



DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

Chair:

Prof. Alberto Berizzi

The main objective of the PhD Program is to allow a direct, prompt and efficient involvement of PhDs in any research body such as an R&D department of a production or service company. A PhD in Electrical Engineering has a solid basic knowledge of mathematics and physics. This is essential, particularly for handling and understanding advanced tools and methods as well as for proper modelling, analysis and design of electrical engineering applications, with particular regard to power applications. A PhD in Electrical Engineering well knows methods and applications in the main disciplines of Basic Electric Circuits and Fields, Power Systems, Electrical and Electronic Measurements, Converters, Machines and Electrical Drives.

The most important part of the PhD program is the development of the research that will be the core of the PhD dissertation.

The main research areas are:

A) Electric Circuits and Fields:

This area is intended to provide the basic knowledge of methods in electrical engineering for power applications. PhD students are specifically trained to develop critical ability and innovative approaches. The training method encourages the development of discussion and debate skills in a team environment. The main research and training subjects are: Nonlinear networks and periodic time-variant networks; Analysis of three-phase and multiphase systems; Switching circuits; Electromagnetic field equations; Electromagnetic field numerical analysis; Electromagnetic compatibility; Design techniques devoted to electromagnetic compatibility

B) Power Systems:

A PhD in the field of Power Systems involves studies in the following subjects: Electrical energy production (e.g., frequency and voltage control, protection systems, renewable energy sources, Dispersed Generation and Smart Grids); Electrical energy transmission (e.g., power system analysis and dispatch, optimization of real and reactive power, security and stability, integration of renewables); Liberalized market issues (e.g., market models, ancillary service management, regulatory issues); Power quality and distribution systems (e.g., line current harmonic distortion, active filters, UPS, interruptions and voltage dips, direct current distribution); Final uses of electrical energy, Microgrids.

C) Electric machines and drives:

This research field is strictly related to the rising demand for improved machine and converter performance, in terms of low price, efficiency, robustness, dynamic response and drive control. This need leads to device optimization and better design and testing criteria. Moreover, a system approach is required for accurate integration of technical and economic aspects for final application.

The main subjects in this field are: Use of new materials; Novel magnetic structures; Methodologies of model development for design and operating analysis; Optimization procedures; Use of finite elements code, simulation programs and environments for device study; Control system definition both on the device and system side.

D) Measurements:

This research field concentrates on the fundamentals of metrology, particularly with respect to characterization of modern measurement systems based on complex structures of digital signal processing. Some of the main subjects of study are: measurement methodology as it relates to power systems, and both digital and analog signal processing. Methodologies and measurement systems associated with industrial automation and, in particular, microelectronic sensor applications, field bus based hierarchical and distributed structures, and advanced algorithms are studied in detail.

The PhD Course in Electrical Engineering is organized on a time horizon of three years. Each year, the PhD both has to follow courses and to carry out research activities and at the end of each year he is evaluated by the PhD Board. During the first year, the students carry out a training activity thanks to courses specifically

designed for the PhD (Main Courses). At the same time, the students must select, among the proposed dissertation subjects, the subject of their research, and must prepare a "Research project". The choice of the subject must be approved by the Supervisor and by the Board. Moreover, they have to deeply investigate the subjects related to the proposed area of research by means of a bibliographical research. The second year is dedicated to complete the training through the basic PhD Courses, as well as to the acquisition of specialized skills necessary for the final dissertation that will be completed during the third year. Students are required to carry out a specific training for research through specialized seminars, conferences, and research activities closely associated with the topic of dissertation, and are encouraged to perform research activities in an international framework. The third year is entirely dedicated to the PhD dissertation. Some months before the deadline to deliver the dissertation, each student is examined by the Board to verify the work done. If the research performed is evaluated as adequate, the student is allowed to write his dissertation, that will be evaluated by an international Commission.

After graduation, PhD are typically employed at:

- Major research centres;
- R&D departments;
- Power generation, transmission and distribution firms;
- Engineering consultant offices;
- Metrology reference institutes and certification laboratories;
- Process and transport automation areas.

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POWER SYSTEM OPTIMIZATION IN THE PRESENCE OF LARGE AMOUNT OF RENEWABLES

Javad Allahdadian - Supervisor: **Alberto Berizzi**

Nowadays, the penetration of Renewable Energy Sources (RES) in power systems is increasing, especially wind and solar generation that are characterized by intermittency and high variability in time: this results in the need of studying many issues related to their integration into power systems. Many problems make the integration of such sources challenging, both on long-term and short term. However, the availability of significant amount of RES generation, in particular at the subtransmission level, can be seen as an opportunity to exploit new control resources, adopting for such networks the same approach used for the so-called microgrids at lower voltage levels: i.e., the possibility to exploit the generation plants to allow islanded operation of the whole subtransmission grids or of a part of it in case of problems on the bulk power system.

In power systems, an island is formed when an area of the electrical grid gets disconnected from the main system but continues to be energized by local generation. Islanding can occur either due to intentional events, e.g. emergency controls or even maintenance, or due to unintentional events, e.g. faults and the consequent protection tripping. In both cases, some critical issues can be identified,

such as: loss of control of voltage and frequency, safety issues, transient stresses and reactive power problems, as well as cascading effects. In order to solve the problems of islanding in subtransmission systems, an optimization problem approach is used in this project.

The main idea of the research project is to define the possibility, for the subtransmission network or a part of it, to survive from a disconnection from the bulk power system and guarantee a stable islanding operation thus avoiding its blackout. Therefore, an optimization problem is designed to: (i) maximize the loads and generation that can be kept in service after any islanding, considering both any available regulating resources and a significant RES generation, and (ii) in the same time, define the control actions needed to be carried out in case of islanding to maintain the island feasible. As the control actions should be applied immediately after the islanding, they need to be computed off-line, e.g. every 10 minutes, based on the current network conditions, and the set of control actions are memorized for every computation cycle and applied only in case of actual islanding. For the practical implementation of the procedure, a control architecture is designed. Therefore, devices

that are responsible for monitoring and controlling the substation system elements (connected loads, transformers linked to the distribution grids, connected power plants etc.), called Substation Automation Systems (SAS), are supposed to be installed in all the buses in the monitored subtransmission area. The role of SAS is to collect the necessary information (measurements, breakers status, capability of generators etc), transmit the information to a Master SAS which solves the optimization problem and transmit back the a set of control actions for each triggering event that can result in the islanding. In the case of islanding, each SAS immediately applies the set of control actions relevant to that islanding configuration.

Two optimization models are defined for the islanding procedure, characterized by different objective functions; one maximizes the total load and the other one maximizes the total load and generation in the islanded grid. The objective functions are subject to the same set of constraints that are related to both, real and reactive power of the network. The real power constraints are designed to deal with the long-term real load fluctuation after islanding and to mitigate the initial real power imbalance between the

total load and total generation immediately after islanding. The real power constraints mitigate the frequency variations and hence they are defined for the entire islanded area. However, the lack of voltage regulation ability of many wind turbines/photovoltaic plants can lead to voltage deviation or blackout in the islanded grid. To mitigate these aspects, reactive power constraints are designed to: (i) assure that after islanding there is enough reactive reserve for balancing the reactive power of the connected loads, and (ii) assure that the final voltages are in a desirable range. As the reactive power has a local behavior in power systems, reactive power constraints are applied locally by dividing the islanded subtransmission system in small areas based on electrical distance parameter. In this way, it is also possible to define not only the control actions that make the island feasible, but also to determine the part of the network that can be safely islanded.

The optimization problem is a mixed integer nonlinear programming model and has been solved using both GAMS with COINBONMIN solver and Genetic Algorithm (GA) in MATLAB. Then, in order to test if the designed procedure provides results applicable in real life,

the output of the optimization procedure has been verified by means of dynamic simulations within Digsilent, where the behavior of SAS apparatuses is modeled. The procedure has been tested on two 150 kV subtransmission networks. The first one is a small grid to assess the performances of the proposed optimization model and the second one is a typical size subtransmission network characterized by a significant penetration of wind generation to evaluate the methodology in real-life situations. The results of the dynamic simulations are considered in the light of the typical settings of protections for the generators.

The general conclusions of the performed simulations are:

- if properly set, the feasibility procedure finds solutions and allows to continue to supply significant amount of load, depending on the size of the island considered;
- the dynamic simulations show that the optimization procedure is robust and is able to define feasible island areas. Therefore, the proposed method has a great potential to improve the operation of power systems by exploiting significant amount of RES. Also, by using this procedure it is possible to avoid the blackout of large areas in the power system.

DESIGN AND OPTIMIZATION OF REFLECTARRAY ANTENNAS

Van Ha Bui - Supervisor: Riccardo Enrico Zich

Reflectarray antennas are nowadays a quite popular technology, used in several applications, thanks to their advance features, e.g. low-cost, conformal deployment, and the reconfigurability. Nevertheless, they still suffer for some limitations, that are partially due to their intrinsic reduced bandwidth, that could be enlarged, but generally with a drastic increase of the structure complexity. Therefore, in this thesis new types of re-radiating element for reflectarray design will be presented. Moreover, the design will exploit the capability of optimization algorithms to support the design of RAs and enhance their bandwidth. The developed activity was mainly focused on the following two research areas:

- the development of enhanced optimization techniques;
- the study of innovative, wide bandwidth printed Reflectarray Antennas (RAs).

For what concerns the activity on the optimization algorithms, different available solutions, including evolutionary algorithms (e.g. PSO, GA), Bayesian optimization algorithm (BOA), and compact genetic algorithm (cGA), have been firstly investigated. Modified versions of BOA and cGA, which greatly improved their performances with respect to the original algorithms, have been then

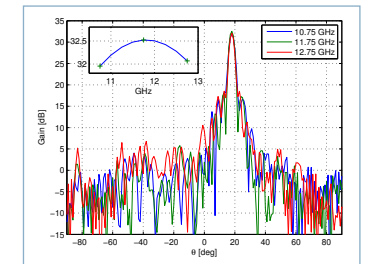
developed.

The compact Genetic algorithm, cGA, which uses probability vector (PV) to represent a possible solution is firstly considered. Originally, the cGA uses only one PV, and at each generation, two individuals are generated from the current PV. The cGA is later modified by increasing the number of generated offspring and applying tournament competition, and by introducing elitism: persistent elitism cGA (pe-cGA) and non-persistent elitism cGA (ne-cGA). The elitism-based cGAs outperform the original cGA in term of function evaluations, unfortunately, they couldn't perform better in term of solution quality. Starting from the n-cGA, I have further improved the cGA by implementing more PVs and learning mechanism between PVs. PVs are involved in two updating processes: local update, as traditional cGA, and global update, thank to which each PV will learn from the best PV. The results of the application of this modified version of cGA) on several mathematical test and antenna syntheses have shown that the M-cGA combined with non persistent elitism is outperforming all previous versions of cGA and GA both in term of solution quality and computational cost. The Bayesian Optimization Algorithm, which uses

probability theory for estimating the distribution of promising solutions for a specific problem, is also studied in the thesis. In the BOA, the interaction between parameters are considered to build a probabilistic model, i.e. a Bayesian Network (BN), that evolves during an iterative process towards increasingly good solutions, until the achievement of a global optimum. At each iteration, new candidate solutions are generated by sampling the BN, and then they replace worst individuals in the population. BOA performances greatly depend on the distribution of the current good solutions. In the absence of available prior knowledge of the problem, the initial population for the BOA is randomly generated. Therefore, in some cases, it could be possible that all the best solutions in the initial population would not provide good enough distribution, e.g. they do not represent properly the solution space dimensionality, affecting the convergence capability of the algorithm itself. In thesis, I here introduced a variation of the standard BOA obtained by adding mutation scheme into BOA, indicated as Modified BOA (M-BOA). The basic idea of the M-BOA is that of using not only the BN for generating a new offspring, but also a mutation scheme.

Thank to it, some individuals will be used to explore candidate solutions out of the considered distribution space and therefore, the algorithm will avoid being trapped in local optima, and could find good solutions out of the initial population. The M-BOA was applied to several EM design problems, such as microstrip filter design, and sparse array syntheses, which proved its increased performances with respect to BOA, and also to other stochastic-based algorithms. Passive reflectarrays are flat arrays of passive printed elements, whose resonant behavior allows a phase shaping of a beam incident on the array, thus replacing the curvature of a conventional reflector. Despite of their advantages, RAs present also some drawbacks, the main of which is their narrow bandwidth. In order to enhance this bandwidth, new possible configurations of reflectarray unit elements have been studied. After an exhaustive analysis of different types of elements, the most promising have been used to design several entire RAs with increasing size; their full-wave numerical analysis has shown the obtained bandwidth improvement. The RA re-radiating element considered consists of two square concentric rings, each one characterized by its side length l and width w . The unit

cell offers multi-degrees of freedom for the RA design, which allows the use of a double parameter design method to enhance the RA bandwidth. In Fig. 1, the computed radiation patterns in the vertical plain at three different frequencies for a 32x32 RA are shown: the main lobe is almost coincident in the three cases, and no shift of main beam occurs changing frequency. The side lobes increase slightly with the frequency, but in any case they are well controlled. Moreover, in the figure inset it is reported the frequency behavior of the gain, showing that it remains almost constant on the entire bandwidth. Reconfigurable reflectarray antennas (RRAs) have been also studied. RRA offers the possibility of dynamically control and reconfigure the antenna's beam patterns, feature which is highly demanded in radar and satellite communication applications. The research was focused on the design of a RRA unit cell, simple and easy to implement in RRA. The selected configuration shows characteristics that make it suitable for the design of a whole RRA. In particular, the considered RRA element consists of three dipoles with attached varactors, backed by air substrate and ground plane. Since each dipole is loaded with a single varactor, the RRA element is characterized



1: ??

by three degrees of freedom. By controlling the capacitance values on each dipole independently, we are able to obtain different reflection phase from the unit cell as well as to control the mutual coupling with adjacent elements. The RRA element has then been implemented to design of reflective surface with harmonic suppression at unwanted modes. The results of the optimization reveal the capability to control the mutual coupling between elements by properly adjusting the capacitance values of the varactors.

OPTIMAL PLACEMENT AND CONTROL OF ENERGY STORAGE DEVICES TO IMPROVE EFFICIENCY OF DISTRIBUTION GRIDS

Meisam Farrokhi Far - Supervisor: Prof. Enrico Tironi

Summary:

The considerable investment requirements of electricity distribution grids along with the duty of feeding customers' loads have turned them into a very important part of power systems. In fact, distribution grids must satisfy load growth and should be able to provide the best possible service to the customers. Also, the introduction of distributed generation resources to distribution grids has made changes to their managerial system causing optimal planning of generation and consumption to be placed at the center of attention of grid designers and planners. Consequently, efficiency increase in distribution grids has become a major consideration for electricity distribution companies. Nowadays, various methods such as optimal placement of distribution substations and network reconfiguration are being incorporated to reduce losses in distribution grids. In the recent research, deployment of energy storage devices is investigated in order to reduce losses in distribution grids. Novel technologies of higher storage capacities have opened new position for energy storage devices in power systems. Also, environmental considerations suggest deployment of distributed generations and energy storage devices for

generating and saving energy in the vicinity of consumers as an appropriate solution. In this dissertation, a new approach is represented based on energy storage devices application to increase the efficiency of distribution grids. First, the necessity of this research is contemplated through reviewing the presented methods in other researches. Then a comprehensive objective function is introduced to calculate losses in electricity grids considering limitations of energy storage device deployment in the grid. In the sequel, three optimization methods of Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Dynamic Programming (DP) are considered to solve the problem. The effectiveness of these methods is shown with several experiments. CIGRÉ medium voltage and CIGRÉ low voltage grids are selected for tests as standard grids and the efficiency of the introduced methods are proved through several experiments on the mentioned grids. Achieving acceptable results in terms of loss reduction, simultaneous deployment of photovoltaic (PV) and energy storage device is considered. Results of the last experiment show more loss reduction in the grid. Finally, the economic evaluation of used technologies in energy storage devices is performed

and the most appropriate technologies in terms of economic considerations are introduced. This dissertation is finalized representing suggestions and visualizing future road map to make this research complete.

Introduction:

Distribution grids constitute an important part of power systems. Investment in these grids is about 40% of total investment in a power system. In addition these grids are very vast and close to customers. Thus, improving efficiency in such grids should be considered. The rate of losses is a factor to evaluate the economic development of countries. Nowadays, the problem of loss reduction is a cutting edge research topic within electrical engineering society. Negative economic effects and high costs have led to ongoing research to decrease the losses in electrical grids. One of the significant issues regarding distribution grids is the importance of finding proper methods for the reduction of electrical losses. Although there are a variety of methods for loss reduction in distribution grids, it is mostly recommended to apply the methods while a new distribution grid is designed and installed. In this dissertation, optimal operation of energy storage

devices is done for loss reduction in distribution grids. Energy storage systems include a large span of applications in distribution systems. On one side of these applications stand applications such as the improvement of the power quality which requires energy discharge with high power in a short time-span, for instance in less than a second. On the other side stand the energy management applications requiring energy discharge in much bigger length, in some hours, for example. Among the most important applications stands the load management of distribution grids. Generally, load management refers to a set of planned activities to control and optimize the consumption pattern of the various costumers in the distribution system. The mentioned method enables the system to provide the energy demand for all times at the least costs. Also, the reliability of the system is improved by load management in the grid.

Methodology:

In this problem, the energy storage device is applied to improve the efficiency of distribution grids by reducing the amount of the power loss. There are some constraints to find the best charge and discharge profiles of the energy storage device. Constraints related to the problem are: all loads should be fed, storage device current should not violate the given maximum value, storage device energy should not be zero at any time interval (there should be a minimum amount of energy at each time interval), summation of absorbed and injected energy by the storage

device should be zero at the end of each full optimization cycle (full optimization cycle is a day in this study). To obtain final results, the use of two distinct methods of Newton-Raphson and the standard backward/forward sweep power flow studies on distribution grids are studied and compared. Further, to optimize the problem, some methods are used in this dissertation. These methods are classified in two categories of heuristic and deterministic. Heuristic algorithms belong to artificial intelligence field in computer science. These algorithms are used to solve several optimization problems recently and have successfully gained popularity among researchers. They have the capability of implementation on a wide range of problems and result in acceptable outcomes. The main drawback of heuristic computing methods is that they do not guarantee the final result to be globally optimal. However, acceptable speed of these methods along with the capability of implementation on a wide range of problems have caused their over growing use and popularity in engineering problems. In this research, genetic algorithm and particle swarm optimization are used as heuristic methods. Deterministic techniques are widely used to solve different mathematical problems. These techniques have longer history in mathematics and result in a global minimum. Although the results are the best possible solutions for the problem, the possibility of implementing them on all problems is under serious doubts. Considerable computational time and

limitations of implementation on problems with discrete solution space are main drawbacks of deterministic techniques. In this research, dynamic programming is used as a deterministic technique.

Results:

The proposed algorithms are examined on two standard grids CIGRÉ medium voltage and CIGRÉ low voltage grids. To show the performance of the proposed methods, several experiments are carried out on the mentioned grids. Also, a PV is used along with energy saving device in some case studies to improve loss reduction process. Efficiency of the energy storage device and its connecting elements to the grid is also considered in the modelling of this problem. Finally, the economic comparison between the existing technologies is performed to introduce the most economically efficient solution for the energy storage device.

MODELING OF DISTRIBUTED GENERATORS INTERFACED WITH POWER ELECTRONICS TO THE MEDIUM VOLTAGE NETWORKS: analysis of Power Quality, Fault Ride Through and coordination of the protections

Chiara Gandolfi - Supervisor: Prof. Morris Brenna

The increasing widespread of the Distributed Generators (DG) connected to the Medium Voltage (MV) and Low Voltage (LV) distribution networks has come to point out a series of new phenomena and new issues related to interactions between the networks themselves and new types of generators, mainly interfaced through electronic power converters. The areas involved in these new problems are very different and cover, for example, aspects of Power Quality, network operating and automation, regulation and standardization of service and market.

From the point of view of Power Quality, the activity performed, in the context of an Executive PhD in the research center RSE Ricerca sul Sistema Energetico S.p.A., in collaboration with the Department of Energy of the Politecnico di Milano, has sought to deepen the knowledge base of the interaction between inverter and electrical network phenomena. In particular, it is oriented toward the analysis of both the harmonic impact into the distribution network due to the interface converters and the effects of the variability of the primary source, typical of renewable energy sources. In addition, in the frame of the recent update of national and international Grid Codes and Standards, it has been evaluated

the behavior of distributed generators in case of voltage dips and the possibility that the electronic power devices support the network. This new perspective makes it necessary also to consider new DG control strategies, instead of those currently implemented, for voltage dips overcoming (Fault Ride Through - FRT). Finally, the distributed generation connection to the network implies a critical revision of the network protection coordination even considering a greater level of network automation itself.

The analysis has been conducted through digital simulation in ATPDraw and DIgSILENT environments after the modeling of MV and LV distribution network and distributed generation, with particular attention to the typologies and controls of the inverters. The study has been focused on photovoltaic and wind generation but the used method and the obtained results can be extended to every type of distributed generators connected to the network through electronic converters. The discussion begins with the study of the interaction phenomena between inverter and electrical network by analyzing in particular harmonic pollution and flicker emission. In the study, peculiarities and

problems related to the presence of electronic converters interface for distributed generators connected to the distribution network have been analyzed. The spread of the DG connected to the network through electronic converters has led to the necessity to define strategies to overcome voltage dips to avoid sudden loss of generation as a result of network disturbances. These new strategies allow maintaining the generators connected to the network during voltage dips and they are different from the usual practice, that, in case of fault, requires the generators disconnection to avoid unintentional islands in the distribution network. The study highlighted what are the characteristics of the inverters design and which are the control logic to enable these devices to overcome the network fault in accordance with the requirements of different European Grid Codes. Various advanced inverter control solutions for the optimal management of static generators in presence of unbalanced networks have been also investigated.

A laboratory experimental activity has also been carried out, supported by theoretical analysis/modeling, oriented to the functional tests of inverter for the network connection

of photovoltaic generation, considering new requirements imposed by the recent national Standard (CEI 0-21). The tests have been performed both on an "old conception" inverter, i.e. designed according to the previous Standard and on an "advanced" inverter, that is designed to provide the new required functionalities. The main laboratory tests purpose has been the deepening of issues to implement these new inverters capabilities, in particular it has been found that "old conception" devices can satisfy the new Standard requirements with a firmware update and a revision of the capability curves.

The activities have highlighted that the impact in terms of Power Quality and the capability to provide ancillary services to the network are dependent on the electronic network interface characteristics. In particular the main issues are design/capability, power configuration, modulation strategies (multi-level structures, interleaved solutions) and management control strategy. To control the inverter can be used FRT strategies during voltage dips. The simulation results have shown that stand-by condition during the voltage dip is preferable to avoid the inverter current limitation operation. In this way the device is ready to exchange with the network the

pre-dip power after the normal network conditions restoring. To improve the inverter operation in presence of unbalanced steady state networks, control techniques optimized for these conditions have been studied.

Finally, it has been proposed and analyzed a possible protections coordination scheme based on logic selectivity. This scheme can be applied with success both in passive and active distribution networks using directional over-current protections relay installed along the feeders and introducing a communication channel to exchange the commands between the relays themselves and between the relays and the DG interface protection.

The simulations, which took into account different types of network faults, have shown that this scheme reduces the possibility of unintentional island operation and allows the line fault segment selection. In this way, the DG installed upstream the fault remains connected to the network, thanks to the FRT logics, and the number of users affected by the interruption is reduced thanks to the possibility of reverse feeding.

The presence of the communication channels introduces delays that increase protection relay tripping time that implies a greater thermal

stress to the lines during failure. This effect can be quantified by the index I_{2t} . These delays cause also a general voltage dips duration increasing, with negative implications to network performance in terms of voltage quality.

In conclusion the activity offers a general methodology for classification and analysis of the issues related to the DG connection through power electronic converters, regardless of the type of primary source, pointing out possible actions to be taken for their resolution. The results, especially in relation to the evolution of the protection systems in distribution networks, may represent a starting point for their laboratory and/or field activities to test the technological limits of the current products and evaluate their possible development to be effectively used in the future networks.

IMPACT OF WIND POWER PENETRATION ON POWER SYSTEM SECURITY BY A PROBABILISTIC APPROACH

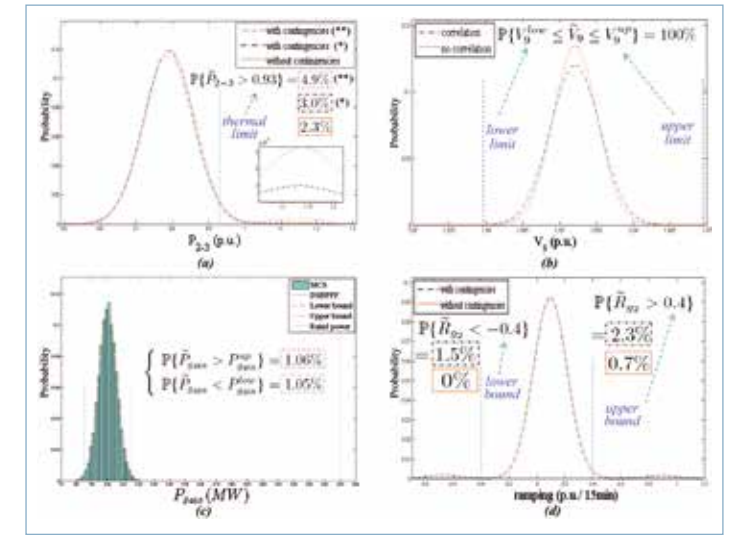
Dinh-Duong Le - Supervisor: Prof. Alberto Berizzi

Nowadays, in order to achieve environmental and economic benefits, Renewable Energy Sources (RES), such as wind and photovoltaic solar, are widely used. The integration of RES into power systems is one of the major challenges in planning and operation of modern power systems. It has introduced additional uncertainty into various study areas of power system, further to the conventional sources of uncertainty (loads and the availability of generation resources and transmission assets); this makes clear the limitations of the conventional deterministic analysis and security assessment approaches. To manage the uncertainties, probabilistic approaches can provide a valuable contribution. They have been introduced and are gaining wider application in power systems with increasing levels of RES. At first, the research developed Probabilistic Power Flow (PPF) tools capable of managing the wide spectrum of all possible values of the input and state variables so as to provide a complete spectrum of all possible values of outputs of interest such as nodal voltages, line power flows, etc., in terms of probability distributions. Such type of output is useful for power system analysis and security assessment by probabilistic approaches.

Similarly to the very important role of the conventional deterministic power flow in power system analysis, security assessment, operation, planning and control, a PPF tool is a crucial need to deal with high levels of uncertainty in power systems. Various approaches have been investigated in the research; in particular, an in-depth analysis and comparison of the cumulant-based methods in PPF studies are provided in the thesis. Extensive testing indicates good performance of PPF techniques in comparison with the result obtained by the computationally more demanding Monte Carlo Simulation (MCS). First, the methods are computationally less intensive while maintaining an appropriate level of accuracy, suitable for application to large power systems. Second, the effect of active-reactive coupling in PPF has been evaluated: the decoupled techniques cause small effects on angles and real power flows but can significantly affect and make worse nodal voltage magnitudes and reactive power flows accuracy. Moreover, further researches on cumulant methods have been developed to increase the accuracy and the computational efficiency. The methods can take into account the correlation between input power injections (e.g., among load and among wind) so the impacts of explicit

representation of correlation on the output can be explored. In this way, the correlation of load/RES production forecast errors (e.g., due to weather forecast errors) over geographic areas can be taken into account. In addition, the contingencies due to random outages of branches and generating units can also be straightforwardly accounted for: this gives added value of PPF in security analysis. Finally, the PPF variants illustrated in this research are found to be suitable for different applications depending on the types of distribution considered. In particular, the results coming from the application of the PPF methods to a small and a large test systems allowed the comparison of the different methods under different aspects, i.e., computational burden, accuracy, etc., and the assessment of the most suitable one depending on the application requirements. Moreover, PPF with distributed slack bus (DSBPPF) is also proposed so as to explicitly represent the steady-state behaviour of the frequency control. The approach is developed so that any power imbalance in power system can be shared among a set of dispatchable generators, for example, as a response to a signal from the secondary frequency regulation, so reflecting the actual power

system operation. The formulation is fully general and it can be applied to primary, secondary, and tertiary regulation. Specific metrics can be obtained from DSBPPF such as probability of line overloading (Fig. 1.a), probability of over-/under-voltage (Fig. 1.b) as well as probability of violation of over-/under-regulation limits (Fig. 1.c) and probability of not meeting ramping requirements (Fig. 1.d) of conventional generators in systems with deepening penetration of highly variable generation and load resources. The proposed methodology has been extensively tested on both the IEEE-14 bus test system and the Sicilian power system, giving good results. To be taken into account in computations for power system security assessment by a probabilistic approach, modeling of various stochastic factors in power system, such as stochastic behaviour of load, wind power generation, random outages of generating units and branches, is required. Their probabilistic models are also considered in the research. Among RES, wind power generation is one of the most important and challenging because of its stochastic features: that is why in the research it is particularly studied. Building a model of wind power generation from multiple wind farms for



1: (a) Probability of line overloading; (b) Probability of over-/under-voltage; (c) Probability of violation of over-/under-regulation limits; (d) Probability of ramping violation

power system planning and operation is a critical need. An effective approach to characterize all salient features of wind data from multiple wind sites and a spatio-temporal model of wind generation are proposed. In the model, principal component analysis is adopted combined with time series analysis that enables us to capture both spatial and temporal correlations for wind data. In building the model for high-dimensional and correlated data like wind data at multiple wind sites, the problem becomes much more complicated when the dimensions of the data set are very high; however, the proposed model is useful for both decorrelating data and reducing computational burden. As wind power is a time-varying, intermittent, uncertain, and non-dispatchable resource while wind speed is a non-Gaussian and non-stationary stochastic process with distinct diurnal and seasonal patterns, the proposed model adopts techniques in

statistics, i.e., pre-processing and transformation techniques, without any further assumptions: this is why it can be used for any real wind data. In terms of applications, the spatio-temporal model proposed provides a very good direction for dealing with many problems in power systems involving wind power production from multiple sites. The model results can be directly exploited in PPFs to assess the power system security for the next hours or in the planning environment for studying new network reinforcement taking into account spatio-temporal correlation, etc. Also, such kind of result is very appropriate for solving decision-making problems under uncertainty for both operating and planning horizons. Eventually, for the purpose of mapping wind speed to wind power for an entire wind farm or location, an effective method to build an aggregate power curve is also developed in the thesis.

GENERATOR CIRCUIT-BREAKERS: STUDIES TO SUPPORT THE IEC/IEEE STANDARDISATION AND NOVEL APPLICATION ASPECTS

Mirko Palazzo - Supervisor: **Prof. Maurizio Delfanti**

In a deregulated electricity market scenario, where power stations are held by different generating companies, outages are more critical and may have significant economic consequences. Therefore the problem of operating power stations with the highest possible availability has become more and more important in recent years. Obviously, how a generator is connected to the high-voltage grid and how the power supply to the unit auxiliaries is secured has a decisive influence in this respect. For this reason, generating companies are beginning to pay more attention on optimized maintenance strategies and on the reliability of power station equipment because they are a key point in reducing operative costs and improving the availability of a power station.

Two basically different ways of connecting a generator to the high-voltage grid are in use today, namely the connection without a circuit-breaker between the generator and the low-voltage terminals of the step-up transformer (this solution is normally referred to as *unit connection*) and the connection with a generator circuit-breaker (GenCB). The layout with a GenCB has several advantages over the unit connection, e.g. simplified operational procedures, improved protection

of generator, step-up and unit auxiliary transformers, increased security and higher power station availability, along with economic benefit. GenCBs are nowadays available for application in all kinds of new power stations as well as for replacement or retrofit in existing power stations when they are modernized or extended.

The requirements imposed on GenCBs greatly differ from the requirements imposed on general purpose transmission and distribution circuit-breakers. Due to the location of installation, high technical requirements are imposed on GenCBs with respect to rated normal current, short-circuit currents and fault currents due to out-of-phase conditions. Furthermore, the currents of very high magnitude which GenCBs have to deal with are associated with very steep transient recovery voltages (TRVs). The test quantities given for general purpose transmission and distribution circuit-breakers for the short-circuit and out-of-phase current switching tests do not cover adequately these requirements. The only standard which covers the requirements for GenCBs is IEEE Std C37.013-1997 (R2008) with its amendment IEEE Std C37.013a-2007. This standard in particular covers the requirements imposed on GenCBs regarding the degree of

asymmetry of the fault currents and specifically addresses the phenomenon of delayed current zeros (DCZ).

The present PhD thesis is specifically focused on a comprehensive analysis of the major aspects concerning the application of GenCBs. The main motivation comes from the project started within IEC and IEEE to jointly develop an international standard for GenCBs. This project represents an important step in standards development, especially because it will be the first IEC standard for GenCBs (the scope of IEC 62271-100 specifically excludes GenCB). The question whether the requirements laid down in IEEE Std C37.013-1997 (R2008) and in IEEE Std C37.013a-2007 are still adequate for the application of GenCBs in modern power stations is considered in the present work.

In order to quantify the requirements for the application of GenCBs, a comprehensive survey has been carried out on 185 power stations. Generators ranging from 16 to 2002 MVA have been surveyed. Technical parameters of power station equipment have been collected from combined cycle, gas turbine, conventional thermal, nuclear, conventional hydro and pumped storage power stations. The current and the TRV associated to its interruption

have been analysed for different fault conditions by means of simulations: Electromagnetic Transients Program (EMTP) has been used for this purpose. The peak values, the a.c. and the d.c. components of the system-source and generator-source short-circuit currents, as well as of the fault currents resulting from synchronising under different out-of-phase angles, have been analysed. The degree of asymmetry of those fault currents has been studied too. The DCZ phenomenon has been thoroughly studied and fault conditions which can lead to DCZ have been identified. Because some of the related fault cases are not considered in published literature, a detailed mathematical analysis has been carried out to explain the origin of those DCZs. In order to set the requirements for the application of GenCBs in case of DCZs, a mathematical model of the arc of the GenCB has been developed and validated by means of tests carried out in power testing stations.

A comparison between different GenCBs arc-extinguishing technologies is also provided. Based on the results of this analysis, a new type test procedure has been developed to reproduce the stress imposed on GenCBs due to the occurrence of DCZs.

A detailed analysis of the TRVs peak value, rate-of-rise and time delay has also been performed. A method based on genetic algorithms has been developed to investigate the adequacy of the TRV requirements laid down in IEEE Std C37.013-1997 (R2008) and in IEEE Std C37.013a-2007. Additional investigations have

been carried out on different aspects that concern the application of GenCBs with respect to overvoltages either generated by the GenCB's operation or by its sole presence in the open position.

Furthermore, a comprehensive study on the impact of GenCBs on the availability of power station layouts has been performed. A survey on major failures occurred to GenCBs has been carried out. Failure data obtained from the operating history of air-blast and SF₆ GenCBs operating in 108 countries from January 1970 to June 2011 have been analysed. A sample of 52696 GenCB-years installed in different types of power stations has been surveyed. This sample is by far the largest one ever analysed for GenCBs reliability analysis according to published literature. The analysis provides reliability parameters which are used to develop an empirical model of air-blast and SF₆ GenCBs. The average failure frequency of air-blast GenCBs is 2.7 times higher than that of SF₆ GenCBs with pneumatic drive and even 5.6 times higher compared to SF₆ GenCBs with hydro-mechanical spring drive. Air-blast GenCBs exhibit a much lower reliability compared to SF₆ equipment. This difference can be mainly attributed to the higher complexity of the former technology and to the aging of its components. The reliability of the operating mechanism plays an essential role in the estimation of the reliability of a SF₆ GenCB being responsible for the majority of major failures. The same tendency is observed on HVCBs. Specifically, the average failure frequency of SF₆ GenCBs

with hydro-mechanical spring operating mechanism is 0.4 times that of HVCBs. Finally, the use of a hydro-mechanical spring operating mechanism for GenCBs results in a lower average failure frequency compared to spring, hydraulic or pneumatic operating mechanisms installed on HVCBs. An algorithm based on sequential Monte Carlo method has been developed to quantify the availability of power station layouts. The proposed method is specifically intended to quantify the impact of a GenCB in addition to a circuit-breaker installed at the higher voltage side of the unit auxiliary transformer on the availability of a power station layout taking into consideration the simplified operational procedures and the higher protection brought about by the use of these circuit-breakers.

The results show that the presence of a GenCB, in conjunction with a circuit-breaker installed at the higher voltage side of the unit auxiliary transformer, increases the throughput power of the generator thus making the investment for these circuit-breakers cost effective. It can be concluded that the installation of SF₆ GenCBs can thus free the choice of alternative power station layouts not commonly considered till today.

A NEW APPROACH TO UNCERTAINTY EVALUATION IN COMPLEX MEASUREMENT SYSTEMS

Marco Prioli - Supervisor: **Prof. Alessandro Ferrero**

It is well known that the experiments represent the cornerstone of the nowadays scientific way to knowledge. However, it is often disregarded that experimental results are largely based on measurement activity. A specific scientific field, namely the measurement science, deals with the study of the measurement processes. The key point of the measurement science is that no measurement process can ever provide complete knowledge about the quantity subject to measurement, i.e. the measurand. In other words, any measured value is affected by uncertainty. The evaluation of measurement uncertainty is a relevant and challenging topic. In fact, measurement uncertainty is the parameter that allows one to assess the reliability of a measurement result and also to compare different measurement results. The standard approach to uncertainty evaluation is defined in a document published by the Joint Committee for Guides in Metrology (JCGM): the Guide to the Expression of Uncertainty in Measurement (GUM). This guide defines the fundamental requirements and the operative procedure for uncertainty evaluation focusing on specific measurement systems: the systems for which random effects represent the only (predominant) uncertainty source, since

every effort has been made to identify and compensate for the systematic effects, and for which an exact probabilistic model can be defined. Of course, this has an immediate, though often neglected, impact on the choice of GUM mathematical framework, which falls automatically on the well-known probability theory. In the last years, the GUM approach has been criticized, arguing that more general measurement systems exist than the ones considered by the GUM. In other words, complex measurement systems can be met for which an exact probabilistic model cannot be defined, e.g. the probabilities of some events are ill-known (or total unknown), since they are based on poor experimental observations or subjective beliefs, or for which random effects do not represent the only (predominant) uncertainty source, e.g. the systematic effects cannot be compensated or effects of unknown nature are present. For such measurement systems, the GUM approach to uncertainty cannot be applied and a more general method shall be considered for uncertainty evaluation. In this respect, the so called RFV approach, based on random-fuzzy variables (RFVs), appears to be a valid alternative to the GUM approach to uncertainty from its very

mathematical foundations. Its mathematical framework consists, indeed, in a different and more general uncertainty theory than probability: the evidence theory by Dempster and Shafer that encompasses, as a particular case, the possibility theory by Zadeh. This framework makes the RFV approach particularly suitable for uncertainty evaluation in complex measurement systems. Moreover, since the evidence theory encompasses also the probability theory as a particular case, the present approach to uncertainty remains valid when the ordinary measurement systems are considered. This thesis deals with the development of the RFV approach to uncertainty. The main goal of this work is to provide a more robust mathematical and metrological background to the combination of measurement results when they are expressed in terms of random-fuzzy variables. RFVs are fuzzy variables of type-2 since they are composed by two possibility distributions (PDs), one called random PD, which represents the random contribution to uncertainty, and one called internal PD, which represents all non-random contributions to uncertainty. First of all, in this thesis it is shown that the random contribution and the non-random contributions to

uncertainty have to be combined according to different rules and, therefore, the random PDs combination and internal PDs combination are discussed separately. The combination of random and internal PDs is derived from the definition of random and internal joint PDs, i.e. PDs of two variables, thanks to a mathematical rule known as the Zadeh's extension principle (ZEP). In particular, the random and internal joint PDs are built starting from the available relevant metrological information and taking into account the different random and non-random nature, respectively, of the considered uncertainty contributions. The random joint PD represents random contributions to uncertainty that are usually expressed in terms of probability density functions (PDFs). Therefore, the relationship between joint PDFs and joint PDs is analyzed and discussed in this work. In particular, starting from the available one-dimensional probability-possibility transformations, an original two-dimensional probability-possibility transformation is proposed such that the maximum amount of information associated with a given joint PDF can be translated into an equivalent joint PD. This thesis proves that the joint PD induced by this transformation can be considered as the reference random joint PD. Therefore, when the available relevant metrological information is expressed in the possibility domain, a method to obtain the joint PD that provides the best approximation of the reference joint PD is defined. This method leads to a propagation of the random contributions in the

possibility domain equivalent to the propagation of the same contributions in the probability domain. The internal joint PD represents non-random contributions to uncertainty (and contributions of unknown nature) that are better expressed in terms of PDs than in terms of PDFs. Therefore, an original procedure is proposed in this thesis to obtain the internal joint PD when the available relevant metrological information is expressed in the possibility domain. This procedure leads to an effective method for the propagation of the non-random contributions, including the uncompensated systematic contributions. Another significant contribution of this thesis is the identification of a simplified method for the propagation of the random and non-random contributions. Thanks to the (generalized) Nguyen's theorem, this method is derived from interval arithmetic. Its main advantage is that the PDs can be combined by means of simple algebraic operations and, consequently, the propagation of the random and non-random contributions results simple and fast. Moreover, the application of a conditioning process when measurement results are expressed in terms of RFVs is discussed. In particular, a definition of random conditional PDs and internal conditional PDs is proposed in this thesis. Thanks to this definition, the obtained RFVs are capable of expressing the whole metrological information about the measurand also when an *a priori* knowledge about the measurand itself is available, based on a previous measurement result or a

subjective belief. An additional aim of this thesis is to show how the proposed development of the RFV approach leads to an effective and more general uncertainty propagation in simple, though meaningful, measurement examples. The results provided by the RFV approach are compared with the experimental data and with the results provided by the standard GUM approach to uncertainty. The experimental results confirm the reasons for which the RFV method can be considered as a more general and more effective approach to measurement uncertainty. In particular, the considered examples show that the developed RFV method leads to the same uncertainty estimate as the one provided by the GUM when only random contributions to uncertainty are considered, thus confirming the compatibility between the two approaches. Moreover, they show that, in the presence of different uncertainty sources like uncompensated systematic effects, or in the presence of partial (or total) ignorance about the PDFs associated with the uncertainty contributions, the RFV approach yields a more realistic uncertainty estimate than the one provided by the GUM.

VOLUME TEMPERATURE DISTRIBUTION RECONSTRUCTION FROM BOUNDARY MEASUREMENT DATA

Nima Seifnaraghi - Supervisor: Prof. Gabriele D'Antona

The operation and control of distributed systems usually requires precise information on the spatial dynamic variables of interest as a function of time. Often due to budget considerations one is not able to dedicate as many sensors as desired to achieve the required information. The reduction of sensors numbers requires introducing the model of the process as prior information. Typically in complex systems there is no analytical solution to this kind of models. In addition geometry and the physics of the problem may imply certain constraints for positioning the sensors. Hence, a systematic approach capable of enhancing the optimized solution for field reconstruction in terms of spatial resolution and stability is quite crucial. The class of system considered here is the scalar field which can be described by partial differential equations (PDE). The thesis mainly focuses on temperature field; however, the presented method can be expanded to the whole class of problems mentioned earlier.

This work presents a method that is able to reconstruct the temperature distribution as a function of time over a desired domain using just a few measurements placed in a sub domain of the object under study. To achieve this goal data

assimilation is implemented in propose of fusing the observed data with the process model. The model is extracted from the physics of the problem described by PDE. Unfortunately most of the presented methods in literature become limited to number of dimensions and complexity of the geometry of the object under interest, since in such cases the process model gets too complicated. However, the developed approach here is capable of handling three dimensional objects having arbitrary shapes regardless of whether they consist of homogeneous or non-homogeneous materials. Considering the physics of heat evolution process the model can be expressed via famous heat equations. The well known solutions to heat equation problem can be categorized in two main analytical and numerical groups. Due to the fact that the existing analytical approaches lose their efficiency as the complexity of the problem increases -such as complicated boundary conditions, complexity of geometry or variety of consisting materials- for the sake of the generality and practicality of the algorithm the numerical approach has been preferred here. It worth noting that here the major part of computation burden is done off line and once for all providing the necessary

ground for the algorithm to be applied on line at a low cost.

The heat equation can be treated as a special case of initial boundary value problems (IVBP). In the case of applying the eigenfunction expansion technique, the problem will boil down to Sturm-Liouville eigenvalue problem. One of the main privileges of this class is yielding orthogonal eigenfunctions with corresponding real eigenvalues as their solution. Taking advantage of this property of resulted eigenfunctions, they can be used as the basis of the solution space and the temperature at any desired location of the domain can be reconstructed over time using properly weighted summation of these bases. The eigenfunction evaluation has been performed numerically off line by a Finite Element Method (FEM) based software. In order to evaluate the weight coefficients as a function of time an inverse problem should be solved where the forward model is built based on the eigenfunctions and observations are the sensed temperatures at the boundaries. These infinite number of orthogonal eigenfunction bases span the infinite dimensional solution space where the weight coefficients lie. Since computation cost and time

consumption while dealing with such a solution space can be expensive or even impossible, a novel technique is developed to reduce the size of the system representation by only taking to account the most relevant bases. This technique involves the eigenfunctions based on the predefined target uncertainty and forms the reduced model space.

Typically even in the reduced model the number of observations is much less than the dimensions of the solution space forcing the inverse problem to be under determined with no unique solution. Therefore, the position and number of sensors over the allowed observation sub domain should be chosen in a way that the reconstruction field contains the minimum expected error. The error is constituted by combination of resolution error and sensor noise propagation. These sources of error are in contrast with each other (low noise reconstruction has low spatial resolution and vice versa). This objective requires an optimization approach which is able to maintain the tradeoff between the resolution of the reconstructed temperature distribution and its sensitivity to noise. This optimization problem consists of selecting a subset of sensor positions from the finite set of all possible candidates which makes the problem to

be classified as combinatorial optimization problem. Here genetic algorithm optimization is applied as one classical solutions to such type of problems. The available boundary measurement surfaces and maximum number of sensors to be used are inserted to optimization as constraints to be satisfied.

Few case studies are performed for instance (i) the reconstruction of temperature distribution on the top surface of a work piece located on the glassy surface of an induction cooktop by measuring the temperature from below the glass and (ii) reconstructing the temperature of the center of microchip placed below a heat sink. In all cases the results confirm the capabilities of the method in reconstruction of temperature distribution. In summary the method has the main advantage of being able to be performed in practical situations where the object can be composite, non-homogenous having a complex geometry while still being able to be applied on line. The method can offer the user a preview of the observation error that will be present over the final reconstructed temperature based on the constraints over the observable sub domains; therefore, prevents the user to include ineffective extra sensors in hope of increasing the accuracy making the method

economically reasonable as well. In addition the algorithm has the potential to be extended to other physical phenomenon other than heat evolution which can be formulated with quasi-linear partial differential equations.