Title: Distribution Grid Security Management with High DG Penetration Rate: Situation in France and Some Future Trends

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***Abstract*-Basic guidelines for the preparation of a technical work for the IEEE Power Engineering Society are presented. This document is itself an example of the desired layout (inclusive of this abstract) and can be used as a template. The document contains information regarding desktop publishing format, type sizes, and typefaces. Style rules are provided that explain how to handle equations, units, figures, tables, abbreviations, and acronyms. Sections are also devoted to the preparation of acknowledgments, references, and authors' biographies. The abstract is limited to 150 words and cannot contain equations, figures, tables, or references. It should concisely state what was done, how it was done, principal results, and their significance.**

Index Terms--**Power distribution reliability, Voltage control, losses, Load management, Fault location, Power system stability.**

I. Introduction: Difference and Convergence Between Transmission and Distribution Networks

Distribution grids are facing tremendous challenges due to several factors among them the most important is the increasing penetration of Distributed Generation especially those based on renewable energies. These challenges have to put a special emphasis on the evolution of distribution grids with respect to the security of the whole electrical power system. Indeed, the transmission grid will no longer be "decoupled" from distribution grid. In addition, given the current practices regarding the generation disconnecting protections and the increasing number of DG interconnected at the distribution level, it is important to reconsider the concept of "security assessment" of the distribution grid without necessarily being independent from the transmission grid.

It is to be noted that the security concept is considered differently when considering transmission network or distribution network. Below is reminded the main characteristics of the both systems:

Transmission network are meshed. In case of a line trip (following for example a short-circuit and fault clearing) all substations remains fed. Customers connected to these networks may see voltage sag of short duration but no disconnection.

For the network operator, he has to balance between two problems: if the network is too strongly meshed, the short circuit currents may be too strong and he will face equipment problem on his network (lines, switchgear, ..). He then may have to open some lines or split some electrical nodes (in substations) to reduce short circuit currents. One of the major parameter he has to manage is the critical short circuit clearing time. This duration is related to network topology and rotating machines control system. It is directly linked to the stability of the system. It is well known that the stability problem is crucial for a transmission network and the operator has to take any needed action in order to avoid the problem or minimize its consequences. The stability of transmission network is often the process that leads to a blackout. For transmission systems, managing security means avoiding blackouts.

Distribution networks are built with another principle concerning its security. It is considered that in case of short circuit, as the number of customers concerned is limited, the interruption of the supply service during a short period (say some minutes) can generally be accepted. The average interruption time for customers is less than 50 minutes in France. This load curtailment has no dangerous effect on stability of the transmission network. The distribution networks are operated radially, the energy comes mainly from the substation (transformer) connected to the upper voltage level. If a short circuit occurs in the distribution network following by a feeder disconnection (trip), the operator has to localise the fault and to reconfigure the network so that most of the customers will be re-energized. Often, the main objective to be fulfilled is the increase of availability. The criterion is the minute losses or SAIDI. In order to allow some reconfigurations, the network topology is structurally meshed but radially operated with switches which remain normally open.

This architecture was chosen when DG were very rare and so did not present significant problems. Recently, due to environmental issue, and progress of production technology, more and more small size generations are being interconnected to the distribution network. This type of generation is often renewable, dependant on whether conditions, and finally random and highly variable. Nowadays, for some countries and networks, distribution networks with significant local

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generation have already been observed even above the local consumption. Electrochnical problems related to DG interconnection to distribution networks are now well known.

When a distribution network is operated with DGs, we may have the classical philosophy of fit and forget. All the problems have to be coped with when we interconnect DGs. In order to guarantee a good security level, operators consider the worst case and adapt the network to the DG interconnection (or forbid interconnecting DGs in case of any problem). In the future, distribution system may be operated more dynamically, ie verify that constraints and security criteria are fulfilled in real time, and choose the configuration and the production means allowed to operate the whole system in real time. Differences between operation of distribution and transmission network will reduce.

II. Current Practices of EDF Distribution Concerning Automation and Interconnection of DGs

In order to guarantee a good quality of service supply and optimal costs the French distribution grid is operated radially but has spear feeding ways to reconfigure the network in case of faults. Typically, each feeder is built to have the ability to feed another feeder in emergency scheme. When a fault occurs on a feeder, using remote controlled switches, it is possible to separate the feeder into three to four sections, and isolate the fault. Generally, each section can be re-fed by another line or cable. Inside of each section, it is possible to separate the network in smaller subsections using manual switches. In order to localise the fault, remote detected fault passage indicators are used. A control center accesses to all this information and operators control all the remote controlled switches.

With this strategy, the average minutes losses of the French network is about ….. and 85% of the disconnections have a duration of less than 3 minutes.

When there is a DG interconnection request into the network, a specific study is undertaken by the network operator. The potential technical problems that are assessed are the following:

Curent constraints, voltage constraints, protection, etc.

When some constraints occur in the distribution network due to the DG interconnection, a solution is studied and the cost of this solution (restricted to the part of the network of the same voltage level as the interconnection point) has to be taken in charge by the DG owner. When we look at the case of wind farm, whose rated power is typically between 5 to 20 MW, they are often interconnected to the substation with a separated MV cable. This practice, decided by the French government, guaranties a good quality of service for all the customers and very few over costs for the distribution network operator due to DG interconnection. The growing presence of DG on the Medium Voltage grid has been treated up to now by fitting the Medium voltage grid and the DG units to guarantee a satisfactory operation of the system at all times. The Distribution System Operator (DSO) would operate the grid with very limited knowledge if not no knowledge at all of the real time state of DG units. We are expecting this approach to reach limits in the future. To facilitate the interconnection of DGs, and to solve some remaining problems, we undertake some research activities [1].

III. New Topics and Challenges in Distribution Networks

In the future distribution networks, two major evolutions are expected to occur. The first one is related to the management of generation and load to provide services to the network operator. We will go from a fit and forget approach to the concept of active network.

The other major evolution will consist in going to more flexible networks. The progress of information and communication technology (ICT) allows having more remote controlled devices.

A. Voltage management and control

Large scale integration of DG in distribution networks is often limited by voltage issues. The voltage profile along the feeder, which was simple as the voltage was just decreasing along the feeder, is now more complicated due to power injections. These voltage violations are the consequences of a high penetration rate of distributed generation. However it is possible to change the reactive power production / consumption set point for each DG and, therefore, avoid some voltage constraints hence allowing the maximum DG penetration rate to be increased. In order to implement this solution, the distribution system operator (DSO) needs to control reactive power production of some DG interconnected to its network. Additional grid automation can provide a finer optimisation of grid losses. Grid configurations are usually optimised using peak demand situations. When interconnecting DG, the VAR flows are not optimised: a coordinated VAR control of generation and substation would ensure that the generated and consumed VARs are optimised. The value of a coordinated VAR control will increase as the presence of DG increases. These systems will involve monitoring and control of capacitor banks and/or voltage regulators on distribution circuits including on-line tap changers.

Voltage control problem could be seen as a mathematical optimisation problem. Several solving methods exist but their implementation on real time systems seems tricky as computation times could be too extensive. Different strategies will be tested. A first approach transposed from transmission network practices is based on an optimal power flow calculation which is done during the day-ahead process, and results in specified values for voltages in some pilot points. In real time, the control system uses these pilot point voltages as set point to a coordinated reactive power control for DGs. [2, 3,4]]

B. Management of generation and load

The presence of DG units on the MV system adds uncertainties on the total active and reactive power flows seen on the primary side of HV/MV transformers when there is no way to observe. Variations in DG active and reactive power output can move the system from its optimal point that is calculated every year in order to prepare the next year contractual values with the TSO. When active and reactive flows exceed contractual levels, EDF Distribution has to pay penalties to the TSO. In order to control the flows between the TSO and our primary substations, it will be necessary to forecast, then monitor closely and control the DG active and reactive power injections. Today, these are the limits of the fit and forget approach on the transmission and sub-transmission systems. The recent experience shows that the fit and forget approach is not always chosen for HV systems: in windy regions with scarce loads the power injection can reach peaks that leads to congestions on the HV system in certain conditions; these limitations reduce DG output.

This is the first example where the network operator has to control the production of DG to solve his own business. In the future we can also consider the case where congestions on the distribution network will need management of generation or load to be solved. Increasing expectations of customers, regulatory bodies, local governments, assets aging and new occurrence of peak loads in summer time are foreseen to increase the constraints on the distribution grid. On the other hand, the development of DG can release some constraints but can also increase the constraints (voltage constraints, power flow constraints when major loads are not close enough to a generation site, etc.). In the long term, the peak load may be increased by new loads such as heat pumps, or rechargeable hybrid vehicles. This may lead to new ways for the distribution system to deal with peak demand (to send broadcasted or individualized signals to customers about peak time or low load time periods, to implement different interconnection contracts depending on the load curve, etc).

Let us consider the case where one of two parallel feeding transformers is out of order. Due to some other cable unavailable in the network, it is not possible for the operator to find an adequate configuration, fulfilling all the constraints. In this case, which is rather rare, the best approach would be to manage local production or load to reduce the peak flows of approximately 10%. This flow management is necessary during 6 hours in the day.

Using only thermal load management (space heating), which represents 30% of total load at peak hour, and limiting the curtailment to one hour for each customer, we could conclude that simple approach is not sufficient to solve the overload of the feeder we were looking at. We need a more sophisticated strategy, for instance by taking into account the real inertia of each building, or by managing other loads.

The other aspect to be solved so that this kind of service could be offered to the distribution operator is the financial problem. An approach is developed in the European project FENIX in which we are involved. It consists of a transposition of the redispatching principle used by transmission system operators. This will need a major change of the DSO role: it will be for instance involved in the redispatching operation made by TSO [4].

C. Stability analysis for distribution network with distributed generation

Although considerable attention has been dedicated to DG generation technologies based on non synchronous machines, e.g. fuel cells and photovoltaic, the great part of generation on the medium voltage network are synchronous generators, particularly for Combined Heat Power applications. However, the fault clearing time of distribution network is normally very long whereas the inertia constant of DG is typically low. Therefore, following a large disturbance (short-circuits, line outage voltage dips…), they are disconnected from the network by the decoupling protection. When the penetration of DG is still low, the influence of this disconnection may be neglected. However, when the DG penetration rate increases, this disconnection may lead to significant load shedding. As seen from the transmission network the behaviour of the interconnected distribution network during the disturbance is very important. The stability of the whole network depends on all the components. Therefore in order to study the stability of the whole network it is necessary to model all these components, especially those having an impact on the overall dynamic behaviour of the electrical system.

As the distribution network is a large system, representing all the elements is a complicated task. The first principle used to solve this is to develop methods to simplified equivalent models of the network. This approach drastically reduces the computation time while keeping a good accuracy.

In a study going on in our team, the transient stability of synchronous generators which are connected to distribution systems is investigated. The conventional method to assess the transient stability of power system is based on time domain simulation of system dynamic equations. The determination of index of transient stability limits, and hence the Critical Clearing Time (CCT), is performed by around ten or hundreds of repetitive simulations. This method provides the most accurate and reliable results and it has unlimited modeling capabilities. However, the method is very slow because of numerical integration of dynamic equations and it does not provide sufficient information about the index of stability of the system.

Thus, to quickly assess the ability of the DG to withstand severe disturbance while ensuring the continuity of service and then apply the preventive action to safeguard them, two hybrid methods are studied: the Individual Transient Energy Function and the SIME methods [REF]. The direct outcomes of these methods are: substantial gain in the computing time over time-domain methods on one hand and assessment of margin and identification of the system critical machines on the other hand.

D. Optimal Number and Positions of Fault Passage Indicators

Distribution networks perform the connection to final customers and have to fulfill services and ensure a good power quality. The service continuity is one of the most important concerns to the utility company but a fault is often unavoidable and results in power interruption. Faults detection and localization is therefore of first importance in the network management by the DSO.

In order to localize the fault before isolating it and reconfiguring the network, the classical means may give false results and need to be adapted [1], [2].

Fault Indicators (FI) are main devices used for faults detection and spread along the feeder [3]. As a permanent fault occurs, they make it possible to localize the faulty part of the network and to isolate it from the sane parts (fast fault localization). FI may deliver the following information:

- local visual signs,
- remote information to SCADA.

With this information, the DSO and the maintenance crew can isolate the faulty part of the feeder, supply the customers and repair the conductor. For the moment, the FI placement is performed by the maintenance crew or the DSO when the feeder is created or modified. One can ask whether a help tool could be useful to propose a relevant FI placement.

Besides distribution networks are nowadays facing new challenges with the probable massive introduction of dispersed generation. One of them is to continuously ensure the safety and the security of the network in spite of many versatile actors. The efficiency of FI placement is therefore influenced. We have performed a study which deals with the optimization of FI placement and analyzed the DG effect upon the efficiency of this placement.

An optimization tool of FI placement was developed. The method makes it possible to select the optimal placement by knowing the characteristics of the network (load, type of conductor, switches, fault probability, etc.).

Among the different existing optimization methods, the genetic algorithms have been selected to perform the placement process. Guidelines are proposed to tune this optimization process for the considered application.

The DG insertion influence (islanded functioning or not, cost of non-supplied energy) on the efficiency of FI placement in this network has also been analyzed.

E. Towards a More Automated Post-Fault Restoration

When a fault occurs on an MV feeder, the control engineer downloads data from fault passage indicators, locates the remotely controlled switches that need to be open to isolate the fault and then performs the fault isolation. Usually power can be restored on the healthy segments in the upstream part of the feeder. Downstream from the fault, restoration is usually possible in N-1 conditions. These actions are usually taken within three minutes, thus keeping the number of long interruptions low. When power to a whole busbar or a whole substation is lost, or during storms, restoration is a far more complex operation. The presence of DG makes the evaluation of the restoration more challenging as well if the control engineer wishes to use the DG capacity when backup feeders do not have sufficient capacity. The number of solutions that need to be evaluated can be far greater.

Innovation in Distribution Automation (DA) uploading of fault passage indicators, automatic localization and isolation of faults, automatic restoration of healthy feeder segments, and integration of DG capacity in restoration schemes can bring significant value in these situations. Especially as the number of substations per control centre increases. By providing a significant help to the control engineer in improving his reaction to faults, the control engineer can handle a larger number of substations. This is particularly valuable at night or during storms.

The value will eventually be for both customers and DG owners who will benefit from higher grid reliability. We expect these improvements to reduce the customer minutes lost by 2 to 5 min depending on the region of France.

The challenges for these innovations are mainly in the quality of topological and load data, in the quality of the communication with DER units, and the robustness of the optimal solutions proposed when DER units are included in the restoration schemes.

F. Choice of the configuration and impact on security levels

The Distribution Networks (DN) are designed as looped or meshed structures and are operated radially. Normally opened switches (generally remotely controlled) are chosen considering fault management, network losses and voltage control purposes. Their positions are changed especially when the grid is reconfigured after a permanent fault or for maintenance actions.

Nowadays, because of the increasing amount of DG, these practices should be modified for a better network operation. A more flexible topology may be useful in order to reduce the network losses and to optimise the voltage profile.

This aspect should be considered, taking into account the emergence of ICT technologies in DN. For instance, remote measurements make a better possible DN state estimation and an increasing amount of remotely controlled devices should allow a more flexible operation to be achieved.

In this context, optimal DN topology computation tools have to be developed. They should consider the losses reduction and/or the voltage profile optimisation into the cost function. Topology constraints (staying radially operated) and security constraints (accepted voltage and currents values) should be considered. This is a non linear constrained combinatorial optimisation problem. Heuristic optimisation methods, which are frequently employed, may only converge to a local minimum. Moreover, DG presence increases the risk of converging to a local optimum.

A stochastic optimisation method (genetic algorithm) is developed for the optimal solution computation. Graph theory and matroïd properties are used to ensure a good topology modelling constraint and efficient genetic algorithm process.

The optimal topology has determined that to minimize losses could not be optimal for reliability concerns. The integration of a reliability index computation in the optimization process can be a very consuming time task. A first approach based on electric moments computation (active load multiplied by conductor length) can be used in order to consider the reliability aspects in the optimization process.

Table 1 presents the results of the optimization for one hour of the day, near peek hour. For each considered criterion, the results are reduced compared to those of the initial configuration.

	Initial Configuration	Optimal configuration for Power Losses	Optimal configuration for Reliability
Network Losses [% Total Active Load]	3.31 %	2.87 %	3.22 %
Non Served Energy [MWh]	1.7	1.73	1.53

Table 1: optimisation at peek hours

G. Distribution system availability assessment

The major changes in distribution systems brought by the introduction of DG, make their operation as well as their operational reliability more complex to be assessed and need to be modified. A re-evaluation of system reliability is therefore needed. The two often used approaches for power system reliability evaluation are the analytical and simulation methods. Analytical techniques represent the system by a mathematical model, often simplified, and evaluate the reliability indices from this model using direct mathematical solutions. Simulation techniques estimate the reliability indices by simulating the actual process and random behaviour of the system and are generally more flexible when complex operating conditions and system considerations (bus load uncertainty, weather effects, etc.) have to be taken into account. The type of simulation involving the sampling of values of stochastic variables from their probability distribution using random numbers is denoted as Monte Carlo simulation. There are two basic techniques used in Monte Carlo simulation: sequential and non-sequential. The sequential simulation permits chronological issues to be considered and the reliability indices distribution calculation. The Monte Carlo simulation needs many trials to obtain a reasonable accuracy in the result of the estimate and each trial requires significant computational effort.

The distinctive way to handle this issue is the simulation of the dynamic behaviour of the system, meaning that, along the time axis, not just one event is modelled but a sequence of events. During simulation, different system states can be reached, involving even the blackout and the restoration of the system. The reliability indices are computed for each system state and for each load bus.

IV. Interdependency with Information and Communication Technologies (ICT) Infrastructure

The increasing use of information technologies within the electrical supply networks (production, transmission and distribution) reveals the concepts of vulnerability and interdependency. The three essential infrastructures, namely, electrical, information and communication networks are so closely dependent that it is essential to have an "integrated" vision of the safety of the whole system by taking properly into account their interactions.

The reliability of the critical infrastructures is the aptitude to deliver a justified confident system and to avoid most frequent failures or more serious than acceptable: it results from the causes analysis (failures, faults, errors, etc.) in a cycle of prevention, tolerance, elimination of the expected faults in order to offer the necessary services and reliability: availability, harmlessness, confidentiality, integrity, maintainability. Many blackouts are due to accidental causes such as natural events, errors of use, loss of essential services and internal malfunction. Malicious acts such as data hacking or virus introduction then come in addition to these traditional “safety” incidences. However, accidents in large technological systems are not always due to simple cause and effect, but sometimes due to chains of disruptions, which can mean masses of damaged lines at the same time, cascading effects or emergency systems that are supposed to prevent failures being out when they are needed.

Considering security in distribution networks including this type of failures shows that a lot of efforts have to be done to model and analyse these interdependencies. This is a major concern for a distributor.

V. Conclusion

Distributed resources will introduce tremendous changes on generation business as well as on electrical energy distribution and management. It will require redesigning planning strategies and tools, design methodologies, operations and control of electrical networks. Indeed, these networks were not designed and built in this perspective (interconnecting large amount of distributed resources) and the integration of such resources into the grid may have significant consequences on system performance and security and hence on the philosophy of the management systems and robustness.

In addition, with significant DG penetration rate into distribution grid, the interaction between distribution and transmission grid will be stronger. They will be more interdependent particularly with regards to security management. Depending on the situation, the security may be improved or jeopardized.

In this context and beyond the distributed resources aspect, the whole distribution network should be redesigned with innovative equipment, more automation, new control and supervision functions, specific network architectures, intelligent protection systems where information and communication technologies can achieve low cost goals regarding these new functions. Hence, the whole electrical system and its philosophy of planning, design and management is in profound mutation. In this paper we presented some examples of new features or methods adapted to future distribution grid management.

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VII. Biographies

Christophe KIENY was born in 1956. He graduated from Ecole Polytechnique (X77) and received the engineer degree from the Ecole Supérieure d'Electricité in 1982. He has been with Electricite de France- R&D department - since that date. He is now, deputy director of IDEA.

Nouredine HADJSAID received his Ph.D. degree in Electrical Engineering and “Habilitation à Diriger des Recherches” degree from the Institut National Polytechnique de Grenoble (INPG) in 1992 and 1998, respectively. From 1988 to 1993, he served as a research and teaching assistant at the Ecole Nationale Supérieure d’Ingénieurs Electriciens de Grenoble (ENSIEG) and at the Laboratory d’Electrotechnique de Grenoble (LEG). He is a professor at INPG.

Raphael Caire (SM’00, M’04) received his Diplôme d’Etudes Approfondies (MSc) and Doctorat de l’INPG (PhD) degrees from the Institut National Polytechnique de Grenoble (INPG) in 2000 and 2004. He was working in Power Electronic field, in USA at the Center of Power Electronic System (CPES). He is now assistant professor at Grenoble InP at the Ecole Nationale Supérieure d’Ingénieurs Electriciens de Grenoble (ENSIEG) in the Grenoble Electrical Engineering laboratory (G2Elab). His research is centered on the impacts, production control of dispersed generation on distribution system, planning and critical infrastructures.

Tuan TRAN-QUOC (M' 93, SM' 99) received his Ph.D. degree in Electrical Engineering and “*Habilitation à Diriger des Recherches* ” degree from the Institut National Polytechnique de Grenoble (INPG) in 1993 and 2000, respectively. His research interests are in the fields of power system analysis, operations and electromagnetic transients.

Olivier DEVAUX was born in 1969 in France. He received his degree of Electrical Engineer from the Ecole Supérieure d’Electricité in 1992. He joined the EDF‘s R & D Division in 1993.