three disturbances, as assessed by the MORE CARE Neural Network function based on proposed operation.

7.8 Conclusions

The development and use of SA applications is of crucial importance in helping defining the operation policies of isolated power systems where non-controllable power sources (like wind power) have important share of the production. In this paper the application of tools that exploit functional knowledge of the system (gathered off-line) was the key for the success of the dynamic security assessment and monitoring. Further research is needed to address issues related with automatic adaptation of the SA structures to system expansion.

7.9 References

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8 State-Of-The-Art in Wind Power Forecasting

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Abstract: Wind power is a necessary addition to traditional power market. Wind power prediction therefore is necessary because of the low utilization factor of wind farms and the intermittence nature of wind. A lot of studies have been performed to accurately predict wind power and local wind speed. This paper reviews the state-of-the-art in short-term prediction of wind power. It also investigates the performance of a hybrid method for wind speed forecasting. The hybrid approach utilizes a nonlinear filter in conjunction with artificial neural networks. Experiments are performed with the data from Crete. The experimental results of the hybrid algorithm are compared with those of linear regression approaches.

8.1 Introduction

Wind generated power, as a clean and renewable source, is paid more and more attention nowadays, especially when fossil fuel begins to deplete. However, the intermittent nature of wind makes the utilization factor of wind farms so low that wind energy could never be the major source unless its output can be exactly anticipated. Wind energy therefore is usually regarded as a necessary addition to traditional power. Even in this case, accurate prediction of wind power is beneficial for power grid management, matching demand and supply, stabilization of power market.

For the integration of wind power in the electrical grid, one can distinguish the following types of applications [1]:

1. Optimisation of the scheduling of the conventional power plants by functions such as economic dispatch etc. The prediction horizons can vary between 3-10 hours depending on the size of the system and the type of conventional units included (i.e. for systems including only fast conventional units, such as diesel generators or gas turbines, the horizon can be below 3 hours). Only few on-line applications of this type are met today in island or isolated systems and the approach remains marginal.
2. Optimization of the value of the produced electricity in the market. Such predictions are required by different types of end-users such as utilities, transmission system operators,

energy service providers, independent power producers, energy traders, etc. and for different functions such as unit commitment, economic dispatch, dynamic security assessment, participation in the electricity market, etc. Generally, the time scale given by the electricity markets is from 0-48 hours.

3. Additionally, even longer time scales would be interesting for the maintenance planning of large power plant components, wind turbines or transmission lines. However, the accuracy of weather predictions decreases strongly looking at 5-7 days in advance, and such systems are only just now starting to appear. Also shorter horizons can be considered for maintenance, when it is important that the crew can safely return from the offshore turbines in the evening.

8.2 Typical Models and Results

8.2.1 Typical Models

The models for wind power forecasting can be classified as either involving a Numerical Weather Prediction model (NWP) or not [2]. Whether the inclusion of a NWP model is worth the effort and expense of getting hold of it, depends on the horizon one is trying to predict. Typically, prediction models using NWP forecasts outperform time series approaches after 3-6 hours look-ahead time. Therefore, all models employed by utilities use this approach.

Two different schools of thought exist in short-term prediction: the physical and the statistical approach. In some models, a combination of both is used, as indeed both approaches can be needed for successful forecasts. In short, the physical models try to use physical considerations as long as possible to reach to the best possible estimate of the local wind speed before using Model Output Statistics (MOS) to reduce the remaining error. Statistical models in their pure form try to find the relationships between a wealth of explanatory variables including NWP results, and online measured power data, usually employing recursive techniques. Often, black-box models like advanced Recursive Least Squares or Artificial Neural Networks (ANN) are used. The more successful statistical models actually employ grey-box models, where some knowledge of the wind power properties is used to tune the models to the specific domain. Some of the statistical models can be expressed analytically; some (like ANNs) cannot. The statistical models can be used at any stage of the modeling, and often they combine various steps into one.

If the model is formulated rather explicitly, as is typical for the physical approach, then the stages are downscaling, conversion to power, and up scaling:

1. The wind speed and direction from the relevant NWP level is scaled to the hub height of the turbine. This involves a few steps, first finding the best-performing NWP level (often the wind speed at 10 m above ground level or at one of the lowest model or pressure levels).

   The NWP model results can be for the geographical point of the wind farm or for a grid of surrounding points. In the first case the models could be characterized as "advanced power curve models", in the second case as a "statistical downscaling" model. The next step is the so-called downscaling procedure. Whether the word comes from the earliest approach, where the geostrophic wind high up in the atmosphere was used and then downscaled to the turbine hub height, or whether it is used because in some newer approaches the coarser resolution of the NWP is scaled down to the turbines surroundings using a meso- or micro scale model with much higher resolution, is not clear.

The physical approach uses a meso- or microscale model for the downscaling. This can be done in two ways: either the model is run every time the NWP model is run; using the NWP model for boundary conditions and initialization, or the meso-scale model can be run for various cases in a look-up table approach. The same is true for micro scale models. The difference between the two is mainly the maximum and minimum domain size and resolution attainable. Note that the use of a meso-scale model is not needed if the NWP prediction is already good enough on its own. In some cases, however, the NWP resolution is too coarse to resolve local flow patterns, and additional physical considerations of the wind flow can be helpful.

2. The downscaling yields a wind speed and direction for the turbine hub height. This wind is then converted to power with a power curve. The use of the manufacturer's power curve is the easiest approach, although newer research from a number of groups has shown it advantageous to estimate the power curve from the forecasted wind speed and direction and measured power.

   Some statistical models leave this step out and do a direct prediction of the power production, but all physical and some statistical models have this intermediate step explicitly or at least implicitly.

   Depending on forecast horizon and availability, measured power data can be used as additional input. In most cases, actual data is beneficial for improving on the residual errors in a MOS approach. If online data is available, then a self-calibrating recursive model is highly advantageous. This is part of the statistical approach. It can have the form of an explicit statistical model employed with advanced auto-regressive statistical methods, or as an ANN type black-box. However, often only offline data is available, with which the model can be calibrated in hindsight.

3. If only one wind farm is to be predicted, then the model chain stops here (maybe adding the power for the different turbines of a wind farm while taking the wake losses into account). Since usually, utilities want a prediction for the total area they service, the up scaling from the single results to the area total is the last step. If all wind farms in an area would be predicted, this would involve a simple summation. However, since practical reasons forbid the prediction for hundreds of wind farms, some representative farms are chosen to serve as input data for an up scaling algorithm. Helpful in this respect is that the error of distributed farms is reduced compared to the error of a single

farm.

Not all short-term prediction models involve all steps. Actually, leaving out a few steps can be an advantage in some cases. So is e.g. Predictor independent of online data, and can bring results for a new farm from day 1, while the advanced statistical models need older data to learn the proper parameterizations. However, this is bought with a reduced accuracy for rather short horizons. Alternatively, models not using NWP data have a quite good accuracy for the first few hours, but are generally useless for longer prediction horizons (except in very special cases of thermally driven winds with a very high pattern of daily recurrence). A simple NWP plus physical downscaling approach is effectively linear, thereby being very easily amenable to MOS improvements – even to the point of overriding the initial physical considerations [3].

The opposite is a direct transformation of the input variables to wind power. This is done by the use of grey- or black-box statistical models that are able combine input such as NWPs of speed, direction, temperature etc. of various model levels together with on-line measurements such as wind power, speed, direction etc. With these models, even a direct estimation of regional wind power from the input parameters in a single step is possible. Whether it is better for a statistical model to leave out the wind speed step depends on a number of things, like the availability of data or the representative of the wind speed and power for the area of the wind farm or region being forecasted.

Table 1 presents an overview of operational models for wind power forecasting [1,4-6].

Table 1: Overview of operational models for wind power forecasting.

Prediction Model	Developer	Method	Operational Status	Operational Since
1. Prediktor	Risø	Physical	Spain, Denmark, Ireland, Germany, (US)	1994
2. WPPT	Technical University of Denmark and University of Copenhagen	Statistical	1 GW, Denmark	1994
3. Zephyr (combination of Prediktor and WPPT)	Risø and Technical University of Denmark	Physical, Statistical	-	-
4. Previento	University of Oldenburg, Germany	Physical	-	-
5. AWPPS (More-Care)	Armines/Ecole des Mines de Paris	Statistical, Fuzzy-ANN	Ireland, Crete, Madeira	1998, 2002
6. RAL (More-Care)	Rutherford Appleton	Statistical	Ireland	-

	Laboratory (RAL), UK			
7. Sipreólico	University Carlos III (Madrid) and Red Eléctrica de Espana	Statistical	4 GW, Spain	2002
8. LocalPred-RegioPred	CENER	Physical	La Muela, Soria, Alaiz	2001
9. HIRPOM	University College Cork (Ireland) and Danish Meteorological Institute	Physical	Under development	-
10. AWPT	ISET	Statistical, ANN	10 GW, Germany	-

8.2.2 Typical Results

The verification of these models is not trivial, since it depends on the cost function involved. The usual error descriptors are the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE), the Mean Error (ME), histograms of the frequency distribution of the error, the correlation function and the R or R^2 values. Mostly, the standard error figures are given as percent of the installed capacity, since this is what the utilities are most interested in (installed capacity is easy to measure); sometimes they are given as percent of the mean production or in absolute numbers. The typical behavior of the error function for models using time series approaches or NWP is shown here for the case of Prediktor applied to an older Danish wind farm in the mid- nineties, using RMSE as the error measure.

Figure 1 shows the root mean square error for different forecast lengths (periods) and different prediction methods. The forecast period is from 0-36 hours. The wind farm is the old Nøjsomheds Odde farm (before re-powering) with an installed capacity of 5175 kW. NewRef refers to the New Reference Model. HWP/MOS refers to the HWP approach (HIRLAM/WAsP/Park, nowadays called Prediktor) coupled with a MOS model (Model Output Statistics). Persistence (also called the naïve predictor) is the model most frequently used to compare the performance of a forecasting model against. It is one of the simplest prediction models, only second to predicting the mean value for all times, i.e. a climatology prediction. In the persistence model, the forecast for all times ahead is set to the value it has now. Hence, by definition the error of the persistence model for zero time steps ahead is zero.

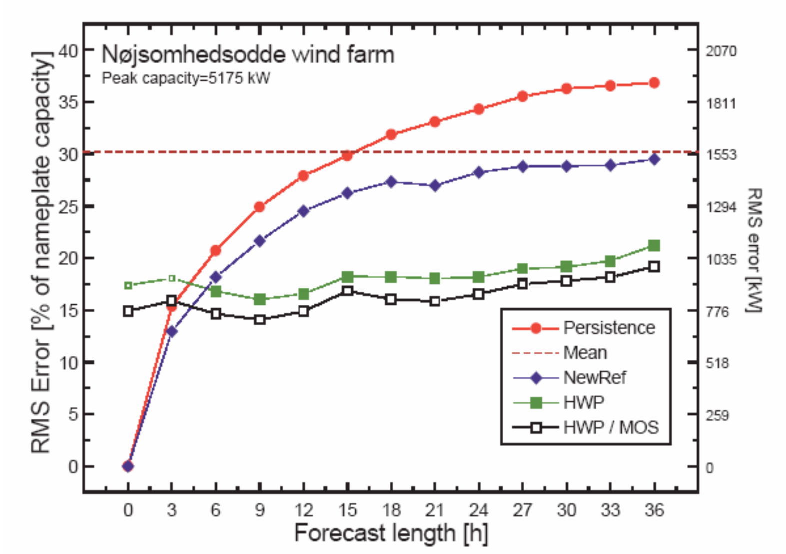

Figure 1: RMS error for different forecast lengths (periods) and different prediction methods.

For short prediction horizons (e.g. a few minutes or hours), the persistence model is the benchmark all other prediction models have to beat. This is because the time scales in the atmosphere are in the order of days (at least in Europe, where the penetration of wind power is highest). It takes in the order of days for a low-pressure system to cross the continent. Since the pressure systems are the driving force for the wind, the rest of the atmosphere has time scales of that order. High-pressure systems can be more stationary, but these are typically not associated with high winds, and therefore not so important in this respect. To predict much better than persistence for short horizons using the same input, that is, online measurements of the predicting, is only possible with some effort.

Figure 1 shows that persistence beats the NWP-based model easily for short prediction horizons (3-6 hours). However, for forecasting horizons beyond 15 hours, even forecasting with the climatology meaning (the dashed line) is better. This is not surprising, since it can be shown theoretically [4] that the mean square error of forecasting by mean value is half the one of the mean square error of a completely de-correlated time series with the same statistical properties.

After about 4 hours, the quality of the “raw” NWP model output (marked HWP in Figure 1) is better than persistence even without any post-processing. The quality of the New Reference Model is reached after 5 hours. The relatively small slope of the line is a sign of the poor quality of the assessment of the current state of the atmosphere by the NWP. However, calculating forward from this point onwards introduces hardly any more errors. This means that the data collection and the assessment of the current state of the atmosphere for the NWP is a weak point, while the mathematical models are quite good. The first two points in the HWP line are fairly theoretical; due to the data acquisition and calculating time of HIRLAM (~4 hours) these cannot be used for practical applications and could be regarded as hindcasting. The improvement attained through use of a simple linear MOS (the line marked HWP/MOS in Figure 1) is quite pronounced.

The behavior shown in Figure 1 is quite common across all kinds of short-term forecasting models and not specific to Prediktor, although details can vary slightly, such as the values of the RMSE error or the slope of the error quality with the horizon. Typical model results nowadays are RMSEs around 10% of the installed capacity. The improvement over the graph shown here is mostly due to improvements in NWP models.

8.3 Wind Speed Forecasting Using a Nonlinear Filter in Conjunction with Ann

8.3.1 Methodology

ANNs have been proved to be effective to simulate nonlinear systems. Hidden patterns, which could be independent to any mathematical models, can be found from the training data sets. If the same or similar patterns are met, ANNs come up with a result with minimum mean square error. ANNs have been widely utilized in various different fields including transient detection, load prediction. ANNs can also be applied in wind speed prediction to grasp hidden patterns. However, the signals of wind speed are highly nonlinear random process, which changes its mean and standard deviation at any time. One example of wind data is shown in Figure 2. Prediction for such kinds of data requires special care. The patterns are classified into short-term and long-term categories.

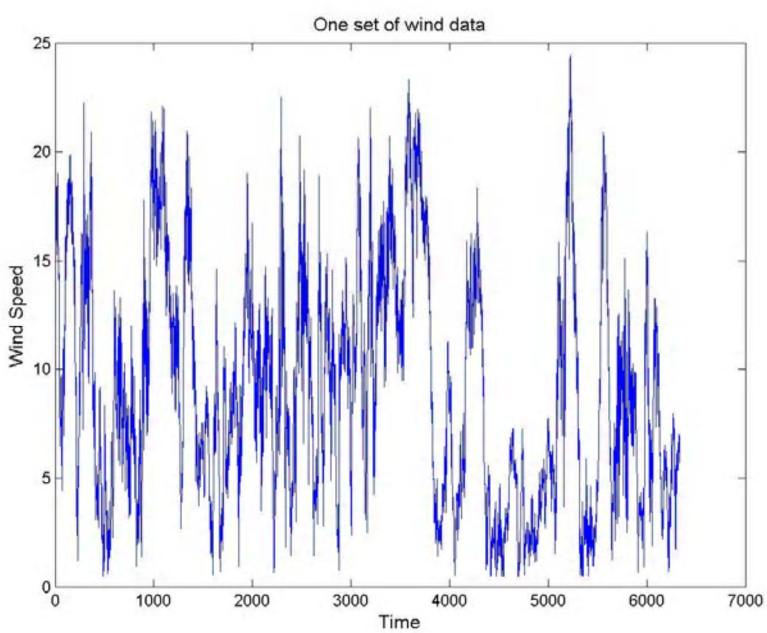

Figure 2: One set of wind speed data from Crete

Autocorrelation analysis shows that the predicted value only closely relates with recent several historical values. It means that the hidden pattern can be found in a small time horizon, which allows fewer inputs and simple topology of ANNs. More complicated ANNs may not improve the accuracy. In this research, all the ANNs have less than 5 inputs and no more than 12 neurons. This topology is capable of grasping short-term patterns.

It can be seen from Figure 2 that the mean value of the wind speed is changing continuously. Sometimes the mean value increases continuously such as in the interval between 4000 and 4300. Sometimes the mean value decreases continuously such as in the interval between 5200 and 5300. Therefore the long-term pattern can be summarized approximately as three categories. The first one, which is called type 1, has the mean value of the wind speed almost constant while the standard deviation is large. The second category, which is called type 2, has its mean value increasing in a long run. The last one, which is called type 3, has its mean value decreasing.

The proposed methodology takes both short-term and long-term patterns into consideration and handles them separately. Therefore the whole algorithm is composed of two modules [7]. In the first module, ANNs handle short-term patterns. According to the correlation analysis, the predicted value is only close correlated with several past values. Too many inputs may complicate the ANN architecture and hence impair the performance of the predictor. In order to catch timely response of the system, only several past values are used as inputs.

Final prediction is provided by the nonlinear filter, which modifies the provisional results based on trend information including increasing, decreasing or stable situation. The operations on the data belonging to different categories are also different. The prediction is acquired based on the following rationalities: the wind speed is determined by two factors. One is the short-term pattern. Another one is the long-term trend. In the training process, the ANNs are provided training patterns, which covers the short-term features. In reality, both the short-term and long-term information should be referred. Otherwise the performance degrades.

8.3.2 Results

The parameter mean square error (*mse*) is used to measure the performance of different wind power prediction strategies. Its definition is as follows:

$$\mathrm{mse} = \sqrt{\frac{1}{N}\sum_{k=1,N}\left|L_{actual} - L_{prediction}\right|^2}$$

where L represents wind speed, and N is the length of the time window taken.

Another parameter, which is called mean relative error (*mre*), is also used in some situations. Its definition is:

$$\mathrm{mre} = \frac{1}{N}\sum_{k=1,N}\frac{\left|L_{actual} - L_{prediction}\right|}{L_{actual}}$$

8.3.2.1 One-Step Ahead Wind Speed Prediction

In case studies, the algorithm is tested using the wind speed data from some wind farm sites on Crete, which is the largest island of Greece. Every year, the wind power takes almost

10% of the total power generation in this isolated unit. Therefore wind speed and wind power prediction are both important for this island. There are altogether four sites are studied. Local wind speed is sampled every twenty minutes. One set of data is shown in Figure 2. There are altogether 6336 data points, which covers about 90 days (from February to April). It can be seen that wind speed is oscillating significantly. The inputs include the wind speed information in the past one hour (three data points for twenty minute interval data). The trend information is estimated based on the wind speed in the past eight hours (twenty four data points for twenty minute interval data).

Preliminary results show that the ANNs grasp some of the short-term regularities. It shows that the results provided by ANNs only are a little better than that persistence model. In Figure 3, the original data and the prediction for as many as 400 hours are shown. When using ANNs only, *mse* is about 10%. The persistence model provides *mse* of 11%, which is only a little worse than that of ANNs. By applying the nonlinear filter, the final prediction is improved by about 20%. It can be seen clearly from Figure 4, the final prediction is much better than the provisional result, because the long-term trend (decreasing trend in this case) is taken into consideration.

The results are also compared with those of ARIMA, which models non-stationary random process. From the autocorrelation analysis, it is shown that the optimal model may be time varying ARIMA(0, 2, 2). The results show that the result of ARIMA(0, 2, 2) is only a little better than persistence model and does not match the ANN-based model.

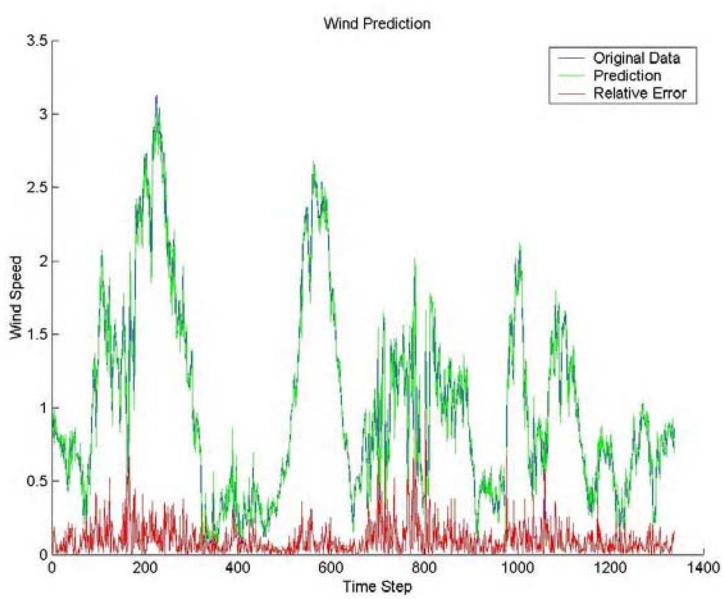

Figure 3: One-step ahead wind speed prediction.

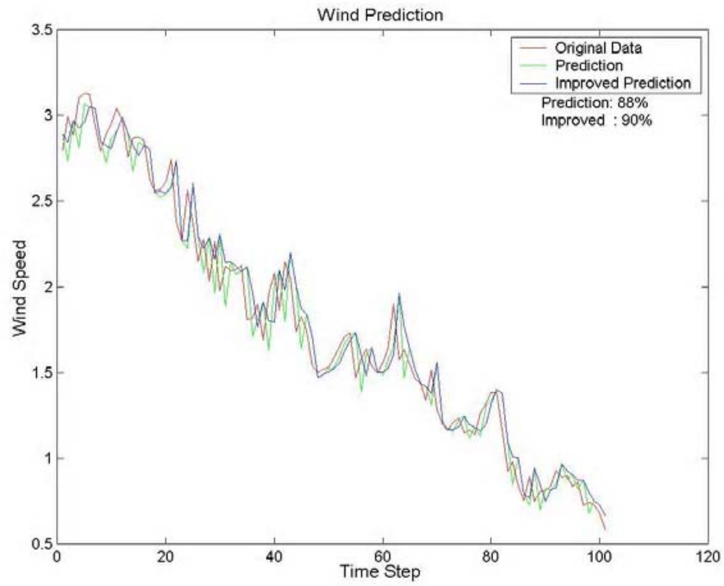

Figure 4: One-step prediction on a decreasing slope.

8.3.2.2 Multi-Step Ahead Wind Speed Prediction

Time series models are only good for short term prediction because they do not make use of meteorological and geographical information. It has been proposed that long-term prediction (more than 6 hours) can not provide satisfactory results without considering meteorological information. We also tried this new method for long term prediction up to 48 hours. One set of the results is shown in Figure 5. It shows that the nonlinear filter also helps ANNs improve their prediction in this case. Some *mse* results are also summarized in Table 2. It shows that the improvement increases along the lead time. For 12 hour (36 steps) ahead prediction, the *mre* is about 51%. However, after the time horizon is extended to more than 36 steps (about 12 hours), although the performance of the new algorithm outperforms the persistence model more, they both cannot catch up with physical models. Therefore, this algorithm cannot handle predictions more than 12 hours ahead at this time.

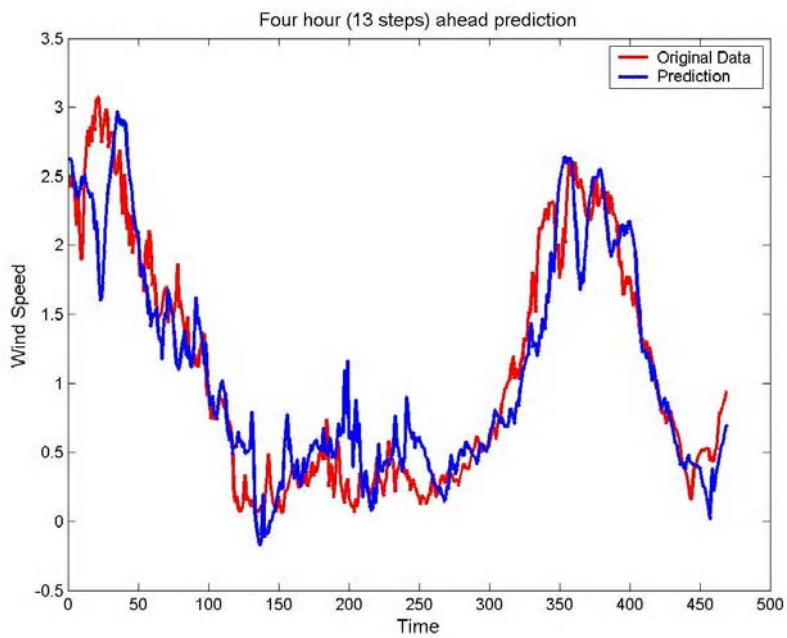

Figure 5: Four hour (13 steps) ahead wind speed prediction.

Table 2: Multi-step ahead prediction.

Time horizon	Persistence	ANNs	Proposed Method	Improvement
4 hour	**0.3903**	**0.3869**	**0.3266**	**16.33%**
6 hour	**0.4541**	**0.4204**	**0.3934**	**13.37%**
8 hour	**0.5671**	**0.4965**	**0.4203**	**25.89%**
12 hour	**0.6420**	**0.5475**	**0.4624**	**27.98%**

8.4 Conclusions

Short-term forecasting has come a long way since the first attempts at it. Often, running the grid would not be possible without wind power forecasting, especially in situations with high wind power penetration. The current crop of models, typically combining physical and statistical reasoning, is fairly good, although the accuracy is limited by the employed NWP model.

Short-term prediction consists of many steps. For a forecasting horizon of more than 6 hours ahead, it starts with a NWP model. Further steps are the downscaling of the NWP model results to the site, the conversion of the local wind speed to power, and the up scaling from the single wind farms power to a whole region. On all these fronts, improvements have happened since the first models. Typical numbers in accuracy are an RMSE of about 10-15% of the installed wind power capacity for a 36 hour horizon.

Artificial neural networks (ANN) are now the tool of choice for wind speed forecasting. ANNs are independent to any mathematical models and adapt themselves to training data. In this paper, a nonlinear filter is utilized in conjunction with ANNs. The ANNs summarize short-term pattern in the wind speed data and the nonlinear filter takes the long-term pattern into consideration. Experiments are performed with the data from the largest island of Greece. The results show that ANNs outperform persistence model just a little. Considering the long-term pattern, the results further improved by 15% on average. Although this algorithm handles short-term prediction very well, multiple hours ahead prediction show that meteorological and geographical information must be included if longer term prediction is needed. It is also necessary to study more advanced ANN tools to improve the short-term prediction.

8.5 References

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9 Distribution Management System Software for Isolated Power Systems: an Overview

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Abstract: This paper presents an overview of a distribution management system (DMS) software that aims at optimizing the overall performance of isolated and weakly interconnected systems in liberalized market environments by increasing the share of wind and other renewable energy sources, taking into account pumped hydro storage facilities and providing advanced on-line security functions, both in preventive and corrective mode. The main features of the control system comprise advanced software modules for load and wind power forecasting, unit commitment and economic dispatch of the conventional and renewable units and on-line security assessment capabilities integrated in a friendly Man-Machine environment. Pilot installations of advanced control functions have been implemented on the islands of Crete, Ireland and Madeira.

9.1 Introduction

The population of European Union islands is about 12 million persons without taking into account the British islands and Ireland. These islands are characterized by high costs of electricity production because they are based on imported fuel, mainly diesel. The import costs are further increased by the cost of transportation. On the other hand, many islands possess a significant potential of local resources of wind and solar energy, which, if used to produce electricity, contributes to their economic development and moreover helps protecting their fragile environment. However, there is a number of technical problems limiting this strategy: the grid is relatively weak, wind is a volatile power source, reserve needs to be a high percentage of the installed power and security might face increased risks. In consequence, these systems tend to be managed in a conservative way that under-exploits the renewable energy sources and increases the already large costs of electricity in islands. Alternatively, the system might be operated with lower security margins. Advanced control systems can substantially help operators to manage efficiently these systems allowing increased penetration of renewable energy sources in a secure way, as shown initially in [1].

The DMS that is presented in this paper has been developed within CARE & MORE CARE, two European R&D projects financed within the 4th and 5th Framework Energy Programmes. In particular, the advanced control system CARE has been developed previously and installed in Crete, an island with a peak load exceeding 400 MW and more than 60 MW of installed Wind Power [2]. A number of different models of MORE CARE DMS have been integrated in the pilot installation of Crete, Madeira and Ireland [3-5].

The objectives of MORE CARE are to produce enhanced capabilities of the CARE software. This aims at optimizing the overall performance of isolated and weakly interconnected systems in liberalized market environments by increasing the share of wind energy and other renewable forms, taking into account pumped hydro storage facilities and providing advanced on-line security functions, both in preventive and corrective mode.

More specifically, the work comprises collection and analysis of renewable, electrical and operating data and identification of the needs for the following developments of on-line control functions [5]:

- Improved wind power forecasting modules for short-term (0-8 h) and medium time (4-48 h) horizons.
- Hydro power forecasting functions.
- Unit Commitment (UC) and Economic Dispatch (ED) modules that take into account the availability of hydro-storage, liberalized market conditions and increased security conditions.
- On-line security modules that provide both preventive and remedial advice in case of predetermined disturbances.
- Installation of the enhanced and new forecasting, operational planning and security modules on Crete, in order to face the new operating conditions.
- Installation of the enhanced and new forecasting, operational planning and security modules on Madeira, in order to face effectively the operating conditions with very high wind power penetration.
- Development of wind power forecasting modules for the power system of Ireland.

In this paper a general description of the software, including functionalities, general constraints, the characteristics of the user, operational environment, etc. are provided.

9.2 System Architecture

The MORE CARE system aims to assist the operators of island systems by proposing optimal operating scenarios for the various power units, as well as the various actions needed to avoid dangerous situations, which might result from a poor prediction of load or weather or preselected disturbances. The insurance of increased security and reliability of the system will allow maximization of renewable penetration. The product under development includes various modules of forecasting, operational planning and security assessment. Due to the diverse needs of targeted medium and large scale systems, the software under development is highly modular, allowing integration of the options that are best suited to the particularities of each system.

Fig. 1 shows the general CARE system architecture, also retained in the MORE CARE system and the various functions that will be implemented. Figure 2 shows the execution cycles and the succession of the MORE CARE modules to generate the power system operation schedules. This flow-chart is appropriate for relatively larger systems comprising steam and diesel or gas units. The power system of Crete is typical of such island systems. Units requiring both longer and shorter scheduling times characterize these systems, therefore both longer and shorter horizon forecasts and unit commitment functions are included. For island systems comprising only diesel units or gas turbines, e.g. the Madeira system, it is possible to simplify these execution cycles.

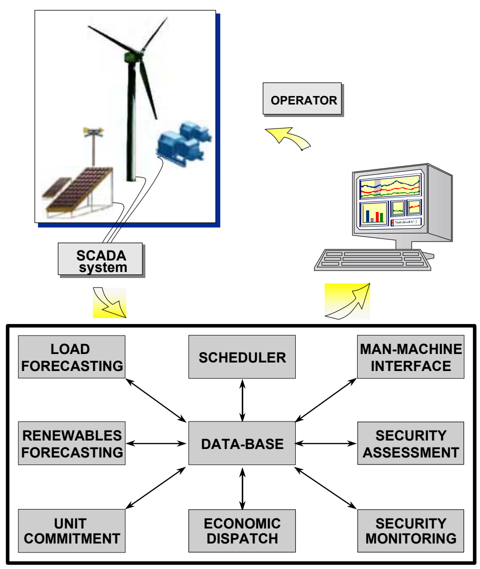

Fig. 1: System architecture.

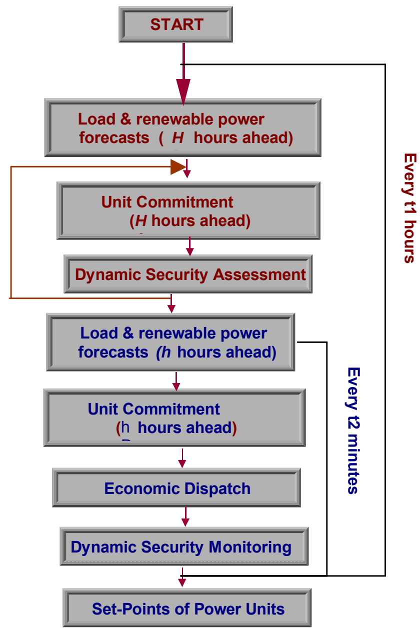

Fig. 2: Main operations of the DMS algorithm. (For the pilot control installation of Crete it is: H=48 hours, h=4 hours, t1=1 hour, t2=20 minutes).

Unit commitment has an horizon of 8 hours ahead (moving window) but tests showed that an outer cycle of 48 hours was needed to define guidelines that take into account the daily cycle of the load.

Security assessment follows the unit commitment and dispatch modules, leaving to the operator the decision whether or not he wants to activate the module for validation of the proposed dispatch (or pre-dispatch resulting from the unit commitment). In this case, another solution will be presented to the operator, if the first is considered insecure.

In the next sections, the main modules of the system are described.

9.3 Load Forecasting

In order to perform the Unit commitment and Economic Dispatch functions for the next planning horizon, it is necessary to have a forecast of the profile of the total load of the power system for this horizon. As “forecasted load profile” is characterized a set of consecutive spot forecast values as well as confidence intervals for these forecasts.

Usually in conventional systems forecasts are produced once per day. In autonomous systems with high penetration, it is necessary to update forecasts several times per day.

Several methods are being developed for the load forecasting task [6]:

1. Simple forecasting

A simple algorithm has been implemented using the load value from the same time the previous week, scaled by a factor representing the change in load between the two weeks.

2. Fuzzy neural network model

This model receives past load values to produce forecasts for the next 48 hours. The model parameters are adapted as new data arrive. Special attention is paid for predicting the load of weekends and special days. Temperature forecast is not considered as input to the model since such data is not available. However, the model compensates on this factor through auto-adaptation. The model produces hourly forecasts.

3. ARMA model

This model is an autoregressive model.

All the above methods have been integrated in the LF-module. However, when the software runs on-line only one method will provide forecasts to the rest of the modules (UC, ED) of the MORE CARE software.

9.4 Wind Power Forecasting

The purpose of the Wind Power Forecasting (WPF) module is to provide forecasts for the power output of each wind farm connected to the power system, as well as the corresponding confidence intervals. Forecasts are required by the ED and UC functions of MORE CARE software.

The following methods have been developed [6]:

1. Simple Forecasting

Persistence consists on using the most recent value of wind speed or power as forecast for the entire planning horizon. Instead of using Persistence, one can use averages of past values as predictors (Naive predictors). Off line analysis permits to define the outperforming simple method for each case study.

2. Linear ARMA models

3. Fuzzy-neural models

Fuzzy autoregressive models are applied to predict wind speed or power up to 8-10 hours ahead. The input is past wind speed or power values as well as exogenous input (i.e. wind direction). The model parameters are self-adapted as new data arrive. Several tests using wind speed or power time series have shown that fuzzy logic based models outperform persistence.

4. Meteorological information based model A

A long-term (up to 48 hours) wind power forecasting module has also been developed. The module will be as adaptable as possible to varying availability of input data. To achieve the long term forecast, data input from a meteorological forecast model (HIRLAM), is required for one or more wind farms in the system. To make a shorter term, statistical correction, on-line SCADA data is required for one or more wind farms in the system. Where no time series input data is available for a wind farm, multipliers are be used to estimate the output from neighboring locations. This feature is also useful in the event of temporary communications problems.

5. Meteorological information based model B

This module makes site-specific wind speed forecasts based on the information produced by the SKIRON system of the Atmospheric Modeling & Weather Forecasting Group of the University of Athens. The SKIRON meteorological forecasts cover a grid of 15x15 km of Crete.

The operator will have the possibility through the man-machine intefrace, to choose any of the above methods for on-line use. Special attention is paid to combine the short-term and long-term wind forecasts provided by the statistical and meteorological models, respectively.

9.5 Unit Commitment

The objective of the Unit Commitment (UC) function is to determine the combination of production units that will supply the expected demand of energy over the future period in question. This combination is the result of an optimization procedure that takes into account economic criteria and is subject to different types of economical, technical and security constraints.

The UC module of the MORE CARE software suggests to the operator of the power system a secure operating scenario for the next hours. In an interconnected power system, Unit Commitment is performed usually once a day or more, and is based solely on load forecasts. In isolated systems with high penetration from renewable (i.e. >20%), it is necessary to update regularly the proposed Unit Commitment schedules in order to account for the variability in the production of the renewable. Thus, the UC models developed operate in a "*sliding window*" scheme. The length of the look-ahead time (*planning horizon*) depends on the type of the installed power units. On operator's request, the operating restrictions will include preventive control measures on the UC module, coming from the security assessment module.

Two models are developed within the MORE CARE project for the UC task [7]. Both models are based on Genetic Algorithms (GA) and are able to simulate systems with steam units, gas turbines, diesel and combined cycle power units including renewable like wind farms and small hydro stations. The operator will have the possibility to select one of them for on-line use.

9.6 Economic Dispatch

The objective of the Economic Dispatch (ED) function is to distribute the load among the generator units selected in the Unit Commitment so that the total cost of the power system operation is minimized. The ED function is performed only for the *basic time-step* (e.g. 20 minutes ahead) of the planning horizon in order to provide the generators *set-points* to the operators.

The ED module is possible to compute the optimal generation production satisfying constraints of circuit loads, bus voltages and reactive generation to satisfy the load demand and losses of the system. It can also consider constraints related to bilateral contracts and *independent producers* of renewable power sources according to specific terms and conditions. On operator's request the output of the Economic Dispatch module (set-points) can be checked against *security constraints* with the security monitoring module, but these constraints will not be fed back as input to the ED modules.

Two different approaches are developed in MORE CARE to perform the economic dispatch function [7].

1. Optimal Power Flow based on Linear Programming

This module uses a linear model of the power system, which relates the generation production rescheduling and the other control resetting to the operating cost and the transmission network constraints. For the operation of a conventional unit the operating cost is specified by a cost curve expressing either running cost, or bidding price in case of open market operation.

2. Genetic algorithms technique

The Economic Dispatch module based on GA uses a real-coded genetic algorithm to minimize the operating cost while satisfying operating limits (ramp rates included), power balance and network constraints (optional).

9.7 On-Line Dynamic Security

In autonomous power systems, dynamic security assessment is a key issue in the operation and management of the networks. Sudden changes of system operating conditions must be quickly and efficiently compensated by generators to avoid frequency excursions or high df/dt variations, which may trigger the operation of system frequency relays, like under frequency protection relays of generators, provoking system collapse. This means that expected system frequency excursions and df/dt values, for some disturbances, must be assessed in a fast way to help in defining the more robust operating strategies. In addition, under- or over-voltages might disconnect generation and have to be guarded against.

On-line dynamic analysis of system behavior for a number of pre-specified disturbances is practically impossible using conventional tools. "Learning from examples" techniques, e.g. Decision Trees (DT) or Artificial Neural Networks (ANN), are used to provide accurate and fast evaluation of system stability by defining security rules and security functions. These structures need to be extracted from a "Learning Set" and can be used for on-line monitoring of the appropriately defined security margin and as security restrictions in the UC and ED modules, in order to arrive at the most economic and secure operating strategies. Two main approaches are developed for the fast security assessment task [8]:

1. Decision Trees Method

The Decision Trees method, uses an inference inductive procedure, and derives classification structures of the type "*if-then-else*", able to provide a fast secure or insecure classification of each operating point. The DTs provide an overview and understanding of the dependence of the system's security on its pre-disturbance state. They are suitable for corrective control purposes. Thus, if the proper control variables are used as candidate attributes, they are able to provide explicit and quantitative information about the actions to be taken, if a potentially unsafe operating state is detected. The DTs are readily converted to a set of rules that can be very easily stored and incorporated in the security assessment software.

2. Artificial Neural Networks Method

The Artificial Neural Networks (multi-layer perceptron type), uses as inputs relevant system attributes to provide as output an emulation of the system robustness degree for the disturbances under analysis, i.e. the frequency deviation and the derivative of frequency relatively to time (df/dt). A previous feature selection stage is performed to select from the initial set of characterizing features the most relevant ones that are less correlated among each other. A new approach is used here for this purpose, consisting in exploiting sensitivities of the outputs of an initial ANN, relatively to the input variables.

9.8 Conclusions

This paper presents the main features of MORE CARE DMS, an advanced control system that aims to provide advice to power system operators for the optimal operation and management of isolated power systems with large integration from renewable power sources. A number of different models for performing each main task have been integrated in the pilot installation of Crete, Madeira and Ireland.

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10 RESY-PAN tool: Overview

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10.1 Introduction

PAN software is used for planning and analysis of power systems, both for transmission and distribution. One of the main characteristics of this software is its modularity. For example, each analysis method defines a module. The program is capable of analysis of power systems with up to 2000 nodes.

10.2 Overview

The program is composed of:

- Project manager
- Database manager
- Graph editor
- Analysis tools
- Graphical display
- Report generating tool

The main window is displayed in the next figure.

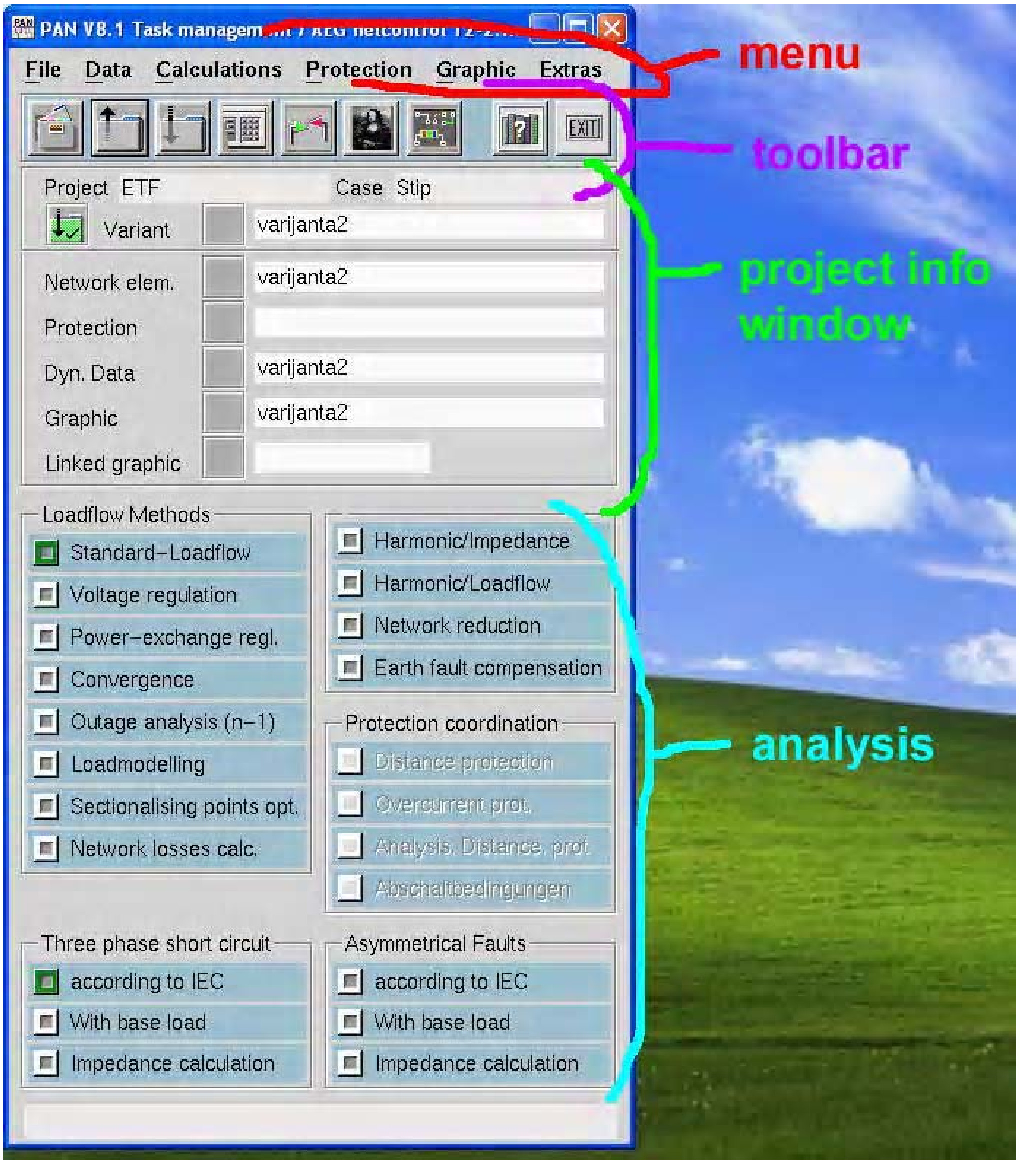

Figure 1 – Main window

10.2.1 Project manager

Project manager can be accessed both from the menu and by using the toolbar. This program allows working with multiple projects, each one with several defined cases, each of them with multiple variants. In the next figure is shown a project organization diagram:

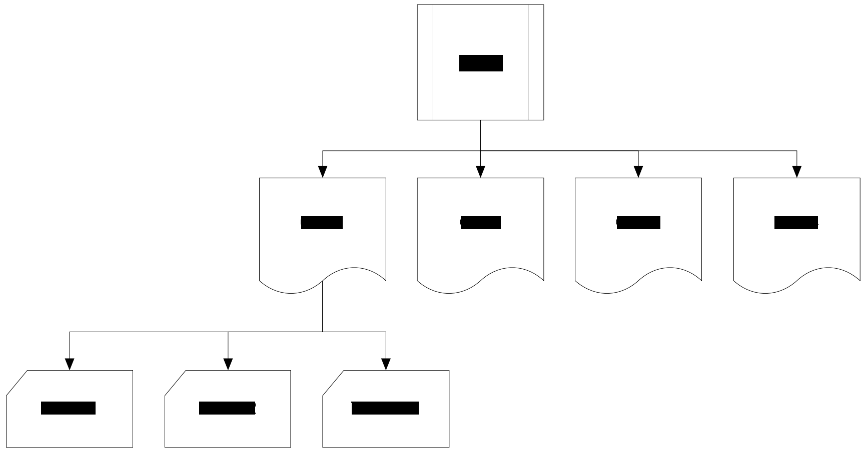

Figure 2 – Project management

For each project, besides the name, we can give comments and define attributes such as: permission to read/write the project to different users. Comments can be attached to cases also. Each variant consists of: network elements section, protection devices section, dynamic data section, and graphic section. Though, not all of the sections need to be defined for a variant to exist. Also, projects can be organized in different directories witch enables grater data safety. The picture of a project manager is:

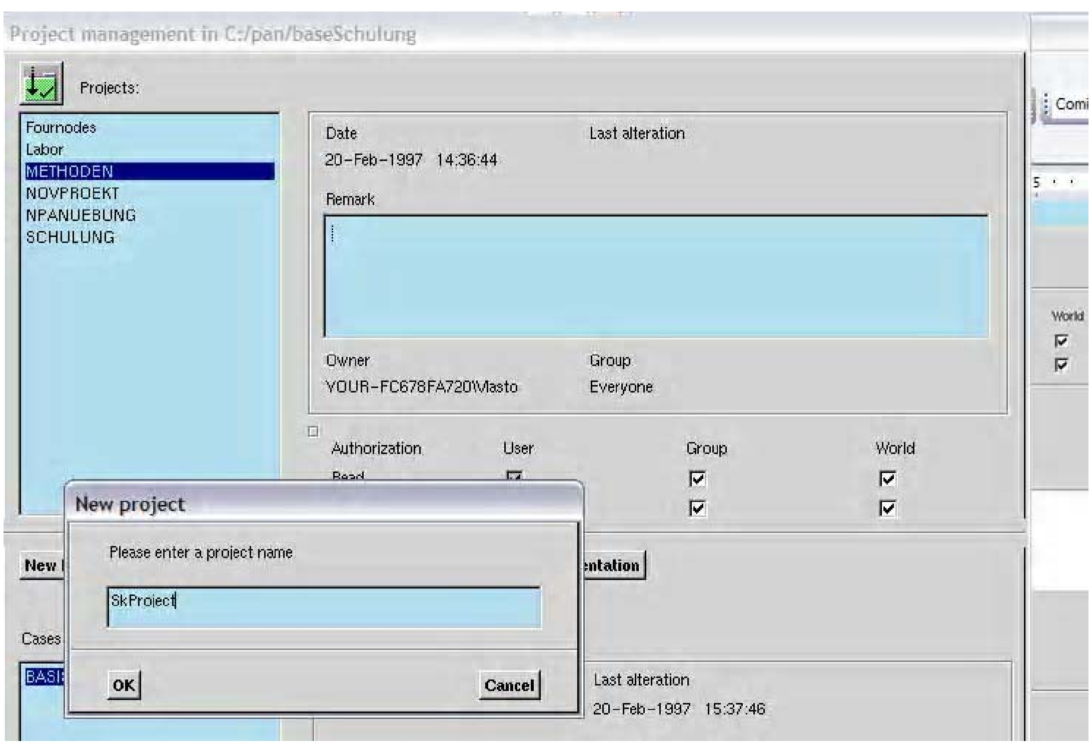

Figure 3 – Project manager

10.2.2 Database management

The project database is created automatically for each defined project. It contains data for the types of elements and elements used in the project and their connections with each other, the associated group, etc.

Good thing about it is that we can copy data from one project to another, so if we are using same type of elements we don't have to enter them twice. Here is a picture of a data input window for a line type:

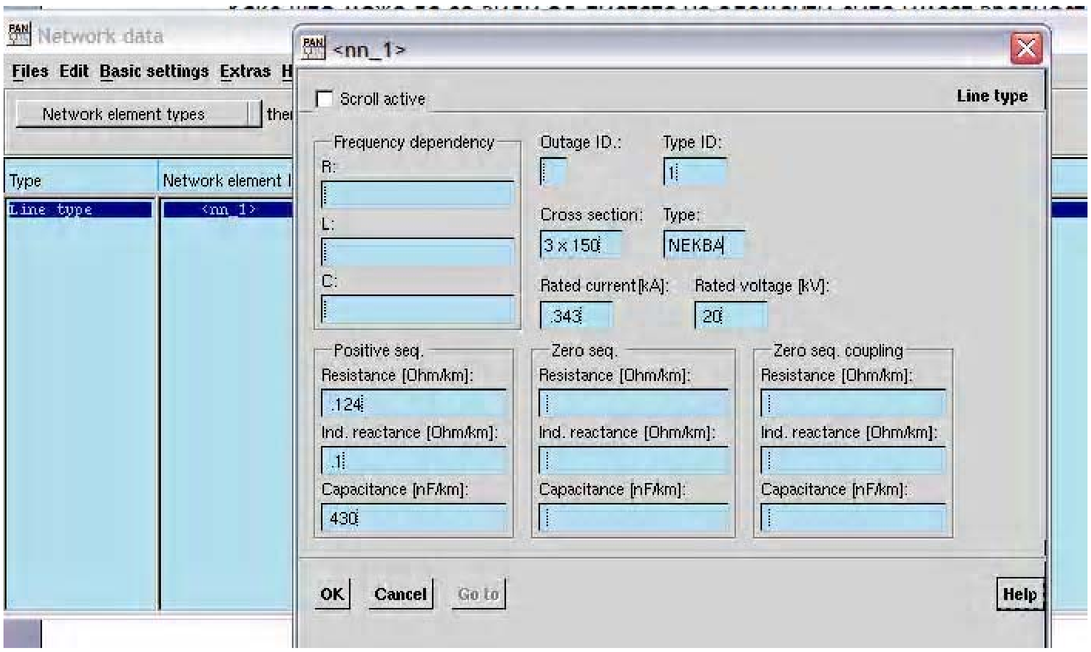

Figure 4 – Data input window

There are similar data input windows for each type of element.

10.2.3 Graph editor

The graph editor is used for graphic presentation of the power system defined by the project we are working on and is shown in the next figure.

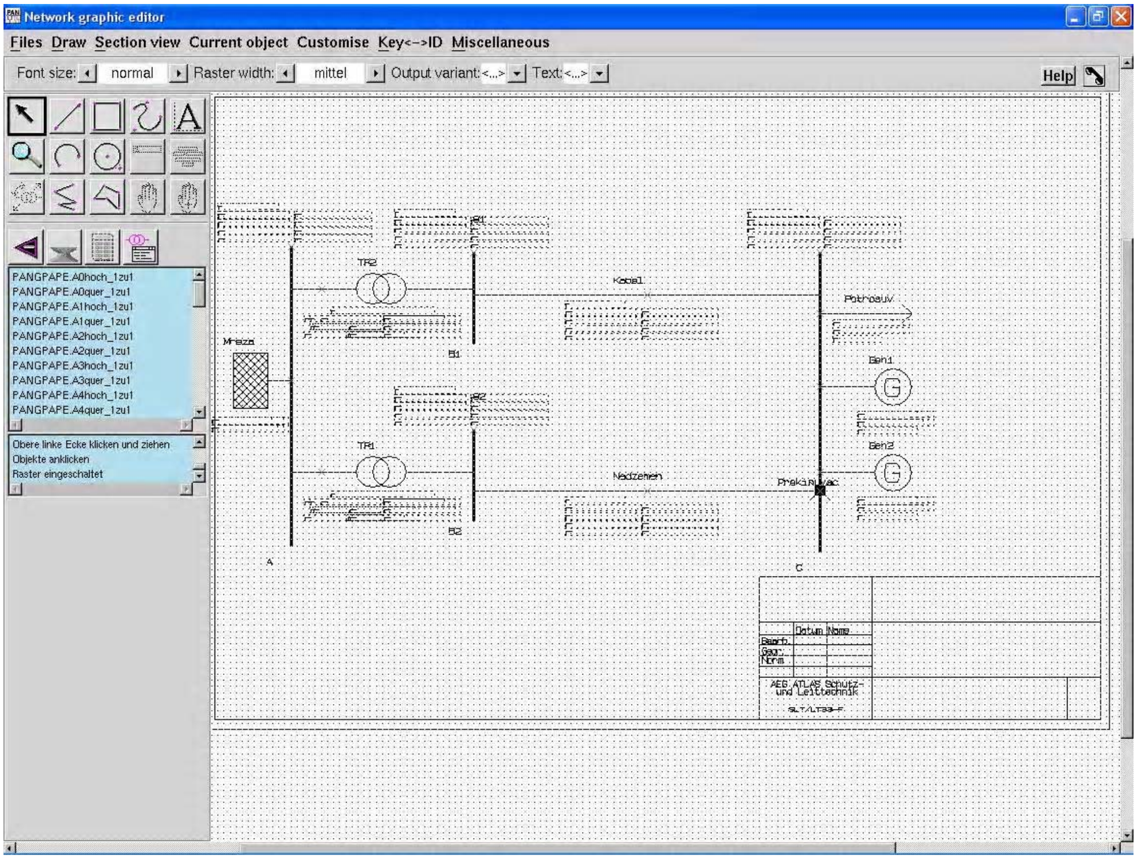

Figure 5 – Graph editor

The graphic presentation of the network is not necessary for power system analysis, but it is a nice tool of getting the picture about processes in the system. Each element of the graphic presentation of the network must be connected with the same element from the data base by using tools which are available in the graphic editor. Also here we define the data tables witch are needed for presenting the results of analysis.

10.2.4 Tools for analysis

The following type of analysis can be performed:

1. Load flow methods:
   - Standard-load flow
   - Voltage regulation
   - Power-exchange regulation
   - Convergence
   - Outage analysis (n-1)
   - Load modeling
   - Sectionalizing points operations

  - o Network losses calculations
2. Three phase short circuit
   - o According to IEC
   - o According to VDE
   - o With base load
   - o Impedance calculation

   (Three phase short circuits can be performed for all the nodes at the same time and for one node at a time)

- Harmonics calculation
  - Harmonics/impedance
  - Harmonics/load flow
  - Network reduction
  - Earth fault compensation
- Protection coordination
  - Distance protection
  - Over current protection
  - Analysis of distance protection
  - “Abschaltbedingungen”
- Asymmetrical faults
  - According to IEC
  - With base load
  - Impedance calculation

10.2.5 Graphic Display

As mentioned earlier, the best way of getting the picture of the power system is the graphic presentation. When we finish drawing of the given power system and activate the graphic display we are getting the following window:

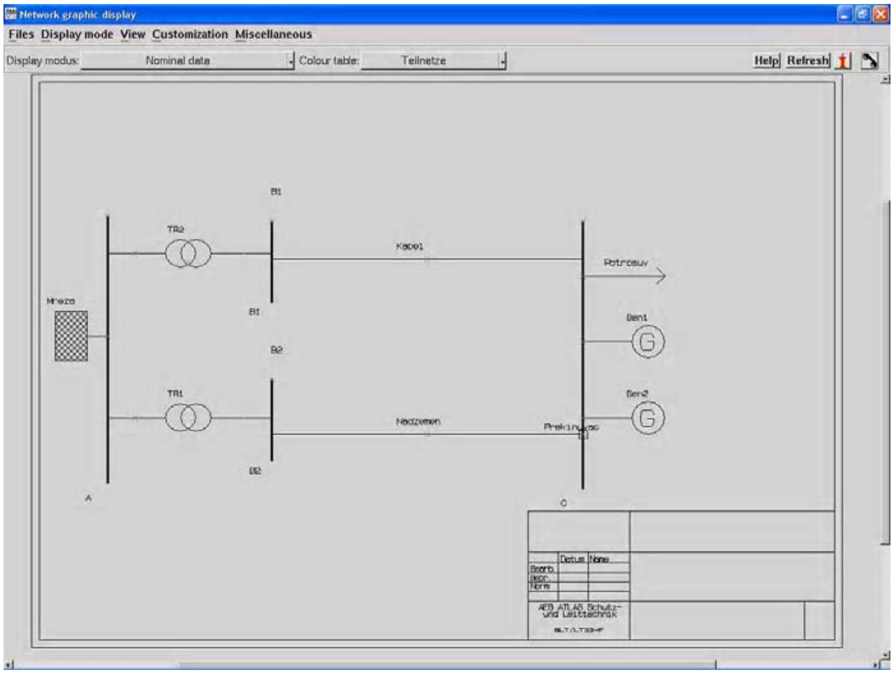

Figure 6 – Graphic display

This is the basic way of displaying the system. All elements are presented in black. There are several color tables defined in the graphical display for nominal data, such as: voltage level color table; group color table, etc. All analysis can be performed from the graphical display. And as mentioned we are getting the whole picture here. The story about the coloring table stands here as well. The next figure shows how does the graphical display looks like after performed standard-load flow analysis.

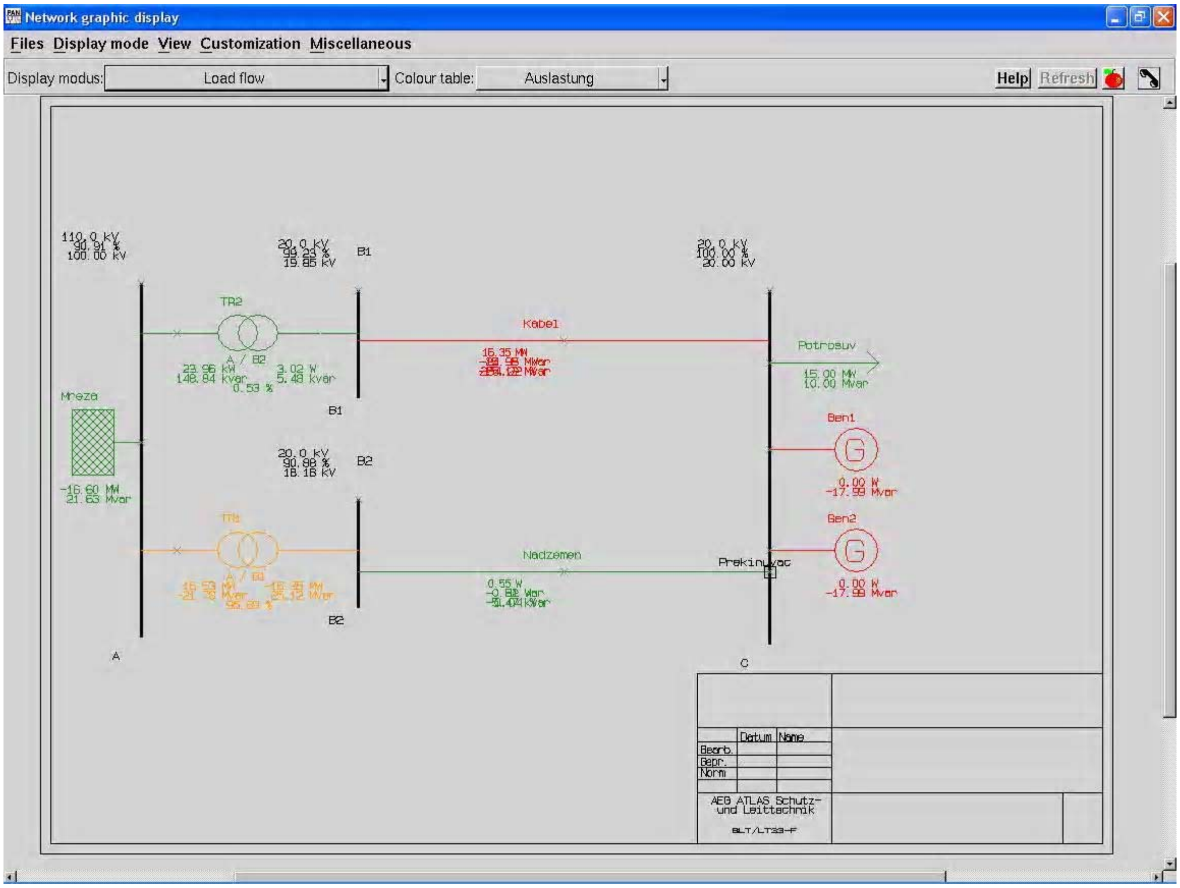

Figure 7 – Graphic display of load flow

All relevant data is presented in the display, such as: voltage levels, active and reactive powers and their directions. The coloring table is defined by the percentage of load for each element. As we can see the first transformer is presented in green and is loaded with approx. 58%, the second one in orange and loaded with 98%. The elements presented in red are overloaded. The great thing about this graphic display is that we can access the database directly, and can modify the system without leaving the display. Thus we can see the results immediately. Example: One of the line sections is overloaded. We can access the database, change the line type and see what kind of effect we made. The same goes for reconfiguring the network by switching on or off different elements or setting up different type of protection devices, or reconfiguring the same protection.

The presented type of work with the graphic display stands for every other analysis included in the program.

Also, we can start more graphical displays at the same time and lock all but one, and observe different settings and analysis of the same system at the same time.

10.2.6 On-Line connectivity

PAN software can also be connected with SCADA systems and with GIS systems. This feature offers great advantages such as:

- Real time information about system settings (switches, transformer tap positions, etc.)
- Location of system faults, etc.

10.2.7 Report generating tool

For each and every performed analysis, the program is generating reports about all data for all elements of the power system. Reports can be generated in several different ways: standard notepad, MS Word, browser or can be directly printed. Also, this program can generate different charts and diagrams for the settings of protection devices.

10.3 Conclusion

This software is valuable toll for analysis of power systems, coordination of protection devices, locating faults in the system. Also it can be used for planning of power systems in short (operating) and long term (planning) terms. It can be used by power system companies and different scientific and research institutions.

11 Quality of Living And Working Environment – EMS Of Micro Generations Unit

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ABSTRACT: Electromagnetic compatibility (EMC) is the capability of electric and electronic devices or systems to function in coordination with their purpose in their electromagnetic environment without any negative effects on other equipment and people's health by means of conduction or radiation electromagnetic emission. Producers of dc/ac inverters are convinced that their products are immune or resistant to external electromagnetic occurrences; at the same time emissions, disturbing to other devices or living beings, shall not be produced. Industrialized countries have a regulative that establishes the limits of the maximum value of electromagnetic emissions. The comparison of standards in the field of electromagnetic compatibility (EMC) for Australia, Europe, Japan and the United States indicates differences in evaluation of the electromagnetic emission parameter. The acquired results are welcome when planning a dispersed generation of electricity from small and micro cogeneration systems, which operate or will operate in the Slovenian public system.

11.1 Introduction

Our daily life is being increasingly more surrounded by electronic systems and devices, where the mutual influence of the devices is not negligible. Due to a possible electronic mutual influence of the devices, a collapse of data processing systems in banks or insurance companies can occur and it can cause enormous damage.. Also, modern aircrafts are completely controlled by electronics; here the outcome of possible interruptions could be catastrophic. As a result, there are many countries with existing regulations concerning limits of electronic device emissions and demands regarding minimal values of immunity against electromagnetic emissions.

In most cases the countries have accepted certain standards that „set limits" – they recommend the level of the electromagnetic emission produced by electronic devices. With research came an overview of various countries' approaches to treatment of electromagnetic compatibility (EMC). An inverter is the main source of emissions in a solar power plant, so the information will focus on these devices. Emissions also depend on the length od DC cables, path of photovoltaic (PV) module connection, the influence of frames of the module in comparison to frameless modules and the path to the modules in relation to the installation (on the roof, on the ground). Much research for a better understanding of possible influences has been made in this area, as well as many recommendations to optimise the obtained results.

11.2 Theoretical Results of The Research

Electromagnetic occurrences are, by convention, divided into four groups:

1. Radiological emission and
2. conductive emission to which emissions from the inverter belong and can interfere with other devices, as well as
3. Sensitivity to radiological occurrences and
4. sensitivity to conductive occurrences, both of which belong to the
5. external influences immunity group

It is of course expected that all equipment is designed in such a way that there are no unexpected emissions, neither in the inner nor in the outer part of the device. This is hardly so in real life, therefore many different standards on electronic device operation all over the world exist, all being connected to prices of filters for a desired quality level.

11.2.1 Europe

It is a general tendency in Europe to harmonize national standards. All EU and EFTA members are also members of CENELEC and are bound to transfer harmonized standards into their national legislations. Since 1 January 1996 all electronic devices must be quipped with the CE symbol, which assures that the device in question is in accordance with the demands of corresponding EMC standards.

European standards from this area are divided into three groups:

11.2.1.1 Basic standards

They define measuring methods for EMC measurements. In Europe the following standards are generally in use:

Emissions (examples)

- CISPR 16.1 (area of radio interference and measuring device immunity)
- EN 61000-3-2 (area of measurements of current harmonics)
- EN 61000-3-3 (area of flicker measurements)

Sensitivity (examples)

- EN 61000-4-2
- EN 61000-4-4
- EN 61000-4-5
- EN 61000-4-8
- EN 61000-4-11

It comprises areas of sensitivity measurements with steady-state discharge, transient occurrences, voltage peaks, voltage dips and voltage oscillations.

11.2.1.2 General standards

General standards define emission limits and electronic device sensitivity, providing there is no special standard set for a specific product. The following general standards exist:

EN 50081-1

Electromagnetic compatibility – On emission in general, part 1: Private, commercial and light industry (limit values of emission for equipment used predominately in local environment). The following examples in the chart are the tests required by EN 50081-1. The measurements are generally noted in basic standards.

Chart 1: Tests according to EN 50081-1 requirements

Occurrence	Frequency area	Suitable basic standard	Notes
Radiological emission	30 … 1000 MHz	EN 50022 group B	
Conductive emission	0 … 2 kHz	EN 60555-2 EN 61000-3-2	Harmonics
Conductive emission	0 … 2 kHz	EN 60555-3 EN 61000-3-3	Flicker
Conductive emission	0.15 … 30 MHz	EN 55022 group B	Permanent
Conductive emission	0.15 … 30 MHz	EN 55022 group B	Occasional (manoeuvres)

EN 50081-2

Refers to emission limit values of equipment used predominately in industrial environment. The classification is similar to the one in the previous chart. Some limitations allow for a higher level of emissions, which mainly refers to heavy machinery equipment used in industrial environment.

EN 50081-1

Electromagnetic compatibility – General immunity, part 1: Private, commercial and light industry (Standard for the sensitivity of equipment used predominately in local environment). The following chart shows as an example the details of all tests required by EN 500082-1.

Chart 2: A review of tests according to EN 50082-1

Test refers to:	Test of sensitivity against:	Suitable basic standard
Enclosure (chassis)	Electrostatic discharge (8 kV air discharge to enclosure)	IEC 801-2
Enclosure (chassis)	RF area 27 … 500 MHz, field strength 3V/m CV	IEC 801-3
Signalling and communication lines	Limit 0.5 kV	IEC 801-4
DC clamps	Limit 0.5 kV	IEC 801-4
AC clamps	Limit 0.5 kV	IEC 801-4

EN 50082-2

It is a standard for the sensitivity of equipment predominately used in industrial environment. The chart is similar to the previous one, with the immunity level of the equipment being somewhat higher.

11.2.1.3 Products and standards

Product standards have defined limit emission values and sensitivity of a specific product or a group of produced products in large quantities (e.g. radio and TV equipment, household appliances, computers). For example, a standard for a household appliance manufacture consists of:

EN 55014 –includes the area of electromagnetic influences (=emissions)

EN 55104 –includes the area of electromagnetic sensitivity (=immunity)

11.2.2 Japan

Does not have any general standards for EMC regulation of electromagnetic devices. It also lacks these requirements in network interconnections for low voltage distribution network. In Japan, the manufacturers of PV inverters have voluntary councils for EMC standards called VCCI (Voluntary Control Council for Interference). Their limit values match CISPR pub. 22.

11.2.3 The United States of America

High voltage electromagnetic influences are regulated by FCC (Federal Communications Commission). For FCC apply the rules and regulation 47DFR, Ch I, Chapter 15, 1992 publication, part B. Basically the conductive emission amounts to 250 µV within the frequency band of 450 kHz and 30 MHz. Radiological emission is measured 3 m from the device and the value must therefore not exceed:

- 100 µV/m for frequencies 30 … 88 MHz
- 150 µV/m for frequencies 88 … 216 MHz
- 200 µV/m for frequencies 216 … 960 MHz
- 500 µV/m for frequencies over 960 MHz

The inverters must also comply with these criteria of prescribed interference.

11.2.4 Australia

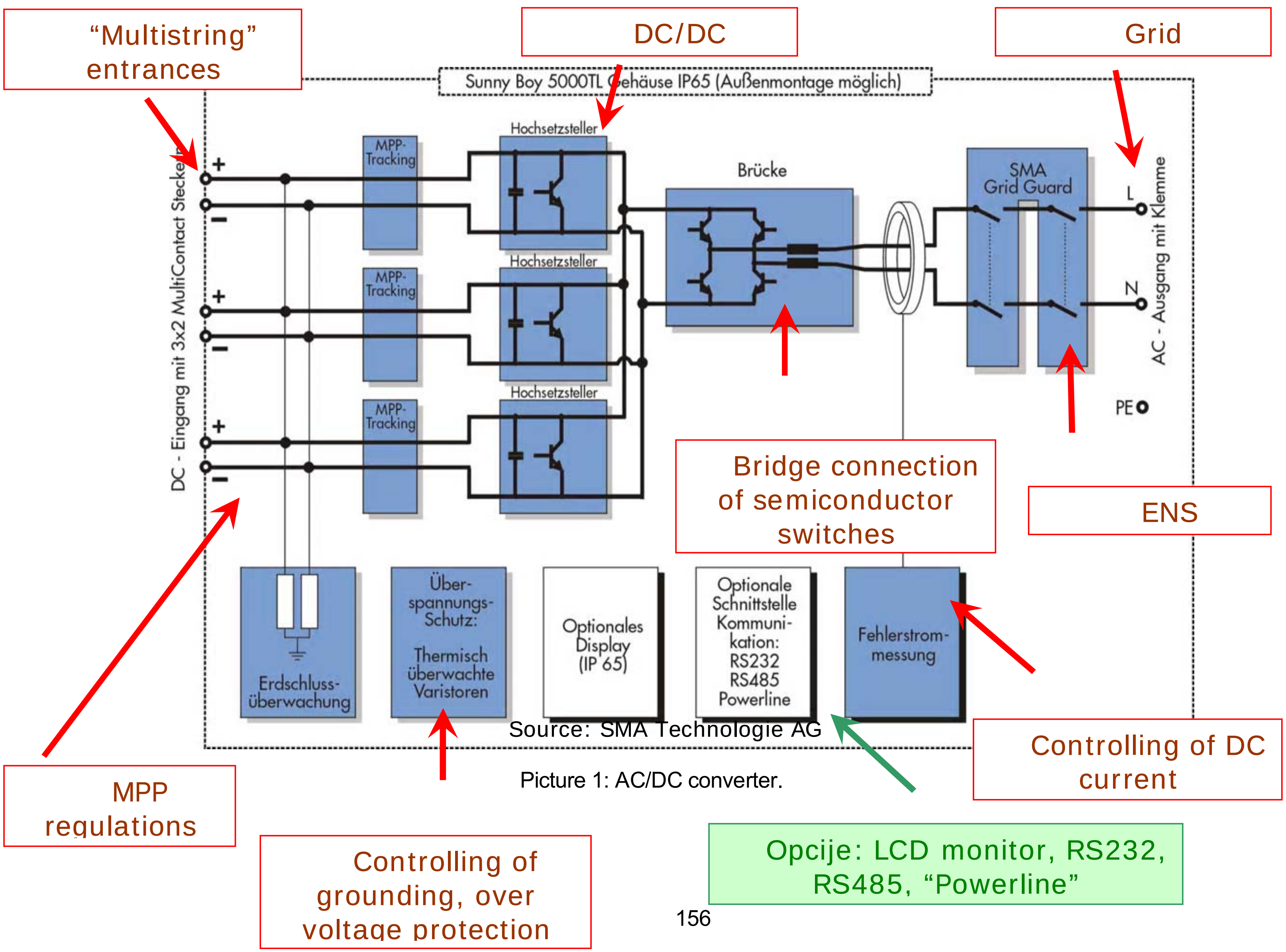
The Australian system is very similar to the European. The last issue in question was whether PV systems can be treated as household appliances or not. Current Australian conductor AS 1044 is very similar to the contents of EN 55014. The new standards AS 4251.1 and AS 4252.1 are technically equivalent to CENELEC/EN 50081-1 in 50082-1.

11.3 Experimental Results of the Research

A few years ago the majority of inverters were not synchronized and within emission limits, but the situation has changed in Europe with the introduction of the CE symbol. The new devices are given the symbol only in case they successfully pass the EMC test. It has been found that modern inverters used in solar power plants produce very little interference compared to other commercially useful devices, which is encouraging since these elements will in future more often appear in public network.

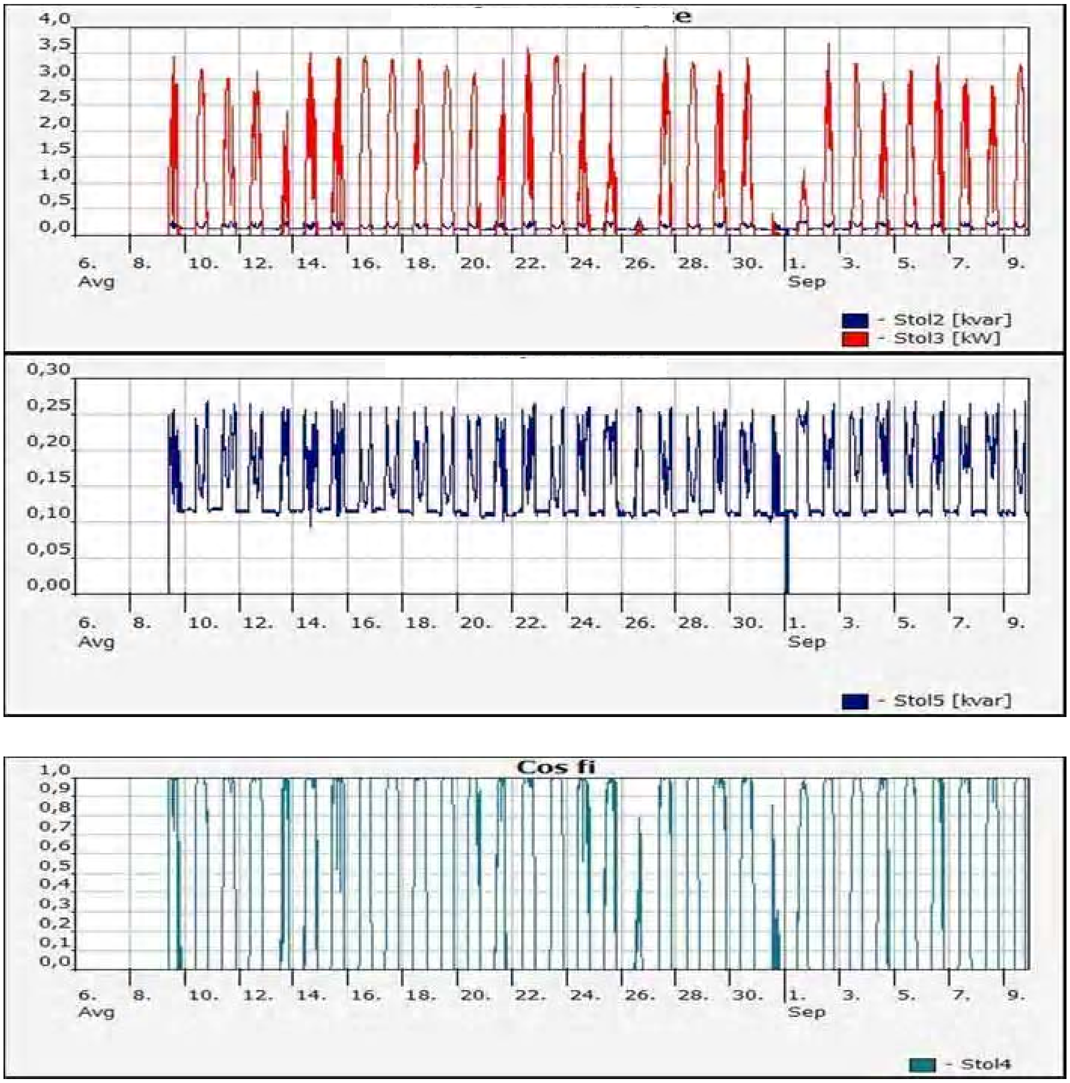
11.4 Measurement results of PV power plant

In additionally we have done some measurements of PV power plant of active and reactive power and power factor see picture 1. These experimental results have shown that the shape and THD depends often from quality of the electronic elements and devices of PV system as all. Also the mode of voltage and current transformation from DC to AC value inside of most complicated device such as DC/AC converter has great influence on the shape and amplitude of outgoing AC voltage and current from the converter.



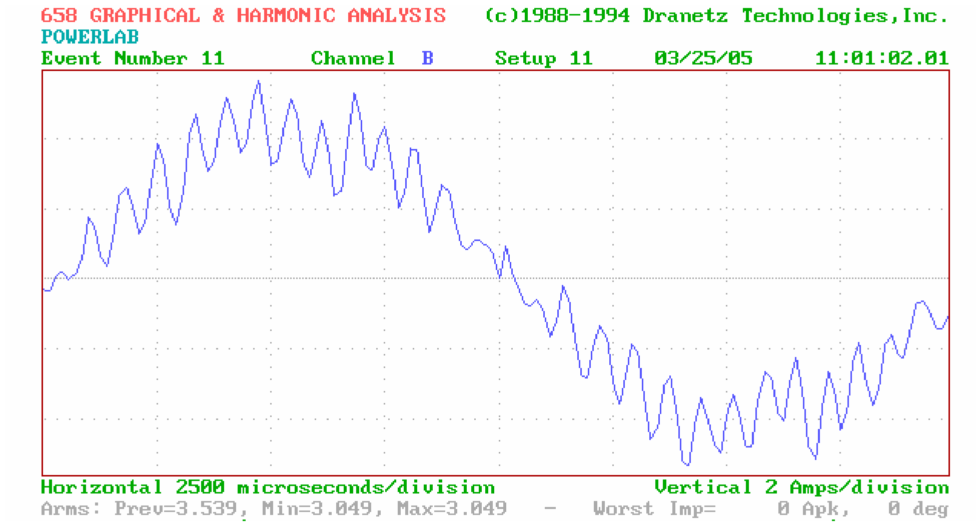
Source: SMA Technologie AG

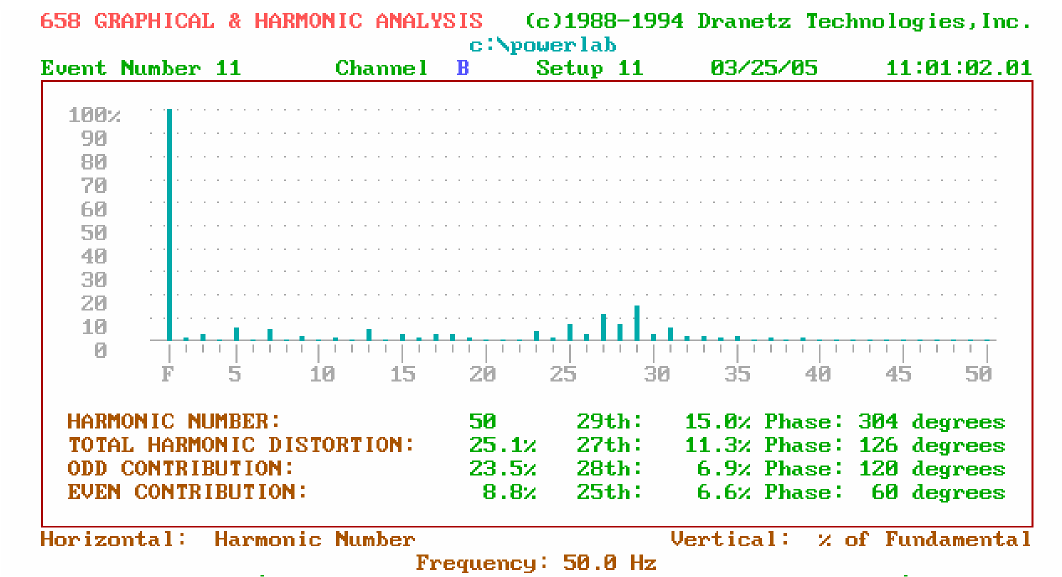
Picture 1: AC/DC converter.



Picture 2: Measurements of PV power plant of active and reactive power and power factor

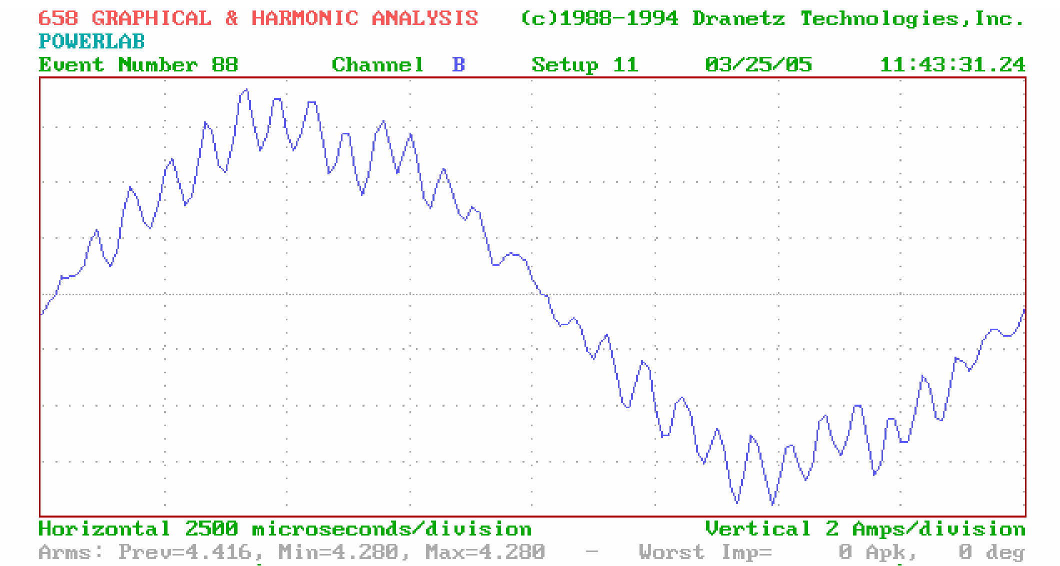
We have done current analyzes of DC/AC converter by 20 %, 50 %, and 80 % loading.

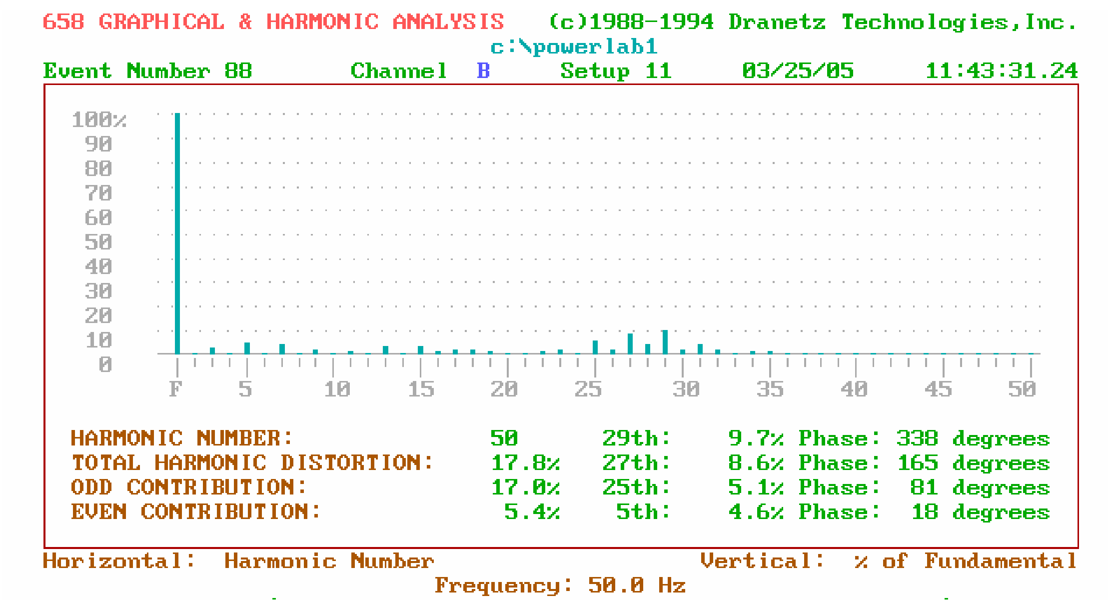




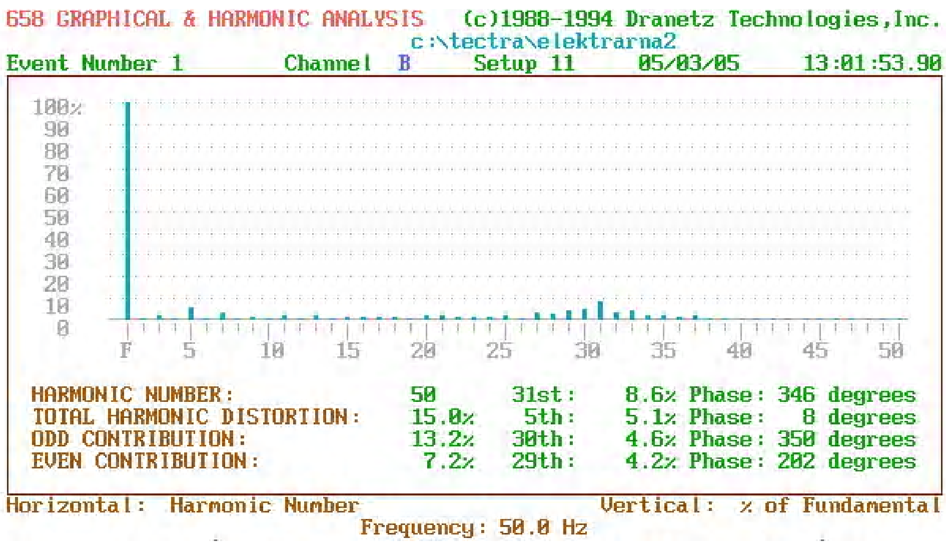
Picture 3: Current analyzes of DC/AC converter by 20 % loading

Due to DC to AC conversion of current inside the DC/AC converter, we can see that the shape of AC current has not have smooth sinusoidal characteristic during our measurements. That is more likely at small load on the DC side of DC/AC converter. So if the load increase we can se that the shape of the sinusoidal Ac current from DC/AC converter is smoother (picture 5).





Picture 4: Current analyzes of DC/AC converter by 50 % loading



Picture 5: Current analyzes of DC/AC converter by 80 % loading

658 GRAPHICAL & HARMONIC ANALYSIS (c)1988-1994 Dranetz Technologies,Inc.
c:\tectra\elektrarna2
Event Number 1 Channel B Setup 11 05/03/05 13:01:53.90

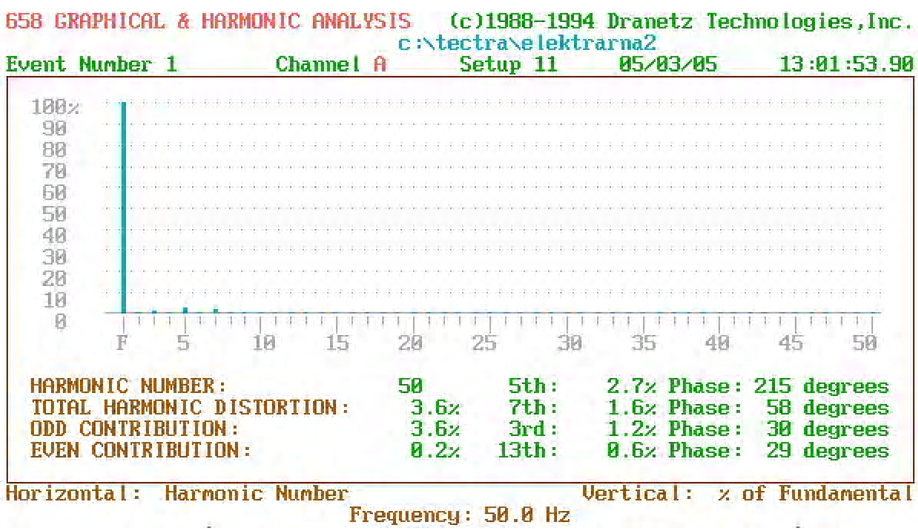
Fnd:	4.99A	90 deg	18th:	1.0%	270 deg	35th:	1.7%	137 deg
2nd:	0.3%	28 deg	19th:	0.4%	269 deg	36th:	0.9%	51 deg
3rd:	1.9%	186 deg	20th:	2.0%	325 deg	37th:	1.6%	52 deg
4th:	0.3%	57 deg	21st:	1.7%	128 deg	38th:	0.2%	40 deg
5th:	5.1%	8 deg	22nd:	1.3%	100 deg	39th:	0.7%	13 deg
6th:	0.3%	2 deg	23rd:	1.1%	17 deg	40th:	0.5%	146 deg
7th:	2.9%	209 deg	24th:	0.7%	178 deg	41st:	0.4%	51 deg
8th:	0.2%	19 deg	25th:	1.7%	58 deg	42nd:	0.2%	191 deg
9th:	1.4%	79 deg	26th:	0.5%	105 deg	43rd:	0.1%	66 deg
10th:	0.3%	39 deg	27th:	3.0%	112 deg	44th:	0.2%	199 deg
11th:	1.5%	347 deg	28th:	2.6%	273 deg	45th:	0.3%	35 deg
12th:	0.5%	306 deg	29th:	4.2%	202 deg	46th:	0.3%	292 deg
13th:	1.8%	181 deg	30th:	4.6%	350 deg	47th:	0.2%	315 deg
14th:	0.1%	270 deg	31st:	8.6%	346 deg	48th:	0.2%	20 deg
15th:	1.1%	88 deg	32nd:	3.0%	169 deg	49th:	0.1%	312 deg
16th:	1.1%	297 deg	33rd:	3.6%	244 deg	50th:	0.2%	315 deg
17th:	1.0%	325 deg	34th:	2.0%	91 deg			

T.H.D.: 15.0% ODD CONTRIB.: 13.2% EVEN CONTRIB.: 7.2%
Frequency: 50.0 Hz

Chart 3: Records of current harmonic analyzes at 80% of installed power.

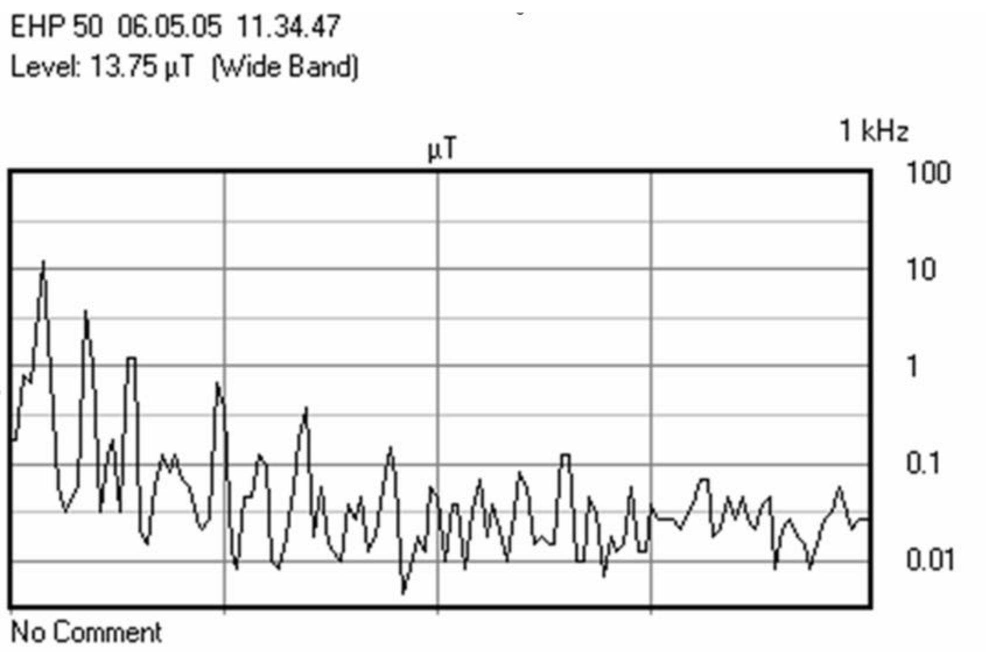
As we can see from measured results the THD is much higher at lover load. If the photovoltaic system is operating during the day at lover load then the THD is relatively high and can influence on the shape and quality of voltage and current of electrical net.

If we are comparing the voltage shape of PV power plant at 80 % of installed power with current sinus shape at 80% of installed power we can see that the influence of higher harmonics is higher on the shape of current than the voltage.

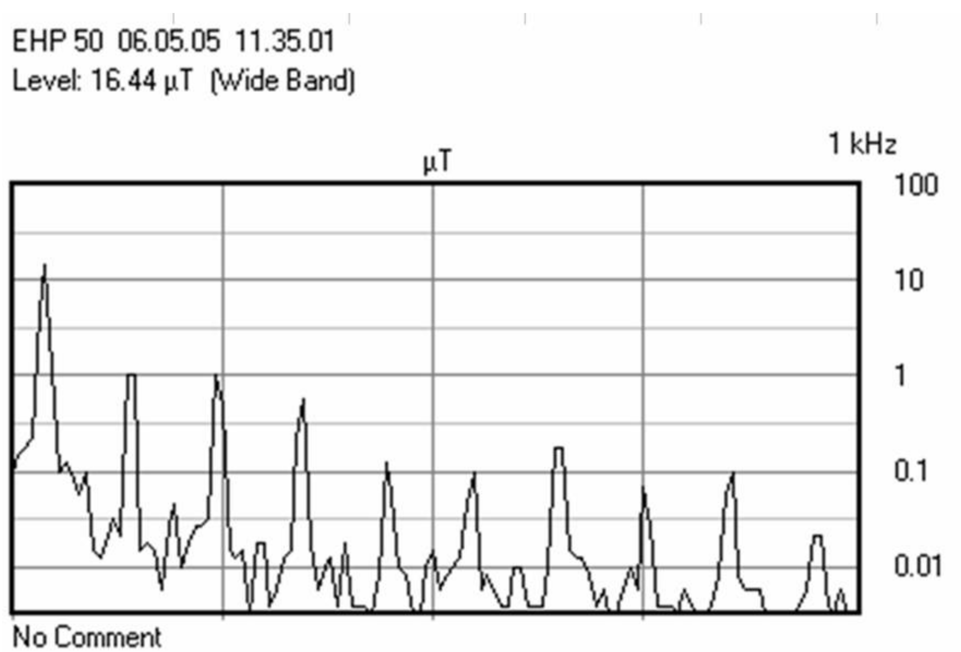


Picture 6: Graphical harmonic analyzes of voltage at 80 % of installed power.

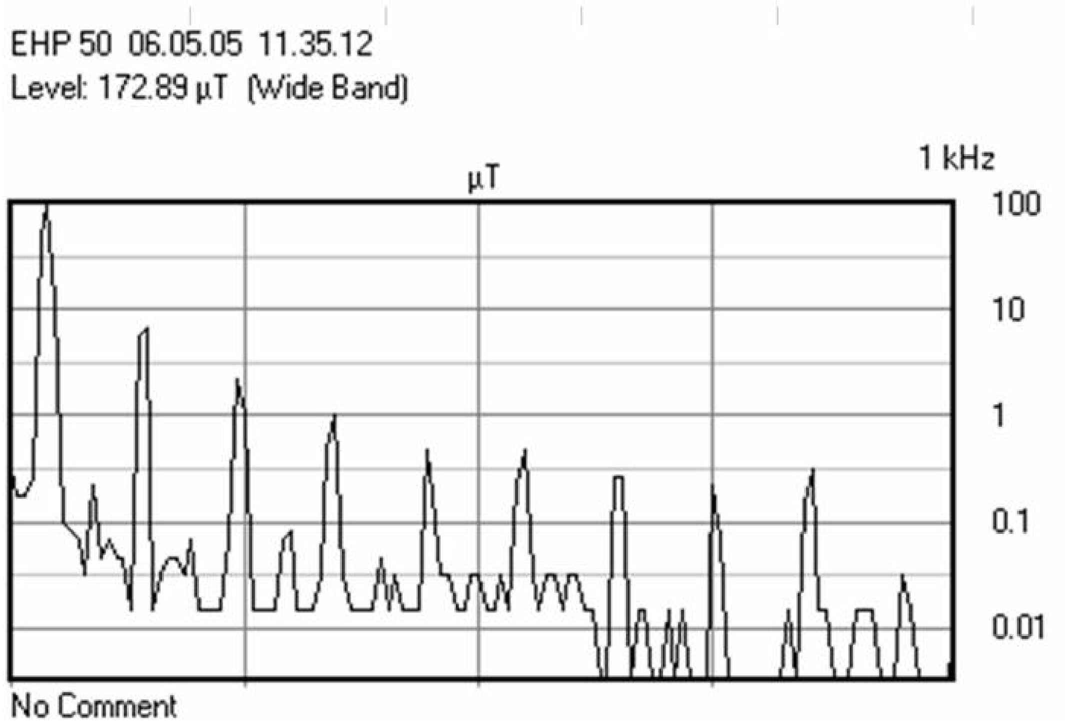
We have done also measurement of magnetic field density outside and inside of electrical cabinet of PV system.



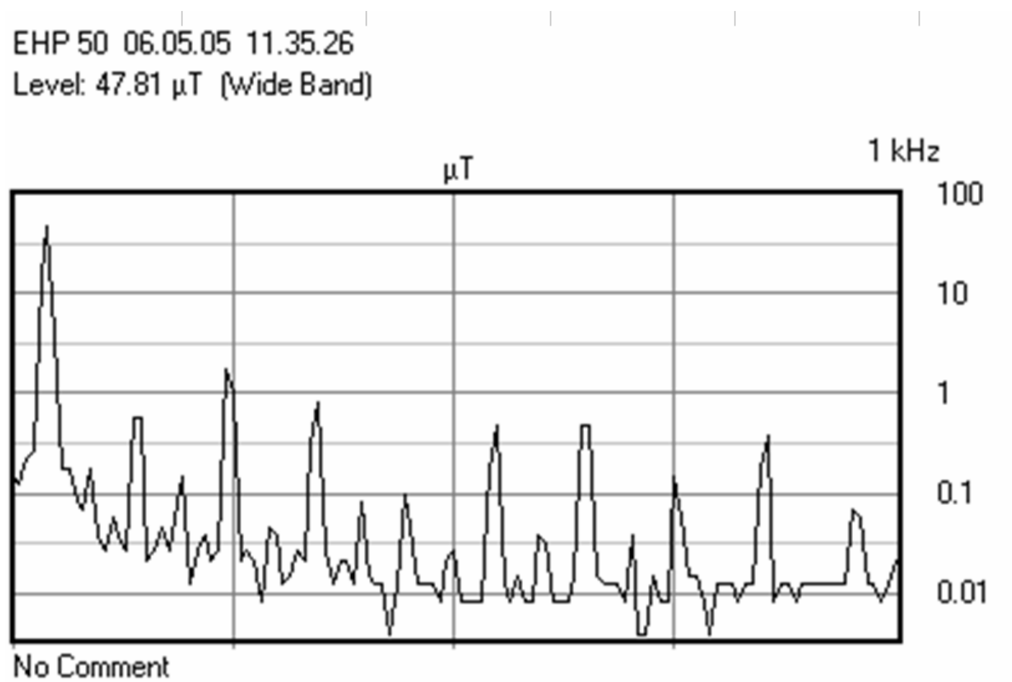
Picture 7: Measured on DC/AC converter at 70 % of installed power



Picture 8: Measured on current collection conductors at 70 % of installed power.



Picture 9: Measured on power switcher gear at 70 % of installed power



Picture 10: Measured on power switcher gear at 70% of installed power

Zunaj omare (raster 4x3)		Zunaj omare (raster 4x3)	
Probe: EHP50		Probe: EHP50	
Acquisition Mode: Manual		Acquisition Mode: Manual	
Start Date: 06.05.05		Start Date: 06.05.05	
Start Time: 11.24.44		Start Time: 11.30.15	
Total Duration: 52 s		Total Duration: 40 s	
Average:	1.61 µT	Average:	9.9 V/m
11.24.48	1,33	11.30.17	26,5
11.24.54	1,91	11.30.20	28,1
11.24.58	1,07	11.30.24	20,7
11.25.04	1,95	11.30.28	19,4
11.25.09	2,34	11.30.32	3,5
11.25.12	3,74	11.30.34	2,1
11.25.17	1,14	11.30.38	4,2
11.25.21	0,93	11.30.41	1,2
11.25.26	1,16	11.30.46	4,6
11.25.29	2,22	11.30.49	3,2
11.25.32	0,72	11.30.52	2,6
11.25.34	0,84	11.30.54	2,3

Picture 11: Measurement results of magnetic and electric field density outside of electrical cabinet.

From picture 7 to 10 we can see that the magnetic density is highest on the switch gears measured inside of electrical cabinet and electrical density is highest on the transformers also measured inside the electrical cabinet. Raster of the measurement points was 4 x 3.

1	5	9
2	6	10
3	7	11
4	8	12

Picture 12: Raster of measured points on the electrical cabinet of PV system.

Znotraj omare			Znotraj omare		
Probe: EHP50			Probe: EHP50		
Acquisition Mode: Manual			Acquisition Mode: Manual		
Start Date: 06.05.05			Start Date: 06.05.05		
Start Time: 11.31.49			Start Time: 11.33.21		
Total Duration: 32 s			Total Duration: 23 s		
Average:	319.2 V/m		Average:	48.98 µT	
11.31.52	78,9		11.33.24	14,49	zbiralke
11.32.01	268,8		11.33.30	11,72	pretvornik
11.32.12	269		11.33.36	126,64	kontaktorji
11.32.20	660		11.33.44	43,09	transformatorji

Picture 13: Measurement results of magnetic and electric field density inside of electrical cabinet.

At small loads on DC/AC converter THD exceed 30 % that infect the shape of sinusoidal signal in electrical grid.

Measurements of emissions (disturbances) on electrical conductors on AC and DC side are good defined so that there is at the time no need, to change the existed regulation.

Measurements of radiation emissions need to be standardized for different solar module, different length of conductors, impedances of DC sources and grounding mode of solar module.

Simultaneously measurement of solar module and DC/AC converters parameters are also needed.

11.5 Conclusion

In the majority of industrialized countries there are rigid rules as far as testing of EMC devices is concerned. Much experience and work has been invested into our currently set standards, but this does not mean that the standards differ when we speak about inverters. Measurements of conductive emission on the alternating and direct side are well defined and do not dictate any changes in the existing regulation. Measurements of radiological emission need a standardized test as a distinction in module connection, length of direct current cables, impedance of direct source and path of module earthing.

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/13/ SIST EN 61000-3-3 Electromagnetic compatibility (EMC) - Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current <= 16 A per phase and not subject to conditional connection (IEC 61000-3-3)
/14/ SIST EN 61140 Protection against electric shock - Common aspects for installation and equipment (IEC 61140)
/15/ HD 384/60364 niz Electrical installations of buildings (IEC 60364, mod.)
/16/ HD 384.5.54 Electrical installation of buildings - Part 5: Selection and erection of electrical equipment - Chapter 54: Earthing arrangements and protective conductors (IEC 60364-5-54, mod.)
/17/ IEC 60364-5-55 Electrical installations of buildings - Part 5-55: Selection and erection of electrical equipment - Other equipment
/18/ SIST IEC 60725 Considerations on reference impedances for use in determining the disturbance characteristics of household appliances and similar electrical equipment
/19/ SIST IEC 61034 niz Measurement of smoke density of cables burning under defined conditions
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