Studies on Grid Impacts of Distributed Generation in a Combined Real-Time Simulation Environment

K. Mäki, A. Kulmala, S. Repo, P. Järventausta

Abstract—The increasing amount of distributed generation in public networks sets new requirements for the traditional network protection schemes. Actual problems have been experienced relating for instance to fault levels, reclosings and earth faults. As the complex protection is often considered a barrier against more wide-scale use of distributed energy resources, new development is needed. New generation units are often equipped with power electronic converters, whose behavior during faults and disturbances requires accurate modeling.

This paper focuses on protection impacts of distributed generation and on the possibility of applying a novel simulation environment for these studies. The environment is described and some motivation for building such system is discussed. An example case is studied using the simulation environment. Some observations are made based on the results.

Keywords: distributed generation, protection, RTDS, dSPACE, real-time simulation

I. INTRODUCTION

THE amount of distributed generation (DG) located at the distribution level of electrical networks is showing rapid growth worldwide. Certain aspects promote this more wide-scale usage, for instance novel energy resources and possibilities of increasing the efficiency of the network. DG has positive impacts on the usage of the electrical network, but it may also result in significant problems. These problems include especially voltage levels and more complicated protection of the network.

The power system has traditionally been studied more or less apart from the operation of power electronic blocks. In power system studies, the power electronic components are modeled with simplifications as the focus is on power system behavior. Vice versa, the power electronic studies often model the power system as an ideal source. It can be thought, that the interaction between these sides should be studied more closely. Institutes of Power Electronics and Power Engineering in Tampere University of Technology (TUT), Finland, have recently integrated their real-time simulators to create a novel, combined research environment for more wide-scale studies [1]. In the first phase this environment has been used for studying the grid impacts of DG.

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II. NETWORK PROTECTION IMPACTS OF DG

The distribution network is traditionally designed for a unidirectional flow of power and currents. In other words, the power is assumed to be fed from higher voltage levels and distributed further to lower voltages to the final customers. Same applies to the protection of the network; the fault current is assumed to flow downwards, which enables relatively simple schemes for achieving a fast and selective operation of protection. Protection settings can be found by calculating typical worst-case fault situations.

DG located on the distribution level changes this basis radically. DG units contribute to all faults and may thereby disturb the network protection. The directions and amplitudes of fault currents can change significantly. [2] The thermal limits of network components may also be exceeded due to the presence of DG.

Feeder relay coordination related problems include certain typical cases, which are considered detailed in the following.

A. Failed reclosing

As a first significant problem, DG unit may interrupt the autoreclosing sequence performed by the feeder relay. Autoreclosings are widely applied at the distribution level to clear temporary faults. [3] The dead time of the reclosing is typically only few hundred milliseconds, which does not cause major harm to the customer.

If the protection of the DG unit does not operate during the dead time of the reclosing, the unit remains connected to the network and may maintain the voltage in the network. Hence the arc will not decay and the fault seems permanent. This causes a longer interruption experienced by the customers. [4], [5] It must be noted, that even if the DG unit becomes disconnected during the dead time, the time available for arc extinction is decreased by the operation time of DG relay.

Another reason for disconnecting the DG unit rapidly is the safety of the unit itself. If the DG unit remains in the network, its rotational speed is likely to change due to the power imbalance. As the feeder breaker is closed again, an asynchronous connection may be experienced by the unit. This can result in stresses and damages of the unit. [5]

The reclosing settings used must be coordinated with the operation of DG protection to avoid problems. Applying a longer reclosing dead time is one possible solution, but results also in reduced power quality. The operation of the DG unit protection can also be adjusted to be more sensitive. This could, on the other hand, result in nuisance trippings during other types of faults and disturbances.

B. Sympathetic tripping

Another possible problem may occur when a fault is located outside the feeder including DG. This means another feeder fed from the same substation or even higher voltage levels. In such a case, the DG unit contributes to the fault and feeds a fault current 'upstream' towards the fault. It is possible, that the relay located at the beginning of the DG feeder is tripped by this fault current. This is possible when the direction of the current is not sensed by the relay, which is the typical situation in many present installations. [6], [7]

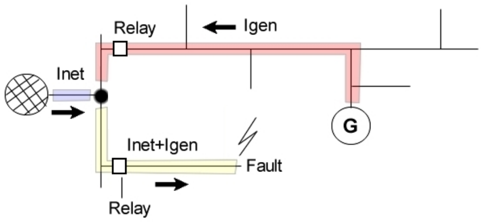

Fig. 1. Sympathetic tripping in distribution network.

The type of the DG unit's generator affects the situation essentially. In the case of traditional induction generator, the current contribution is likely to decay quickly enough not to cause problems. On the contrary, a powerful synchronous generator might feed a prolonged fault current and result in unnecessary trippings.

The sympathetic tripping is, above all, a power quality problem, especially where normal customers are located on the same feeder with the DG. The co-operation of feeder relays and DG protection should be coordinated properly in cases where such problems are possible. [6]

C. Protection blinding

As a third potential problem, the operation of feeder overcurrent protection may become interrupted by the presence of the DG unit. This is possible when DG is located between the fault point and the feeding substation. The DG unit contributes to all faults and increases thereby the fault levels. However, the fault current measured at the feeder relay is actually decreased due to the DG contribution. This happens as the total current is divided between the feeding sources. Thus the protection might become inoperative in the worst case faults for which it has been adjusted prior the presence of DG. [8], [9], [10]

In the case of induction generator the impact is more likely to result in relay operation delays rather than totally undetected faults. A synchronous generator is able to feed prolonged fault current and may thus result in more severe problems. It must also be noted, that DG may cause a delay of feeder relay operation even when disconnected properly. This is due to the operation time of DG protection.

D. Loss-of-mains protection

Another problematic issue is the operation of protection during unintended islanding. DG units are typically not designed for feeding the public network alone. Thereby they are not able to maintain an adequate level of quality in the network. They may also result in severe safety problems to the network personnel by energizing a part of the network assumed to be tensionless. Islanding situation must thus always be detected by the DG unit so that the unit is disconnected rapidly. Reserve power units are a case apart as they are planned for running alone.

There are many techniques available for detecting the islanding. However, practically all of them have a non-detection zone. This means, that the loading of the islanded part of the network can always match the momentary generation so, that the transition to the islanded operation can not be detected. The possibility of matching generation-load combination is in many cases theoretical, but, on the other hand, always possible. Traditionally, islanding is assumed to be detected by voltage and frequency relays located at the DG unit terminal. Methods based for instance on ROCOF (rate of change of frequency) or vector surge have been developed to provide reliable islanding detection. These methods are more reliable than plain voltage and frequency relays, but they still suffer the non-detection zone. [4]

III. The combined simulation environment

The idea of combined simulation environment is based on integrating real-time simulators RTDS (Real Time Digital Simulator) and dSPACE. RTDS is used for modelling the power system components whereas dSPACE is used for modelling power electronic equipment and complex control circuits. The aim is to integrate the strengths of the systems to one system for more wide-scale studies.

The combined real-time simulation environment consists of RTDS rack, dSPACE simulator and two computers, which are used to control the simulators. The two simulators are connected with analog signals through their D/A- and A/D-converters. Figure 2 shows the principle of the connection.

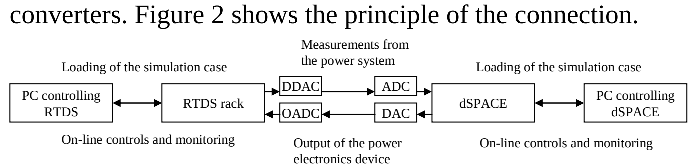

Fig. 2. The connection of RTDS and dSPACE simulators.

When using this kind of connection the simulation is similar to testing physical devices in the RTDS environment. This kind of tests have been carried out in TUT before. On the other hand, considering the situation from the dSPACE simulator's point of view, the situation is similar to controlling a real device. This has also been done in TUT before.

External devices, e.g. protection relays, can be connected similarly to the combined environment. Amplifiers are usually needed when connecting external devices. Between RTDS and dSPACE this is not necessary as the signals can be scaled in both sending and receiving end to transfer the data correctly.

A. RTDS

RTDS is a power system simulator for real-time studies. The simulator environment includes two essential parts; the hardware equipment and the control software.

Hardware of the RTDS comprises different types of processor cards, signal channels and communication modules. An Ethernet connection is used to transfer data between the hardware and the controlling computer. Real external devices can be connected to the system via digital and analog I/O channels. The system performs power system simulations usually with a time step of 50 microseconds.

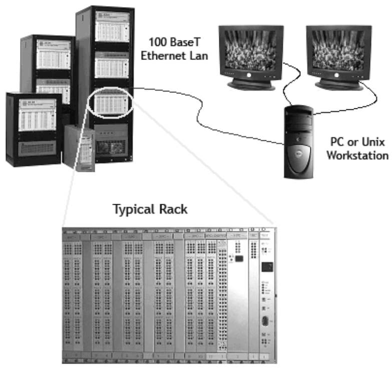

Fig. 3. Typical RTDS configuration. [11]

Software used to control the physical system is called RSCAD. The most important purpose of the RSCAD is providing a graphical user interface for controlling the hardware. It also provides libraries for typical power system components and models. User can construct the power system studied by drawing circuit diagrams and using the component models. Predefined control-blocks and scripts can be used to control the simulations. Outputs and results can be processed and saved in numerous ways.

B. dSPACE

dSPACE is a design tool for computer-aided control systems. Similarly to RTDS, the hardware comprises of processors, I/O channels and a signal interface panel for connecting signals. dSPACE operates as a real time system. Calculations are performed during a simulation step using the data collected in the beginning of each step. dSPACE is designed to work with Matlab as automatically as possible. Figure 4 shows the connections between Matlab and dSPACE.

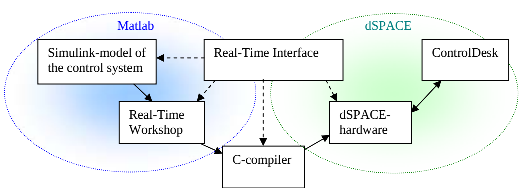

Fig. 4. The connections between dSPACE and Matlab.

When using dSPACE, the control system is first modelled with Matlab/Simulink. The I/O connections to other systems are added to the Simulink-model from the real-time interface library. The model of the control system is compiled to C-code with help of the Real-Time Interface. After that, the dSPACE hardware performs a real-time simulation like in the Simulink model. The real time simulation can be controlled from a PC with the ControlDesk program.

C. Possibilities from the power system point of view

From the power system's viewpoint, the integrated research platform enables more realistic studies in the cases in which power electronic devices are connected to the network. Determining the adequate level of modeling the more complex devices has been observed to be a problematic issue. The integrated platform may offer a solution for this in the form of predefined modules and components for typical power electronic devices. Where no suitable models are available, Matlab/Simulink environment provides well-known tool for modeling these components.

Using the dSPACE for power electronic modeling saves the calculation resources of RTDS. Saved resources enable more complicated network models.

The interface between RTDS and dSPACE is clear and clarifies thereby the simulation arrangement. Explicitly defining the inputs and outputs needed between the power system and the power electronics forces the user to consider the interactions more literally.

D. Possibilities from the power electronics point of view

From the power electronics viewpoint, it is very useful to see how the whole power system affects the converter performance. It is also useful to see how the converter actually influences the power system interface while running. Normally these experiments are completed by making a prototype and testing it in real power system. Integrated simulation environment is useful when advancing from offline-simulation. It could help to test the simulation models without building prototypes.

The real time simulation can also help to simulate an operation of converters and a power system in fault situations without breaking the real prototype or disturbing the power system. It is also possible to build the actual prototype and connect it with real time simulators for testing.

IV. Example Case

An example case was used for studying the operation of DG unit and the distribution network during faults and disturbances. The case comprises of a medium-voltage distribution network with two feeders and a DG unit connected to one of the feeders as shown in figure 5. The DG unit is an actual wind power plant with realistic data.

The wind power unit is relatively small-scale with a nominal output of 500 kW. In the case studied, the generator is a simple induction generator with soft starter. One aim of the studies performed was to compare the operation of traditional induction generator and a converter-based unit. Thereby a synchronous converter with similar initial data was modeled as an alternative unit.

The network scheme is a typical Nordic network. The medium-voltage network has an isolated neutral, which affects the earth-faults significantly. Feeders are equipped with one overcurrent relay and dedicated earth-fault relay located at the substation. Fast autoreclosings are used to clear temporary faults. The block transformer of the DG unit is a Dyn transformer earthed on the low voltage side. DG connection point is equipped with typical protection devices (overcurrent, under-/overvoltage, under-/overfrequency and ROCOF).

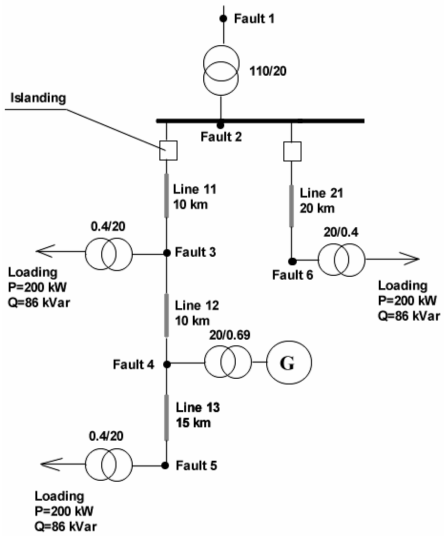

Fig. 5. The example case used in the simulations.

The case was modeled in the combined research environment. The network, including the protection devices and transformers, was modeled in RTDS. dSPACE was used for modeling the wind power unit, including the converter, generator, control blocks, gearbox and wind turbine. Wind data can be used as an input of the model.

The connection between the systems formed a realistic interface. Voltage waveforms of the connection point were fed from RTDS to dSPACE. dSPACE fed the output currents of the converter bridge to the RTDS. As the current reference was received from the dSPACE, the DG unit was modeled as a current source in the RTDS.

V. Studies performed

The cases presented in figure 5 were studied in the simulations. These cases comprise:

- six different fault locations with different fault types (three- and two-phase short circuits and one-phase earth fault)
- islanding of feeder 1 by opening the feeder breaker

A. *Faults on the DG feeder*

As a first case, faults occurring on the same feeder with the DG unit were studied. During these faults, the DG unit must not disturb the operation of feeder protection and must become disconnected from the network. If the possibility of disturbing feeder protection exists, the DG unit should become disconnected due to the fault faster or simultaneously with the feeder protection.

For faults occurring in point 5, the blinding phenomenon presented earlier can be hardly observed. This impact should not cause any problems in any circumstances. This is mainly due to low rated output and generator types studied (induction generator and synchronous converter) of the DG unit. Figure 6 shows the impact of blinding on measured feeder fault currents. Induction generator and converter behave quite similarly. As it can be seen, the impact is maximum 10 amperes. It must be noted, that the network topology and generator rating influence this impact. Far more dramatic influences have been observed in earlier studies [6], [8].

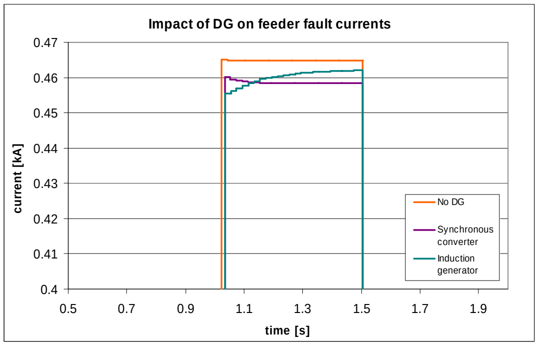

Fig. 6. The blinding effect remains minor.

As observed, the DG is not likely to result in blinding problems. In this sense it would be adequate to disconnect the unit after the tripping of feeder relay. On the other hand, this might be problematic when considering the autoreclosings applied in the network, as it will be shown later.

Deviations of voltage and frequency in the DG connection point are easily observed during the faults. Thereby the unit becomes disconnected reliably during the fault.

B. *Faults elsewhere in the network*

As a second case, faults occurring on the adjacent feeder were studied. In this situation, the DG unit does not need to be disconnected from the network. The closest breaker is used for separating the fault according to the principle of selectivity. Tripping the DG unit is thus unnecessary. If the upstream contribution exceeds the limits of the DG feeder relay, the unit should, however, become disconnected rather than the whole feeder. The important issues are the upstream fault current contribution of DG and the operation of DG protection during these faults.

The upstream current waveforms of the two types of units are different. Contribution of a network magnetized induction generator decays rapidly. The operation of the converter depends strongly on its design. In the converter type used in these studies, the output current is limited to certain value.

The maximum upstream contributions illustrated in figure 7 are negligible in comparison to the lowest possible fault currents in the initial situation. A two-phase short circuit in the last point of the feeder results in fault currents of 450 A. Thereby the sympathetic tripping should not occur. It must be noted, that the upstream currents increase proportionally as more DG capacity is installed on the feeder.

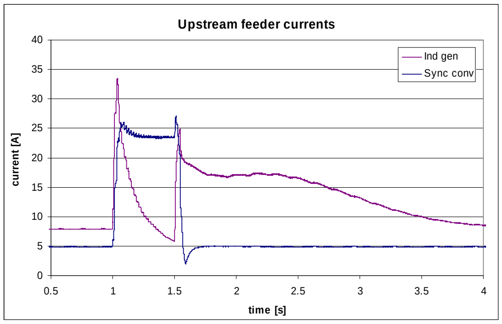

Fig 7. Upstream currents during a short circuit located at the substation bus. Fault occurs at 1 s and becomes cleared after 0.5 s.

Another important issue during faults elsewhere in the network is the possibility of nuisance tripping of DG protection. Fault location 6 presented in figure 5 was used for these studies. As expected, the fault current contributions of generator types are not great enough to trip the DG protection. This is directly related to the upstream currents in the previous chapter and was thereby expected. However, more attention must be paid to the variables of islanding protection; frequency, ROCOF and voltages.

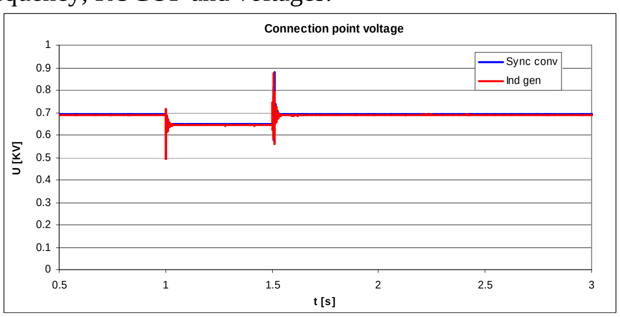

Fig. 8. Voltage drop at the DG connection point during fault in point 6.

The voltage of the connection point behaves similarly in the case of converter-based unit and induction generator unit. During a three-phase fault, the voltage drops less than 10 percents, which should not result in DG tripping.

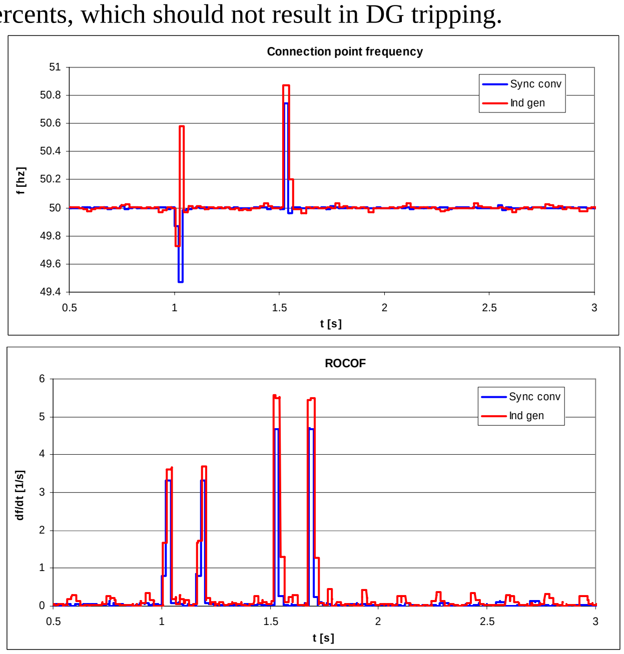

Fig. 9. Frequency and ROCOF measurements.

Frequency and ROCOF measurements show similar characteristics. The induction generator tends to result in slightly larger frequency deviations, but the difference is not very significant. Frequency protection is not likely to trip the DG unit, but ROCOF might do it if adjusted for sensitive operation. Especially in the case of synchronous converter there may be a need for applying sensitive setting as it will be shown later.

C. *Islanding situations*

As a third important case, operation of the DG protection during islanding was studied. The island was formed by opening the breaker of feeder 1 as shown in figure 5. Loading of the islanded part matched the DG output relatively well, yet not exactly.

Islanding detection is especially significant in areas where fast autoreclosings are applied for fault clearing as presented earlier. It is also vital for staff safety during network maintenance. Earth faults are a typical cause of islanding problems as the earth fault is difficult to detect by the DG unit applying Dyn-type block transformer.

The induction generator used in the studies was a traditional one taking its magnetizing energy from the network. This kind of unit is not able to operate during islanding and loses its stability rapidly. Thus the situation is easy to detect for instance by means of frequency protection. The simulations confirmed this.

The operation of synchronous converter seems more problematic during islanding. Voltage shows some distortion and only a small rise (few percents) which is not detected by DG protection. Same applies to current. Frequency shows rapid peak, after which it continues to increase slowly. This frequency rise is due to the PLL-control of the converter model applied in the studies. The final level above 53 Hz is limited by the saturation of PLL circuit. During a planned islanding, a real converter is able to maintain the desired frequency and operates thus in a different way. During an unexpected islanding (which can be caused for instance by breaker opening during a fault) the actual behavior should remind the simulated behavior of figure 10. On the other hand, a modern converter may also be able to detect the island itself thus shifting to the island mode or, alternatively, disconnecting from the network. These functions were not modeled in the converter model used in the studies.

Typical frequency protection limits typically allow deviations of ±2…3 Hz with operation delays of few hundred milliseconds. In this case, frequency is likely to trip the DG unit after 1.5…2.5 seconds, which is not acceptable in a network applying fast autoreclosings. Further, nor the voltage or current measurements can be used for detecting the situation. ROCOF measurement might be applied for a rapid tripping but it would require sensitive limits which would probably result in nuisance trippings during other network disturbances.

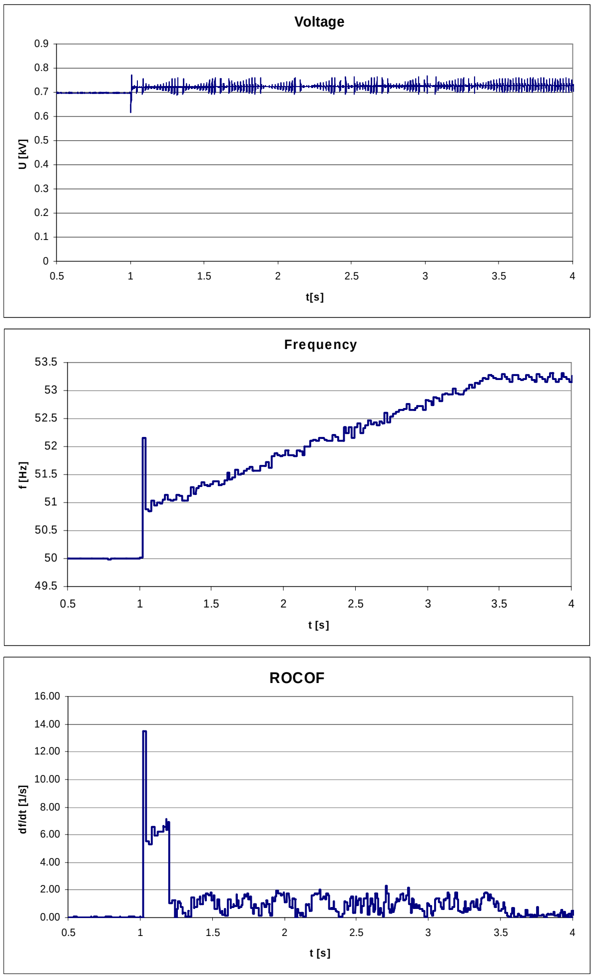

Fig. 10. Islanding detection measurements.

VI. Conclusions

In this paper, impacts of distributed generation on network protection have been analyzed. Typical problems have been described and some solutions have been proposed. A novel real-time simulation environment combining simulators for power system and power electronic studies has been described. Need for such system has been discussed. An example case has been studied using the environment.

The typical theoretical problems were observed in the simulations. The research environment and modeling shared between two systems seemed suitable for the case studied. However, the wind power model used was slightly underpowered to result in significant problems in the network used. The wind power models were based on a project which focused on this scale and realistic data was available for building the models. The network model was also authentic and included all interesting characteristics for such studies.

The comparison between induction generator and synchronous converter showed no significant differences during faults. The most interesting observation was the operation during islanding; whereas the induction generator loses its stability and becomes disconnected, the converter may be able to maintain an island for while. Although there is no risk of prolonged islanding, the reclosing sequence could be disturbed. At the same, the risk of asynchronous reconnection is probable.

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VII. Biographies

Kari Mäki received his M.Sc. in Electrical Engineering from Tampere University of Technology in 2003. He is currently Researcher at the Institute of Power Engineering of Tampere University of Technology. His current research interests include grid integration of distributed generation, especially protection issues and distribution planning for distributed generation.

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