Distributed Generation: Challenges and Possible Solutions

J.Driesen, *Member, IEEE, and* R.Belmans, *Fellow, IEEE*

***Abstract*--This contribution starts from the observation that there is a renewed interest in small-scale electricity generation. The authors start with a discussion of the drivers behind this evolution indicating the major benefits and issues of small-scale electricity generation. Attention is paid to the impact of a massive penetration of distributed generation in the grid on the system safety and protection. An overview of the impact on voltage quality and stability is given, both static and dynamic. A practical example is discussed in order to show the problems and indicate solutions. Different types of generators and grid interfaces are treated. In a final chapter, an attempt is made to correctly define small-scale generation also commonly called distributed generation, embedded generation or decentralized generation.**

***Index Terms*-- Distributed generation, voltage stability, dispersed generation, grid safety**

I. INTRODUCTION

DISTRIBUTED generation (DG), for the moment loosely defined as small-scale electricity generation, is a fairly new concept in electric energy markets, but the idea behind it is not new at all. In the early days of electricity generation, distributed generation was the rule, not the exception. The first power plants only supplied electric energy to customers connected to the 'microgrid' in their vicinity. The first grids were DC based, and therefore, the supply voltage was limited, as was the distance covered between generator and consumer. Balancing demand and supply was partially done using local storage, i.e. batteries, directly coupled to the DC grid. Along with small-scale generation, local storage is also returning to the scene.

Later, technological evolutions, such as transformers, lead to the emergence of AC grids, allowing for electric energy to be transported over longer distances, and economies of scale in electricity generation lead to an increase in the power output of the generation units. All this resulted in increased convenience and lower per-unit costs. Large-scale interconnected electricity systems were constructed, consisting of meshed transmission and radially operated distribution grids, supplied by large central generation plants. Balancing demand and supply was done by the averaging effect of the combination of large amounts of instantaneously varying loads. The security of supply was guaranteed by the build-in redundancy. In fact this interconnected high-voltage system made the economy of scale in generation possible, with the present 1.5 GW nuclear power plants as a final stage in the development. Storage is still present, with the best known technology being pumped hydro plants.

In the last decade, technological innovations and a changing economic and regulatory environment resulted in a renewed interest for DG. This is confirmed by the IEA [1]. This paper presents the technical challenges and possible solutions when large amounts of distributed generation are introduced.

II. DRIVERS FOR DG

The IEA identifies five major factors that contribute to the renewed interest in DG. These five factors can be grouped under two major driving forces, i.e. electricity market liberalization and environmental concerns. The developments in small-scale generation technologies have been around for a long time, but were as such not capable of pushing the ‘‘economy of scale’’ out of the system. Although it is sometimes indicated, it may be doubted that DG is capable of postponing, and certainly not of avoiding, the development of new transmission lines, as, at the minimum, the grid has to be available as backup supply.

A. Liberalization of Electricity Markets

There is the increased interest by electricity suppliers in DG, because they see it as a tool that can help them fill in niches in the market, in which customers look for the best suited electricity service. DG allows players in the electricity sector to respond in a flexible way to changing market conditions. In liberalized markets, it is important to adapt to the changing economic environment in the most flexible way. DG technologies in many cases provide flexibility because of their small sizes and assumed short construction lead times compared to most types of larger central power plants. However, the lead time reduction is not always that evident. For instance, public resistance to wind energy and use of landfill gasses may be very high.

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1) Standby Capacity or Peak Use Capacity (Peak Shaving)

Many DG technologies are flexible in several respects: operation, size and expandability. Making use of DG allows a flexible reaction to electricity price evolutions. DG then serves as a hedge against these price fluctuations. Apparently, this is the major driver for the US demand for DG, i.e. using DG for continuous or peaking use (peak shaving). The energy efficiency sometimes is very debatable. In Europe, market demand for DG is, for the moment, driven by heating applications (through CHP), the introduction of renewable energies and potential efficiency improvements.

2) Reliability and Power Quality

The second major driver of US demand for DG is quality of supply or reliability considerations. Reliability problems refer to sustained interruptions, being voltage drops to near zero (usually called outages). The liberalization of energy markets makes customers more aware of the value of reliable electricity supply. In many European countries, the reliability level has been very high, although black-outs were seen over the last years.

Customers do not really care about supply interruptions as they do not feel it as a great risk. However, this may change in liberalized markets. A high reliability level implies high investment and maintenance costs for the network and generation infrastructure. Because of the incentives for cost-effectiveness that come from the introduction of competition in generation and actions from regulators aiming at short-term tariff reductions for network companies, it might be that reliability levels decrease. However, having a reliable power supply is very important for society as a whole, and industry in specific (chemicals, petroleum, refining, paper, metal, telecommunications, …). Companies may find the grid reliability of a too low level and decide to invest in DG units in order to increase overall reliability of supply to the desired level.

Apart from voltage drops to near zero (reliability problems), one can also have smaller voltage deviations. The latter deviations are aspects of power quality. Power quality refers to the degree to which power characteristics align with the ideal sinusoidal voltage and current waveform, with current and voltage in balance [2]. Thus, strictly speaking, power quality encompasses reliability.

Insufficient power quality can be caused by failures and switching operations in the grid, mainly resulting in voltage dips, interruptions, and transients and by network disturbances from loads yielding flicker (fast voltage variations), harmonics, and phase imbalance. The nature of these disturbances is related to the 'short-circuit capacity', being a measure for the internal impedance in the grid, depending on its internal configuration (e.g. length of the lines, short-circuit capacity of generators and transformers) [3].

3) Alternative to Expansion or Use of the Local Network

DG could partially serve as a substitute for investments in transmission and distribution capacity (demand for DG from T&D companies) or as a bypass for transmission and distribution costs (demand for DG from electricity customers). This is only possible to the extent that alternative primary fuels are locally available in sufficient quantities. For example, increased use of DG could result in new congestion problems in other networks, such as the natural gas distribution network.

4) Grid support

Finally, DG can also contribute in the provision of ancillary services, including those necessary to maintain a sustained and stable grid operation of the, but not directly supplying customers. This may be the capability to generate active power on demand of the grid operator, for instance to stabilize a dropping frequency due to a sudden under capacity in generation or excess demand, or reactive power to support the voltage.

B. Environmental Concerns

At present, environmental policies are probably the major driving force for the demand for DG in Europe. Environmental regulations force players in the electricity market to look for cleaner energy solutions. Here, DG can also play a role, as it allows optimizing energy consumption of firms that have a large and constant demand for heat. Furthermore, most government policies aiming to promote the use of renewables also results in an increased impact of DG technologies, as renewables, except for large hydro and wind parks (certainly off-shore), have a decentralized nature.

Especially on sites where there is a considerable and relatively constant demand for heat, it makes sense to consider the combined generation of heat and electricity instead of generating the heat in a separate boiler and buying electricity from the grid. These so-called cogeneration units form a large segment of the DG market. Compared to separate fossil-fired generation of heat and electricity, CHP (Combined Heat and Power) generation may result in a primary energy conservation, varying from 10% to 30%, depending on the size (and efficiency) of the cogeneration units. The avoided emissions are in a first approximation similar to the amount of energy saving, although the interaction with the global electricity generation system also plays a role [4], [5].

Installing DG allows the exploitation of cheap fuel opportunities. For example, in the proximity of landfills, DG units could burn landfill gasses. Other locally available biomass resources may also be envisaged.

III. GRID PROTECTION AND DG

Power can flow in a bidirectional way within a certain voltage level, but it usually flows unidirectionally from higher to lower voltage levels, i.e. from transmission to distribution grid. An increased share of DG units may induce power flows from low into medium-voltage grid. Thus, different protection schemes at both voltage levels may be required [6].

Safe operation and protection are to be guaranteed at all times. In addition, the protection system has to be sufficiently selective, in order to optimize reliability and availability of 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 form the DG units, making detection far more complicated and the conventional hierarchy (selective) protection methods might fall. Therefore, a more 'active' protection system with some form of communication is required to keep up the required level of safety in future.

The protection problems are illustrated by using a distribution system with five feeders in Fig. 1. If a short circuit occurs at F2 or F3, the short-circuit current is supplied by the generators connected to this feeder (G1 and G2), other DG units in adjacent feeders, and the main grid. If the contribution to the short-circuit current of G1 and G2 is large compared to that of the grid and the other feeders, the current through the circuit breaker and fuse CB1 might be too low to operate in order to eliminate the short circuit in the feeder. On the other hand, if the contribution to the short-circuit current from generators in adjacent feeders is significant, healthy feeders (feeder 4) might be disconnected before the faulty feeder is disconnected.

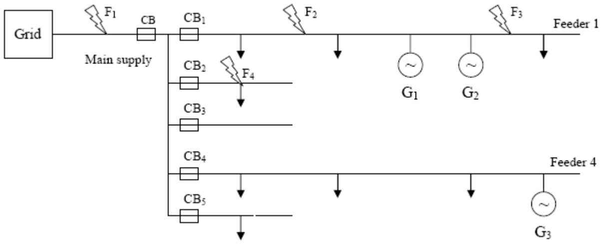

Fig. 1 Grid with safety problems due to high DG penetration.

As long as islanding is not intended to backup a loss of mains, it should be avoided [7]. According to technical standards (e.g. IEEE 1547), DG must be automatically disconnected, when faults or abnormal conditions occur, with the assumption that interconnection systems detect such conditions. In this way, conventional protection selectivity can be restored, guaranteeing person and equipment safety. In future, when more DG will be used, this requirement would reduce 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 [8].

DG flows can reduce the effectiveness of protection equipment. Customers wanting to operate in 'islanding' mode during an outage must take into account important technical (e.g. the capability to provide their own ancillary services) and safety considerations, such that no power is supplied to the grid during the time of the outage. Once the distribution grid is back into operation, the DG unit must be resynchronized with the grid voltage.

IV. VOLTAGE QUALITY AND DG

A. System Frequency

Imbalances between demand and supply of electricity cause the system frequency to deviate from its rated 50/60 Hz value. These deviations should be kept within very narrow margins, as the well functioning of many industrial and household applications depends on it. In economic terms, system frequency can be considered as a public good. As a consequence, the transmission grid operator is appointed to take care of the system frequency as well as of other services with a public good character that need to be provided.

The installation and connection of DG units are also likely to affect the system frequency. These units will free ride on the efforts of the transmission grid operator or the regulatory body to maintain system frequency. They will probably have to increase their efforts and having an impact on plants efficiency and emissions. Therefore, the connection of an increasing number of DG units should be carefully evaluated and planned upfront.

B. Voltage Level

The relation between DG and power quality is an ambiguous one. On the one hand, many authors stress the healing effects of DG for power quality problems [1], including the potential positive effects of DG for voltage support and power factor corrections [6].

On the other hand, large-scale introduction of decentralized power generating units may lead to instability of the voltage profile: due to the bi-directional power flows and the complicated reactive power equilibrium arising when insufficient control is introduced, the voltage throughout the grid may fluctuate. Eventually an 'islanding' situation may occur in which a local generator keeps a part of a disconnected grid energized leading to dangerous situations for the repair personnel coming in.

Others also stress the potential negative externalities on power quality, caused by the installation of DG capacity. According to [9], the impact on the local voltage level of DG connected to the distribution grid can be significant. A same reaction was noted through the CIRED questionnaire [10], where, next to the general impact on power quality, a rise in the voltage level in radial distribution systems is mentioned as one of the main technical connection issues of DG. The IEA [1] also mentions voltage control as an issue when DG is connected to the distribution grid. This does not need to be a problem when the grid operator faces difficulties with low voltages, as in that case the DG unit can contribute to the voltage support. But in other situations it can result in additional problems.

C. Reactive Power

Small and medium-sized DG units often use asynchronous generators that are not capable of providing reactive power. Several options are available to solve this problem. On the other hand, DG-units with a power electronic interface are sometimes capable to deliver reactive power.

D. Power Conditioning

Some DG technologies (PV, fuel cells) produce direct current. Thus, these units must be connected to the grid via a

DC–AC interface, which may contribute to higher harmonics. Special technologies are also required for systems producing a variable frequency AC voltage. Such power electronic interfaces have the disadvantage that they have virtually no ‘inertia’, which can be regarded as a small energy buffer capable to match fast changes in the power balance. Similar problems arise with variable wind speed machines [9].

V. PRACTICAL DISTRIBUTION NETWORK

A. *Distribution Grid Lay-Out*

An existing Belgian medium voltage distribution system segment is used to study the power quality and voltage stability with different DG units (Fig. 2). The system includes one transformer of 14 MVA, 70/10 kV and four cable feeders. The primary winding of the transformer is connected to the transmission grid and can be considered as an infinite node. Normal operation of the distribution system is in radial mode and the connections at node 111 with feeders 2, 3 and 4 are normally open.

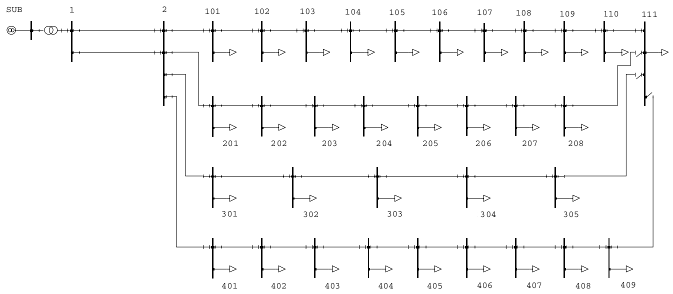

Fig. 2. Practical distribution system.

B. *Steady-State Voltage Rise*

A DG unit is connected at node 406 of feeder 4. The total load in the system is 9.92 MW, 4.9 Mvar. A synchronous and an induction generator are simulated with different power output. The synchronous generator is simulated at power factor 0.98 leading at 3 and 6 MW. The induction generator is simulated at power factor 0.95 lagging also at 3 and 6 MW. The power of the DG for both synchronous and induction generators raises the voltages of feeder 4, compared to the base case without DG (Fig. 3). For higher active and reactive power generation (synchronous 6 MW), an overvoltage occurs at node 406 and its neighbors.

Fig. 4 illustrates the voltage at node 406 with different power generation levels and power factors. Compared to the case that DG only injects active power or operates at unity power factor, synchronous generators raise the voltage of the system faster due to reactive support. For induction generators, the voltages rise is slower and at a certain level of power generation, the voltage starts to decrease. This is due to the fact that induction generators need reactive power, yielding in a reduction of the voltage rise.

Through this study, it can be seen that the impact of induction generators is less than that of synchronous ones in terms of voltage rise (Fig. 5). If there is an overvoltage with a synchronous generator, it has to operate under-excitated and to absorb reactive power instead of injecting it.

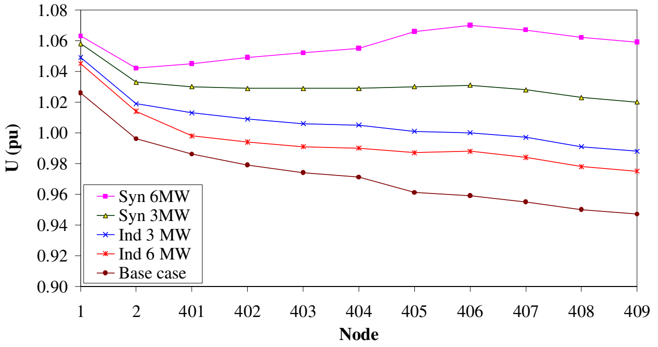

Fig. 3. Voltage profile of feeder 4 with DG connected at node 406

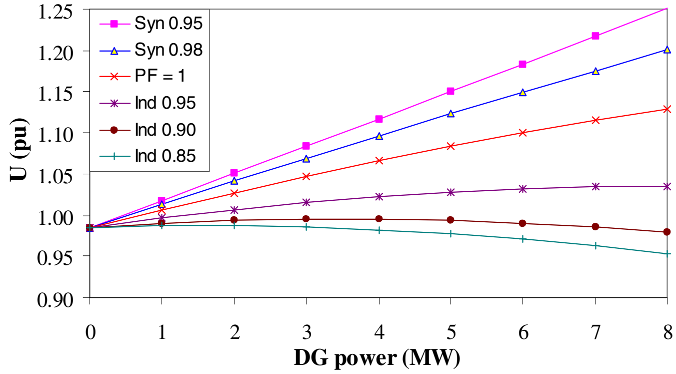

Fig. 4. Voltage at node 406 with different power factors

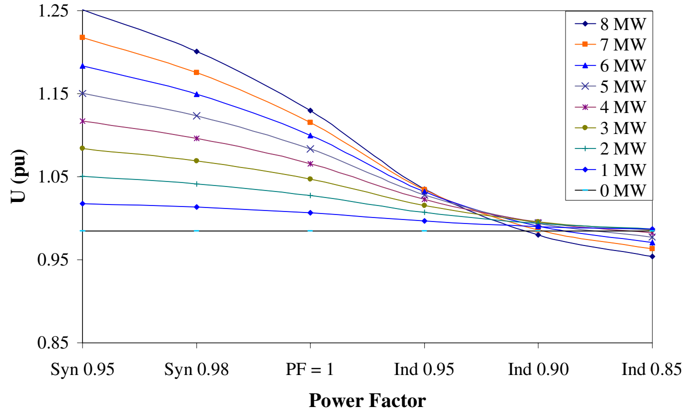

Fig. 5 Voltage at node 406 with different power generation levels

C. *Voltage Fluctuations*

In order to see the voltage fluctuation problem with DG, a photovoltaic (PV) system is used. The reactive power is produced by a capacitor of the inverter’s grid filter and is almost constant. The PV system is treated as a PQ node with negative active power. The PV power is calculated from 5-s average irradiance data measured during one year in Leuven – Belgium. In this study, a PV array with 50 kW rated peak power is connected at node 304. Fig. 6 shows the one-hour power output of the PV system at noon of a slightly clouded summer day. In order to isolate the voltage fluctuation impact of PV from short-time load variation at individual nodes, the loads are assumed constant during the calculation. The total load in the system is 4.4 MW, 1.9 Mvar. In Fig. 6, the voltage fluctuations correspond to the variations of injected active power of the PV system. At times when clouds cover the sun, the power generated can quickly drop by 60%, causing sudden variations in node voltages in the range of 0.1%. The installed capacity of PV in this study is rather low compared to the capacity of the distribution system and the loads, so the value of voltage fluctuation is limited. However, with a high connection density or the connection of a large PV system, the voltage fluctuation problem might become more severe.

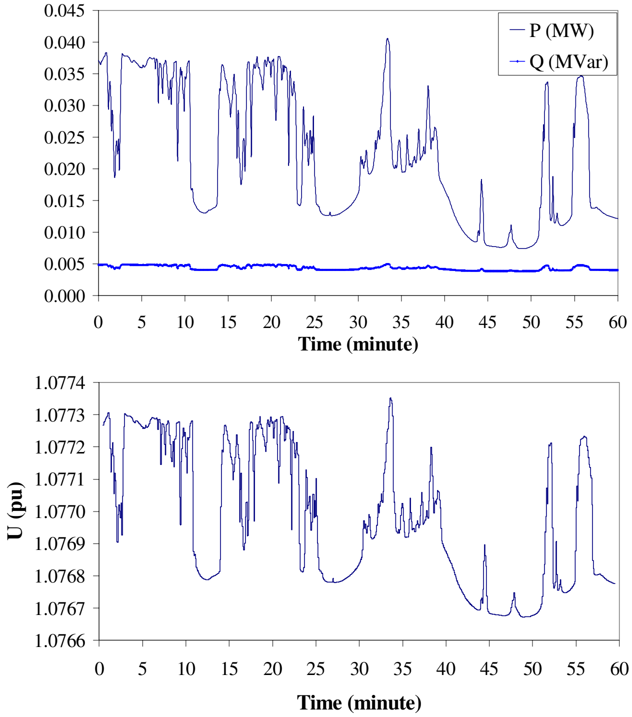

Fig. 6. Injected power and voltage at node 304

D. *Voltage Dip*

1) Opening of One Branch

A total DG capacity of 30% of the total system load is distributed equally over nodes 108, 204, and 406. The simulations have been carried out for induction and for synchronous generators. All operate at power factor 0.98 lagging. One of the 1-2 lines is opened during dynamic simulations at time t = 100 s. The distributed generators are connected at node 108, 204 and 406 with rated power 1 MW for both synchronous and induction generators.

The voltage dips are highest with constant power load characteristic and lowest with impedance load characteristic for both synchronous and induction generators (Fig. 7 and Fig. 8). With synchronous generators, after a short voltage dip, the voltage recovers close to the voltage before the disturbance. For induction generators, the voltage does not recover due to the lack of reactive power support. There is not so much difference between a voltage dip in the base case and with DG connection, being around 1%. So the connection of DG in the distribution system does not affect dynamic voltage stability significantly. In most cases it reduces the voltage dip value.

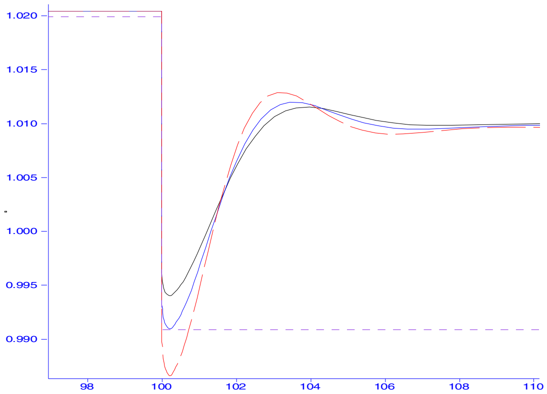

Fig. 7. Voltage dip at bus 2 with synchronous generator

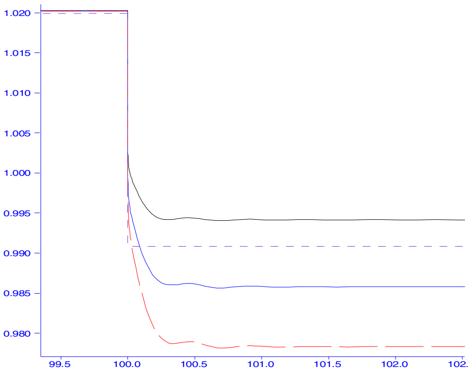

Fig. 8. Voltage dip at bus 2 with induction generator

2) Generator Start-Up

In order to see the voltage dip problem when a DG starts up, an induction generator connected at node 108 with rated power of 3 MW is tested at lagging power factor of 0.9. When the induction generator starts up, it causes a transient and a voltage dip up to 40% in the system and lasts for several seconds (9). It is due to an initial magnetizing inrush transient and power transfer to bring the generator to its operating speed [11]. This results in a major problem for sensitive loads connected near the DG. If the distribution system is equipped with an under-voltage relay and DG unit has islanding protection, the voltage dip may lead to an action of the protection relay resulting in an outage of the system. A soft-start circuit is required for large connected induction DG.

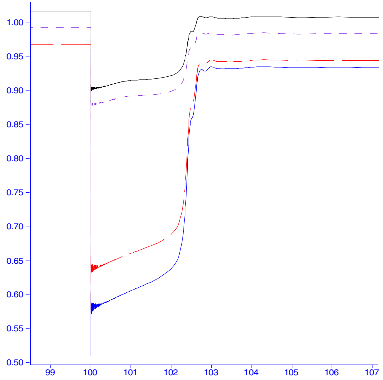

Fig. 9. Voltage dip when starting-up of an induction generator

E. Static Voltage Stability

The voltage stability is studied for synchronous and induction generators with three cases of DG connection: a) one DG unit connected at node 108, b) one at node 2, c) DG units distributed in the system at nodes 108, 204, 406. The total load of the system is 9.92 MW, 4.9 Mvar, all impedances. The total installed capacity of DG units in all cases is 3 MW. The voltage stability at node 111, at the end of feeder 1, is studied. DG units generally increase the voltage and support stability in the system (Fig. 10 and Fig. 11). The connection point of DG influences the voltage stability in the system. DG strongly supports the voltage at nearby nodes and has less impact on distant ones. This is also true for the other load characteristics. Compared to induction DG, the synchronous generator has a larger impact on the voltage stability because of its capability of reactive power injection. On the other hand, the influence of induction DG on voltage stability is not so different frothe base case (without DG).

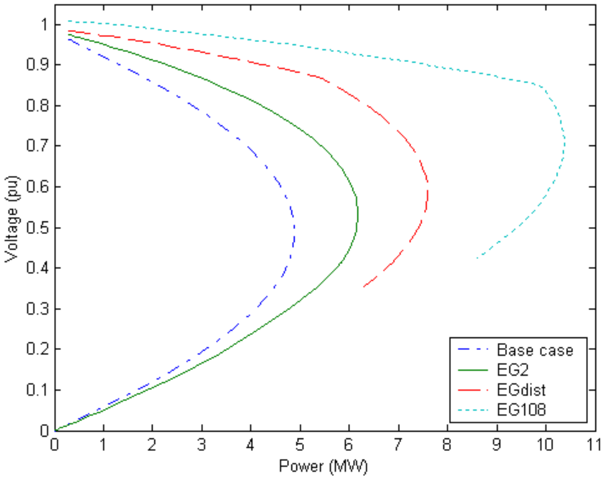

Fig. 10. Static voltage stability at node 111 with a synchronous generator

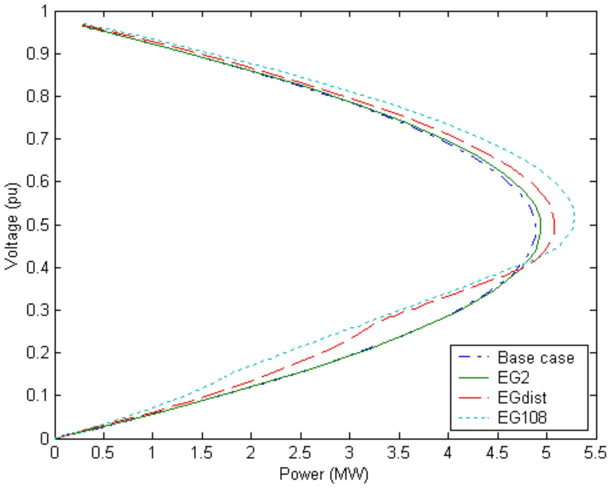

Fig. 11. Static voltage stability at node 111 with an induction generator

VI. ENERGY SECURITY

In some discussions, energy security is linked to the diversification of primary energy supplies, while in others, it is interpreted as the reliability of the electricity system. Under the first interpretation, energy security improves as the diversification of primary energy supplies increases. In this case, the advantages of DG are limited, as most technologies - with the exception of systems based on renewables - directly or indirectly depend on natural gas.

Under the second interpretation, it is felt by many authors [1], that DG can contribute to reduce the risks and costs of blackouts. Here, DG is seen as an instrument that helps to reduce the private costs and risks for electricity customers of system failures. Others, like [10], claim that DG does not contribute to system security. On the contrary, it would have a negative effect. Such a negative impact on the system security occurs when the share of non-dispatchable generation capacity increases. Examples of such units are wind turbines, photovoltaic systems and cogeneration units closely tied to heat demand. The latter units cannot be centrally controlled because of the natural variability of their power supply. As a consequence, there is an increased need for regulating (backup) power.

VII. DEFINITION OF DISTRIBUTED GENERATION

A. General Considerations

In the previous sections, DG was loosely defined as small-scale electricity generation, but what exactly is small-scale electricity generation? Different technologies can be used for DG [12], but is it possible to give an overall, concrete definition? A short survey of the literature shows that there is no consensus. This is confirmed in [10], on the basis of a questionnaire submitted to the member countries. Some countries define DG on the basis of the voltage level, whereas others start from the principle that DG is connected to circuits from which consumer loads are supplied directly others as having some basic characteristic (e.g., using renewables, cogeneration, being non-dispatched).

CIRED has a working group that devotes efforts to DG. It defines DG as all generation units with a maximum capacity of 50 to 100 MW, usually connected to the distribution network and neither centrally planned nor dispatched [10]. Clearly, this latter part of their definition implies that DG units are beyond the control of the transmission grid operator. Thus, generation units built by the transmission grid operator as a substitute for grid expansion and that have measures implemented for dispatching, are not considered to be DG according to this philosophy.

The IEEE defines DG as the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system.

On the basis of the definitions surveyed [6] DG is defined as a small source of electric power generation or storage (typically ranging from less than a kW to tens of MW) not part of a large central power system and located close to the load. Storage facilities are also included in the definition of DG, which is not conventional. Furthermore, this definition emphasizes the relatively small scale of the generation units as opposed to CIRED and CIGRE.

DG is also defined DG as relatively small generation units of 30 MW or less [13]. These units are sited at or near consumers to meet specific needs, to support economic operation of the distribution grid, or both. With the exception of the CIGRE definition, all definitions assume that DG units are connected to the distribution network. This is also the case for the definition used in [1], which sees DG as units producing power on a customer's site or within local distribution utilities, and supplying power directly to the local distribution network. IEA, however, makes no reference to the generation capacity level as opposed to all other definitions.

It should be clear by now, that many definitions of DG exist, allowing for a wide range of possible generation schemes. Some definitions allow for the inclusion of larger-scale cogeneration units or large wind farms connected to the transmission grid, others put the focus on small-scale generation units connected to the distribution grid. All these definitions suggest that at least the small-scale generation units connected to the distribution grid are to be considered as DG. Moreover, generation units installed close to the load or at the customer side of the meter are also commonly identified as DG. This latter criterion partially overlaps with the first, as most of the generation units on customer sites are also connected to the distribution grid.

However, it also includes somewhat larger generation units, installed on customer sites, but connected to the transmission grid.

This leads to the definition proposed in [9], defining DG in terms of connection and location rather than of generation capacity. It is defined as a DG source of an electric power generation connected directly to the distribution network or on the customer side of the meter. We favor this definition, even though it is rather broad. Indeed, it puts no limit on technology or capacity of potential DG application. Therefore, some additional criteria can be helpful and necessary to further narrow the definition in function of the research question tackled. The following paragraphs list a (non-exhaustive) number of these criteria along with a short discussion.

B. Voltage level at grid connection (transmission/ distribution)

Although some authors allow DG to be connected to the transmission grid, most authors see DG as being connected to the distribution network, either on the distribution or on the consumers' side of the meter. In all cases, the idea is accepted that DG should be located closely to the load. The problem is that a distinction between distribution and transmission grid, based on voltage levels, is not always useful, because of the existing overlap of these voltage levels for lines in the transmission and distribution grid. Moreover, the 'legal' voltage level that distinguishes distribution from transmission can differ. Therefore, it is best not to use the voltage level as an element of the definition of DG. It would be more appropriate to use the concepts 'distribution network' (usually radial) and 'transmission network' (usually meshed).

C. Generation capacity (MW)

One of the most obvious criteria would be the generation capacity of the units installed. However, the short survey of definitions illustrated that there is no agreement on maximum generation capacity levels and the conclusion is that generation capacity is not a relevant criterion. The major argument is that the maximum DG capacity that can be connected to the distribution grid is a function of the capacity of the distribution grid itself. Because this latter capacity can differ widely, it is impossible to include it as an element of the definition of DG.

However, this does not imply that the capacity of the connected generation units is not important. On the contrary, many of the policy issues and benefits are related to capacity of generation units. Thus, a narrowed definition of DG could, among other things, be based on the capacity criterion.

D. Services Supplied

Generation units should by definition at least supply active power in order to be considered as DG. The supply of reactive power and/or other ancillary services is possible and may represent an added value, but is not necessary.

E. Generation Technology

In some cases, it can be helpful to clarify the general definition of DG by summing up the generation technologies taken into account. It would however be difficult to use this approach to come to a definition because the availability of (scalable) technologies and of capacities, especially in the field of renewables, differs between countries. Also conventional systems such as gas turbines are available over wide ranges (a few kW to 500 MW and more).

Sometimes, it is claimed that DG technologies should be renewable. However, it should be clear that many small-scale generation technologies exist that do not use renewables as a primary source. On the other hand, not all plants using 'green' technologies are supplying DG. This would, for example, depend on the plant size or on the grid to which the installation is connected (transmission or distribution). Should a large off-shore wind farm of 100 MW or more be considered as DG? And what about a large hydro power plant located in the mountains?

F. Operation Mode

The operation mode (being scheduled, subject to pool pricing, dispatchable) is not considered as a key element in the general definition of DG [9]. This is a correct view, but at the same time it must be recognized that many problems related to DG, essentially have to do with the fact that these generation units being beyond control of grid operators. So, it can be meaningful to use (elements of) the operation mode as a criterion to narrow the definition.

G. Power Delivery Area

In some cases, DG is described as power generated and consumed within the same distribution network. As correctly stated in [9], it would be difficult to use this as a criterion, even for a narrowed definition, because it requires complex power flow analyses.

H. Ownership

Also ownership is not considered as a relevant element for the definition of DG [9]. Thus, customers, independent power producers (IPPs) and traditional generators can own DG units.

VIII. SUMMARY AND CONCLUSIONS

This paper started from the observed renewed interest in small-scale electricity generation. General elements of the drivers for this development are discussed both from the economic and environmental point of view. Small-scale generation is commonly called DG and we try to derive a consensus definition for this latter concept. It appears that there is no agreement on a precise definition as the concept encompasses many technologies and many applications in different environments. In our view, the best definition of DG that generally applies seems to be 'an electric power generation source that is connected directly to the distribution network or on the customer side of the meter'. Depending on the interest or background of the one confronted with this technology, additional limiting aspects might be considered. A further narrowing of this 'common divider' definition might be necessary depending on the research questions that are looked at. However, the general and broadly understandable description as proposed here, is required to allow communicating on this concept.

From a technical viewpoint, the paper discusses the impact on the protection and the safety of the grid. A lot of attention is paid to the interaction of the DG units with the quality of the grid voltage. Both static and dynamic voltage analysis are used to demonstrate the interactions. The choice of generator type has a major influence: two types are distinguished, synchronous and induction; the impact of the power electronic converter that may be used, is treated. An actual grid is used for supporting the results by simulations.

IX. REFERENCES

[1] IEA, *Distributed Generation in Liberalised Electricity Markets*, Paris, 128 pages, 2002.

[2] Eto J., Koomey J., Lehman B., Martin N., "Scoping Study on Trends in the Economic Value of Electricity Reliability to the US Economy," LBLN-47911, Berkeley,2001, 134 pages.

[3] Renner H., Fickert L., 1999. Costs and responsibility of power quality in the deregulated electricity market, Graz.

[4] Voorspools K., D'haeseleer W., "The evaluation of small cogeneration for residential heating," *International Journal of Energy Research*, 26, pp.1175–1190.

[5] Voorspools K., D'haeseleer W. "The impact of the implementation of cogeneration in a given energetic context," *IEEE Transactions on Energy Conversion,* 18, 2003, pp.135–141.

[6] Dondi P., Bayoumi D., Haederli C., Julian D., Suter M., "Network integration of distributed power generation," *Journal of Power Sources*, 106, 2002, pp.1–9.

[7] Woyte A., De Brabandere K., Van Dommelen D., Belmans R., Nijs J, "International harmonisation of grid connection guidelines: adequate requirements for the prevention of unintentional islanding," *Progress in Photovoltaics: Research Applications*, 2003, Vol.11, No.6, pp.407-424.

[8] Gatta F.M., Iliceto F., Lauria S. Masato P. "Behaviour of dispersed generation in distribution networks during system disturbances. Measures to prevent disconnection," Proceedings CIRED 2003, Barcelona, 12-15 May 2003.

[9] Ackermann T., Andersson G., Soder L., "Distributed generation: a definition," *Electric Power Systems Research*, 57, 2001, 195–204.

[10] CIRED, 1999: Dispersed generation, Preliminary report of CIRED working group WG04, June, p. 9+Appendix (p.30).

[11] Jenkins N., Allan R., Crossley P., Kirschen D., Strbac G., *Embedded Generation*, *The Institute of Electrical Engineers*, London, 2000

[12] Pepermans G., Driesen J., Haeseldonckx D., Belmans R., D'Haeseleer W., "Distributed generation: definition, benefits and issues," *Energy Policy*, Vol.33, Issue 6, April, 2005; pp. 787-798.

[13] Chambers A., *Distributed generation: a nontechnical guide*. PennWell, Tulsa, OK, 2001. p. 283.

X. BIOGRAPHIES

Johan Driesen (S'93–M'97) was born in 1973 in Belgium. He received the M.Sc. degree in 1996 as Electrotechnical Engineer from the K.U. Leuven, Belgium. He received the Ph.D. degree in Electrical Engineering at K.U.Leuven in 2000 on the finite element solution of coupled thermal-electromagnetic problems and related applications in electrical machines and drives, microsystems and power quality issues. Currently he is an associate professor at the K.U.Leuven and teaches power electronics and drives. In 2000-2001 he was a visiting researcher in the Imperial College of Science, Technology and Medicine, London, UK. In 2002 he was working at the University of California, Berkeley, USA. Currently he conducts research on distributed generation, including renewable energy systems, power electronics and its applications, for instance in drives and power quality.

Ronnie Belmans (S'77-M'84-SM'89-Fellow '04) received the M.S. degree in electrical engineering in 1979, the Ph.D. in 1984, and the Special Doctorate in 1989 from the K.U.Leuven, Belgium and the Habilitierung from the RWTH, Aachen, Germany, in 1993.

Currently, he is full professor with K.U.Leuven, teaching electrical machines and variable speed drives. He is appointed visiting professor at Imperial College in London. He is also President of UIE.

He was with the Laboratory for Electrical Machines of the RWTH, Aachen, Germany (Von Humboldt Fellow, Oct.'88-Sept.'89). Oct.'89-Sept.'90, he was visiting associate professor at Mc Master University, Hamilton, Ont., Canada. During the academic year 1995-1996 he occupied the Chair at the London University, offered by the Anglo-Belgian Society. Dr.Belmans is a fellow of the IEE (United Kingdom). He is the chairman of the board of Elia, the Belgian transmission grid operator.