Interconnection of Distributed Generators and Their Influences on Power System

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ABSTRACT

The increasing penetration of distributed generation (DG) in the power system creates new challenges and problems for network operators. The generation of electricity comes to a new era with a variety of small-scale technologies from conventional generators to sources connected to grids through power electronic converters. The impact of different technologies and installed capacity on a distribution system changes from the one technology to the other. In this paper, the interconnection of DG units with power systems is discussed. Secondly, the influences of DG technologies on the operation of a distribution system are studied in detail.

1. INTRODUCTION

A distributed generation unit can be considered as a small generator connected to the customer's side of the distribution system and normally not being dispatched by the network operator [1, 2]. In most of the cases, DG is treated as a 'lump load'. DG technologies include photovoltaics, wind turbines, fuel cells, small and micro gas turbines, Stirling-engines, run-off river hydro turbines, and internal combustion engines.

Many governments have been supporting renewable energy sources for environmental reasons, and the competition on generation imposed by electricity market liberalization has pushed the development of DG technologies and their connection to grids [3]. Currently 35% of the total industrial electric power demand in the USA is met by DG [4]. For industries with a stable demand, it is generally cheaper to produce electricity locally, in order to avoid charges for transmission, distribution and billing.

Distributed generation may have a significant impact on the system and equipment operation in terms of steady-state operation, dynamic operation, reliability, power quality, stability and safety for both customers and electricity suppliers. This impact may manifest itself either positively or negatively, depending on the distribution system, distributed generator and load characteristics [5, 6].

This paper aims at investigating the influences of DG technologies on the operation and its ability of interconnecting DG units with power system. The distribution system and distributed generation units are modeled using the Eurostag software package [7]. Some aspects of interconnection of DG with power systems are discussed. The impact of DG on power system loss, voltage profile and protection are studied. A distribution system is used to illustrate the influences of DG on the operation of the power system.

2. INTERCONNECTION OF DG WITH POWER SYSTEM

2.1 Grid Connection Guidelines

Grid-connected distributed generators are coupled *directly* or *indirectly* through a DC-AC or an AC-AC converter to the power system. Sometimes only part of the power passes through a converter as for instance in cascade type of variable speed generator for wind turbines. Every DG unit connected to the public grid has to comply with common technical rules, safety standards and requirements from the grid operator or the regulator.

Grid connection guidelines are still a major controversial subject with regard to distributed generation. The connection rules and technical requirements that differ from region to region make it all ever more complicated. With the need for a single document of consensus standard technical requirements for DG interconnection rather than having to conform to numerous local practices and guidelines, the first version of IEEE 1547 provides uniform criteria and requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection [8, 9]. However, this guideline focuses much on 60 Hz systems (American). When applying to other 50 Hz systems, adaptations are necessary.

Concerning DG technologies, there are several guidelines for individual technologies such as wind turbines, photovoltaics, etc [10-12]. These guidelines can serve as input to develop a general connection guideline for all types of distributed generation systems.

2.2 Benefits and Impact of DG

2.2.1 Benefits

The idea behind the connection of DG is to increase the reliability of power supplied to the customers, make use of a locally available resource and, if possible, reduce losses in transmission and distribution systems. The overall diminished investments in centrally dispatched power plants and transmission systems have contributed to the recent blackouts in many places. Due to the innovation technology and cost reduction, distributed generation is playing a more and more important role in electric power generation. In many cases, for instance, in remote areas or in times of high tariffs at peak load, DG might be a cost-effective solution.

The connection of DG to the power system might improve the voltage profile, power quality and support the voltage stability. This allows the system to withstand higher loading conditions and defers the construction or upgrading of new transmission and distribution infrastructures. Compared to the conventional power plants, DG has a shorter construction time and payback period. Many countries are subsidizing the development of renewable energy projects through a portfolio obligation and a system of green power certificates. This gives an incentive to invest more in small generation power plants.

Some DG technologies have high overall efficiencies and low pollution such as combined heat and power (CHP) and some micro-turbines. In addition, many DG units are using renewable energy resources. This, in one way or another, contributes to the reduction of greenhouse gases.

2.2.2 Impact on Power System Operation

The connection of DG to the network might cause a significant impact on the power flow, voltage profile, voltage stability, protection selectivity, and the power quality for both customers and electricity suppliers [6]. On one hand, the power injected by DG might support the voltage profile and stability of the system. On the other hand, many DG units are connected to the grid via power electronic converters. This might inject harmonics. The connection of DG might cause over-voltage, power factor, dip, fluctuation, harmonics, and unbalance of the system voltage. The variation in power output, along with the virtually inertia-less nature of the power electronic front-ends, of some DG technologies such as wind turbines and photovoltaics might cause voltage fluctuations.

The power injection of DG may decrease or increase the power losses in the distribution system, depending on the penetration and dispersion level and the using DG technology. Distribution network characteristics and load demand levels play a role in power loss level as well. This impact is studied in more detail in the next section.

The penetration level can be calculated as a function of the total DG power generation, or the total of generation factor times DG installed capacity, over the peak load demand.

$$\text{Penetration level} = \frac{\sum (\textit{Generation factor x DG installed capacity})\ \textit{MW}}{\textit{Peak load demand MW}} \quad (1)$$

2.3 Voltage Regulation

One of the main purposes of system operation is to keep the voltage supplied to the customers stable and reliable, with magnitude and frequency at the terminals of all equipment within the allowed operating range.

The voltage of the distribution system is normally regulated by using load-tap-changing transformers, voltage regulators and shunt capacitor banks at substations or along the lines. Voltage regulation in practice is based on one-way power flow and almost voltage regulators are equipped with line drop compensation. The connection of DG may result in changing in voltage by the generator offsetting the load current and attempting to control the voltage.

2.4 Location and Size of DG

Most distributed generation units are owned by customers. The grid operators cannot decide optimal locations and sizes of DG units. In case the electricity suppliers want to invest in DG in order to gain benefits and to release the burden on transmission and distribution networks, an optimal size and location of DG units should be studied in detail. Due to the available sources and connection ability to the network, several factors should be taken into account. The geographical location of resources, typically renewable, the potential of connection points with distribution network, the impact of DG technologies and penetration on voltage level, power quality and stability of the system, local load behaviors, etc must be considered.

The overall electrical losses are influenced by the changing power flow pattern. Normally, one would assume that losses decrease when generation is brought closer to the load site. However, a local increase in power flow in low voltage cables with higher resistance and current may have opposite consequences.

The distribution system is normally operated in a radial mode. In case the location of DG units can be more or less freely chosen, it is recommended to use the two-third rule, which is used for locating and sizing of a capacitor in a radial distribution system with distributed loads [9, 13]. However, since DG generally injects active power and might inject or absorb reactive power depending on the applied technology and the distribution system is normally weakly meshed or network, another technique to determine the location and size of DG units is required.

2.5 Safety and Protection Consideration

Safe operation and protection of the system are to be guaranteed at all times. In addition, the protection system has to be sufficiently selective, in order to optimize the reliability and availability of the supplied power. This is less simple than it seems since the fault current not only comes from the main power system grid in a unidirectional way, but also from the DG units (dispersed current sources), making the detection far more complicated and thus the conventional hierarchy protection method might fail. Therefore, a more *'active'* protection system with some form of communication will be required to keep up the requirement level of safety in the future.

The protection problems are illustrated by using a distribution system with five feeders in Fig. 1. If a short circuit occurs at F_2 or F_3, the short-circuit current is supplied by the generators connected to this feeder (G_1 and G_2), other DG units of adjacent feeders, and the main grid. If the contribution to the short-circuit power from G_1 and G_2 is large compared to the one from the grid and other feeders, the current through circuit breaker or fuse (CB1) might be too low to operate in order to eliminate the short circuit on the feeder. On the other hand, if the contribution to the short-circuit current from generators of adjacent feeders, healthy feeder (feeder 4) might be disconnected before the faulted feeder is disconnected.

As long as islanding is not intended to backup a loss of mains, it should be avoided [14]. According to technical standards (e.g. IEEE 1547), DG must be automatically disconnected from the public network when faults or other abnormal conditions occur, with the assumption that interconnection systems can detect such conditions. In this way, conventional protection selectivity can be restored. This guarantees person and equipment safety. In future, when more DG will be used, this requirement would reduce the expected benefits of DG. To make optimal use of DG, unnecessary disconnection of DG should be avoided. Generators should be able to ride through minor disturbances. This possibility is discussed in [15].

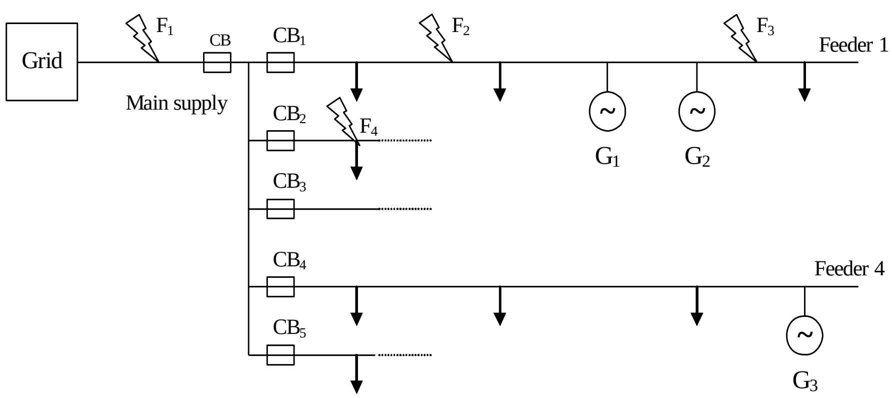

Fig. 1 Example grid with safety problems due to high DG penetration

2.6 Reliability and Cost Consideration

One of the main purposes of developing DG is to increase reliability of the power supply. Customers always want to have a continuous and reliable electricity supply, especially with the sensitive loads. Due to infrastructure costs and the willingness to pay by customers, the power suppliers can only guarantee a certain level of reliability. DG might be a good solution to reduce cost and increase reliability in many cases. DG can be used as a back-up system or as a main supply. The portion of electrical power not supplied by DG is coming from the grid. DG can also operate to shave peak demand in order to avoid additional charges. Depending on the electricity tariff and the production cost of DG, the DG owner could optimize how to operate at the lowest costs.

3. IMPACT OF DG ON POWER SYSTEMS

3.1 Tested radial distribution system

The impact of different DG technologies on the power system is studied using a 34-bus radial distribution system connected to a substation with a 35/12 kV transformer. They are modeled using the Eurostag computer software package. The total load is 4.63 MW and 2.87 MVar. The network is a revised version of the one given in reference [16]. The full parameters of the system and loads are given in Appendix 1.

The distribution lines and transformer are represented by a general series model containing resistances and reactances. The shunt capacitance of distribution lines can be neglected as the feeders are short and distribution voltage level is used. The magnetizing current of the transformer is small compared to normal load current and its magnetizing impedance is negligible.

The tested DG generators units contain synchronous and induction machines. Electrically excited synchronous generators, having the ability to control reactive power output, can be operated at constant active and reactive power, constant active power and power factor, or constant active power and voltage depending on the requirement of the network operator. The synchronous generator bus is modeled as PV or PQ node depending on the operation mode. The reactive power consumption of an induction generator is a function of the terminal voltage. In normal operation, the terminal voltage is kept near 1.0 p.u., so the reactive power is assumed constant during the calculation. In general, induction generators can be considered as a PQ node, i.e. operated as a load with injected current.

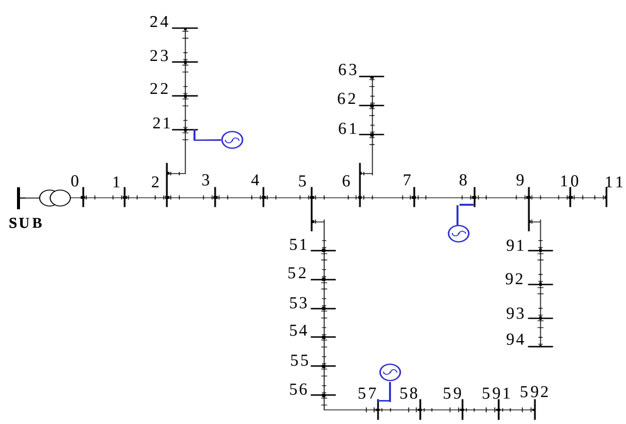

Fig. 2 34-bus distribution system

3.2 Impact of DG on power loss and voltage profile

The injected power of DG might improve the voltage profile or cause over-voltages in the system. The voltage profiles of feeder 5 and feeder 9 up to the substation are studied with different penetration levels and technologies of DG (Figs. 3 and 4). Three generators are connected at nodes 8, 21, and 57. Every technology is tested separately. The synchronous and induction generators operate at power factors 0.9 leading and lagging, and the generators connected via converters operate at unity power factor. With the ability of reactive power generation, synchronous generators raise the voltages in the system faster compared to induction generators and generators operated at unity power factor. With a high penetration level of DG, it might cause over-voltage in the system like the case of 150% penetration of synchronous generators. However, in most cases, the power generation of DG improves the voltage profile in the system.

The power losses in the system are also calculated with different penetration levels and technologies of DG. Both active and reactive power losses are reduced in the beginning. But when penetration increases, the power losses increase due to a larger amount of power flows in the system (Figs. 5 and 6). The reactive power losses will become a real problem when a reactive power market is created.

The optimal level of DG penetration depends on the used technology. This might change with other combinations of DG connection. Further on, the output power of some DG, such as photovoltaic and wind turbines, depends on the weather and cannot be anticipated exactly. The operation modes of CHP are mostly based on the customer-driven heat demand. In order to find the global optimum, many load scenarios with different anticipated power output should be studied in detail.

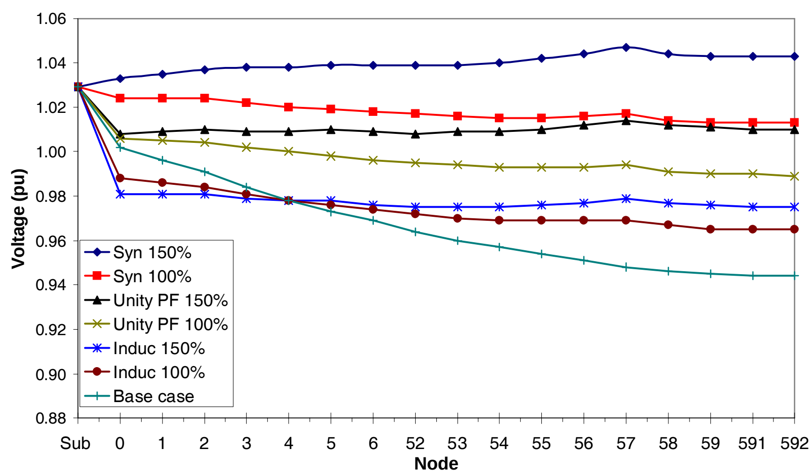

Fig. 3 Voltage profile of feeder 5 with different technologies and DG penetration levels

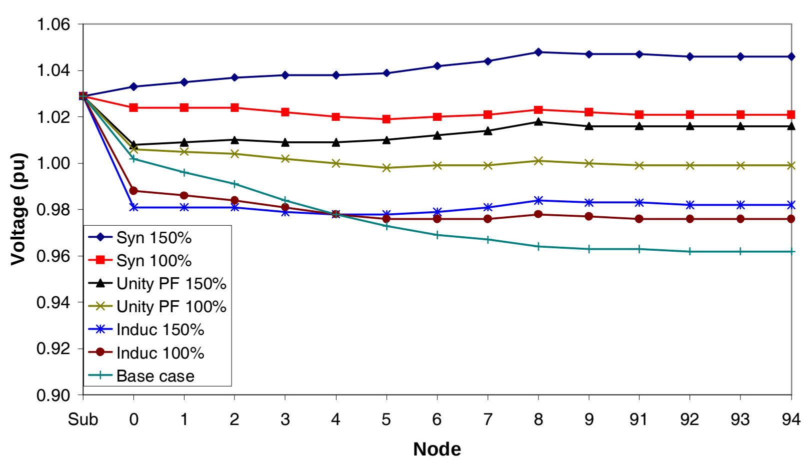

Fig. 4 Voltage profile of feeder 9 with different technologies and DG penetration levels

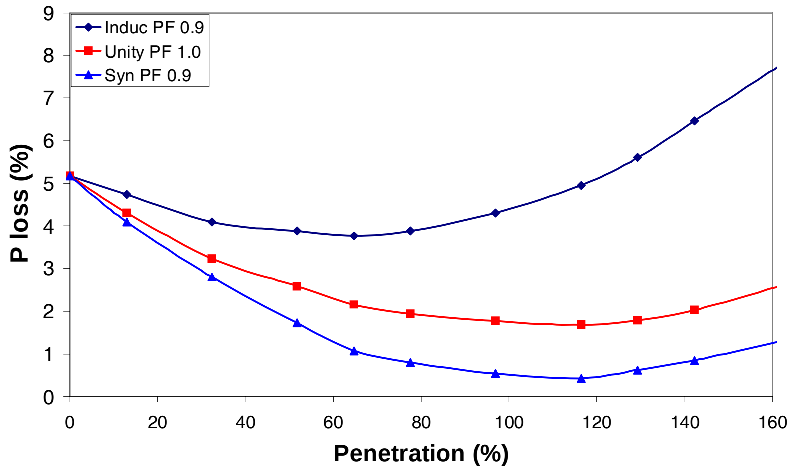

Fig. 5 Active power loss with level of penetration

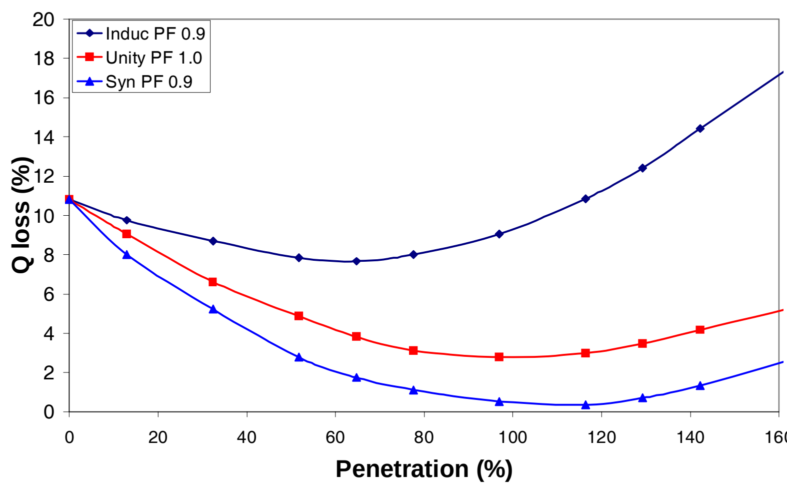

Fig. 6 Reactive power loss with level of penetration

3.3 Short circuit in the system with DG

In order to see the effect of DG on magnitude of the short-circuit current, a big synchronous generator with 2 MVA installed capacity is connected at node 10. The short circuits at node 11 and 91, nearby the generator and in different feeders, are studied in detail with and without the contribution of DG. The load of the system remains the same as in the above example.

A three-phase solid fault at node 11 occurs at time 100 *s* and it is eliminated at time 100.5 *s* during simulation. The short-circuit resistance and reactance are zero. The short-circuit current flowing through branch 10-11 with the DG connection is higher than without DG (Fig. 7). The reason is that the generator supplies more short circuit current to the fault. But the short-circuit currents running through branch 9-10, where normally a circuit breaker is installed at node 9 to protect feeder 10, are almost the same for the cases with and without DG (Fig. 8). The operation time of the protection system does not change too much in both cases.

The short circuit current through the circuit breaker of branch 9-10 is also investigated when there is a fault at node 91 (Fig. 9). The fault occurs at time 100 *s* and is eliminated at time 100.5 *s* too. The generator supplies power to the short circuit via branch 10-9 and 9-91. The short circuit current in branch 9-10 is quite high in this case. The oscillation current after eliminating the fault is higher than the short-circuit current in this case. This is due to the acceleration of the generator. If this value is higher than the threshold of setting current, the protection may react and trip this healthy feeder.

The short circuit current through branch 9-91 is also higher with DG connection. With this higher current, the protection system of feeder 9 might react faster. This can help to eliminate the fault faster and reduce the operation of another feeders and up-stream protection systems. In terms of power quality, it reduces flicker of the system. Fig. 11 shows a voltage dip at node 9 with a short circuit at node 91. There is a voltage fluctuation with DG connection due to the transient behavior of the DG unit.

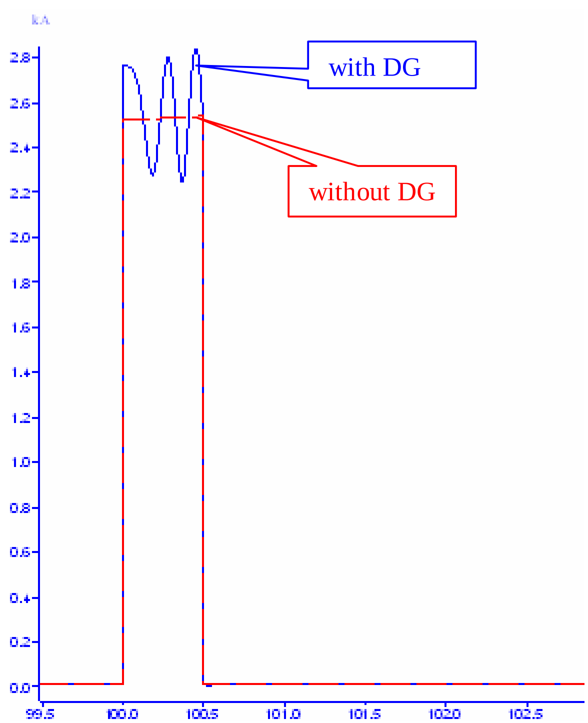

Fig. 7 Additional short-circuit current branch 10-11 with a fault at node 11

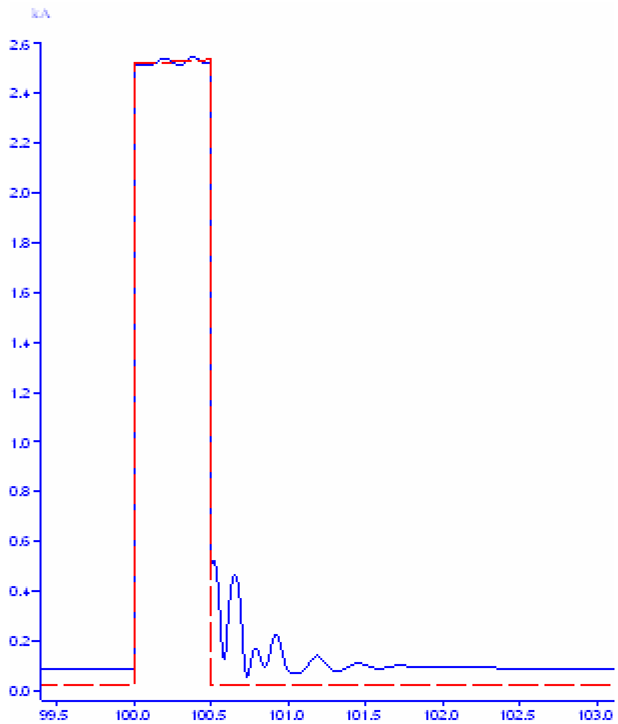

Fig. 8 Short circuit current of branch 9-10 with a fault at node 11

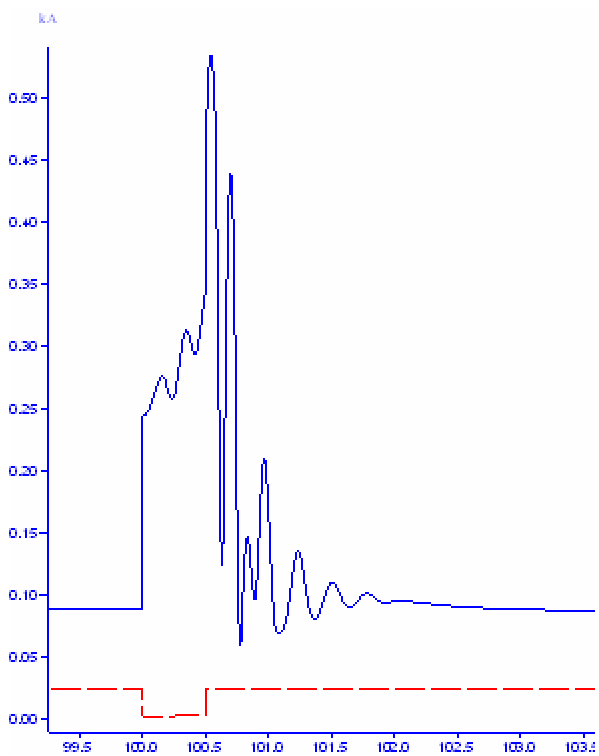

Fig. 9 Additional short-circuit current of branch 9-10 with a fault at node 91

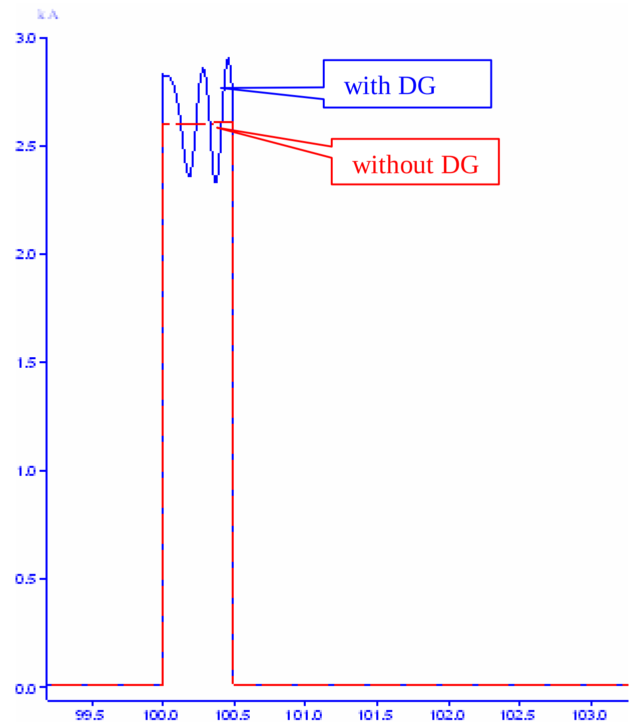

Fig. 10 Short circuit current of branch 9-91 with a fault at node 91

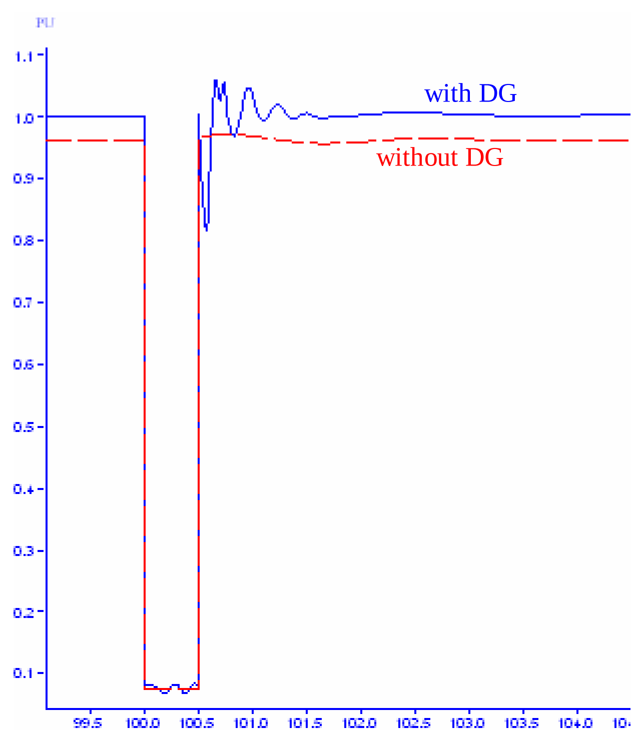

Fig. 11 Voltage at node 9 with a short circuit at node 91

4. CONCLUSIONS

Distributed generation systems are playing an increasing important role in electric power supply. They come with different small capacities and are normally dispersed in the power system. This creates many new problems concerning the network operation. It is necessary to have concrete connection guidelines and standards where the system operators and new investors can follow. This contributes to the creation of competitively and environmentally minded market conditions in the electricity sector.

The connection of DG units to the power system, in general, improves the voltage profile and reduces losses. The loss reduction depends on the applied technology, the injection capacity and the network characteristics. If the network is not properly designed and the power injection of DG units is high, this might cause local over-voltages in the system. Reduction of the installed capacity or network reinforcement is recommended in this case. Before choosing a good plan of DG development in a specific distribution system, the network operators should have a powerful tool and study thoroughly different combinations of available technologies, locations, sizes, capable of network assessment, loads, etc.

Through this study, the contribution DG unit results in increasing short-circuit currents, even in the healthy feeder, to which DG units are connected. This might trip the healthy lines before clearing the faulted lines. At present, DG represents only a very small fraction of total electricity production. Classical protections can still be used since, in most cases, power flow in feeders remains unidirectional. With the newly emerging DG, power systems will have to cope more and more with two-way power flow. Future protection systems will have to offer producers sufficient freedom and flexibility, while keeping up the requirement safety level.

5. ACKNOWLEDGEMENTS

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7. APPENDIX

Table 1 Line parameters

Line	R (Ω/km)	X (Ω/km)	Length(km)	CSA(mm2)	I (A)	S_{max}(MVA)
0.-1	0.195	0.08	0.6	185	445	9.249
1-2	0.195	0.08	0.55	185	445	9.249
2-3	0.299	0.083	0.55	120	350	7.275
3-4	0.299	0.083	0.5	120	350	7.275
4-5	0.299	0.083	0.5	120	350	7.275
5-6	0.524	0.09	0.6	70	257	5.342
6-7	0.524	0.09	0.4	70	257	5.342
7-8	0.524	0.09	0.6	70	257	5.342
8-9	0.524	0.09	0.4	70	257	5.342
9-10	0.524	0.09	0.25	70	257	5.342
10-11	0.524	0.09	0.2	70	257	5.342
2-21	0.524	0.09	0.3	70	257	5.342
21-22	0.524	0.09	0.4	70	257	5.342
22-23	0.524	0.09	0.2	70	257	5.342
23-24	0.524	0.09	0.1	70	257	5.342
5-51	0.299	0.083	0.6	120	350	7.275
51-52	0.299	0.083	0.55	120	350	7.275
52-53	0.378	0.086	0.55	95	308	6.402
53-54	0.378	0.086	0.5	95	308	6.402

Line	R (Ω/km)	X (Ω/km)	Length(km)	CSA(mm2)	I (A)	S_{max}(MVA)
54-55	0.378	0.086	0.5	95	308	6.402
55-56	0.524	0.09	0.5	70	257	5.342
56-57	0.524	0.09	0.5	70	257	5.342
57-58	0.524	0.09	0.6	70	257	5.342
58-59	0.524	0.09	0.4	70	257	5.342
59-591	0.524	0.09	0.25	70	257	5.342
591-592	0.524	0.09	0.2	70	257	5.342
6-61	0.524	0.09	0.3	70	257	5.342
61-62	0.524	0.09	0.3	70	257	5.342
62-63	0.524	0.09	0.3	70	257	5.342
9-91	0.524	0.09	0.3	70	257	5.342
91-92	0.524	0.09	0.4	70	257	5.342
92-93	0.524	0.09	0.3	70	257	5.342
93-94	0.524	0.09	0.2	70	257	5.342

Table 2 Transformer

S rated (MVA)	V/V, kV	X (%)	Cu loss (%)
10	35/12	7.74	0.67

Table 3 Loads

Node	P (MW)	Q (Mvar)
1	0.23	0.1425
3	0.23	0.1425
4	0.23	0.1425
7	0.23	0.1425
8	0.23	0.1425
10	0.23	0.1425
11	0.137	0.084
21	0.072	0.045
22	0.072	0.045
23	0.072	0.045
24	0.0135	0.0075
51	0.23	0.1425
52	0.23	0.1425
53	0.23	0.1425
54	0.23	0.1425
55	0.23	0.1425
56	0.23	0.1425

Node	P (MW)	Q (Mvar)
57	0.23	0.1425
58	0.23	0.1425
59	0.23	0.1425
591	0.23	0.1425
592	0.137	0.085
61	0.075	0.048
62	0.075	0.048
63	0.075	0.048
91	0.057	0.0345
92	0.057	0.0345
93	0.057	0.0345
94	0.057	0.0345
Total	*4.6365*	*2.8735*