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Interactions of Dispersed Energy Resources with power system in normal and emergency conditions

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SUMMARY

Distributed Energy Resources (DER) are already operating in Europe, for instance wind turbines or combined heat and power presently mostly in industry. However there is a trade-off between the potential benefits of DER and the adverse effects at the distribution level, at the transmission level, and even at the system level. These adverse effects are often presented as being responsible for the relatively limited development of DER. A comprehensive analysis of the electrical power system operation in normal and emergency conditions is necessary in order to classify these problems and to suggest practical solutions. Practical solutions mean those which can be implemented efficiently, balancing adequately investments and costs of reliability failures.

The paper summarizes the methodological approach which is developed in the EU-DEEP project to assess the integration of DER in power system. Some results of Work Package 2 "Integration", obtained during the first two years of the research program, are presented. These results are classified in three categories.

Results from the first category are coming from in depth studies unveiling the basic principles governing power system operation in normal and in emergency conditions. The approach is developed considering small systems where 100% of the electrical energy is supplied by DER. This allows for analyzing in a simple and comprehensive manner the consequences of the presence of DER on common distribution systems and it permits to define possible solutions. This also allows for the development of examples which can be used for training purposes within the project, and outside of the project.

Results of the second category are coming from studies analyzing the progressive penetration of DER in a "traditional" system made of generation, transmission and distribution. The investigation starts from the present status of distribution systems where no DER is operating and examines the different technical problems arising when an increasing proportion of the electricity is supplied by DER. This proportion remains still limited leading mainly to networks problems. These are related to voltage control, protective scheme, anti-islanding protection, power quality, etc., but also to allocation of costs: connection costs, use of system charge, active losses compensation, etc. This is fairly important, as economic performances of DER are presently highly dependent on the way they are integrated in the system and in the market.

Finally the third category of results is built from analyses considering large power systems where the penetration of DER is rather high. This means that the proportion of classical power plants decreases more and more leading to critical system problems. In general power – frequency and voltage controls are concerned in quasi steady-state operation as well as in transient and emergency conditions. This is the object of investigations during 2006.

These technical questions have major interactions with market and regulation. These questions are not treated *per se* in the paper but general comments on the best possible approaches can be deduced from the technical approach. Regulation principles which must be used for distribution and even transmission networks should necessarily integrate the outcome of the technical analyses. Such approach is highly commendable for reaching efficient market integration and regulatory frameworks.

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KEYWORDS

DER, Distributed Generation, Power System

1 INTRODUCTION

The paper summarizes the methodological approach that is developed in the EU-DEEP project for assessing the integration of DER in power systems [1]. Some results about DER integration obtained during the first two years of the research program are presented. These results are classified in three categories.

Results from the first category are coming from in depth studies unveiling the basic principles governing power system operation in normal and in emergency conditions. The approach is developed considering small systems where 100% of the electrical energy is supplied by DER.

Results of the second category are coming from studies analyzing the progressive penetration of DER in a “traditional” system made of generation, transmission and distribution. The investigation starts from the present status of distribution systems where few DER are operating and examines the different technical questions arising when an increasing proportion of the electricity is supplied by DER.

Finally the third category of results is built from analyses considering prospective cases of large power systems where the penetration of DER is rather high. This means that the proportion of classical power plants decreases more and more leading to critical system problems. In general power – frequency and voltage controls are concerned in quasi steady-state operation as well as in transient and emergency conditions.

2 SMALL SYSTEMS

Small systems are easier to overview than large systems and are better suited for illustration purposes. Additionally a small system with DER is relevant for the situation where a distribution system with DER is separated from the overlying system and enters island operation. Some important aspects of small systems when considering DER are 1) control of frequency and voltage, 2) protection and 3) the impact of DER units based on asynchronous generators or power electronic converters.

2.1 CONTROL OF FREQUENCY AND VOLTAGE

Many parameters are different for small and large systems. In small systems individual loads are much larger relative to the total load, which leads to a more challenging disturbance to the frequency control system. Furthermore there is less cancellation between individual load variations, as there are less loads. Together these two factors act to increase the frequency variations in a small system. This is particularly clear when studying a small system that is first interconnected with a large system, but which enters island operation, see Figure 1. Clearly the frequency variations are much larger for the island system, than for the large system including the island. In large interconnected systems the limits for acceptable frequency deviations are related to the ability to control frequency, leading to narrow limits for large systems such as UCTE and wider for smaller systems such as NORDEL. For an island system frequency limits are instead absolute and are dictated by what deviations the connected loads and generators can tolerate without malfunction.

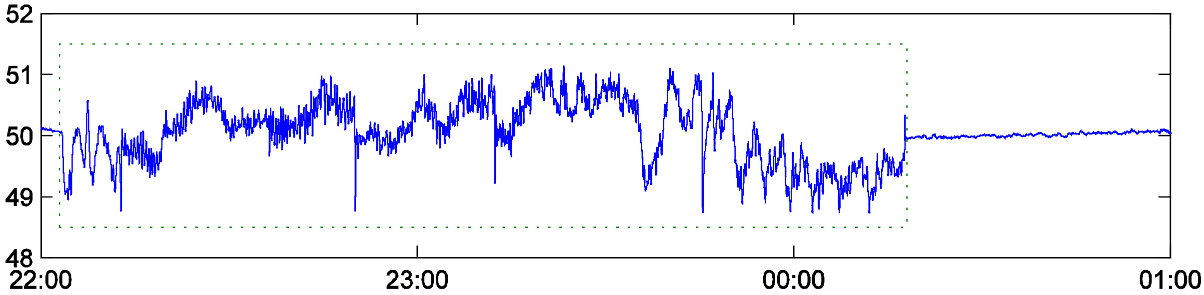


Figure 1, Frequency during normal operation and island operation (in box from shortly after 22:00:00 to near 00:15:00). The island has a load of 15 MW, 30 MW synchronous hydropower generation on-line, while the figures for the large system are near 30 GW. (Field data courtesy of Sydkraft Elnät AB.)

In small system it is important that all means for frequency control are properly exploited. Since the control reserves are very limited, the situation resembles a larger system during emergency conditions. Load shedding to arrest frequency decline is thus very important. It is also necessary to have as many generating units participate in frequency control as possible. It is well-known that controlling active power in proportion to frequency deviation based on the droop concept is an efficient way to coordinate and share control actions without the need for communication.

The droop concept can also be applied for controlling the reactive power in proportion to voltage deviation. Voltage regulation is one of the key barriers preventing large penetration of DER. This is for two reasons: Existing voltage regulation at lower voltage levels where DER is connected is designed based on the assumption of a purely radial network with power flow only in the downstream direction. Furthermore, the network at lower voltage levels is more resistive than inductive, which makes voltage sensitive to active power flows. The situation is thus challenging and also all resources for voltage control should be used. For DER units with controllable reactive output, droop-based voltage control is straightforward to implement and provides very attractive plug-and-play capability. It enables neighbouring DER units of the same type, but also different types of units to share the voltage control effort [2]. This is important since the risk of harmful interaction between voltage controllers hitherto have prevented DER units from participating in voltage regulation.

2.2 NETWORK PROTECTION

Protection of a power system should perform as intended for all probable situations. Protection requirements of a small system that can operate both interconnected and as an island must therefore consider both situations. If the small system is a distribution system, the large system can be considered as synchronous generator contributing with significant steady-state short-circuit current. Transition to island operation can be considered as disconnecting this generator, which changes the situation in the following ways:

- short-circuit current near the interconnection point becomes significantly smaller;
- short-circuit current now comes from DER units often located downstream;
- DER units at remote points may locally increase the short-circuit current compared to the no-DER case.

The changes in short-circuit current affect the selection of switchgear and network protection settings. It may become impossible to find protection settings that guarantee selectivity in all operating conditions. One improvement may be to replace fuses with circuit breakers and directionally sensitive protective relays. If this is insufficient communication and differential protection may be needed.

Island operation of distribution systems may improve reliability by offering a reduction in interruption time to customers. A transition to island operation without service interruption puts high demands on control and protection since they have to handle the two very different situations of interconnected and island operation. This is not possible today, since DER units are equipped with anti-island protection that shuts down when island operation or the preceding transient is detected. An alternative is to enter island operation only after black-start of the DER units. While black-start may be challenging, this option offers a clearer distinction between the operating modes. It may be argued that island operation after black-start improves reliability sufficiently in many cases and that selective clearing of short-circuit faults is not needed [3]. Should a fault occur during island operation it could be cleared by letting the protection of the DER units shut down the units and the island.

2.3 ASYNCHRONOUS GENERATION AND POWER ELECTRONICS

While many DER units have synchronous generators directly connected to the network, asynchronous generators and power electronic converters are also common as network interfaces. This has little importance for the large systems on national level, which will be dominated by large synchronous generators for a foreseeable future. But locally for the individual small system, it may be very important since the generating units may be dominated by units with power electronic converter-interfaces. As a first step, it is important to realize the differences between different interface-types and to promote a mix of the various types. The droop-based control of active power in proportion to frequency deviation is an example of scheme that is applicable to all. Provided that the reactive output can be controlled, droop-based voltage control is equally general. Other properties are less general:

- Fault current contribution: Asynchronous generators have an initial current transient similar to that of a synchronous generator, but deliver no steady state fault current. The output of power electronic converters is controlled and during a short-circuit fault it reaches a current limit of typically 110% of nominal current. This has important implications for clearing of short-circuit faults and may add to the difficulty of using fuses when the short-circuit current is reduced as outlined above. The fact that the converters are controlled and easily detect that the network impedance has changed may on the other hand be used to shut down the DER unit. This combines well with the fault-clearing option of shutting down all DER units and possibly the island network they feed.
- Network frequency: For synchronous machines frequency is proportional to shaft speed and is a measure of the energy balance in the system (in steady state, the frequency deviation reflects the difference between the expected and the effective load.) The mechanical dynamics of asynchronous machines are the same as those of synchronous machines, but frequency and shaft speed differ depending on the loading. For power electronic converters, DC link voltage is a more important indicator of energy balance and network frequency must be estimated from measurements [2]. Traditional simulators for efficient power system analysis use phasor to represent voltages and currents. In such tools frequency is derived from a weighted average of the shaft speed of all. If no synchronous machines are present in the model, frequency is not defined. This is not acceptable today and has stimulated development of new phasor models of converters to permit analysis of power systems without synchronous machines [4].
- DC injection: Imperfections in the switching in power electronic converters may lead to a DC component in the converter output [5]. The phenomenon may occur both for converters that connect motors and generators to the network. DC injection has received limited attention and it is suggested that the standards on this issue for DER units and adjustable speed drives are developed in a coordinated way.

3 T&D QUESTIONS, LIMITED DER PENETRATION

3.1 HOSTING CAPACITY

It is important to know how much DER can be connected to a distribution or transmission system. Uncertainty on this may result in unnecessary barriers against DER and/or in unacceptable network performance. The hosting capacity approach has been introduced to determine the maximum-permissible penetration of DER. The approach is presented in a systematic way in Figure 2.

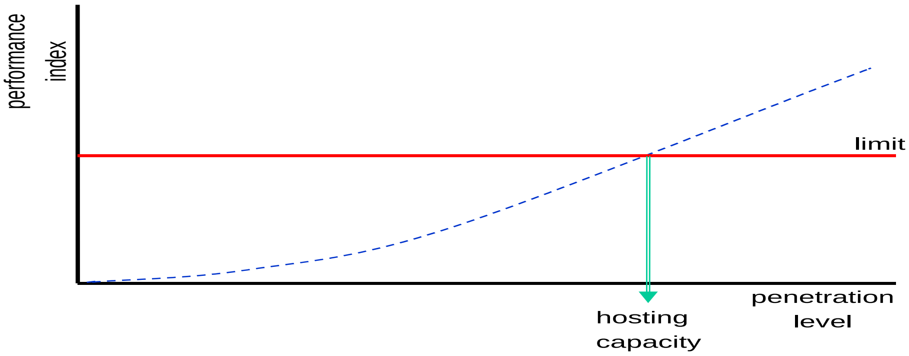


Figure 2, Hosting capacity approach with performance index as a function of the DER penetration level.

Each phenomenon that is adversely affected by DER (e.g. voltage variations, harmonic distortion, voltage or frequency stability, protection operation) is quantified by one or more "performance indices" together with an acceptable limit for each index. The performance index is next calculated as a function of the DER penetration level. The level for which the performance index reaches the limit is the "penetration level". This approach has strong similarities with the concept of power-quality indices and objectives [6]; many performance indices and limits can be obtained from power-quality documents. For non-power-quality phenomena like stability and protection, indices and limits will have to be defined.

Note that the hosting capacity is different for different phenomena; varies with time of day and time of year; and is different for different types of DER and location of DER. It will thus not be possible to give accurate values for the hosting capacity without doing a case-specific study. The importance of the hosting-capacity approach is in providing a systematic method and in forcing the discussion towards a quantification of what is acceptable behaviour. Examples of the use of the hosting-capacity approach are:

- Voltage variations: the increase in RMS voltage due to injection of active power is well documented in the literature. Less documented are short-duration variations due to intended or unintended connection or disconnection of DER units. Suitable performance indices are the 95, 99 or 100-percentile of the 3-second, 1-minute or 10-minute RMS voltages, with an upper limit between 106 and 110% of nominal. It will be obvious that the choice of performance index and limit will have a strong influence on the resulting hosting capacity.

- Voltage fluctuations and flicker are a concern with solar and wind-power. The power fluctuations in the flicker range are mainly limited to those due to the moving of the blades in front of the tower. The main concern is that synchronisation may occur between wind turbines at the same location; no documented proof of this phenomenon exists however. In general, flicker is not a concern with increasing DER penetration.

- Waveform distortion due to DER units is a limited concern for frequencies up to 1 kHz. The additional capacitance due to some kinds of interfaces may lead to harmonic resonances. Inverter-based interfaces inject a relatively high level of current in the frequency range between 1 and several tens of kHz. The lack of data and suitable power-quality objectives makes it difficult to draw general conclusions, but preliminary estimations point to a hosting capacity of only one to five units at some locations.

- The presence of DER units with synchronous-machine interface will cause additional fault-current contributions at distribution level. This may adversely impact the performance of the overcurrent protection used in distribution systems. Numerical studies indicate that the hosting capacity for individual feeders is between 25 and 50% of the transformer size. Other results based on DER using synchronous machines as interface show that 100% penetration (peak generation equals peak load) does not lead yet to selectivity problems.

Further, dissemination of distributed energy sources changes the structure of electric power supply of consumers. In this connection two aspects of DER impact should be considered. New essential advantages may result from penetration of DER – increase of reliability, decrease of energy losses, and improvement of economical parameters. On the other hand, the penetration of DER can cause new problems – deterioration of reliability, problems with power quality and so on. Network connection of DER causes many problems that should be taken into consideration. The main questions include:

- Operational stability of transmission and distribution networks: Penetration of different types of DER causes substantial changes of power flows in distribution and transmission networks. Besides, most of DER units are not controllable and increasing amounts of DER will cause problems of operational stability due to specific parameters of DER units.

- Protection of transmission and distribution networks: Protection schemes are often mentioned as one of the main problems posed by DER in distribution systems. Change of operational conditions in distribution system will influence also operational conditions in the transmission system. In many cases DER are located very close to the transmission system.

- Problem of resynchronization of transmission and distribution networks after their forced disconnection: The method of resynchronisation requires a sensitive balance between the need for fast reconnection and the need for reducing the reconnection transient. DER penetration causes specific transient phenomena that may bring the supply voltage outside of its acceptable limits or that may even lead to another interruption.

3.2 CASE STUDY: INFLUENCE OF DER ON POWER SYSTEM FREQUENCY CONTROL

The power systems of Estonia, Latvia and Lithuania (Baltic IPS) are interconnected with the Unified Power System of Russia and the power system of Belarus via a power loop [7]. Model of the Baltic States electric power system interconnection was developed to illustrate the DER penetration level estimation from the primary control aspect. The situation considers the Latvian power system islanded from the interconnection. The model includes structure and parameters of the real Latvian power system taking into consideration real primary control reserves, equivalent droop values of governors and equivalent load-damping constant (D = 1.6). The worst-case scenario is considered. It corresponds to a wind power penetration level is 8.6% from installed capacity of units participating in primary frequency control. The sudden disconnection of a wind park is the initiating event. Figure 3 illustrates the influence of governor droop to dynamics of transients during load deviation. For the considered primary control reserves the frequency drops down to 49.6 Hz. Assuming that maximal allowed frequency deviation in region (hosting capacity level) is 0.2 Hz, depending on the combination of governors and load parameters, admissible DER penetration level for the region varies from 4.2 to 21.2%.

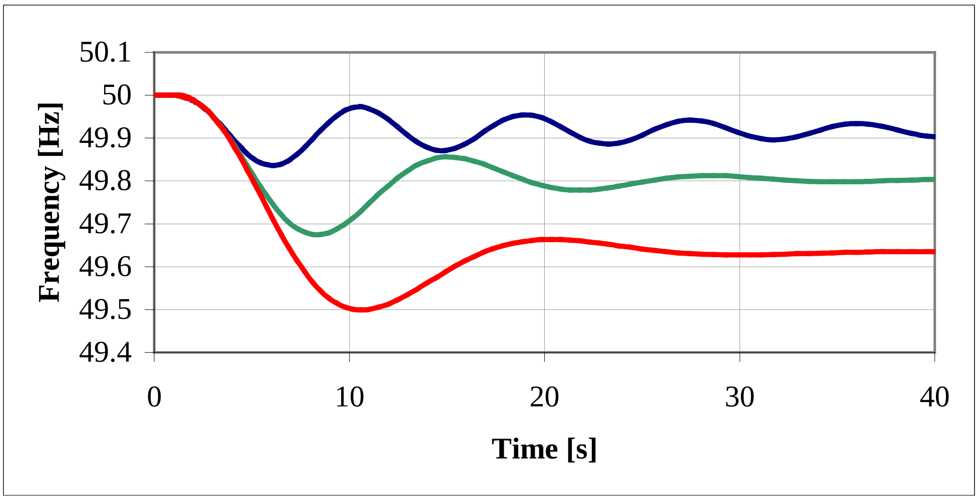


Figure 3 Influence of governor droop R. R=2% (blue line), R=5% (green line), and R=10% (red line)

Besides frequency deviations, changing of wind speed and solar irradiation can lead to inadmissible active power fluctuations in transmission lines. Simulations made for the Baltic States interconnection showed possibility of asynchronous operational condition in a tie line between Lithuanian power system and Kaliningrad due to the change of wind power output.

3.3 CASE STUDY: INFLUENCE OF DER ON OPERATION OF UNDER-FREQUENCY LOAD SHEDDING

Under-frequency load shedding scheme (UFLS) has been modelled for investigation of frequency behaviour during under-frequency conditions. Analysis was made of frequency behaviour for an islanding situation of the Baltic States region. Real parameters of UFLS system were taken into account in the model. Calculations of frequency behaviour were made for different DER penetration values [8].

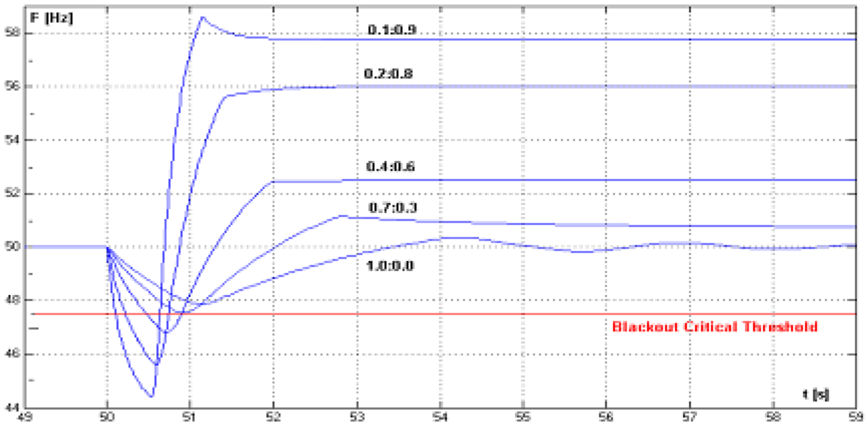


Figure 4 Frequency behavior dynamics for the Baltic States islanded region in case of 30 % of generated power deficiency, existing UFLS system and for different ratio of traditional vs. DER generation

This figure illustrates possible frequency deviations in the isolated power system for different DER penetration levels. It is obvious that, depending on the initial situation, for existing structure of UFLS scheme there is a risk of frequency drop below the blackout critical threshold and extreme over-frequency situation which can cause additional disconnection of generators due to under-speed protection in relation with technological limits.

4 SYSTEM QUESTIONS, LARGE DER PENETRATION

An increasing penetration of DER will have a number of direct and indirect impacts on transmission systems. The active-power loading of the transmission system will decrease. For most types of DER, even the reactive-power loading will be less due to the reduction in reactive-power losses in the transmission transformers. An exception is formed by DER based on induction-machine interface.

An indirect impact of increasing levels of DER is the associated reduction in the number of large generator units connected to the transmission system. The result is a reduction in short-circuit capacity, thus a "weaker transmission system"; power-quality disturbances like harmonics and flicker will be higher; voltage dips due to faults will spread over a larger part of the system; stability limits may be reached sooner. The reduction in the number of large generators will also reduce the control capacity in the form of spinning reserve and reactive-power injection. This will impact frequency and voltage stability.

4.1 VOLTAGE DIPS

A study has been performed after the impact of increasing levels of DER on the expected number of voltage dips per year, due to faults in the transmission system (hereafter referred to as the "dip frequency"). Some of the results of this study are shown in Figure 5. More details of the study and additional results are presented in [9].

The left-hand plot shows the increase in system-average dip frequency (SARFI-70, SARFI-80 and SARFI-90) for penetration levels up to 40%. The average dip frequency increases by about 30% for 40% DER penetration. It should be noted that no performance limits exist for voltage dips in power-quality documents, or elsewhere. One of the reasons for this is that the dip frequency shows large variations for different systems and even for different locations within the same system [6]. Therefore a relative-increase approach is use here.

For individual customers the dip frequency may increase much more than the 30% average. The situation for individual transmission-system busses is presented in the right-hand plot in Figure 5, where each dot gives the change in dip frequency for 40% DER (vertical axis) compared to No DER (horizontal axis). The scale is in per-unit with 1 pu corresponding approximately to the highest dip frequency in the No-DER case.

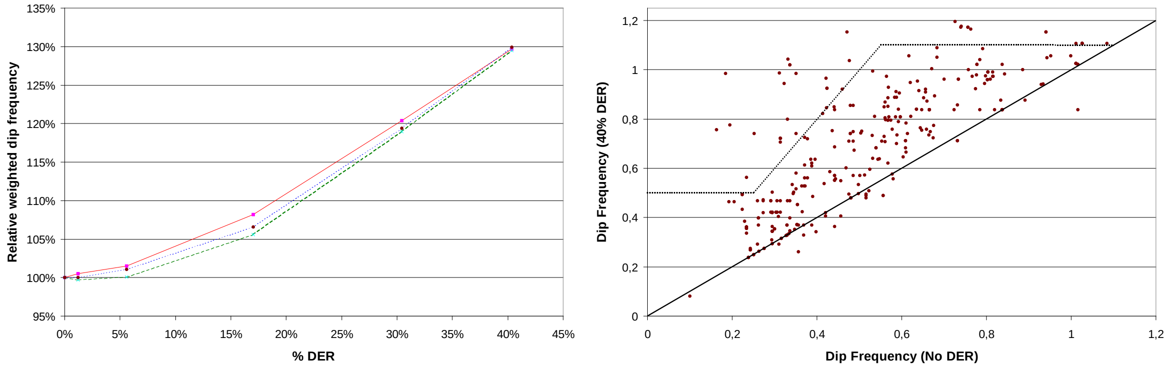


Figure 5, Impact of increasing DER penetration on the dip frequency: system averages for three-phase faults (left) and values for individual sites and 70% residual voltage.

The plane is divided into three parts: improvement (points below the solid line; the diagonal); acceptable deterioration (between the dotted and solid lines) and unacceptable deterioration (above the dotted line). The improvement in performance for some busses is due to an increase in pre-fault voltage with reduced transmission-system loading. The dotted line in the figure corresponds to the performance limit in Figure 2 and consists of three parts: the highest-acceptable dip frequency should not exceed 110% of the highest existing dip frequency; no dip frequency should increase by more than 100%; but a value corresponding to 50% of the highest existing dip frequency should be acceptable for all nodes. The dip frequency exceeds the limit for about 10% of the nodes. Whether this would constitute acceptable system performance is beyond the scope of this discussion. The results strongly depend on the limits for what is considered acceptable performance, for individual nodes and for the system as a whole.

4.2 SYSTEM RESPONSE FACING LARGE DER PENETRATION

4.2.1 DESCRIPTION OF THE INITIAL NETWORK AND OF THE LOAD MODEL

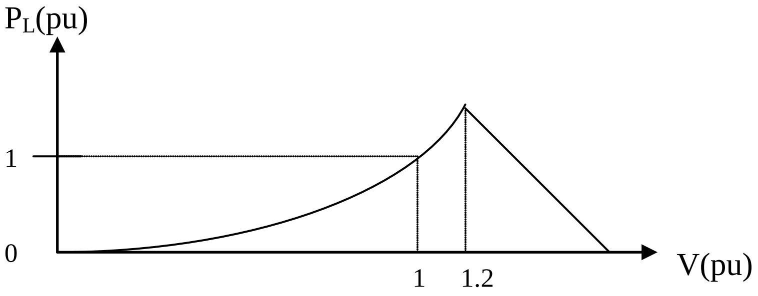
The UK network (England and Wales) is studied based on data found on NGT web site. The system is assumed to be at its peak load, with a penetration of DER of 5% (meaning that 5% of the total demand is already provided by DER connected at distribution level.) In that situation the load “seen” at the transmission level is 57.4 GW which is made of 60.4 GW of demand and 3 GW of DER connected at distribution level. The network is composed of different types of centralized generators: classic thermal units, hydro units, nuclear units and combined cycle units. The load and DER compounds are simulated by a model where equivalent load and equivalent DER are in parallel behind an equivalent impedance Z_S representing the distribution system from 132 kV down to low voltage.

For different types of networks (urban, rural, semi-rural), the mean values for the series impedance Z_S have been determined. The next values have been computed, on a 100 MVA base:

- Rural network: Z_S=0.0494+j0.107 pu
- Urban network: Z_S=0.00972+j0.0728 pu
- Semi-rural network: Z_S=0.028+j0.0896 pu

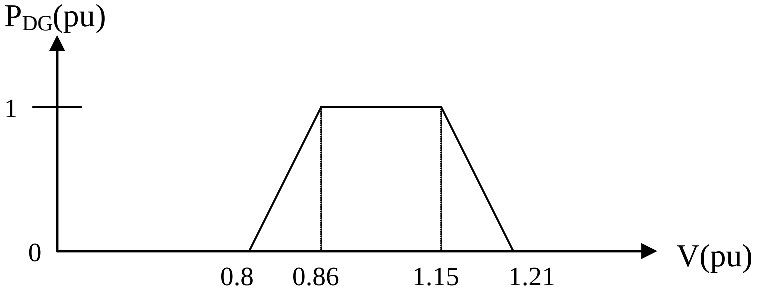
For simplification, in the next results, the semi-rural network characteristic is considered for the whole studied network.

The load – DER compound model has been developed for studying the incidence of power electronic on system behaviour. In the present development, the demand is supposed to be an equivalent impedance with progressive disconnection for voltages above 1.2 pu; therefore the demand characteristic is as follows:



The DER is supposed to be equipped with power electronic interfaces. This means that the output is maintained for a significant range of voltage. The profile is shown below. For voltages between 0.86 and 1.15, the DER output is maintained at 1 pu. As the voltage decreases or increases, some DER start disconnecting from the system, this leads to a decrease of the equivalent output down to 0 for voltages below 0.8 pu or above 1.21 pu. Further analyses are necessary for determining the more relevant voltage limits, which depend on technology and system structure.

It should be noted that in case of under-voltage power electronics is often locked off, whereas for over-voltage the power electronic is only transiently blocked. In that case, the behaviour is highly dependent on the highest acceptable DC voltage. Such behaviour for the load response has been noted, even if not totally fully explained so far, after a significant under frequency load shedding which took place in a country of the Gulf region in 2005.



As explained above, the network is composed of different types of centralized generators. It is assumed in the study that about 60 classic thermal units participate in the primary reserve (with a droop of 5%). This amount of reserve is such that the system can withstand the loss of 2×600 MVA units with a frequency drop of the order of 0.25 Hz.

4.2.2 DIFFERENT PENETRATIONS OF DER IN THE NETWORK

Introduction of DER in the system

The purpose of the study is to see the effect of DER penetration on the transmission system behaviour facing “secured events.” Based on the network previously described, three different penetrations are simulated:

- A DER penetration of 10%
- A DER penetration of 25%
- A DER penetration of 50%

The higher the penetration, the lower is the demand “seen” by the transmission system. Therefore, an increase in DER penetration requires the decrease in centralized generation output. Two different situations are considered. In the first option, the number of centralized generators is kept constant but their output is decreased (not below the technical minimum though), in similar approach as the one developed in [10]. The second option switches-off some of the centralized generators, keeping the output of the remaining ones unchanged.

When DER are connected to the distribution network, the power flowing through the transmission system is reduced. The transmission network becomes capacitive, leading to too high voltages throughout the system. For high penetrations of DER the reactive power compensation of the system has been updated in order to avoid such issues.

Loss of generation in the system

The figures below describe the frequency response of the system after the loss of 2×600 MVA units for different DER penetrations. FIGURE 6 corresponds to the case where the number of centralized generators is held constant. In that case, one can notice that the inertia of the system being kept constant; the initial slope does not change. The increase in DER penetration only leads to slightly lower frequency drops.

FIGURE 7 corresponds to the case where the number of centralized generators is reduced. In that case a higher DER penetration leads to more significant frequency drops. In this figure one can see the changes in the frequency slope after the event, corresponding to the change of stored kinetic energy in the system.

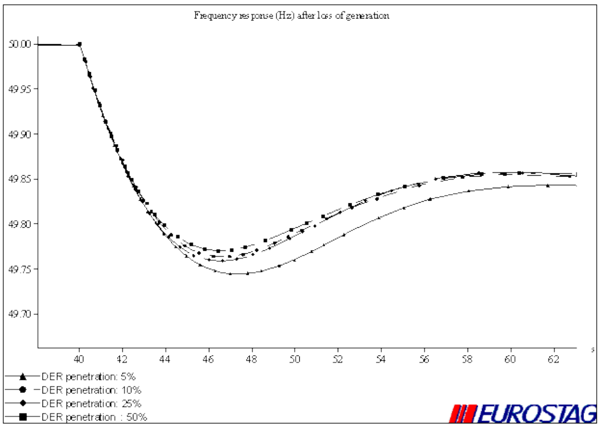


FIGURE 6

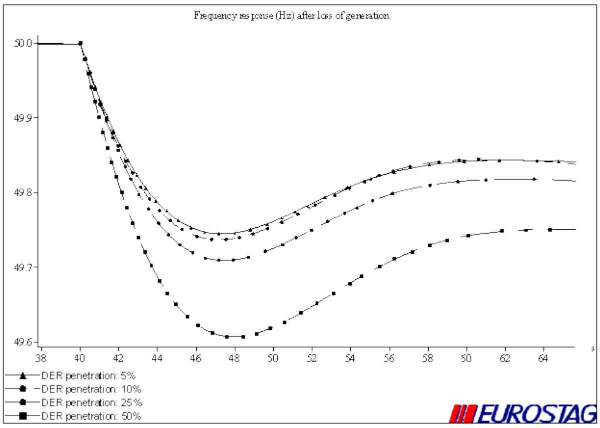


FIGURE 7

Occurrence of a short-circuit in the system

The second type of simulation carried out consists of applying a 3-phase short-circuit in the system and to see the effect of different DER penetrations. The short-circuit is applied in the centre of the UK network where few centralized generators are installed. .

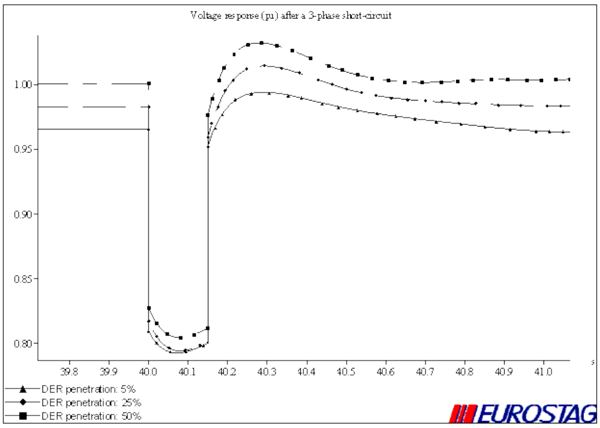


FIGURE 8

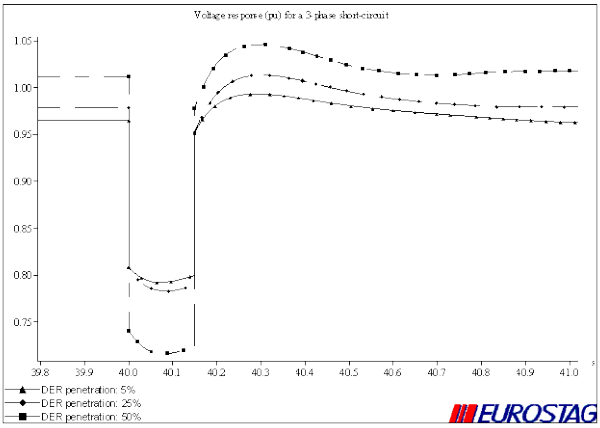


FIGURE 9

In FIGURE 8 one can see that the initial voltage is higher for a DER penetration of 50% because of the capacitive effect of the transmission system for such penetration of DER. This figure represents the voltage dip in the system following a three-phase short-circuit when the number of centralized generators is held constant. On the other hand FIGURE 9 presents the case when the number of generators is decreased. One can see that the voltage dip is more severe in the second case than in the first one, as there are fewer generators in the transmission system leading to a decrease in fault levels.

During 2006 this type of investigations will be largely developed following two complementary axes: DER integration, but also the consequences on power system behaviour of a generalisation of power electronic driven loads.

5 CONCLUSIONS

Taking account of the status of the project when writing this report, it is not possible yet to set up comprehensive conclusions about DER integration. However, a general conclusion can already be drawn: Most of the questions and problems related to DER integration must be studied in detail, using adequate tools and realistic system conditions. Indeed, at principle level a lot of questions seems leading to difficulties, but in fact most of them can be ignored in practical cases because power systems are what they are.

ACKNOWLEDGMENTS

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