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Distributed Power Generation in Europe: technical issues for further integration

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Table of Contents

Acronyms and definitions

AC: Alternating Current
Adequacy: ability of the electric system to supply the aggregate electrical demand and meet energy requirements of the customers at all times, taking into account scheduled and unscheduled outages of system facilities (See also Reliability, Security)
CHP: Combined Heat and Power
CO: Carbon monoxide
CO_2: Carbon dioxide
Control area: portion of the generation and transmission system controlled by a single transmission system operator. It corresponds to a country's area in most cases (See also TSO)
DC: Direct Current
DC Baltija: association of the Baltic system operators of Estonia, Latvia and Lithuania
DG: Distributed Generation
DSO: Distribution System Operator
EC: European Commission
EHV: Extra High Voltage
EMF: Electro-Magnetic Field
ERGEG: European Regulators Group for Electricity and Gas
ETSO: European Transmission System Operators association
EU: European Union
EU15: 15 EU Member States until 30^{th} Apr. 2004
EU25: 25 EU Member States until 31^{st} Dec. 2006
EU27: 27 EU Member States from 1^{st} Jan. 2007
FACTS: Flexible Alternating Current Transmission System
GHG: Greenhouse gas
HV: High Voltage
HVDC: High Voltage Direct Current
ICE: Internal Combustion Engine
ICT: Information & Communication Technology
IEM: Internal Electricity Market
IPS/UPS: Integrated Power System/United Power System, consisting of Independent Power Systems of 12 countries bordering Russia and the Unified Power System of Russia
ISO: Independent System Operator, responsible for the management of the system, but not owning the assets (See also TSO)
NO_x: Nitrogen oxides
NORDEL: association of Nordic electric system operators, comprising Denmark, Finland, Norway, Sweden
Overhead line: electric line suspended by towers or poles. Since most of the insulation is provided by air, overhead lines are generally the lowest-cost method of transmission for bulk electric power. Towers for support are usually made of steel (either lattice structures or tubular poles) or concrete. The conductors are generally made of aluminium, either plain or reinforced with steel or sometimes composite materials
Quality of supply: measures the quality of the electricity service provided to customers, usually in terms of acceptable voltage and frequency values
PMU: Phasor Measurement Unit
Reactive Power: generally expressed in kilo-vars (kVAr) or mega-vars (MVAr), it is that portion of electricity that establishes and sustains the electric and magnetic fields of alternating current

equipment. Reactive power must be supplied to most types of magnetic equipment, such as motors and transformers, and causes reactive losses in transmission facilities. It is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors, and directly influences the voltage of the electrical system

Reliability: The sum of adequacy and security. It describes the degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired. Reliability at transmission level may be measured by the frequency, duration, and magnitude of adverse effects on the electric supply / transport / generation (See also Adequacy and Security)

RES: Renewable Energy Source

SCADA: Supervisory Control And Data Acquisition, a remote control and telemetry system used to monitor and control the electrical system

Security: ability of the electric system to withstand sudden disturbances, such as electric short circuits or unanticipated loss of system components. Another aspect of security is system integrity, which is the ability to maintain interconnected operations (See also Security of Supply)

Security of supply: ability of the electric power system to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner (See also Security)

SO_x: Sulphur oxides

Stability: the ability of an electrical system to withstand normal and abnormal system conditions or disturbances and to regain a state of equilibrium

Tap changer: device on a transformer that adjusts the output voltage of the transformer by changing the number of turns in the windings (See also Transformer)

TEN: Trans-European Networks

TPA: Third Party Access

Transformer: a device, utilizing windings, for transferring alternating current electrical energy from one circuit to another circuit with different voltage and current values (See also Tap Changer)

TSO: Transmission System Operator, which owns the assets and is responsible for the management of the transmission system in its control area (See also Control area and ISO)

UCTE: Union for the Coordination of the Transport of Electricity, the power transmission system of continental Europe

WAMS: Wide Area Measurements System

List of Figures

List of Tables

Executive Summary

The electric power sector in Europe is currently facing different changes and evolutions mainly in response to the three European Union (EU) energy-related challenges – environmental sustainability, security of supply, and competitiveness – within a context of growing electricity demand. These issues may also represent drivers for the further penetration of Distributed Power Generation (hereinafter simply Distributed Generation, or DG) technologies in Europe. In fact, several EU countries are already recording a gradual and steady upward trend in deploying distributed power sources.

This trend is also triggered by emerging technological solutions for more efficient, environmentally-friendly and small-size generating units. Additionally, to address the growing electricity demand, the traditional approach of adding new large generation and transmission capacity to the system is frequently hindered by social, economic and environmental constraints in building new high capacity infrastructures. These impediments may then contribute to further DG utilisation. It has also to be remarked that the recent new targets for Renewable Energy Sources (RES) penetration in the EU (globally 20% of energy consumption covered by RES by 2020) will foster a rising DG deployment in the EU countries.

As stated by the European Commission in the European Strategic Energy Technology Plan (SET-Plan), one of the key EU technology challenges for the next 10 years is to enable a single, smart European electricity grid to accommodate the integration of a large penetration of renewable and decentralised energy sources. Achieving a sustainable, interconnected European energy system requires extensive energy infrastructure changes, which represent one of the most important investments of the 21st century.

The present Report focuses on the potential role of Distributed Generation against the above described background. More specifically, this work aims to investigate the developments related to DG technologies and address the technical issues towards the DG integration into the European power systems.

As a starting point the concept of Distributed Generation is characterised for the purpose of the study. Distributed Generation, defined as an electric power source connected to the power distribution network, serving a customer on-site or providing network support, may offer various benefits to the European electric power systems. DG technologies may consist of small/medium size, modular energy conversion units, which are generally located close to end users and transform primary energy resources into electricity (and in some cases heat and cooling via Combined Heat and Power (CHP) technology).

The most important advantages inherent to the DG concept may be grouped and summarised as in the following points:

- Increase of security and reliability of supply: Renewable and efficient DG technologies can reduce energy imports and build a diverse energy portfolio in the EU. Intentional islanding mechanisms can protect clusters of customers against power outages occurring on bordering networks. DG technology can increase reliability of supply by providing network support and contribute to ancillary services.
- Advantages in transmission and distribution network operation and planning: Distribution networks with high DG penetration reduce congestions on the upstream transmission grid. Expected lower transmission congestions can allow for deferring transmission system development. DG units conveniently located in distribution systems greatly reduce

transmission losses and may cut down distribution losses in properly operated and controlled systems.

- More efficient use of primary energy resources and waste heat: Suitable local position of DG units enables more efficient exploitation of available energy sources like waste products or renewables. Proximity of CHP generation to customers allows for more convenient use of sizeable heat loads via limited heat distribution networks.
- Reduction of noxious pollutant emissions: Renewable and/or efficient DG can reduce fossil fuel consumption and greenhouse gas (GHG) emissions.
- Energy market competitiveness: DG can also stimulate competition in supply allowing more players to enter the electricity market.
- Authorisation and construction facilitation: It is generally easier to find sites for RES and other DG than for large central power plants and such units can be brought online much more quickly.

However, there are also technical issues, generally relevant for most EU countries, concerning the integration of DG technologies into the power distribution networks:

- Distribution planning and operation issues: Local protection systems may need redesign efforts since DG technologies connection not only changes the power flows pattern, but also significantly affects local voltage and fault current levels. A revision of the distribution grids architecture may be needed due to the two-way power exchange resulting from DG deployment. Data collection needed for controlling the distribution and DG systems can be complex, being the distribution system generally not controlled by SCADA (Supervisory Control And Data Acquisition) systems used in the transmission operation.
- Power reserve and balancing: Due to the intermittent output from some DG sources, the DSO (Distribution System Operator) must be able to manage fast reacting local power generation and in some cases procure the needed power reserve from the upstream transmission. By a growing penetration of intermittent renewables and CHP technologies, the costs of imbalances may consistently increase, and the application of priority dispatch mechanisms may become increasingly difficult.
- Power quality: Harmonics may be generated by power electronic converters used to connect DG technologies, thus causing disturbances on the grid, which may however be damped by properly tailored filters.

For every technical problem one or more solutions exist. These depend on the topology, operation and technical requirements of the specific distribution grid as well as the DG type and the local load forecast: all these elements impact on the network's capacity to absorb the connected DG. Depending on these local conditions, the integration of DG into today's European distribution grids may then be possible and technically feasible to a certain extent, provided that all the requirements set out in the connection procedure are met.

Surely, to have a fully exploitable integration of DG technologies and to make them truly replace bulk power generation, measures like the provision of ancillary services by DG are necessary to accompany the connection and operation of distributed generating units.

However, in case of increasing DG penetration, planning and developing new architectures for the distribution grids represent crucial steps to avoid serious effects caused by DG on the power system.

If the growing DG output - fostered also by the rising targets for RES - is not properly and timely handled, portions of the European distribution systems are naturally exposed to risks of reliability worsening and security of supply deterioration.

In addition, the indirect effects of DG growth on the European transmission system cannot be neglected. In fact, recent disturbance and disruption events in Europe prove that, without properly coordinated system interfaces and flexible controlling devices, the consequences of a power disruption at distribution level may be suffered (if not amplified) at transmission level. There is also the need for a clear definition of the borders between electricity transmission and distribution.

For all these reasons, developing new approaches and architectures is vital in order to securely accommodate rapidly growing DG shares. Before reaching the final model(s) of the future power distribution system, a transition process with different temporal stages may be needed. At every stage, the effects of such system and technological developments have to be continuously and carefully monitored in Europe. This approach will permit a smoother coordination and steering over the modifications of the concerned energy systems, thereby reducing the risk of major criticalities and security of supply issues. Final result will be then the shift from the traditional approach of simply connecting DG installations (‘fit and forget’) to a more integrated way of planning and implementing the connection of new DG units. In order to achieve the final stage of a new network architecture, the following steps will be required: the upgrade of the protection systems; the reinforcement of the lower voltage electricity networks; the introduction of new soft control means, based on Information & Communication Technology (ICT); the introduction of new hard control means, based on flexible grid controlling devices like FACTS (Flexible Alternating Current Transmission System).

Three new distribution architectures are presently under development: Active Networks, MicroGrids, Virtual Power Plants. All of these systems - or a combination of them - represent possible schemes towards which today’s distribution systems may evolve in the mid term in order to address the above issues. A MicroGrid project, based on the Cell concept and ongoing in Denmark, may become a paradigm of how to handle distribution and transmission systems with large DG penetration.

Based on the issues highlighted, some technical recommendations for possible actions at DG unit and at transmission and distribution system level are then proposed:

- In order to safeguard the governability of the present and future electricity systems, there is a need for a clear definition of the networks borders and the grid control areas. This is required to delimit roles and accountabilities of the different operators.
- There is a need for a better coordination of the transmission and distribution systems, which have to efficiently and safely work together. Both systems need to be further developed, not necessarily only in terms of carrying capacity but also and mostly in terms of ICT infrastructure and communication platforms. In particular, the transmission system strongly needs clear interfaces with the downstream distribution system.
- Considering the transmission planning issues brought about by the electricity market liberalisation, a cautious approach needs to be followed before extending the same planning procedure to subtransmission and distribution systems. For certain aspects, at the outset, a more regulated approach may be instrumental to effectively draw and partially rebuild the power systems before introducing fully competitive mechanisms.
- Distribution planning and operation practices more oriented to active power flow management need to be carried out by the DSOs, especially where the DG penetration has reached certain levels and cannot be neglected any more. The distribution system may be subdivided in more subsystems by islanding procedure. Each subsystem has to be eventually able to balance supply and demand effectively (i.e. be self-sufficient) for a twofold reason: firstly, to be able to disconnect from the interconnected system and continue running in case

of large and widespread disruptions; secondly, to reduce the burden (in terms of control actions and losses) on the upstream systems.

- The provision of ancillary services by DG, especially by units interfaced via power electronic converter or synchronous machine, is necessary for a complete integration of DG into the system. Such requirement is pushed both by technical grounds (DG may take the place of large generation in providing equivalent operation flexibility and reliability) and economic needs (DG investment may record shorter pay-back periods by entering the market of ancillary services).
- The development and improvement of cost-effective and coordinated high-power energy storage systems, based on different technologies, may play a key role in facilitating a larger penetration of DG resources.
- Innovative network controlling devices like WAMS (Wide Area Measurement Systems) and FACTS need to be inserted and utilised by system operators to better and more effectively control their grids.

Finally, apart from technical and technological aspects, the broad introduction of Distributed Generation and the consequent adaptation of the power systems result also in economic, regulatory and environmental issues. These other aspects, which are generally not addressed in this Report, need also to be accurately investigated, in order to properly manage the transition and identify all the possible attached benefits and drawbacks.

1 Introduction

1.1 Key drivers and issues in the European power system

European society and industry are more and more dependent on the availability of electricity supply and on the efficient operation of the electricity systems. For several years the European electric power sector has been experiencing different issues and trends which may require major changes in the system architecture in the near future.

Firstly, the electricity market liberalisation process has led to a restructuring of most of the electric power system sector. In the European Union (EU) the electricity market opening has been ongoing for some years through the implementation of the EU Directives 96/92/EC [1] and 2003/54/EC [2] at national level. Then, in a more competitive system with an increasing amount of market participants, a growing attention is paid by all electricity market players to the economics of power system operation. Within this background and given the increased environmental awareness, all electricity users require a more efficient, economic, environmentally-friendly and secure power supply system.

Secondly (and more crucially), the constant growth in electricity demand in Europe is putting the electric power system – from generation to transmission to distribution - under strain. In the EU25, the average yearly growth rate of electricity demand has been 1.8 % ca. since 1990 and in a baseline scenario is projected to a 1.5 % up to 2030 [3]. Furthermore, a general increase of inter- and intra-zonal power transactions is also a consequence of the liberalisation of electricity markets and is leading to more frequent network congestions.

Until recently, in order to address these issues and meet an increasing demand, the traditional strategy of adding new power capacity to the system has been pursued. This in general implied construction/upgrading actions of the following system components:

- large generation units;
- long transmission lines with high carrying capacity, connecting large power plants with generally distant substations;
- short distribution lines with limited carrying capacity, connecting distribution substations with generally passive customers (i.e. users not able to produce power).

Before the liberalisation of the electricity system, at national or regional level in Europe, these three tasks were generally all carried out by vertically integrated electricity companies in a (nearly) complete monopoly situation. Today, the approach of adding new power capacity is very frequently restrained by several factors (economic, environmental, political) hindering the system upgrade and the construction of new lines and large plants.

In fact, with economic aspects becoming more and more important in a competitive electricity industry, investment decisions are driven by shorter term profits and have to face market uncertainties. This concerns particularly the generation which is under liberalisation (as the supply), but also impacts on transmission and distribution, although the latter are regarded as natural monopolies operated under regulated conditions.
Furthermore, the authorisation and construction of high voltage lines and large power plants are in some cases restricted by increased environmental awareness translated in legislation at European

and national level. This is mainly because of the environmental and territorial impact (e.g. electromagnetic fields, pollutant emissions) of those power system equipment and devices.
Also in case where legislative provisions and administrative constraints are fully met, social opposition and political concerns may hinder, delay and even block the construction of new electricity infrastructures.
Then, for all these reasons, the traditional approach to address a growing electricity demand is no longer a feasible option.

There are also technical issues related to large power plants and network infrastructures. For instance, it is generally not techno-economically feasible for large fossil fuel-based power plants to utilise the waste heat stemming from the energy conversion process. In fact, being the generating units located generally far from perspective customers, a devoted heat transmission network would be needed. Also, electricity transmission and distribution networks - as they are built and managed today - may cause significant losses. These losses can indeed reach considerable shares - even up to 15-18 % in some European countries (in an average of 7% ca. at EU25 level [5]) - of the total electricity demand. Most of these losses are in the distribution networks.

On the other hand, different trends are ongoing in the European energy sector.

More efficient and environmentally-friendly generation technologies have emerged in the field of cogeneration (Combined Heat and Power, CHP) and renewable energy sources (RES), respectively. These generation technologies are strongly supported [6][7] by European energy policies whose key targets are environmental sustainability, security of energy supply, and system competitiveness [9][10][11]. These technologies are indeed considered to play a significant role for achieving the goals of enhanced security of energy supply, improved system efficiency and reduced carbon dioxide emissions from the power sector. CHP and RES technologies, whose penetration is rapidly growing throughout Europe [8][12][13], may have units with generally small/medium size (up to several tens MW), thus suited for connection to distribution networks.
Within this context, as stated by the European Commission in the European Strategic Energy Technology Plan (SET-Plan) [4], one of the key EU technology challenges for the next 10 years is to enable a single, smart European electricity grid to accommodate the integration of large shares of RES and DG sources. Achieving a sustainable, interconnected European energy system requires extensive energy infrastructure changes, which represent one of the most important investments of the 21st century.

Additionally, steady technological progress makes the utilisation of power electronics-based converters more attractive for several applications in the electric power field. These converters play a vital role in the grid connection of the above mentioned small/medium power units and the operation of electric power systems. For example, they can provide reactive power/voltage support and can be utilised for energy storage applications on the distribution networks.

Also, Demand Side Management (DSM) practices are adopted by an increasing number of system operators, especially on the distribution level. The aim is to control and reduce electricity consumption during peak demand periods or under critical system conditions, in order to safeguard the system integrity.

All the above described issues and trends may then represent key drivers for the increased utilisation of Distributed Power Generation (hereinafter simply Distributed Generation, DG) in Europe. This concept of distributed power generation[1] refers to smaller generation units (respect to the conventional large, centralised generators) dispersed along the distribution system. A DG

[1] See Chapter 3 for the definition and classification of distributed power generation. Sometimes it is referred to as decentralised generation as equivalent of distributed generation, but this is not completely correct, as decentralised generation may be connected to subtransmission or transmission systems.

system, depending on the technology type, may house many little, modular units, generally located close to end users and converting primary energy resources into electricity and eventually heat (and cooling).

However, there are still major issues concerning the integration of DG technology into the distribution networks. In fact, it has to be stressed that at the outset the distribution systems were not generally designed to operate in the presence of DG technologies.

The present work reviews the key characteristics of Distributed Generation, given the potential role DG may play in the European power system. The aim of this Report is to critically analyse and assess the technical issues and developments affecting the grid integration of DG in Europe. Energy storage technologies (such as battery and flywheel), whose utilisation can be an option for managing intermittency of some DG technologies, are not treated in this work.

Regulatory and economic aspects are also generally out of the scope of the present work.

The main questions this work has to address regard whether and how increasing shares of DG may be reliably operated and integrated into the European electric power system.

1.2 Structure of the Report

This Report is structured as briefly described in the following.
Chapter 2 introduces the basic architecture and elements of conventional (centralised) electric power systems, with an overview of the European power system. Particular attention is paid to the power distribution system.
Chapter 3, after a literature review of DG definitions, highlights the most critical aspects towards appropriately defining DG. The main features of DG technologies as well as the potential benefits and issues associated with DG deployment and integration are also described.
Chapter 4 analyses more broadly the state-of-the-art of DG, also comparing operation and performance characteristics of the most promising DG technologies.
Chapter 5 deals with technical DG grid integration issues and their possible solutions considering the further DG deployment in Europe.
Chapter 6 focuses on the possible developments and the future evolutions concerning the distribution systems. The Danish case is analysed more in detail.
Conclusions and technical recommendations for DG integration are finally drawn in Chapter 7.

FOR FURTHER READING ON THIS CHAPTER

[1] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal of the European Communities No. L 027, 30.01.1997 P. 0020-0029.

[2] Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, Official Journal of the European Union No. L 176, 15.07.2003 P. 0037-0055.

[3] European Commission, DG Energy and Transport, European energy and transport, Trends to 2030 – update 2005, May 2006 [Online]. Available: http://ec.europa.eu/dgs/energy_transport/figures/trends_2030_update_2005/energy_transport_trends_2030_update_2005_en.pdf

[4] COM(2007) 723 final, Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, A European Strategic Energy Technology Plan (SET-Plan), 22 November 2007 [Online]. Available: http://ec.europa.eu/energy/res/setplan/doc/com_2007/com_2007_0723_en.pdf

[5] EURELECTRIC – Union of the electricity industry, Statistics and Prospects for the European electricity sector (EURPROG 2005), 2005 [Online]. Available: www.eurelectric.org/CatPub/Document.aspx?FolderID=1540&DocumentID=18870

[6] Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC, Official Journal of the European Union No. L 52, 21.02.2004 P. 0050-0060.

[7] Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, Official Journal of the European Communities No. L 283, 27.10.2001 P. 0033-0040.

[8] ELEP European project. Website: www.elep.net

[9] COM(2006) 105 final, Green Paper of the European Commission, A European Strategy for Sustainable, Competitive and Secure Energy, 8 March 2006 [Online]. Available: http://ec.europa.eu/energy/green-paper-energy/doc/2006_03_08_gp_document_en.pdf

[10] Directive 2005/89/EC of the European Parliament and of the Council of 18 January 2006 concerning measures to safeguard security of electricity supply and infrastructure investment, Official Journal of the European Union No. L 33, 04.02.2006 P. 0022-0027.

[11] COM(2007) 1 final, Communication from the Commission to the European Council and the European Parliament, An energy policy for Europe, 10 January 2007 [Online]. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0001:FIN:EN:PDF

[12] DG-GRID European project. Website: www.dg-grid.org

[13] WADE (World Alliance for Decentralized Energy). Website: www.localpower.org

2 The electric power system

2.1 The architecture of the electric power system

The purpose of the electric power system as a whole is to generate electric power and to deliver it to the users. This rather complex system is formed by a set of several, different components and can be divided into the main subsystems of electric power generation, transmission, distribution and utilisation. These subsystems operate at different voltage levels and therefore the lines linking them need transformers or transformation substations, where the voltage rate is changed and accordingly adjusted to the required level; step-up transformers increase the voltage, while step-down transformers decrease the voltage level. Figure 2.1 shows a schematic representation of the electric power system with the different subsystems interlinked by various types of transformers (step-up, step-down and autotransformers[2]).

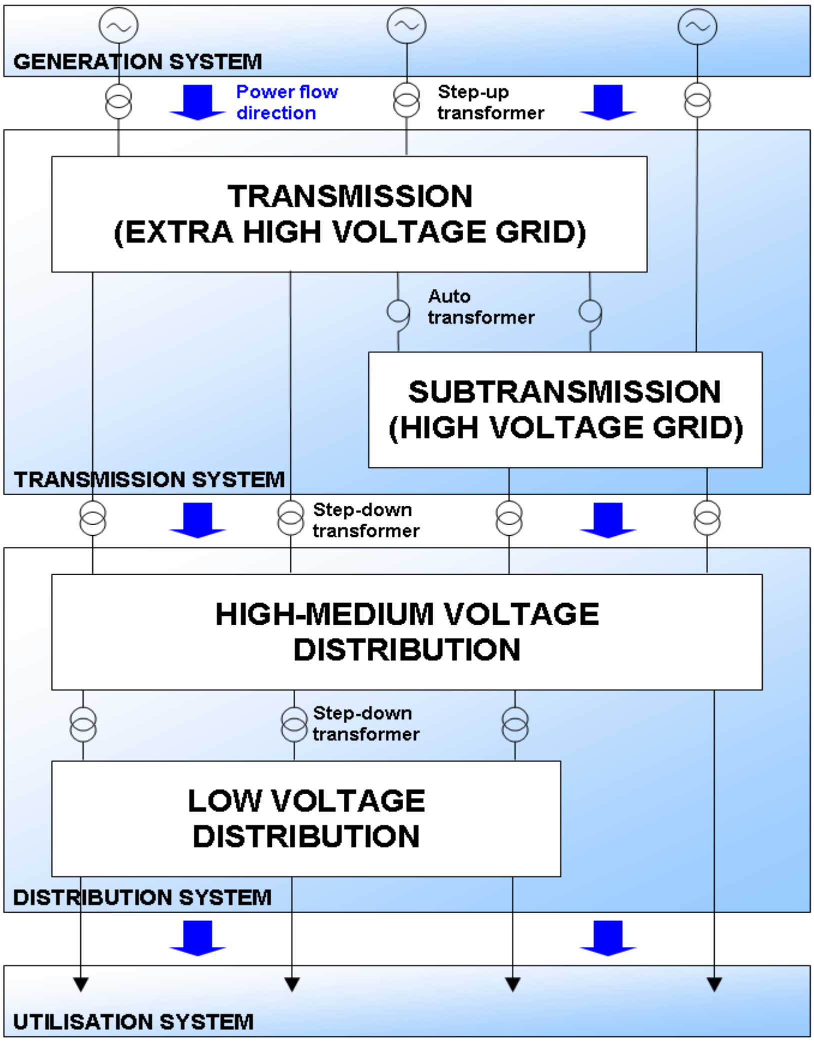

Figure 2.1 – Basic scheme of electric power system.

In the traditional scheme of the electric power system, electricity is mostly generated in large power plants, like thermal, nuclear or hydroelectric plants, which are centrally controlled and coordinated within the power system. (With a large deployment of Distributed Generation, this scheme may be subject to changes (see also Chapter 3, 3.5)).

The power produced in the large plants has to be delivered to the users, which are generally located far away from the generation sites. Hence, it is injected into the grid in order to reach all consumers. Basically, the grid consists of two infrastructures: the transmission system and the distribution system. The former carries extra high and high

[2] An autotransformer is an electrical transformer with only one winding; autotransformers are frequently used in power applications to interconnect systems operating at no largely different voltage levels.

voltage electricity from the power plants and transmits it over long distances (there are also few big industrial consumers directly supplied by the transmission network). The latter draws lower voltage electricity from the transmission lines and delivers it to the customers on a more local basis (utilisation system in Figure 2.1).

The subtransmission network is the lower voltage transmission system and represents the interface between the transmission and the distribution network. Even the distribution system can be generally split at least in two subsystems: a high/medium voltage distribution network and a low voltage one.

The universally adopted approach to supply electricity users is the one in shunt mode, in which the different consumers are subject to the same voltage level (within the range of voltage variation). In other terms, each customer is connected between the powered line and the ground ('in parallel mode') and not inserted serially on the powered line.

The power system mostly operates with alternating current (AC); the other possible mode, that is, by direct current (DC), is used for some specific applications. The amount of electric power, which is transmitted and used, results by the voltage multiplied by the current and is proportional to the amount of energy (through the time). The values of voltage and current in a point of the system are related by Ohm's and Kirchhoff's laws. In the alternating way, the current and the voltage are not constant over time like in the DC supply, but vary sinusoidally with time (see Figure 2.2 for an example). These time functions oscillate with a frequency which is typically 50 Hz (e.g. in Europe) or 60 Hz (e.g. in the United States)[3]. These values result from a compromise between different techno-economic choices concerning the various system components.

Historically, at the beginning (end of 19th century) the electric power system was operated in DC. However, after the introduction of AC electrical machines (like power transformers, induction motors and synchronous generators) the operation of the system in AC became preferable. In fact, the utilisation of power transformers, which are able to change the voltage level in a smooth way, allows a power transmission and distribution in AC at higher voltages. Thus, at constant power the currents and then the electrical line losses (which are proportional to the square of the currents) can be reduced. To minimise the losses in the system, the aim is consequently to transmit power at the highest possible voltage compatible with techno-economic limits. This feature of power transformers, together with the lower maintenance required by these machines and their longer life, is very important for their utilisation. In fact, on one side, power generators are constrained (due to conductor insulation) to operate at a voltage level not higher than a certain value (generally 30 kV maximum). On the other side, the loads, depending on their constructive characteristics and also for safety reasons, have to operate at lower voltage. Then, power transformers step the voltage up from generation to transmission

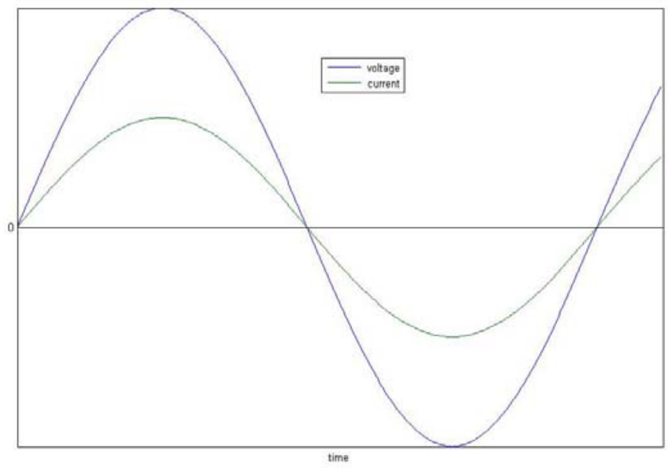

Figure 2.2 – Example of sinusoidal functions of voltage and current.

[3] It occurs constantly that in the system voltage and current waveforms do not have a perfectly sinusoidal shape. In these cases these parameters are then distorted (for example due to the effects of electronic devices) and their waveforms are composed by harmonics (harmonic content) oscillating at multiple frequencies of the fundamental (50 or 60 Hz). These harmonics can be however filtered. The presence of the harmonics is a classic power quality issue.

level and then step it down to distribution and utilisation levels (see also Figure 2.1).

Furthermore, AC rotating components such as induction motors and synchronous generators are undoubtedly more reliable and suitable for industrial applications and power generation, respectively, than the corresponding DC ones. Another reason which led to prefer the AC supply is that an alternating current in its sinusoidal variation crosses the zero value and can be more easily interrupted than direct current.

A consequence of using AC in power system operation is that, in the presence of energy storage elements such as inductors and capacitors, the total power is larger than the real 'true' power. (The real 'true' power is the power that is actually available, e.g. to produce lighting and drive electric motors). This increase is due to the contribution of reactive power which represents energy alternately stored and released by inductors and/or capacitors. Capacitors produce reactive power, while inductors absorb it. The real (also defined active) power and the reactive power are then the components of the total power, known as apparent power. The presence of reactive power reduces the capacity of an AC line or system because it limits the flow of real power that can be transmitted. In fact, the reactive power uses up some of the ability of the line to carry the current. Figure 2.3 shows a schematic representation of the lumped parameter model (also called π-model) of an AC line. The main element in this model is the line series impedance which is composed of line resistance and inductive reactance[4]. Line resistance and inductive reactance model the physical elements of line resistor and inductor whose effect is the absorption of active and reactive power, respectively. The shunt capacitances take account of the capacitive coupling between the line and the ground (capacitive reactance).

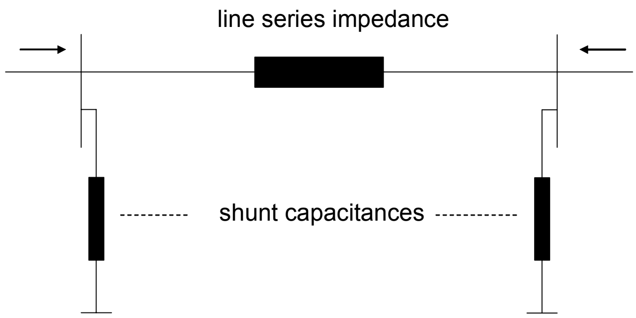

Figure 2.3 – Lumped parameter model of an AC line.

In the AC system, the current and the voltage, as well as the related parameters, can be schematised as phasors, which are space rotating vectors (variable also over space, not only over time). Phasors are mathematically represented as functions of their magnitude and phase which is the angle shift respect to a phasor assumed as reference and having a conventional phase 0°. In a pure reactive system, inductive or capacitive, the phasor of current has a phase of 90°, lagging or leading, respectively, compared to the phasor of voltage assumed as reference. In a pure resistive system (i.e. in presence of only resistances, without any inductances/capacitances) the phasor of voltage is in phase with the phasor of current: the phase is then 0°. These three cases are shown in Figure 2.4 in which φ is the phase between

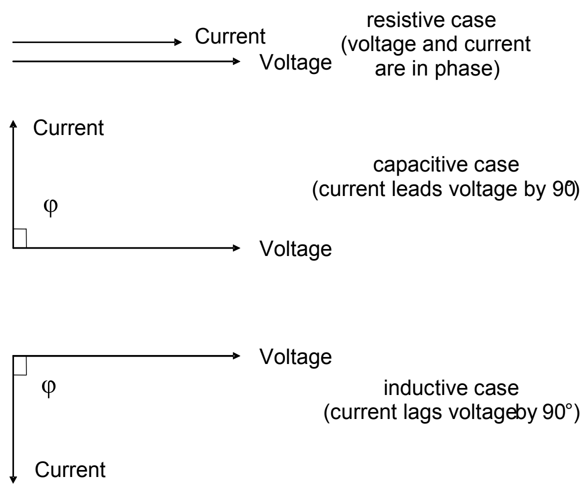

Figure 2.4 – Relationships between the phasors of voltage and current.

[4] The inductive reactance is directly proportional to the inductance.

current and voltage phasors. In the most common situations with resistance-inductance, the phasor of current has a phase comprised between 0° and 90° lagging, with respect to the phasor of voltage. An example of this situation is depicted in Figure 2.5.

Although the electric power system is mostly operated in AC mode, in some specific situations, in which the absence of reactive power is required, DC mode is preferred and used. This occurs for long distance transmission lines, for undersea cables (generally longer than 30 km) and for interconnections between two systems at different frequency or with stability problems. In fact, in case of long lines (due to the conductor's inductance[5]) or undersea cables (due to the large capacitance[6]), the reactive power can reach very high level. This high reactive power tends then to reduce the conductors' capacity, restraining the amount of active power free to circulate in the system. The HVDC (High Voltage Direct Current) system, equipped with AC/DC and DC/AC converters at both ends of the line, is a mature technology for long distance and undersea power transmission [14].

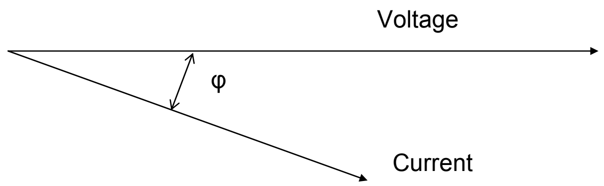

Figure 2.5 – Current lags voltage by an angle φ.

The AC mode is widely operated adopting a three-phase system that utilises three separate wires to transmit the power, each one of which carries the current and represents one phase. In the three-phase system the currents are sinusoidal functions of time, all at the same frequency but with different phases. A three-phase system, in which the phases are spaced equally and separated by 120°, is practically and economically more convenient than a single-phase system. This can be explained for instance in terms of easier exploitation of three-phase induction motors. These machines play a key role, especially in industrial applications, and are simpler and more robust than single-phase induction motors. Also, in specified conditions[7], the total section of conductor material needed for a three-phase transmission is proved to be 25% smaller than the one necessary for the equivalent single-phase transmission. Figure 2.6 shows an example of three-phase system.

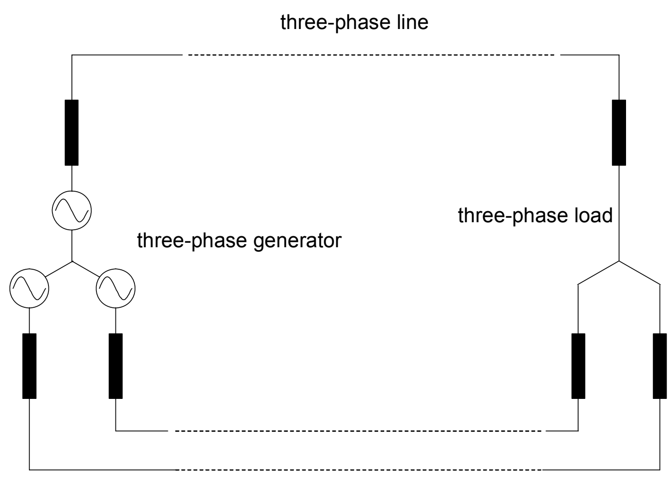

Figure 2.6 – Example of three-phase system.

In a three-phase system there is also a fourth wire, the neutral line, which is normally held at a null voltage. This neutral wire assumes particular importance for the power supply of

[5] The conductor's inductance increases proportionally to line length and is normally compensated by the counterbalancing effects of series capacitors, but inductance for long lines may reach levels at which line compensation becomes uneconomic.

[6] This results from the coupling of the line with the seawater.

[7] This is valid in equal conditions of transmission length, transferred power, voltage magnitude, power factor and transmission losses. The ratio between real power and apparent power in a circuit is called the power factor. With purely sinusoidal functions, the power factor is the cosine of the phase angle (φ) between the current and voltage sinusoid waveforms. It is known as "cosφ" for this reason.

small loads at low voltage by two lines (one phase and the neutral as return wire for the current).

The main components of an electric power system are: synchronous generators with their voltage and speed regulators; transmission and distribution lines (overhead and underground cables), towers, substations with transformers and autotransformers; induction motors and loads in general; different types of switchgears, circuit breakers and protections for the lines and the various devices; mechanical and electronic controllers of parameters like voltage magnitude and angle difference, frequency, active and reactive power flow.

2.2 Overview of the electric power systems in Europe

Figure 2.7 outlines a typical scheme of an electric power system as it can be found in continental Europe. The bulk power system comprises the generation and the transmission down to the subtransmission.

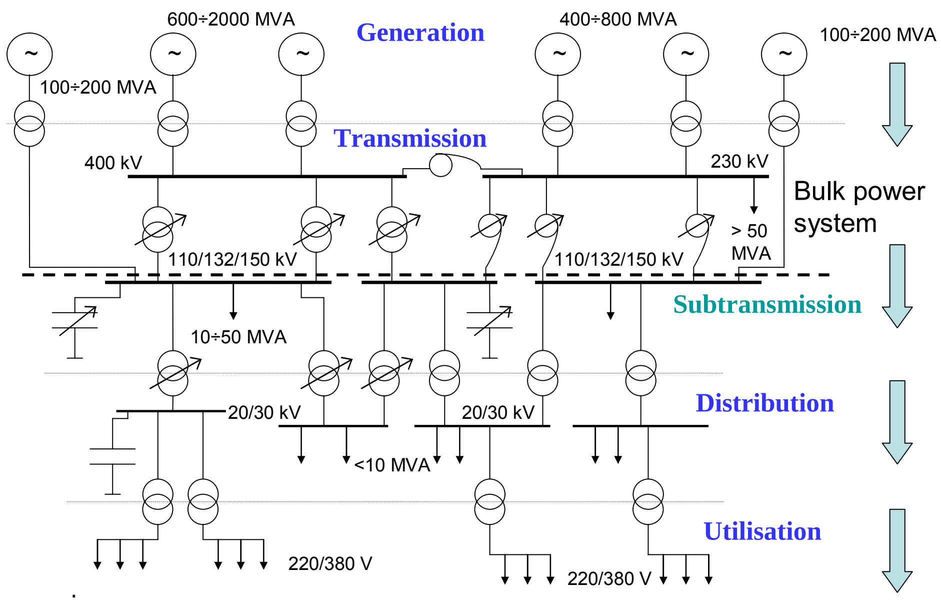

Figure 2.7 – Typical scheme of electric power system structure in continental Europe.

Although at utilisation level the voltage is practically standard (220/240 V for single-phase, 380/440 V for three-phase), for all the other subsystems there is no voltage level uniformity and standard across Europe[8]. Also, the definitions of transmission and distribution grids and their voltage levels vary from country to country (see also 3.2.2).

In continental Europe, the voltage level at which electricity is generated is mostly comprised between 10 and 30 kV. Step-up transformers increase the voltage from the generation to the transmission level (generally at or above 110 kV) before step-down transformers decrease it to the various distribution voltage levels (generally in the range 10÷70 kV up to 110 kV[9]). Then, from

[8] However, throughout continental western and central Europe the extra high and high voltage transmission mostly operates at 380/400 kV and 220/230 kV.

[9] In some countries in Europe distribution voltage levels may reach 110 kV and even 150 kV (like in Italy and the Netherlands) (see also 2.4.2, 3.2.2).

distribution the power is finally transformed to the standard mains voltage at utilisation side (380/220 V).

AC transmission voltage levels in Europe are: 110 kV, 130-132 kV, 150 kV, 220-230 kV, 275 kV, 300-330 kV, 380-400 kV, 500 kV and 750 kV, while DC links operate at 150 kV, 200 kV, 250 kV, 270 kV, 285 kV, 350 kV, 400 kV, 450 kV.

Historically in the 50ies, the national electric power systems in continental Europe started interconnecting their high voltage transmission grids. At the beginning this was mainly intended for occasional mutual assistance between power system operators of neighbouring countries and in case of lack of domestic generating power resources. These were the first steps in the creation of the former UCPTE (Union for the Coordination of Production and Transmission of Electricity). UCPTE was the association of the European power utilities responsible for electricity generation and transport at the respective national level. Before the electricity market opening process, these companies were state-owned, vertically integrated operating the generation, transmission, distribution systems on nation-wide (or regional) basis in a monopolistic condition. Nowadays, due to electricity liberalisation and market opening, the function of production has been separated ('unbundled') from transmission and distribution and most utilities have been restructured, and some privatised as well.

As a consequence of the liberalisation process in Europe, in 1999 the UCPTE became the UCTE (Union for the Coordination of Transmission of Electricity). UCTE coordinates then the transmission system and is currently the largest European association of power TSOs (Transmission System Operators). In most European countries a single TSO operates the transmission network at national level. A TSO is responsible for the secure, reliable and stable system operation, for continuously balancing supply and demand, for maintaining and developing the transmission grid infrastructure (networks and related technical facilities). The power dispatch activities are carried out by the TSO in a centralised way. The dispatch aims at minimising the global cost of production needed to supply the load, provided that all system constraints (line capacity limits, power plants output limits, network balance, voltage limits) are met. In a vertically integrated system, a TSO was part of a utility controlling also the generation park: in this situation the dispatch activities were mostly carried out within a single company. In a liberalised environment, a TSO has to guarantee the fair and non-discriminatory access to transmission services by market participants and the dispatch is more complex. In fact, the TSO has to dispatch power also considering all the additional constraints related to the bids of market players on both supply and demand sides.

The power dispatched to a load does not necessarily come from the closest generator but depends on the market bids and prices as well as on the physical topology of the network[10]. This aspect will need the due consideration with Distributed Generation taking part in market activities.

The interconnection of electricity systems offers the following main benefits: the mutual support of TSOs in maintaining the system reliability,

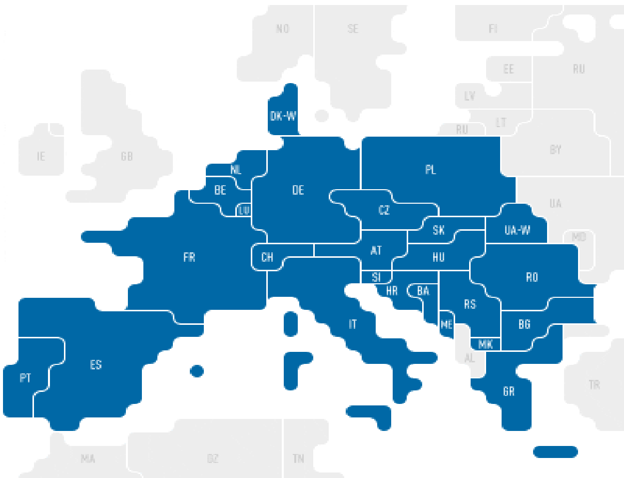

Figure 2.8 – Map of UCTE members [15].

[10] In fact, the subdivision of power flows along network branches depends on physical laws: the power follows the least impedance path according to Kirchhoff's and Ohm's laws.

the sharing of reserve capacities, and the possibility of international trade.

Currently, the UCTE supervises one of the largest power transmission systems in the world having a total of over 220,000 km of transmission lines and supplying electricity to about 450 million users. It coordinates the operation and planning activities of the electricity transmission grid of 33 TSOs in 23 countries in continental Europe (see Figure 2.8). Furthermore, UCTE is synchronously connected with Albania, the Burshtin region (Western Ukraine) and with Morocco, Algeria and Tunisia. Synchronisation studies are also ongoing to interconnect UCTE with the Russian system of IPS/UPS and with the Turkish system [15].

However, UCTE does not include some EU countries like the three Baltic and the Scandinavian countries, the United Kingdom and Ireland. The transmission systems of Lithuania, Latvia and Estonia are jointly operated within the DC Baltija system and synchronously interconnected with the Russian system of IPS/UPS; the transmission networks of the Scandinavian countries (Sweden, Finland, Norway, Eastern Denmark) are all interconnected and coordinated within the NORDEL system; the transmission systems of Great Britain and Ireland (including Northern Ireland) are coordinated respectively by the TSOs of NGT (National Grid Transco.) and EirGrid.

2.3 Frequency and voltage control in the centralised power system

In the electric power system, frequency and voltage, due to continuous changes both in demand and supply side in the system, are constantly subject to variations. It is extremely important to keep the frequency at a level as close as possible to the nominal value (50 Hz in Europe) and the voltage amplitude in the due range of variation. This is needed to ensure that all the components and the electric power system as a whole operate in the most appropriate way according to their technical design characteristics.

To tackle this issue, power system operators have developed methods and practices for frequency and voltage regulation at centralised level. These are based on the control possibilities offered by synchronous generators equipped with speed governors and automatic voltage regulators.

These aspects may play a vital role in the connection of DG technologies to the electric power system (see also 5.1.1, 5.1.3, 5.2).

The objective of frequency regulation is the restoration of the normal operating condition of frequency level after a disturbance. The frequency, which may be considered constant throughout the system, is strictly related to the generator speed and depends on active power balance between supply and demand. The frequency control can be carried out at three stages, corresponding to the primary, secondary and tertiary frequency regulation.

The primary frequency regulation, which aims at restoring the most feasible operating system conditions in the short-term (between 0 and 15 seconds) after a disturbance, is completely automatic and is decentralised. It is in fact performed on each generation unit connected to the power system by the respective speed governor.

In presence of large disturbances, the speed governor aims to restore the equilibrium between the mechanical energy (input) and the electric energy (output) at the respective prime mover (turbine)-generator group. For small disturbances (such as those ones caused by load increases) the speed governor of each generator carries out the primary regulation. The governor of each generator shares then the changes required to respond to the disturbance in a proportional way with the governors of the other generators contributing to the primary regulation.

After a load change and the consequent primary regulation, the system frequency is not generally coincident with the nominal one. For this reason a secondary frequency regulation is needed in order to get the system frequency back to the nominal reference value. The secondary regulation is a control action developed at central level in the power system. It is then executed at generation level by means of signals transmitted to a subset of generators in charge of this type of regulation.

The tertiary frequency regulation represents a further longer term subdivision of the effects of a load change among the concerned generators with the scope of cost minimisation. This regulation is operated at a constant frequency level.

The voltage regulation has also the three different stages of primary, secondary and tertiary regulation. The voltage amplitude is strictly related to the reactive power. For this reason the reactive power (either capacitive or inductive) needs to be supplied by generators, helping to maintain the voltage at the required level.

As an immediate consequence of load variation and voltage change, the primary voltage regulation is performed at local, decentralised level by devices able to modify the voltage. Such devices regulate the voltage by changing the reactive power in the system. These elements may be the voltage regulators of the generation units, tap-changers, capacitors, reactors and static and rotating reactive power compensators (mechanically- and electronically-controlled devices). This control is carried out in an automatic way as well as the secondary voltage regulation.

This secondary regulation is centralised at area control level and has the scope of effectively coordinating the voltage variations on generation units. In particular, attention is paid on keeping the voltage values of critical nodes of the system (so-called pilot nodes) in the due range. This control aims also at optimising the reactive power sources and minimising the losses.

The tertiary voltage regulation is carried out at central system level for the preventive control and forecast of the voltage values on the pilot nodes and for the scopes of secondary regulation.

2.4 The distribution systems

Since DG technologies are connected to the distribution networks (see also Chapter 3), relevant technical aspects of the distribution systems need to be duly addressed to better assess the impact of increasing DG deployment.

2.4.1 Distribution compared to transmission

Traditionally, in the past little attention has been paid to the planning, operation, and management of the distribution systems when compared to the bulk power system (generation and transmission). This is also related to the fact that the distribution systems generally differ much from transmission systems, mainly in terms of role, structure and consequent planning and operation philosophies.

Firstly, the transmission systems have been designed in such a way that the TSOs may 'actively' manage and control the power flows circulating in bidirectional ways between the network nodes. On the contrary, distribution systems have been conceived to be 'passive', i.e. to pass power flows unidirectionally from upstream transmission to the downstream utilisation with scarce possibilities to control them. Secondly, the transmission grid has a meshed structure, that is, a node can be supplied from multiple directions. On the other hand, the distribution system generally has a radial or in some cases loop structure[11], in which a node of the network can be fed from two directions at most. Figure 2.9 presents some examples of radial, loop and meshed structure of networks. This different structure implies that the transmission network is generally redundant and more secure. In case of a line trip, in fact, power can be redirected on other lines to continue supplying the network nodes on the affected line. The same principle can be more difficultly applied to the distribution system (in case of loop structure) or cannot be applied at all (in case of radial structure). However, this offers the DSOs (Distribution System Operators) the possibility to 'island', i.e. to disconnect, the faulted part of the network and repair it, and then restore the service.

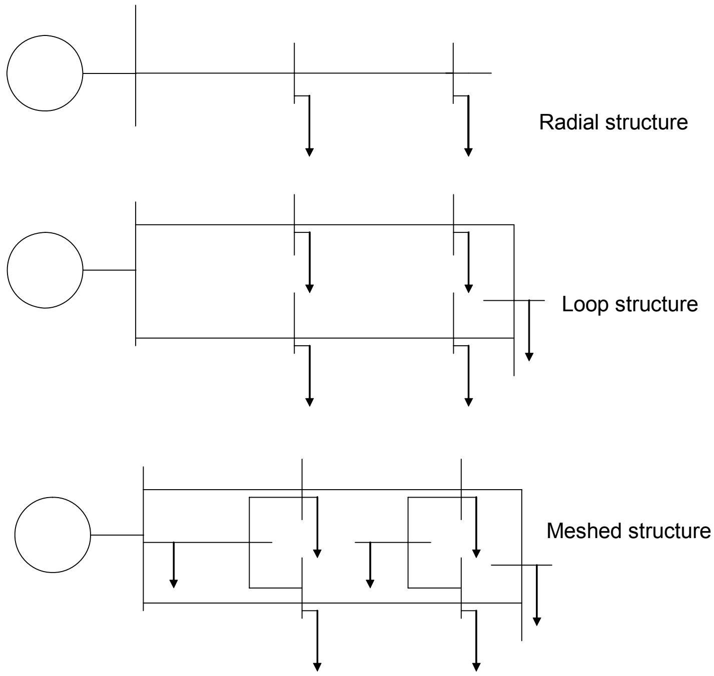

Figure 2.9 – Examples of network structures.

Thirdly, due to the different level of operation voltages and currents, line conductors of the distribution system present a higher resistance than the corresponding one of transmission lines. This feature together with the different network structure and operation characteristics lead to higher network losses in distribution grids compared to those ones in transmission networks. In general, grid losses are calculated by the difference between the respective energy measured by meters located at grid input (supply) and grid output (consumption) [5].

Furthermore, the transmission systems are interconnected and TSOs coordinate their actions and rules at continental Europe level within UCTE (see also 2.2). On the contrary, the distribution systems vary very much throughout Europe and their operators are loosely coordinated even on a national basis and do not generally have common technical rules. This is not only due to the different roles and characteristics of the transmission and distribution systems, but also to the large number of DSOs in Europe. There are currently some thousands of DSOs in Europe. There are countries with just one (dominant) DSO controlling the whole distribution, while in other nations there are tens or hundreds of DSOs operating their distribution networks on a regional or a municipal basis. These differences are due to historical as well as geographical, socio-political, and economic reasons. However, this large number of distribution operators is continuously changing and may decrease in response to electricity market restructuring and utilities merging [16][17].

Other different characteristics of transmission and distribution systems are in terms of voltage level and regulations (see also 3.2.1 and 3.2.2 for the specific situation in the EU).

A common technical and regulatory frame of distribution system operation guidelines in Europe would then have a beneficial impact towards a further integration of Distributed Generation.

[11] This is the case for most distribution systems in Europe (with some exceptions, notably in Germany, where distribution networks are also meshed).

2.4.2 Distribution system structure

Distribution networks generally consist of two parts. The primary circuit (also known as 'feeder') operating at a relatively high voltage carries the electric power to the area where it is to be used. This is the so-called primary distribution and large users and industries may be supplied directly from it. The secondary circuit receives the power from the primary through distribution transformers that step down the voltage to values low enough to deliver electricity safely to small consumers and households. This is the so-called secondary distribution.

Figure 2.10 shows a basic scheme of primary and secondary distribution networks. Devices like circuit breakers are utilised to protect lines from outages (see also 2.4.4). Typical primary circuit voltages in European distribution systems are mostly in the range 10÷70 kV up to 110 kV (with some countries having highest distribution voltages even reaching 150 kV, see also 2.2, 3.2.2). Secondary circuit voltages are typically at 220 and 380/440 V.

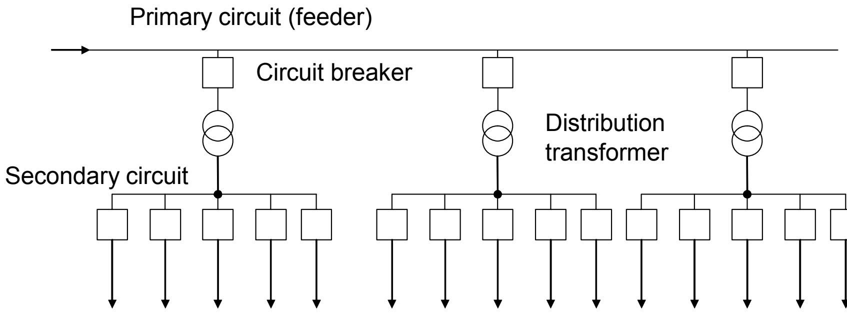

Figure 2.10 – Representation of primary and secondary distribution networks.

As said, the structure of primary distribution systems is generally radial; however, these systems may also have a loop (open or closed) structure.

In a radial system, as the one shown in Figure 2.11, in case of a fault (outage) on a line, a large current will flow and eventually burn the conductor apart, removing ('clearing') the fault, but safety may still be endangered. Substation protection devices, however, will sense the large fault current and operate to open the circuit breaker de-energizing the entire circuit and leaving consumers without power until repairs are made.

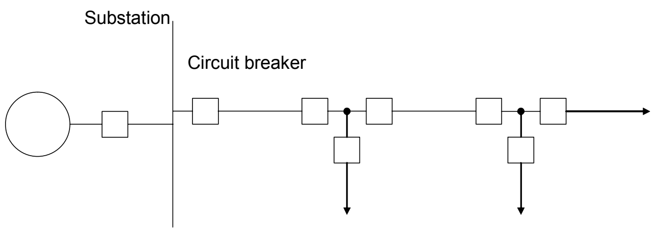

Figure 2.11 – Scheme of a radial system.

If the circuit is made into a loop (see Figure 2.12), with lines ends connected and protected through one or two circuit breakers, the fault can be confined to the section where it has occurred. This can be done by opening the breakers at both ends of the faulted section and closing one or two breakers at the substation. In the closed loop type of circuit, the fault current flowing to the fault is divided into two parts, flowing in each side of the fault. In some cases, one of these two fault currents may also be too

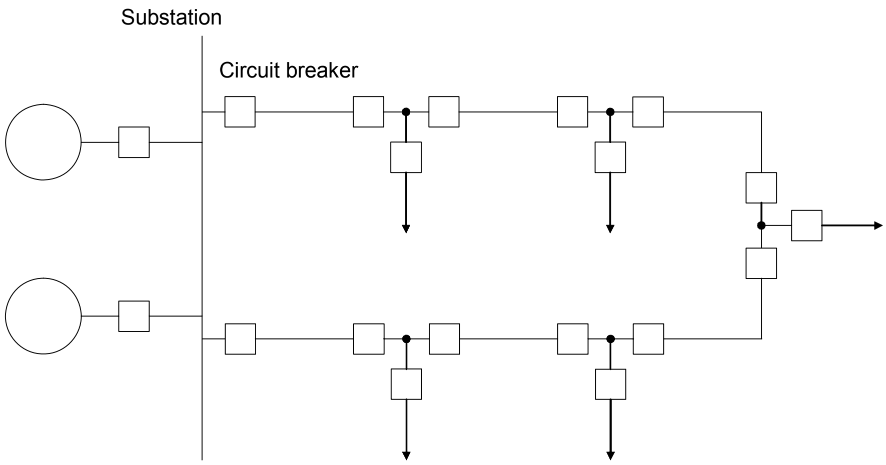

Figure 2.12 – Scheme of a loop system.

small to make the relays operate and open the breaker(s). If the loop is then deliberately open at some point, the entire fault current will flow through the branch between the fault and the substation breaker, assuring its effective operation. The two ends of the circuit at the open point are connected together through a circuit breaker set to close automatically when one end is de-energized. In other terms, the loop system is operated as a radial network. The whole loop circuit, apart from the faulted section, will then be restored to service.

The secondary circuits supplied through transformers from the primary systems are also affected by faults on their associated primary supply, whether from a radial, closed or open loop circuit.

The secondary circuits of the several primary circuits may be connected together to form a network. In this way, the service to any consumer will not be affected when a primary circuit, or any part of it, may be de-energized for whatever reason [18].

2.4.3 Voltage regulation

In distribution systems the primary feeder voltage generally drops when a large load current is drawn and less voltage is available across the primaries of the distribution transformers.

Then, the line voltage is locally maintained at the proper rated value by utilising voltage regulators (see the scheme in Figure 2.13).

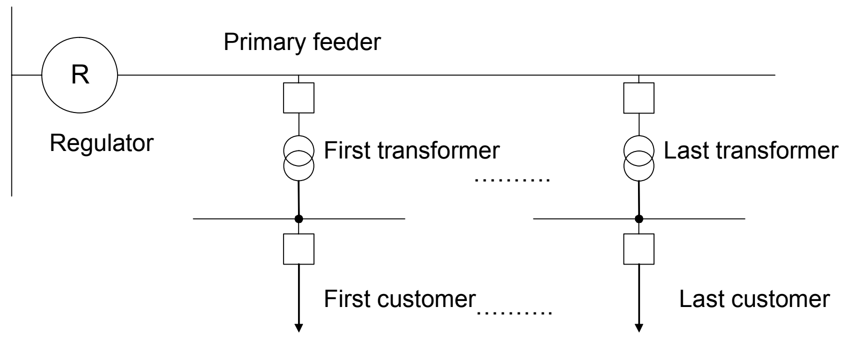

Figure 2.13 – Basic scheme of a distribution branch with voltage regulator.

A regulator is a transformer with a variable ratio (tap-changer). When the incoming voltage varies for any reason, this apparatus automatically adjusts the ratio of transformation to bring the outgoing voltage back to the predetermined value. The adjustment in ratio is accomplished by tapping the windings, varying the ratio by connecting to the several taps [18].

2.4.4 Protection

A fault on an electric device may be due to a technical (e.g. design characteristics failure) or a non-technical (e.g. weather conditions) cause. The occurrence of a fault on an electric component of the power system may have serious consequences on human beings, on the correct operation of the affected device and of the system. In fact, a fault may cause very high currents circulating in the system, while the voltages may reach values out of the allowed ranges. For this reason, protecting the system and its components is of high importance.

In particular, the protection systems of distribution (and also transmission) need to have the following characteristics: selectivity; fast intervention; insensitivity to overloads not caused by faults (within the capability limits of the involved components); capacity of reaction also for fault currents inferior to the normal loading values, if necessary.

The selectivity of protection allows that only the branch affected by a fault is disconnected from the rest of the network. The fast intervention of protection gives the possibility to limit the propagation of the effects of a fault (like stability issues, thermal and electro-dynamic oscillations). The insensitivity of protection to temporary overloads not originated by faults (e.g. caused by the disconnection of a faulted branch) lets the system have a continuous operation. Line protection system has also to ensure a flexible operation of the network but avoiding the resetting of the protecting devices.

Line protections have to intervene in case of faults (e.g. short circuits) involving one or more line phases, with or without earth contact. The protection of transmission and distribution systems is generally based on the operation of various different relays. These relays are furnished with all needed auxiliary components to protect the lines and the related equipment from damage in the event of fault.

A relay is a low-powered device used to activate a high-powered device. In fact, relays are devices sensible to a fault and give the tripping commands to the right circuit breakers or switches.

In effect, the relays are measuring instruments, but equipped with auxiliary contacts which operate when the measured quantities flowing through them exceed or go below some predetermined value. When these contacts operate, they in turn actuate mechanisms which usually operate switches or circuit breakers. Modern relays employ electronic circuitry. Various types of relays exist in accordance with the different modes of operation (electromechanical, static, thermal) and with the different parameters sensed by the relay.

In particular, the protection of distribution systems is most generally based on overcurrent relays. The overcurrent relays are protection devices set to intervene in a determined interval of time when the line current assumes a value beyond a specified limit: the higher the current, the quicker the relay intervenes. These relays can guarantee some selectivity and for this reason they are suitable for radial systems in which supply occurs via just one possible direction of power flow. In fact, in these cases, the selectivity can be obtained by setting the time of relay intervention on the lines. The lowest times are set on the relays of downstream lines (closer to the users) and the highest ones on the relays of upstream lines (closer to generation). In case of radial systems supplied by two possible directions of power flow and in loop systems the overcurrent relays have to be coordinated with directional relays. In this way, the relay intervention can be appropriate and selective (avoiding unwanted circuit opening) in presence of fault currents flowing from two possible directions.

Other components of distribution protection are switches, circuit breakers, and fuses.

Switches are used to interrupt the continuity of a circuit. They fall into two broad classifications: air switches and oil, vacuum or gas (sulphur hexafluoride, SF_6) switches. Air switches are those whose contacts are opened in air, while the other type switches are those whose contacts are opened in oil, vacuum, or gas.

To open lines while current is flowing through them, circuit breakers, which are automatically-operated switches, can be used. The making and breaking of contacts are done under oil. The operation of the breaker is very rapid when opening, and oil serves to extinguish the arc. Circuit breakers of this type are usually arranged for remote electrical control from a suitably located switchboard.

Some circuit breakers have no oil, but put out the arc by a blast of compressed air. These are called air circuit breakers. Another type encloses the contacts in a vacuum or a gas (SF_6) which interrupts the conductive path of the arc.

Secondary distribution networks may be also protected by fuses. A fuse consists of a short piece of metal having low melting characteristics which will melt at a rated temperature caused by an overload and consequently open the circuit [18].

FOR FURTHER READING ON THIS CHAPTER

[12] DG-GRID European project. Website: www.dg-grid.org

[13] WADE (World Alliance for Decentralized Energy). Website: www.localpower.org

[14] R. Marconato, Electric Power Systems, CEI – Italian Electrotechnical Committee, 2002, Vol. 1-2.

[15] UCTE (Union for the Coordination of Transmission of Electricity). Website: www.ucte.org

[16] ERGEG (European Regulators Group for Electricity and Gas), Assessment of the Development of the European Energy Market 2006, December 2006 [Online]. Available: www.ergeg.org/portal/page/portal/ERGEG_HOME/ERGEG_DOCS/NATIONAL_REPORTS/2006

[17] G. Fulli, A. L'Abbate, S.D. Peteves, Power distribution systems in Europe: present status and challenges towards a further integration of Distributed Generation, Proc. of Power-Grid Europe 2007 Conference, Madrid (Spain), 26-28 June, 2007.

[18] A.J. Pansini, Guide to Electrical Power Distribution Systems, 6th Edition, CRC Press, 2005.

3 Distributed Generation: definitions and features

In the present Chapter the notion of Distributed Generation is defined and characterised in more specific terms for the purpose of the study. This stage is crucial since - depending upon the DG definition adopted - the technologies deployed, the system models applied and the infrastructures involved may also vary to a large extent. Main features of DG technologies and different aspects considered for DG definition are also described.

3.1 Brief literature review of DG definitions

In the European Directive 2003/54/EC concerning common rules for the internal market [2], Distributed Generation (DG) is defined as ‘generation plants connected to the distribution system’. In the same Directive, the distribution is defined as ‘the transport of electricity on high-voltage, medium voltage and low voltage distribution systems with a view to its delivery to customers, but not including supply’ [2]. As it will be shown, focus of this study is mainly on DG technologies connected to the high and medium voltage distribution system.

In the scientific literature there is not a common, clear consensus about the definition of DG.

Several, different definitions have been used to distinguish DG from the central, large power generation. There are different classifications utilised at national level. Here, a brief overview of main definitions used at international level follows:

- The Institute of Electrical and Electronics Engineers Inc. (IEEE) defines the DG as generation of electricity by facilities sufficiently smaller than central plants, usually 10 MW or less, so as to allow interconnection at nearly any point in the power system [19].
- The International Council on Large Electricity Systems (CIGRE) defines DG unit as a generation unit that is not centrally planned, not centrally dispatched, usually connected to the distribution network and smaller than 50-100 MW [20].
- The International Energy Agency (IEA) defines DG as generating plant serving a customer on-site or providing support to a distribution network, connected to the grid at distribution-level voltages [20].
- The US Department of Energy (DOE) defines DG as modular electric generation or storage located near the point of use. The DOE considers distributed power systems to typically range from less than a kilowatt (kW) to tens of megawatts (MW) in size as DG unit [22].
- The Electric Power Research Institute (EPRI) treats small generation units from a few kW up to 50 MW and/or energy storage devices typically sited near customer loads or distribution and sub-transmission substations as distributed energy resources [23].
- According to the authors of the reference paper [24], Distributed Generation is an electric power source connected directly to the distribution network or on the customer site of the meter.

3.2 Main aspects considered for DG definition

The approach here is to examine various aspects related to characterisation and definition of DG as used in the present Report. The main aspects below considered are:

- Purpose and location
- Power rating and voltage level
- Power delivery area

3.2.1 Purpose and location

The purpose of DG is to provide a source of electric power; the same purpose applies to large, centralised generation. Electric power is composed by active and reactive power[12]. All DG technologies generate active electric power and several ones produce reactive power as well (as it is shown in Chapter 4). For the scope of DG definition in the present Report, focus is on the active power produced by DG.

As the main concept behind DG is the location of generation close to the load, DG is considered to be connected directly to the distribution network or on the customer side of the meter. This then requires a clearer distinction between the transmission and distribution system. In general terms, according to the European Directive 2003/54/EC [2], transmission can be defined as 'the transport of electricity on the extra high-voltage and high-voltage interconnected system with a view to its delivery to final customers or to distributors, but not including supply', while the distribution is defined as described above in 3.1.

In the reference paper [24], the distinction between transmission and distribution system is based on the respective legal definition of the two systems, particularly in a competitive electricity environment. Though, it has to be remarked that the legal definition of the two systems varies from country to country in the EU.

Also, a distinction between transmission and distribution system based on technical characteristics, such as the voltage level of distribution networks operated by the DSOs (see also 2.2, 2.4.1), is not uniform within the EU. This diversity is shown in Table 3.1, which presents the highest voltage levels of distribution systems operated by DSOs in the EU. Then, for example, in France the voltage level of 63 kV is wholly within the transmission system, while in Italy the highest distribution voltage may reach 150 kV. No generally applicable specification in the EU can therefore be given for this distinction. However, since the highest distribution voltage on average is at 110-150 kV level, for the purpose of the study, such high voltage level is conventionally considered as the distribution voltage limit. It is then included in the distribution system as a whole.

3.2.2 Power rating and voltage level

In this Report the maximum power injected by DG in a single connection point is evaluated in terms of net active power (MW). This net power results from the nodal difference between DG power production and load (if present) and is also known as the nodal aggregate capacity of a DG installation [19].

Such power level depends on the network capacity and thus on the voltage level[13] of the distribution system, which as stated earlier varies across the EU (see Table 3.1). On this basis no generally

[12] See Chapter 2 (2.1) for an explanation of the difference between active and reactive power.

[13] It can be mathematically demonstrated that - with certain fixed parameters - there is a direct quadratic relation between the network capacity and the voltage level.

applicable maximum net power can be stipulated, although various categories of DG have been proposed, generally ranging from few kW to tens of MW (see [22][23][24]). Cases of DG units larger than one hundred MW are rare, especially in absence of a corresponding local load. This is due to the fact that the European distribution networks need special operation and upgrading measures to accommodate these electricity power injections.

Currently, distribution networks in Europe generally connect generating units with a net capacity up to 20-30 MW, otherwise the connection application is handled by the transmission companies.

However, a perspective increase of distribution network capacity – driven by technology evolution and economy of scale in the distribution sector – can be assumed here. Then, the maximum net generating power (production minus load) deemed for the purpose of this study is up to 50 MW at a single connection point.

It should be noted that the above definition applies also to modular power generation. In this case, in fact, the first key factor for considering whether the collective installation is DG or not is the maximum power rating for each module at the single connection point. For instance, a 100 MW generation park with no local load might still be considered as a DG system. This is the case if it can be split in two (or more) different generating hubs, each of these having a maximum rating of 50 MW and connected to the respective point. Otherwise, it cannot be considered as DG and its connection is diverted towards the transmission network.

Table 3.1 - Highest voltage levels in distribution networks in EU countries.

Country	Highest Distribution Voltage [kV]	Country	Highest Distribution Voltage [kV]
Austria	110	Latvia	20
Belgium	70	Lithuania	35
Bulgaria	110	Luxembourg	65
Cyprus	22	Malta	132
Czech Rep.	110	Netherlands	150
Denmark	60	Poland	110
Estonia	35	Portugal	60
Finland	110	Romania	110
France	20	Slovak Rep.	110
Germany	110	Slovenia	110
Greece	22	Spain	132
Hungary	120	Sweden	130
Ireland	110	United Kingdom	132
Italy	150		

Sources: Eurelectric (2004), DG-GRID (2005)

3.2.3 Power delivery area

As reported in [24], in some cases the power delivery area of distributed generation has been considered as the corresponding (part of) distribution network where all power generated by DG is delivered. This is because DG power is generally intended for use close to the point of generation. However, this concept of power delivery area represents a restriction in DG application. The reason is that the possible export of DG power back into the transmission system (e.g. in case of low demand locally) would not be taken into account. This DG grid support to the transmission system is instead a key factor in DG deployment in the electric power system. Moreover, complex power flow analyses in distribution networks would be necessary for a precise definition of the power delivery area.

For these reasons, the power delivery area has to be considered case by case and also in dependence of the penetration level of every present DG technology.
In some countries the notion of power delivery area is adopted to fix a limit to the maximum amount of modular units (e.g. wind turbines) connectable to a certain portion of distribution network.

3.2.4 Adopted DG definition

For the purpose of the present Report, the following definition has been adopted:

Distributed generation is an electric power source, connected to the grid at distribution level voltages, serving a customer on-site or providing support to a distribution network.

This study is mainly focused on DG technologies connected to the high and medium voltage distribution system.

3.3 Other key technical aspects

Other crucial DG aspects considered throughout this study are reported in the following.

- *Technology and application*

Technologies for distributed generation are numerous and varied; the technology is not strictly relevant when speaking of distributed generation. However, selected DG technologies are chosen for closer examination in this study, due to their potential role with respect to the objectives of security of supply, competitiveness and polluting emissions reduction.

The DG systems span from non-renewable (like internal combustion and Stirling engines, combustion turbines, microturbines and fuel cells) to renewable energy source[14] technologies (like wind turbines, small/micro hydroelectric plants, photovoltaic and solar thermal units, biomass units, geothermal plants and ocean energy units) [24]. However, there are more possibilities to classify the DG technologies according to their different properties and features, for example their suitability for combined heat and power (CHP) production. All these properties and the most important and promising of the DG technologies are analysed in 3.4 and in 4.1, 4.2. Energy storage technologies (such as battery and flywheel), whose utilisation can be an option for managing intermittency of some DG technologies, are not included in this work.

[14] Renewable energy is intended as energy derived from natural processes that are constantly replenished.

- *Operation mode*

As stated in 3.2.2, the first key factor to consider deciding whether a cluster (group) of generating units can be inserted into distribution networks is the maximum net power rating at the connection point. Then, a second key factor is the flexibility of operation of such units. The flexibility of DG operation may be intended as the ability of DG units to respond to a demand change (in a timeframe of seconds/minutes). Even if the net power production by a DG installation is lower than the maximum allowed (50 MW, according to the evaluation made), the power production might be curtailed. This production curtailment may be due to operation and management issues in the system (e.g. network constraints or decreasing electricity demand) in presence of intermittent renewable DG like wind and photovoltaic units. In fact, these technologies may generate power when not needed. On the other hand, these intermittent DG technologies may also not inject power when it is required. In these cases, a negative flexibility or inflexibility characterizes DG plants.

Whether or not DG is (centrally) dispatchable within the electricity network depends on the specific operational and control rules pertaining to the network in question. There is therefore no general practice concerning this issue for DG. This feature must however be given due attention as it can have significant operational implications, in particular in high DG penetration situations.

3.4 Technical features of DG power units

In this Section the main general features of DG technologies are presented in view of their further deployment and integration into the existing electric power systems. A more detailed description of DG technical characteristics is in 4.1 and 4.2.

The DG technologies can be schematically presented as in Table 3.2.

The different DG technologies, which have some common characteristics, can be classified in several ways on the basis of some of their features. This classification may be done according to: capability for emission-free operation, type of energy source or prime mover, suitability for combined heat and power (CHP) production, available unit size and modularity feasibility, intermittent power output and type of dispatch (local and/or central) [20][24]-[31].

It has to be remarked that for some technologies in Table 3.2 the upper size level may exceed 50 MW, chosen as threshold (see 3.2.2) for the definition of DG. In fact, those technologies with a power rating exceeding the threshold in a connection point should not be considered as DG and connected to the transmission system. For this reason in those cases only the lower size level is indicated in Table 3.2. Also, power electronics equipment coupled with DG technologies may improve their dispatching properties.

Concerning the classification of DG technologies as in Table 3.2, it is relevant to note that a DG element is considered emission free regarding its operation mode, and not regarding its life cycle.

As noted, energy storage technologies integrated in the distribution systems are not a subject of this Report. However, it is worth remarking that the development and improvement of cost-effective high-power energy storage systems, based on different technologies, may play a key role in facilitating a larger penetration of DG resources.

Table 3.2 - Technologies for Distributed Generation.

Technology	Emission free operation (Yes/No)	CHP capability (Yes/No)	Available size (range)	Modularity (Yes/No)	Intermittency (Yes/No)	Local/Central Dispatch (L/C)
Internal combustion engine	No	Yes	> 5 kW	No	No	L/C
Industrial combustion turbine	No	Yes	> 1 MW	No	No	L/C
Microturbine	No	Yes	1 kW ÷ 1 MW	No	No	L
Stirling engine	No	Yes	< 1 kW ÷ 0.1 MW	Yes	No	L
Fuel cell system	No	Yes	1 kW ÷ 5 MW	Yes	No	L/C
Micro/small hydroelectric unit	Yes	No	> 25 kW	Yes	Yes	L/C
Wind turbine	Yes	No	< 1 kW ÷ 6 MW	Yes	Yes	L/C
Photovoltaic array	Yes	No	< 1 kW ÷ 14 MW	Yes	Yes	L
Solar thermal unit	Yes	No	> 5 kW	Yes	Yes	L/C
Biomass unit	No	Yes	> 10 kW	No	No	L/C
Geothermal unit	Yes	Yes	> 100 kW	No	No	C
Ocean energy unit	Yes	No	50 kW ÷ 5 MW	Yes	Yes	C

3.5 Distributed Generation: potential benefits and issues

As seen in 1.1, different drivers in the current European electric power system may contribute to promote the further deployment of Distributed Generation in Europe. DG technologies offer several opportunities to potentially tackle issues currently pending in the electric power system.

However, there are also some drawbacks which have to be carefully considered concerning the integration of DG technology into the distribution networks.

Distributed Generation is a concept having inherent local features (as seen in 3.2). Then, one risk in aiming to sketch the whole European picture for the DG benefits and drawbacks is at least to overlook some specific problems. For instance, a different approach is needed for a small island, compared to that one of an urban agglomeration, or again the grid supplying a rural community.

Besides, another level of complexity one can come across is related to the variety of distribution system technical features (e.g. voltage levels, as seen in 3.2.2). Also, the different operational philosophies (e.g. radial network operation against looped or meshed configuration, as seen in 2.4.1) governing some networks serving similar aims in the distribution filière of a country may add complexity.

On the other hand, many specific local issues may be considered at European level. The reason is that those issues either are widespread over the European territory or may have effects going beyond the local area where they originated. As an example of the latter motivation one may refer to the recent outage events recorded last 4 Nov. 2006 in Europe. This case showed that the distribution systems played a key role both positively (helping to restore the power supply) and negatively (lack of effective communication and coordination of DSOs with TSOs[15]) [32]. In this respect it is important to remind that a grid effectively working is needed for the operation of some DG technologies. Also, proper training of staff of system operators might be a stringent requirement in presence of further deployment of DG units.

The main potential benefits and issues associated with DG are considered here [20][24]-[26][32].

Some of the key advantages inherent to the DG concept are schematically summarised in the following:

- Convenient local positioning enables better utilisation of available energy sources. For example waste products or renewable resources may be more easily exploited to supplement fossil fuels. The favourable location provides advantages to customers with access to low cost fuels (as landfill gas or local biofuels) and to those who can exploit renewable based units.
- Generation adjacent to loads allows for a more convenient use of heat energy via combined heat and power (CHP) technology. Differently from a centralised production system, no huge heat transmission network would be needed and customers with sizeable heat loads will get advantages. Cogeneration plants may replace some large scale power units and reduce the need for fuel for space heating.
- Wide scale use of renewables will reduce fossil fuel consumption and greenhouse gas (GHG) and noxious emissions, therefore benefiting the global environment.
- From an authorisation/construction point of view it is generally easier to find sites for renewables and other DG than for a large central power plant and such units can be brought online much more quickly.
- Distribution networks with self-sufficient production or with a high DG penetration level considerably reduce the congestions occurring on the existing upstream transmission grids.
- As a direct consequence of transmission congestions decrease - being congestions one of the main drivers for building new lines - some projected transmission system developments can be at least deferred.
- On-site or conveniently located production units greatly reduce transmission losses and may also contribute to cut down distribution losses, whether the multi-voltage interconnected systems are properly operated.

[15] This lack of communication and coordination between DSOs and TSOs concerned especially power DG availability and production scheduling.

- DG technology can provide network support and contribute to ancillary services (e.g. reactive power production), thereby improving reliability and quality of supply for customers.
- Properly operated DG systems can improve the continuity of supply. This can be done on two levels. When a power outage occurs on the main upstream network the so-called islanding procedure (see 5.1.3) allows disconnecting a portion of the systems from the main network. The disconnected portion is then supplied by the DG present there. When a power outage occurs at local level, DG may help restore power in a short time.
- The increased penetration of renewables and other higher efficient technologies will help security of supply by reducing energy imports and building a diverse energy portfolio.
- DG can also stimulate competition in supply. Such system may allow more players access to the market and compete with other producers for backup electricity, voltage or reactive power support, frequency responsive spinning reserve, black-start capabilities and other ancillary services.
- An indirect benefit of CHP-based heat production is further congestions and losses reduction on the upstream transmission and distribution networks, due to possible replacement of electrical heating devices with local heat production.

However, the integration of DG technology into the distribution network must cope with several technical issues, in particular because distribution systems have not generally been designed to operate as the transmission system [20][24]-[26]. Most of them are listed below:

- Within the traditional distribution networks power is under normal operational conditions flowing in one direction - from a central generation unit or a transforming substation to passive loads. Instead, a two-way power exchange may generally result from the spread installation of DG power units in the grid. This means that distributed control systems must be redesigned/reset to handle two-way power flows on distribution lines.
- Given the recorded growth trend of natural gas fuelled CHP technologies integrated in distribution networks, security of supply may be of rising concern due to gas demand/offer unbalances. These may be also linked to possible unscheduled imported gas shortages or constraints in the gas transmission/distribution systems.
- DG technologies connection not only changes the power flows pattern, but also significantly affects local voltage and fault current levels. Therefore there is even a need for redesigning the local protection system to manage more critical voltage and fault current values, while at the same time being able to deal with bidirectional power exchanges.
- Due to the variability of electricity output linked to the availability of natural resources (like sun or wind), the distributed control centres must be able to manage fast reacting local power generation. In addition, they must be able to effectively communicate with the interconnected transmission control systems, in order to make the proper power reserve available in the systems.
- Data collection needed for the control of the distribution system as well as of the DG units can be a very complicate matter. In fact, the distribution system is generally not controlled by SCADA (Supervisory Control And Data Acquisition) systems used in the transmission operation.
- Power quality deterioration might result as an undesired effect of the utilisation of power electronics-based converters to connect DG technologies to the distribution grid. Harmonics

generated by power electronic converters indeed cause disturbances on the main grid, which however may be damped thanks to properly tailored filters.

– Given the expected growth of the market share of intermittent renewables and heat-based CHP, the costs of imbalances will become increasingly important. Also, the application of priority dispatch mechanisms - at transmission and distribution level - may become increasingly more difficult (e.g. signalling for dispatch of resources becomes more complicated).

The most important of the above aspects associated with DG are described in the following in more details.

- *Cogeneration*

Given the proximity to final consumers, especially where there is a significant and relatively constant demand for heat, DG systems suitable for the combined heat and power (CHP) generation may be particularly attractive. In this way local CHP may be preferable instead of purchasing electricity from the grid and producing heat separately. This aspect of DG is of essential importance towards a further DG deployment. Different customers, from households (e.g. for the supply of hot water for space heating) to industries (e.g. for the supply of steam for processes) may benefit from this CHP feature. Cogeneration can greatly increase the overall (heat and electricity combined) efficiency in electricity generation (up to 90% depending on DG type and size [20][26]) with the consequent economic and environmental benefits. Figure 3.1 provides an example of the difference in efficiency between separate and combined heat and power generation. The shown CHP system can convert 85 out of 100 units of input fuel into useful energy (45 heat, 40 electricity). On the other hand, to have the same amount of heat and power by separate heat (in a boiler) and power (in a plant) generation, 160 units of input fuel are necessary.

However, a consequence of CHP deployment is that power supply is dependent on heat demand. This aspect has to be taken into account at planning and dimensioning stage and may impact on the ability of a CHP DG system to follow demand changes.

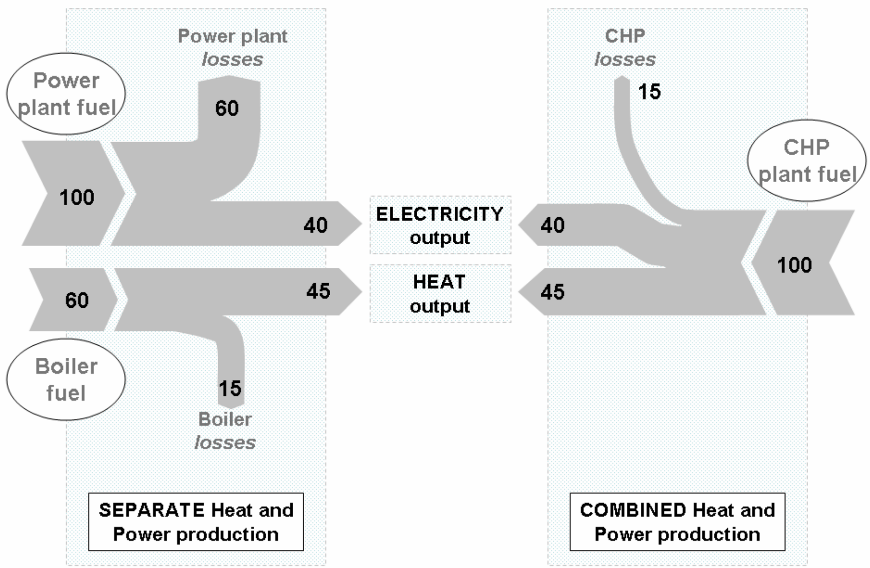

Figure 3.1 – Separate and combined heat and power production.

A list of appropriate technologies suitable for CHP would include internal combustion engines, industrial combustion turbines, microturbines, biomass gasification units, geothermal units, Stirling engines and fuel cells.

- *Transmission and distribution network planning and operation*

The deployment of DG units in convenient locations can have several benefits for the operation and planning of transmission and distribution networks. In fact, strategically placed DG systems, serving customers connected to the distribution system or on-site, may utilise the upstream transmission grids less, thus reducing transmission network congestions.

This would also lead to a reduced need for new transmission lines and equipment, whose planning and building are driven by system congestions, and then to a consequent avoidance/deferral of expansion investments.

Also, conveniently located DG units can considerably reduce transmission losses and may also contribute to decrease distribution losses in properly operated grids.

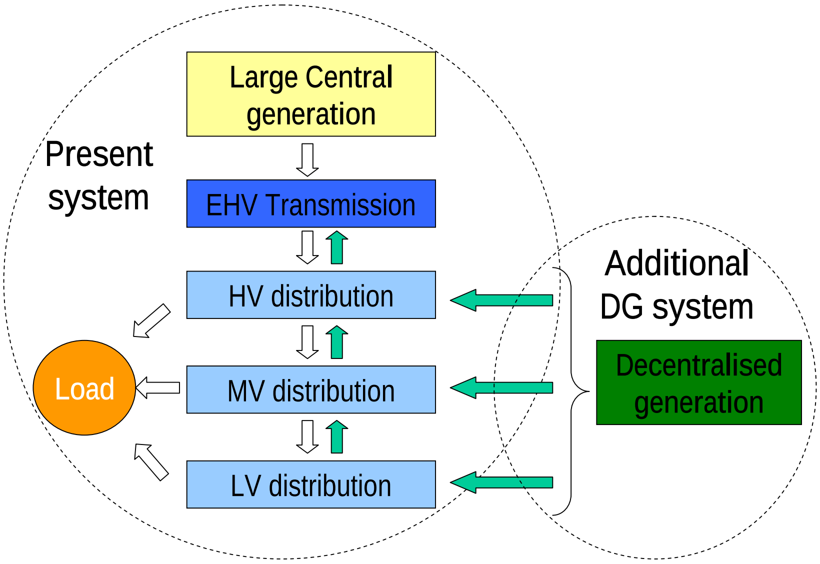

Figure 3.2 – Present grid architecture complemented with DG system.

However, in case of customers not close enough to the DG location, the effect might be an increase of losses and congestions in transmission and distribution systems rather than alleviating them.

Another important aspect which determines performance of DG is related to the network configuration and the resulting power flow in the whole system. Power injection by a DG unit at a specific network node affects the transmission of power on each line differently, depending on the network structure and characteristics. This means that under certain circumstances, a specific DG unit may not be able to relieve transmission congestion [26].

As introduced in 2.1, 2.4.1, distribution systems have not generally been designed at the outset to operate in presence of power generation injection as the transmission system. Power normally flows in one direction within the traditional distribution networks - from a central generation unit or a transforming substation to passive loads (see left part of Figure 3.2 and in particular the white-coloured arrows, and also Figure 2.1).

Instead, in distribution networks with DG systems there may generally be a two-way power flow with power injected by DG into the distribution system which may be transferred to the upstream transmission system (as the whole Figure 3.2 shows, see in particular the green-coloured arrows). This leads to the need for redesigning the distributed control systems to handle two-way power flows on distribution lines.

Furthermore, DG technologies connection may also affect local voltage and fault current levels. Therefore the redesign of the local protection system may be necessary to manage more critical voltage and fault current values as well.

Also, due to the variability of electricity output linked to the availability of natural resources (like sun or wind), the distributed control centres must be able to manage fast reacting local power generation. In addition, they must be able to effectively communicate with the interconnected transmission control systems, in order to make the proper power reserve available in the systems.

Finally, DG technologies may be able to provide network support contributing in the provision of ancillary services. These services are those ones needed to maintain a stable grid operation, but not directly provided to the consumers. The ancillary services by DG may include voltage and reactive power support, frequency support, supplemental reserve and balance, thereby improving quality of supply for customers. However, not all DG types can be utilised for the provision of ancillary services. For this network support the most suitable DG technologies are those ones interfaced by power electronic converters or synchronous machines to the grid (see also Chapter 5) [26][34].

- *Reliability and security of supply*

Properly operated DG systems can improve the reliability of the system by providing continuity of power supply. In case of a power outage occurring on the main upstream network, the disconnection of a portion of the system (containing DG) from the main network can be carried out by means of the so-called islanding procedure. In this way DG units continuously supply power to the customers of the islanded system. In case of a local power outage, a wide range of available DG technologies can provide a continuous power supply together with storage devices. This aspect has a crucial importance particularly for companies with continuous manufacturing process or providing essential services.

The increased penetration of renewable and other higher efficient DG technologies can also enhance security of supply by reducing energy imports and building a diverse energy portfolio.

On the other hand, constraints on gas delivery system and demand/offer unbalances may endanger security of supply, given also the growth trend of gas fuelled DG technologies.

- *Environmental and pollution issues*

The European Union is committed to achieving several environmental targets that, to a large extent, are related to power generation, like: GHG emissions reduction, air quality improvement, fragile ecosystems protection.

DG may play an important role in emissions reduction. Wide scale use of renewable DG can decrease fossil fuel consumption and hence GHG and noxious emissions, therefore benefiting the global environment. However, non-renewable DG technologies without heat generation (no CHP) have higher CO_2 emissions than combined-cycle gas plants and not significantly lower emissions than coal-fired plants. Therefore, displacement of coal plants only with CHP DG technologies can actually reduce CO_2 emissions [20][26].

The environmental impact of DG is not only related to the primary energy resource type but also to the technology efficiency. Distributed power units can hardly match the efficiency of large centralised power plants which use the same technology and fuel (see also 4.1). Moreover, often only peak efficiency figures are generally quoted, but, as distributed power units may frequently work at part loads, this aspect will play an important role.

Furthermore, also with respect to CO_2, centralised generating plants have the ability to capture CO_2 for long term storage in disused gas and oil reservoirs or in saline aquifers. This is not an option for distributed power plants, since such units only produce small amounts of CO_2 making the capture and transmission of this gas to storage sites impractical.

Considering that the fuel of choice for most thermal DG technologies is currently natural gas, on large scale generating plants it is possible to incorporate gas clean up systems for reducing pollutants such as SO_x, NO_x and particulates. Residual pollution can be dispersed through the use of tall stacks. With smaller scale equipment flue gas clean up can add significantly to costs and reduce equipment reliability. This will point to equipment which at the very small scale is generally less polluting and may rely on natural gas, liquid biofuels or hydrogen in the future.

- *Energy trade*

The energy market in Europe is experiencing an ongoing liberalisation process, thus creating a potential for private investors to enter this market under competitive terms.

Within this framework, opportunities may exist for private energy companies to undertake the power supply to specific consumers or groups of consumers. This may be an attractive possibility to be achieved through DG units. Special incentives, e.g. for the exploitation of the renewable energy potential of a site, can also be of interest for investors.

Furthermore, by having DG units installed, market participants have the power to cope with the price fluctuations particularly during peak demand times. The market price is affected by the ability of customers to choose between power from the grid or from their own DG units. This gives DG the opportunity to be used for peak shaving.

- *Generation siting*

Convenient DG positioning can lead to a better utilisation of available energy sources. For example waste products or renewable resources may be more easily exploited to supplement fossil fuels. The favourable location provides advantages to customers with access to low cost fuels (as landfill gas or local biofuels) and to those who can exploit renewable based units.

From an authorisation/construction point of view it is also generally easier to find sites for renewables and other DG than for a large central power plant. DG units can be also brought online more quickly than larger plants.

The sustainability of consumers needs in power and heat requires an approach to generation and supply bringing the least possible environmental and social impact. This "light" approach is inherently well suited to the notion of distributed resources. Characteristics of DG such as the use of local energy resources (mostly renewable), the reduced plant size and volume, and the modularity of several DG technologies can be compatible with this light approach.

- *Centralised generation operation and planning*

Distributed generation has naturally also an impact on the operation and planning of conventional power generation. Future investments in large production plants may be also postponed/avoided through further DG deployment.

However, it has to be remarked that centralised generation remains necessary to maintain a stable operation of the power system in terms of voltage and frequency control. In fact, the control actions provided by the traditional generation towards the stability of the system are recognised to be sufficiently fast and robust. In case of DG an important contribution in this sense may be given by power electronics-controlled technologies. It has also to be noticed that a stable operation of the grid is necessary for the DG units connected to the network via asynchronous machines (see also Chapter 5).

- *Load following and control*

The possibility of fast reacting of power generation output due to a demand change (so-called load following ability) is another key aspect to be analysed in presence of DG. One of the main drivers for the use of distributed power is its ability to balance in real-time the loads on the system. Then, a prime consideration is whether and how various types of distributed prime movers can make their corresponding coupled generators change the electricity power output under request. When, as at the present time, power is mostly supplied from centralised power stations, this matter requires relatively few generating units to either increase or decrease their power output.

The situation might be quite different in presence of many distributed power plants connected to the grid. The various prime movers for distributed power may behave quite differently in presence of big changes in demand (see also Chapter 4). In fact, some types of distributed generators, such as the weather dependent technologies, although producing electricity locally close to loads, cannot guarantee a quick output increase in response to a demand raise. Power electronics interface for DG may play an important role in this respect.

FOR FURTHER READING ON THIS CHAPTER

[21] International Energy Agency (IEA), Distributed Generation in Liberalised Electricity Markets, 2002 [Online]. Available: http://www.iea.org/textbase/nppdf/free/2000/distributed2002.pdf

[22] U.S. Department of Energy (DOE), Distributed Energy Program. Website: http://www.eere.energy.gov/de/

[23] The Electric Power Research Institute (EPRI). Website: www.epri.com

[24] T. Ackermann, G. Andersson, L. Söder, Distributed generation: a definition, Electric Power Systems Research, Vol. 57, 2001, pp. 195-204.

[25] A.-M. Borbely, J.F. Kreider (Eds.), Distributed Generation – The Power Paradigm for the New Millennium, CRC Press, 2001.

[26] Resource Dynamics Corporation, Assessment of Distributed Generation Technology Applications, February 2001 [Online]. Available: http://www.distributed-generation.com/Library/Maine.pdf

[27] H. Zareipour, K. Bhattacharya, C.A. Cañizares, Distributed Generation: Current Status and Challenges, Proc. of North American Power Symposium (NAPS) 2004 Conference, Moscow, (USA), 9-10 August 2004, pp. 392-399.

[28] SUSTELNET European project. Website: www.ecn.nl/en/ps/research-programme/energy-markets/sustelnet/

[29] DECENT European project. Website: www.izt.de/decent

[30] ENIR-DGnet European project. Website: www.dgnet.org

[31] International Energy Agency (IEA), Renewable energy: RD&D priorities, 2006.

[32] ERGEG (European Regulators Group for Electricity and Gas), Final Report, The lessons to be learned from the large disturbance in the European power system on the 4th of November 2006, February 2007 [Online]. Available:http://www.ergeg.org/portal/page/portal/ERGEG_HOME/ERGEG_DOCS/ERGEG_DOCUMENTS_NEW/ELECTRICITY_FOCUS_GROUP/E06-BAG-01-06_Blackout-FinalReport_2007-02-06.pdf

[33] European Commission, Energy Research, Key Advantages of Distributed Energy Resources [Online]. Available: http://ec.europa.eu/research/energy/nn/nn_rt/nn_rt_dg/article_1159_en.htm

4 Distributed Generation technologies

This Chapter describes the available Distributed Generation technologies and compares their operation and performance features. Particular attention is paid to the most promising DG elements.

4.1 Description of available DG technologies

An important characteristic of some DG technologies is their modularity. Smaller units are patterned on standard size and capable of being integrated with other units of the same type into higher output systems. As seen in Table 3.2, modular systems can be created out of elements such as photovoltaic arrays, solar thermal panels, wind turbines, micro/small hydro units, Stirling engines, and fuel cells. The advantages of the flexible design that modularity offers are significant:

- Large range of power output: the output of the DG system can be custom-designed by adding the necessary number of modules.
- High expandability: if demand grows, supply can be increased by adding extra modules.
- Increased reliability: in case of some of the constituent units' failure or stop for maintenance, the operation of the DG system can generally continue with the remaining unaffected modules.
- Shorter commissioning time: modules are available off the shelf, reducing the procurement time.

As seen, there are both conventional and alternative available technologies to be used in DG production. Some utilise renewable sources of energy, whereas other operate with hydrocarbons or hydrogen.

A detailed description of the most used and promising DG technologies is part of this Section [4] [20] [24]-[29] [34]-[36] [38] [60]-[61].

- *Internal Combustion Engines (ICEs)*

  The predominant DG technology is currently given by the internal combustion engines (ICEs) driving electric generators. ICEs have gained widespread acceptance in many sectors of the economy, serving in most cases as backup generators for sensitive loads for which long-duration energy supply failures would have serious consequences. ICEs are currently available from many manufacturers in all DG sizes ranging from few kW to 50 MW (and over). Smaller engines are primarily designed for transportation and can be converted to power generation with little modification. Larger engines are, in general, designed for power generation, mechanical drive, or marine propulsion. A subset of ICE technologies (which also include rotary engines) is given by the reciprocating engines. These engines were developed more than 100 years ago, are still widely used and can be considered the first of the fossil fuel-driven DG technologies. Reciprocating engines are mostly four stroke engines in which pistons move back and forth in cylinders and are based on either the Otto (spark ignition) or the Diesel cycle (compression ignition). For the former type the possible fuels are gasoline, natural gas and also biogas from sewage works while for the latter type diesel and also bio-diesel are the feasible fuels. There are also dual fuel engines with a diesel pilot fuel (instead of a spark) to start the combustion of the primary natural gas fuel. Figure 4.1 shows a diesel-fuelled ICE with the coupled generator. The pressure of the hot, combusted gases drives the piston down the cylinder. Energy in the moving piston is translated to rotational energy by a crankshaft. As the piston reaches the bottom of its stroke the exhaust valve opens and the exhaust is expelled from the cylinder by the rising piston.

The efficiency of earlier ICE was relatively low at around 30%, but more recent designs have average efficiencies of 35-38% reaching even 48% for diesel engines.

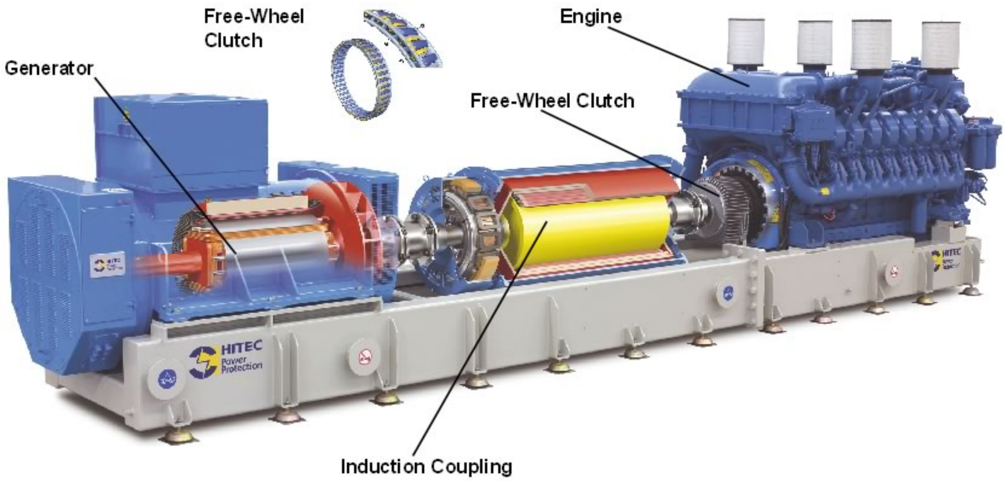

Figure 4.1 – A diesel-fuelled ICE with the coupled generator [37].

Most internal combustion engines are designed to run at 1500 or 3000 rpm driving either a four-pole or two-pole electric generator and have good control features enabling these machines to run in parallel to the grid. Particularly, diesel engines are designed to drive a synchronous generator at 750, 1500 or 3000 rpm: they can be put on line very quickly. ICEs have low start-up times (less than a minute) and are responsive enough to change load rapidly. The power factor can be adjusted. The engines are fairly bulky and normally require a small building to house engine, generator, control equipment and water cooling system. It is possible to incorporate these engines into cogeneration systems as lower grade heat is available from the cooling jacket and lubricating oil, and high grade heat from the exhaust.

The utilisation of such engine generators creates location-specific environmental issues associated with the equipment's operational characteristics as well as potential DG system interconnection issues. In fact, the combustion process of ICEs produces NO_x and, as a result of improper fuel/air mixtures and excessive cylinder cooling, CO, CO_2, and particulate emissions. Furthermore, engine generators represent a potential noise nuisance to their immediate surroundings. While noise abatement materials and enclosures may be applied at fairly low costs to address the latter issue, the remedies for the emissions, such as selective catalytic reduction (SCR), are quite costly. Among ICEs, diesel engines are more polluting. They are primarily being used for emergency or standby applications where their low installed equipment cost, performance track record, and availability of trained mechanics make them the technology of choice. Dual fuel ICEs offer an alternative that combines the efficiency and reliability of a diesel engine with the emission benefits of a natural gas engine. These engines tend to be both more efficient and produce fewer emissions than diesel engines. Diesels can be used, however, for power supply to local communities on isolated islands or localities far from a main grid system. Here, the high efficiency of diesel engines and the transportability and storability of the fuel are of considerable advantage.

Other issues are related to the maintenance demands which are high with spark plugs and lubricating oil having to be regularly changed. For diesel engines maintenance demands are lower than those ones for natural gas engines.

From an electric DG utility perspective, distributed engine generators, with their low installed costs and fairly high operational costs, represent peaking capacity that could be more economically dispatched in peaking demand conditions. Under such operational scenarios, the total contribution of emissions by engine generators, as a percentage of the total from all generation, would be fairly low. With regards to the interactions of these DG technologies with the rest of the power system, most existing engine generators are sized to provide power to critical and emergency loads only.

Diesel-based ICEs, although of currently limited interest due to their pollution features, have a good potential in the future in helping the EU to meet its CO_2 emission requirements as they utilise bio-diesel fuel very efficiently.

- *Industrial Combustion Turbines*

A combustion turbine is a device in which air is compressed and a gaseous or liquid fuel ignited and the combustion products expanded directly through the blades in a turbine to drive an electric generator. The compressor and turbine usually have multiple stages and axial blading. This differentiates them from smaller microturbines that have radial blades and are single staged. Figure 4.2 shows a combustion turbine scheme.

Combustion turbines have been used for power generation for decades and range in size from simple cycle units starting at about 1 MW to over a hundred MW. Unlike in reciprocating engines, in combustion turbines combustion occurs outside the area of the prime mover (the turbine) rather than inside. This allows for greater flexibility in reducing NO_x emissions. Typically, emissions control of combustion turbines is performed in the combustion process.

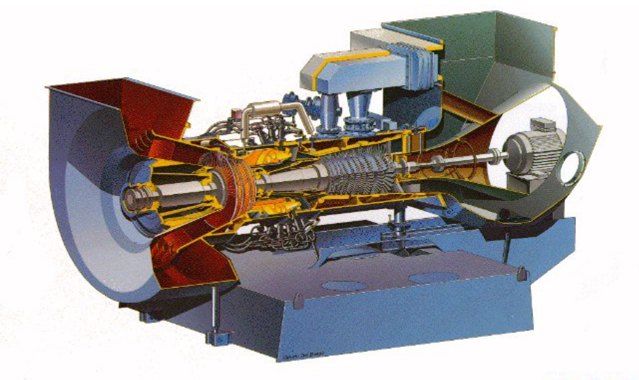

Figure 4.2 – A combustion turbine scheme [37].

Combustion turbines have relatively low installation costs, low emissions, heat recovery through steam and low maintenance requirements, but also reduced electric efficiency (30% on average). With these traits, combustion turbines are typically used for cogeneration DG when a continuous supply of steam or hot water and power is desired, as peakers, and in combined cycle configurations.

In the following, steam turbines for cogeneration and gas turbines can be distinguished.

- *Cogeneration Steam Turbines*. Medium sized steam turbines are being used in cogeneration systems. There are two basic types, back pressure turbines and extraction turbines. The former are sometimes referred to as condensing turbines as all the flow through the turbines leads through to heating system in the cogeneration plant. The exhaust steam then condenses at a relatively high pressure and temperature when giving up its heat. The drawback of such turbines is that the electrical efficiency is relatively low and when there is little demand for heat, it is impractical to run the turbine. In the extractive type of turbine, part of the steam is drawn off or extracted from the turbine and used for heating the cogeneration system. The remaining steam passes down the turbine, exiting at a low pressure before it is finally condensed. The advantages of such a system are that in periods of low heat demand the extraction system can be closed off, maximising electrical output. Also, since the condenser pressure is low, the electrical efficiency tends to be higher than with back pressure designs.

Nevertheless, because steam pressures and temperature for these classes of turbines are restricted and the size of turbines is small, resulting in aerodynamic losses, the fuel to electricity efficiency may be under 25%. The advantage of steam turbine based systems is that, because the steam is generated in a boiler, almost any type of fuel can be used. Future systems may then use biomass or waste, to be in line with EU policies. Natural gas is being used in steam turbine cogeneration systems at the present time, but in the future, where this fuel is available, it may then be used in gas turbine based cogeneration units.

Steam turbines for DG are able to drive synchronous generators, although a gearbox may be necessary to reduce rotational speed. Both types of steam turbine can respond to small changes in demand by opening or closing the steam control valves: then, they are suitable for load following operation and for grid support. For bigger changes in demand, the rate of increase and decrease in steam production from the boiler and the capacity of the cogeneration plant to cope with changes in the heating rate will be the limiting factors. The extraction turbine can route all of its steam for short periods through the condenser to produce significant changes in electricity output: this may support grids where the electrical input from renewables with priority dispatch is high.

- *Gas Turbines.* As mentioned above, a limited number of gas turbines are being used at the present time for reinforcing the distribution grids at points where there is an insufficiency of electrical power. Modern aero-derived turbines can offer efficiencies of over 40% and do not require cooling water as do other off-the-shelf prime movers. They do need, however, high quality fuels such as natural gas or low sulphur easily vaporisable liquid fuels.

  In principle gas turbines are responsive enough to scale up or down their power output, although unlike steam turbines they cannot be operated at very low outputs. However, the larger, industrial type gas turbines (really intended for combined cycle systems) with the turbine mechanically coupled to the synchronous alternator (directly or through a gearbox), are the least suitable for this task. The only practical way of reducing the power output of such a machine is to restrict the airflow through the machine using inlet guide vanes on the compressor and at the same time reducing the fuel flow. This is because the output of a gas turbine is strongly dominated by the airflow through the machine. Below a certain point, if the air flow is too much reduced, the machine will tend to stop, as it will be entering a regime of unstable operation. In these industrial machines this airflow constraint can also be a problem in assisting the grid if the grid frequency drops suddenly. The drop in frequency may be due to an increased power demand, or a sudden loss of intermittent power sources. As the alternator connected to an industrial gas turbine is of the synchronous type, this will slow the whole assembly down, as the frequency drops below 50 Hz. This will lead to a power reduction, adding to the problems on the grid caused by the lack of intermittent power sources. For this reason, aero-derived gas turbines, in which a separate power turbine is connected to a synchronous generator, would be a more appropriate choice for distributed power systems.

- *Microturbines*

Microturbines are essentially very small combustion turbines: in most configurations, the microturbine is a single-shaft machine with the compressor and turbine mounted on the same shaft as the electric generator. With a single rotating shaft, gearboxes and associated parts are eliminated, helping to reduce manufacturing costs and improve operational reliability.

Power outputs for this class of machine range from 1000 kW down to 1 kW. It becomes more difficult to maintain good efficiency as machine rating is reduced: gas turbines of the micro type are limited to efficiencies of 25-30% and this is only achieved with the use of a high temperature heat exchanger called recuperator.

The advantage of microturbines is that their power output is very high in proportion to their volume. Extremely high speed, typically 100000 rpm (however in the range from 50000 to 200000 rpm), enables the generator size to be reduced by a factor of 100 compared to those of spark ignition or diesel engines. This high-frequency electricity output is first rectified and then converted to 50 Hz. Figure 4.3 shows a microturbine scheme.

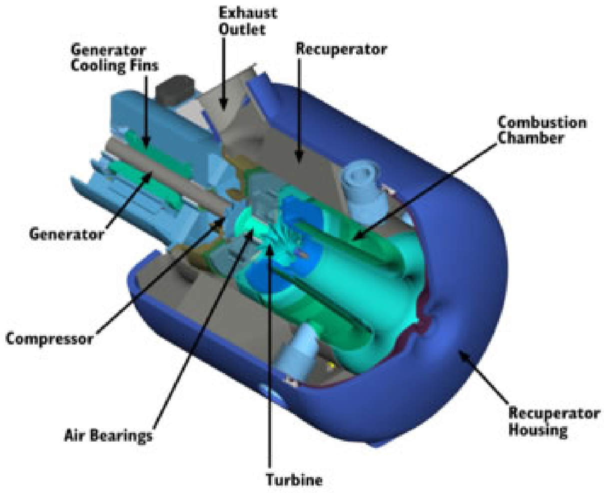

Figure 4.3 – A microturbine scheme [39].

Microturbines are capable of burning a number of fuels at high- and low-pressure levels, including natural gas, waste (sour) gas, landfill gas, or propane.

Hydrogen, since it is much more reactive than natural gas, would be even more suited to catalytic combustion. If the gas turbine was burning biofuels, a small high pressure pump would be needed to get the fuel into the combustion chamber.

Although micro gas turbines are promoted as being suited to cogeneration, the electrical efficiency is not very high. There are also problems with the temperature of the heat emanating from the exhaust: this only permits about two thirds of the heat to be recovered. The development of condensing heat exchangers should improve the heat recovery performance, but such exchangers will have to be carefully designed as the electrical efficiency is very sensitive to pressure drops.

Regardless of the fuel, microturbines have demonstrated that they feature significantly low air pollution emissions, particularly NO_x emissions (mostly at about 1/100th of the NO_x emission level of diesel-fired ICEs). Microturbines emit significantly lower noise levels and generate far less vibration than ICEs.

Two primary concerns associated with microturbines could impact their rate of market adoption: capital cost and equipment lifetime. Specifically, the capital cost of a microturbine, on a per installed kW basis, can be several times that one of an ICE, and the projected equipment life time is significantly shorter than that one of an ICE. The combined result of these impediments is a significantly higher life cycle cost compared to other distributed generation technologies, such as ICEs. Nevertheless, microturbine sales have been increasing in the latest years, driven by environmental concerns and niche applications such as landfills.

- *Fuel Cells*

Fuel cells probably represent the power production technology receiving the most development attention. Because of their high efficiency levels (up to 55-60%), fuel cells offer several good opportunities in terms of CHP and environmental impact. There are many types of fuel cells, but each uses the same basic principle to generate power. A fuel cell consists of two electrodes (an anode and a cathode) separated by an electrolyte. Hydrogen fuel is fed into the anode, while oxygen (or air) enters the fuel cell through the cathode. With the aid of a catalyst, the hydrogen atom splits into a proton (H^+) and an electron. The proton passes through the electrolyte to the cathode, and the electrons travel through an external circuit connected as a load, creating a DC current. The electrons continue on to the cathode, where they combine with hydrogen and oxygen, producing water and heat. Fuel cells have very low levels of NO_x and *CO* emissions because the power conversion process is an electrochemical rather than a combustion one. For this reason, as emission standards become increasingly stringent, fuel cells will offer a clear advantage.

The main differences between fuel cell types are in their electrolytic material. Each different electrolyte has both benefits and disadvantages, based on materials and manufacturing costs, operating temperature, achievable efficiency, power to volume (or weight) ratio, and other operational considerations. The main types of fuel cells are:

- Alkaline fuel cell (AFC): This is one of the earliest fuel cell technologies successfully deployed in space missions. AFCs use a liquid solution of potassium hydroxide as the electrolyte with an operating temperature of 100-250 °C. The lower operating temperature facilitates rapid start-up of the unit. One of the major disadvantages of this technology is its intolerance of CO_2 and the requirement to install expensive CO_2 scrubbers.

- Proton exchange membrane fuel cell (PEMFC): This fuel cell technology (see Figure 4.4) utilizes a solid polymer as the electrolyte. The polymer is an excellent conductor of protons and an insulator of electrons; it does not require liquid management. This unit features a low operating temperature of 70-90 °C, which facilities rapid start-up. The PEM fuel cell has a high power density and is a leading candidate for portable power, mobile and residential sector applications. PEMFC has been in the demonstration and testing stage and is starting to be commercially available.

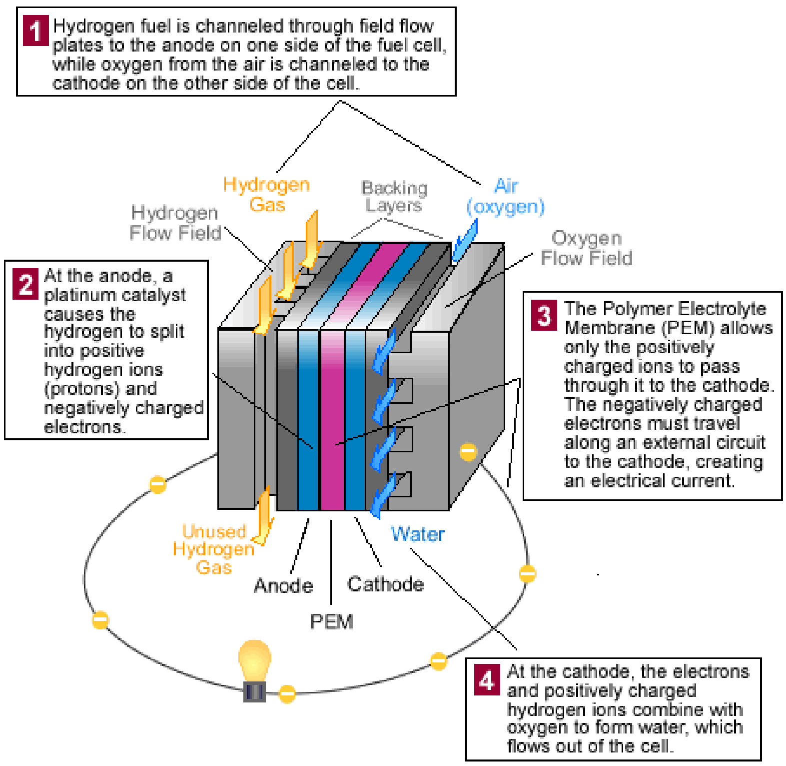

Figure 4.4 – A PEM fuel cell scheme [41].

- Solid oxide fuel cell (SOFC): A solid ceramic material is used for the electrolyte at operating temperatures of 600-1000 °C. This high operating temperature, while hampering rapid start-up as required for most mobile applications, helps to increase the efficiency and frees up the SOFC to use a variety of fuels without a separate reformer. This technology is primarily targeted at medium and large-scale stationary power generation applications.

- Molten carbonate fuel cell (MCFC): A molten carbonate salt mixture is used for the electrolyte and requires operating temperatures of 600-700 °C. This technology is targeted at medium- and large-scale stationary power generation applications.

- Phosphoric acid fuel cell (PAFC): A liquid phosphoric acid contained in a Teflon matrix is used as the electrolyte for these fuel cells. The operating temperature is 175-200 °C to facilitate the removal of water from the electrolyte. This technology is very tolerant to impurities in the fuel stream and is the most mature in terms of system development. It is currently commercially available.

The part of a fuel cell that contains the electrodes and electrolytic material is called the 'stack' and is a major component of the cost of the total system. Stack replacement is very costly but becomes necessary when efficiency degrades as stack operating hours accumulate. Fuel cells require hydrogen for operation. However, it is generally impractical to use hydrogen directly as a fuel source; instead, it is extracted from hydrogen-rich sources such as gasoline, propane, or natural gas using a reformer. Cost effective, efficient fuel reformers that can convert various fuels to hydrogen are necessary to allow fuel cells increased flexibility and commercial feasibility. Individual fuel cells are combined in various series and parallel configurations to constitute a fuel cell system. The fuel cell system is connected to the local utility system by way of a power electronic DC/AC converter (inverter). Available fuel cell system sizes range from few kW up to few MW.

- *Stirling Engines*

Stirling engines are being promoted for production of electricity in domestic CHP (micro-CHP) systems. The Stirling engines are external combustion engines: in these engines the potential energy difference between the hot end and cold end is used to establish a cycle (the Stirling cycle) of a fixed amount of gas expanding and contracting within the engine. Thus, a temperature difference is converted across the machine into mechanical power. The heat is external and the burning of a fuel-air mixture can be more accurately controlled. For these reasons, the creation of pollutants such as NO_x can be mostly avoided or limited and the Stirling engine can be considered a cleaner technology than ICEs. The external combustion aspect enables a Stirling engine to operate equally well on multiple types of fuel producing this external heat, such as natural gas, propane, gasoline, diesel, ethanol, bio-diesel, hydrogen or even solar energy. The best working gas in this engine is hydrogen. There are different configurations and types of Stirling engines, also depending on the respective heat source. The currently available Stirling modules are in size ranging from few kW up to a hundred kW. Figure 4.5 shows a 55 kW Stirling engine.

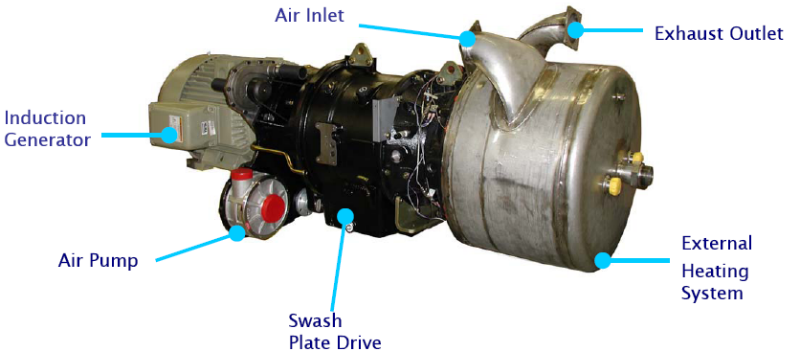

Figure 4.5 – A 55 kW Stirling engine [40].

The Stirling engine as a whole is much less complex than other reciprocating engine types. The thermodynamic efficiency is higher than in steam engines and even in some ICEs: the electrical efficiency is in the range 25-30 % for modern engines of this type, while the overall efficiency in cogeneration applications can reach 80-90 %. The very quiet operation of some types of Stirling engine is also one of the engine's best features. This prime mover can be coupled to power generator (synchronous or induction type) to be connected to the grid. A converter may be also needed for grid connection.

However, the designs on offer have a number of drawbacks. Start-up times can be equal to a few minutes and are not near-instantaneous. There are difficulties in controlling the power output. If the engine is running at normal speed and is put under an increased load, the engine slows down and may begin to overheat. Engine speed is low so that the generator size needs to be disproportionately large.

Because of these constraints, Stirling engines basically have to run in a stop-go mode and to be turned on and off at strategic times: in this way, a useful supply of hot water can be produced for space heating or washing. Because of their low electrical efficiency, Stirling engines produce much heat, and this tends to limit the permissible power output.

- *Photovoltaic systems*

Photovoltaic (PV) systems are composed of arrays of modules of discrete cells connected together that convert light radiation into electricity. The PV cells produce DC electricity, which needs to be converted from DC to AC using a converter (inverter). Figure 4.6 shows a basic PV system.

Photovoltaic systems are currently widely available, produce no emissions during their operation, are reliable, and require minimal maintenance to operate. Photovoltaic systems have not been largely used so far mainly because they are one of the most costly DG technologies. However, the continual decline of manufacturing costs is expanding the range of cost-effective uses including road-signs, home power generation and even grid connected electricity generation.

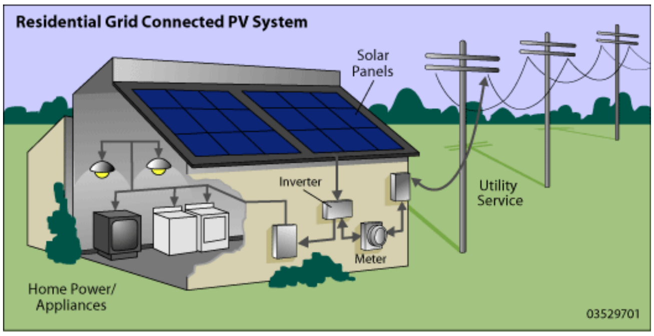

Figure 4.6 – A basic photovoltaic system [41].

Insolation is a term used to describe available solar energy that can be converted to electricity: it is a measure of solar radiation power incident on a surface. The factors that affect insolation are the intensity of the light and the operating temperature of the PV cells. Light intensity depends on the local latitude and climate and generally increases as the site gets closer to the equator. Another major factor is the position of the solar module. In order to maximize light intensity, the panel should be positioned to maximize the duration of perpendicular incident light rays. Even with these adjustments, the maximum efficiency that can be currently obtained by a commercial PV module is about 25%.

- *Wind turbines*

Wind turbines are nowadays widespread in the European power system: Germany, Denmark and also Spain are among the countries with the highest penetration of wind technology worldwide. Wind turbines are commonly employed in remote locations. Most wind turbines currently being used are small units designed for the residential sector, or larger units installed in on-shore or off-shore wind parks. The biggest wind turbine size has reached 6 MW of installed capacity. Figure 4.7 shows a wind turbine scheme.

However, the wind farms (especially the off-shore systems) cannot be considered as DG being necessary to connect them to high capacity or high voltage systems.

Wind turbines are packaged systems that include the rotor, generator, turbine blades, and drive or coupling device. As the wind blows through the blades, the aerodynamic forces exerted by air cause the blades to turn the rotor. Most systems have a gearbox and an induction (asynchronous) generator in a single unit behind the turbine blades. Nowadays, the scheme of DFIG (doubly-fed induction generator) has become the most widespread one for wind turbine connection to the grid: in DFIG the stator is directly coupled to the grid while the rotor is connected to the grid via AC/AC converter. Most of the turbines in service today have a horizontal axis configuration (as shown in the Figure 4.7). Wind conditions limit the amount of electricity that wind turbines are able to generate, and the minimum wind speed required for electricity generation determines the turbine rating. Generally, the minimum wind speed threshold is reached more frequently when the turbine is placed higher off of the ground. Coastlines and hills are among the best places to locate a wind turbine, as these areas typically have more wind.

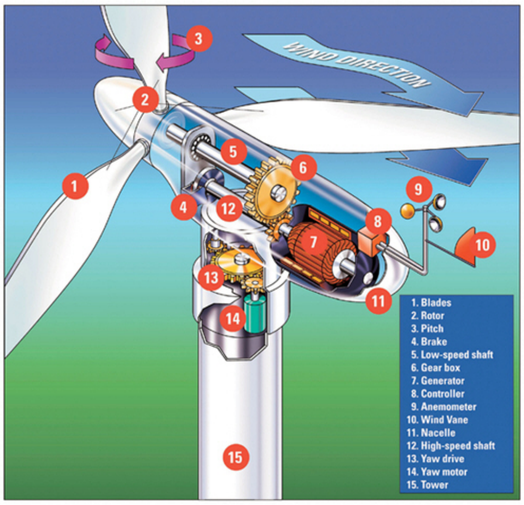

Figure 4.7 – A wind turbine scheme [41].

- *Micro/small hydroelectric units*

Micro/small hydroelectric power units consist of small turbines connected to electric generators and the structures necessary to regulate the flow of water to the turbines.

Hydroelectric power currently represents the largest share of power production from renewable energy, both world-wide and in the EU. Hydropower units convert the kinetic energy of water into electricity. The vertical difference between the upper reservoir (where water is stored) and the level of the turbine(s) is known as the head. The water falling through the head gains kinetic energy which it then imparts to the turbine blades. The fast-moving water pushes the turbine blades, thus turning the rotor and generating electricity. Thanks to the modern forecasting tools for hydrology resources, long-term planning for hydro energy is now also possible. This has made hydro power suitable for load control, also due to the fast start-up time of hydraulic turbines. Hydropower plants can be classified by their capacity as it follows:

- Micro and mini hydropower plants: up to 100 kW;

- Small hydropower plants: 100 kW to 10 MW;

- Large hydropower plants: > 10MW.

However, there is no consensus in EU Member States on the definition of small hydropower and the threshold of 10 MW is widely discussed.

The large majority of small hydro plants are 'run-of-river' schemes, meaning simply that the turbine generates when the water is available and provided by the river. When the river dries up and the flow falls below some predetermined amount, the generation ceases. This means that small independent schemes may not always be able to supply energy, unless they are sized in a way that there is always enough water. On the contrary, energy storage in a reservoir can more easily guarantee the energy supply. It permits to store energy during off-peak hours and to release it during peak hours.

Concerning environmental impact, this is highly location and technology specific: electricity production in small hydro plants is very advantageous having no emissions of carbon dioxide and other pollutants, but at the same time the local territorial and social impacts have to be carefully considered, especially when locating these plants in sensitive areas. The significant global advantages of small hydropower must not prevent the identification of burdens and impacts at local level nor the taking of necessary mitigation actions.

- *Biomass power units*

Biomass can be seen as an alternative to conventional fuel. According to the EU Directive 2001/77/EC [6], biomass is intended to be the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste. Biomass can not be considered as a real DG technology, but as a fuel. In fact, it can remain unaltered and can be used directly to be burnt (e.g. in the Rankine cycle for traditional steam turbines) both separately and together with coal in the co-firing process, or it can be converted into liquid or gas and used as a fuel for DG technologies like microturbines, gas turbines, fuel cells, ICEs, Stirling engines.

Biomass-fuelled schemes are suitable for CHP and therefore include installations designed to run on solid, liquid and gaseous fuels. Biomass-fuelled CHP is widespread in countries such as Sweden, Finland and Austria, e.g. for using forestry residues. Typical fields of application are wood-processing industries, district heating systems, industries with a high process heat demand, and co-combustion of biomass in existing fossil fuel-fired CHP plants.

For biogas plants a number of waste products from households, industry and agriculture can be used as fuels: municipality waste is the dominant fuel in incineration plants.

Distributed biomass-fuelled CHP can provide important environmental benefits in terms of reduced greenhouse gas emissions and preservation of the limited global stock of fossil fuel resources. Biomass combustion is CO_2-neutral under the condition that the amount of biomass burnt is replaced, thereby keeping the overall stock of biomass constant. In addition, biomass combustion produces less toxic gases like NO_x.

Concerning the technology development, combustion of biomass and waste is a mature and proven technology. At present, the sizes of the combustion plants are relatively small compared to fossil-fired plants. However, for commercial exploration larger plants with capacity higher than 20 MW are preferred. According to the definition of distributed power generation as introduced in this work, future biomass combustion plants will have to be considered as centralised power plants.

As a pre-treatment technology at mainly coal fired power plants, gasification is also a mature technology. In the gasification process, wood and other biomass materials are gasified to produce so-called 'producer gas' for electricity generation. With gasification becoming also a competitive technology, as for the combustion, gasification plants will have to be considered as centralised power plants as well.

- *Solar thermal units*

  Solar thermal energy aims at exploiting solar power for practical applications spanning from solar heating to electrical power generation. For electrical power generation a solar thermal power plant generates electricity via the heat resulting from concentrating the sun's energy and driving a thermal power plant. For this reason this type of electricity production is also known as concentrated solar power generation. Different types of concentrating solar panels exist: among these technologies, the solar dish coupled to a Stirling engine has the highest solar energy conversion efficiency, equal to ca. 40%. These coupled systems are still in the development stage and may be applied for DG purposes.

  In the United States there are the largest solar thermal power plants, reaching several hundreds of MW of capacity. In Europe the biggest plant is in Spain and reaches the capacity of 50 MW. Other projects are under development. However, for bigger plant capacities it is inappropriate to consider them for DG applications; high capacity or high voltage transmission networks are the most suitable systems to accommodate this power.

Table 4.1 schematically summarises the main technical features of DG technologies.

Table 4.1 - Summary of technical characteristics of DG technologies.

Technologies	Energy source	Efficiency level[16]	Emission level [17] [kg/MWh]	Technology level
Combustion engines				
Spark ignition engines	Gaseous hydrocarbons (mainly natural gas, also biogas)	25-42% 85-90% in CHP	CO_2: 430-620 NO_x: 0.2-24 CO: 0.5-27	Mature
Diesel engines	Liquid hydrocarbons (mainly diesel)	30-48% 85-90% in CHP	CO_2: 580-760 NO_x: 4-22 CO: 0.2-8	Mature
Stirling engines	Hydrocarbon fuels, hydrogen, biomass, and solar energy	12-30% 80-90% in CHP	CO_2: 670 NO_x: 0.25 CO: 0.45	Still under development
Turbines				
Microturbines	Gaseous (and also liquid) hydrocarbons, hydrogen	14-30% 70-85% in CHP	CO_2: 580-870 NO_x: 0.09-0.6 CO: 0.12-0.8	Established, but not consolidated
Industrial gas turbines	Gaseous (and also liquid) hydrocarbons	20-45% 75-85% in CHP	CO_2: 480-1030 NO_x: 0.2-4.3 CO: 0.05-0.55	Well established
Fuel cells[18]				
PEMFCs	Gaseous hydrocarbons (mainly natural gas), hydrogen	25-45% 70-80% in CHP	CO_2: 520-620 NO_x: 0.007-0.05 CO: 0.01-0.04	Established/ under development
PAFCs	Gaseous hydrocarbons	35-45% 80-90% in CHP	CO_2: 430-520 NO_x: 0.007-0.03 CO: 0.01-0.03	Established, but not consolidated
MCFCs	Gaseous (mainly natural gas) hydrocarbons, hydrogen	40-60% 80-90% in CHP	CO_2: 400-450 NO_x: 0.02-0.03 CO: 0.01-0.02	Still under development
SOFCs	Gaseous (mainly natural gas) hydrocarbons, fuel oil, hydrogen	40-60% 80-90% in CHP	CO_2: 400-430 NO_x: 0.004-0.025 CO: 0.01-0.02	Still under development
Renewable[19]				
Photovoltaics	Solar irradiation	5-25%	Zero	Established
Wind turbines	Kinetic energy of wind	20-50%	Zero	Well developed
Micro/small hydroelectric units	Kinetic energy of water	25-55%	Zero	Mature

[16] Nominal efficiency values (in general, at the rated power output in standard ISO conditions) calculated as the ratio between the output energy and the input energy. Efficiency generally decreases at partial load conditions (see also Table 4.2)

[17] Emission values are referred to DG technology operation (and not to the whole DG technology life cycle). For the fossil fuel-based DG technologies, the emissions values refer to DG units without exhaust control options. Emission values for Stirling engines are based on a 55 kW-sized, hydrogen fuelled unit developed at STM Power [40].

[18] Fuel cells are emission free when fuelled by hydrogen.

[19]Efficiency for photovoltaic units depends on several parameters like type of semiconductors, solar irradiation, ambient conditions, construction features. For wind turbines the efficiency depends on airflow. For micro/small hydroelectric units the efficiency is function of the water head.

4.2 Comparison of operation and performance characteristics

This Section focuses on a summarised comparison of the characteristics relevant to the operation of DG units. In this way, the decision maker can choose the most preferable between the various technological options that best meet the patterns of power and heat demand for the respective application. Table 4.2 shows a summary of economic and operation characteristics of main DG systems [20] [24]-[29] [38] [60]-[61].

Table 4.2 – Economic and operation characteristics of main DG technologies.

Technologies	Part load operation	Start-up time	Availability[20] [%]	Capital and installation costs [21] [€/kW]	Operation and maintenance costs [€/MWh]
Spark ignition ICEs	8-17% ca. efficiency decrease for 50% load; lower load limit 25-30% ca.	5 s - 1 min	90-95	300-1400	7-20
Diesel ICEs	quasi steady efficiency down to 50% load; lower load limit 25% ca.	10 s - 1 min	90-95	300-1300	5-15
Microturbines	10-15% ca. efficiency decrease for 50% load; lower load limit 20% ca.	30 s - 2 min	92-95	600-2600	5-20
Industrial gas turbines	20% ca. efficiency decrease for 50% load; lower load limit 40% ca.	2 min - 10 min	85-95	200-1900	3-10
PEMFCs	quasi steady efficiency for 50% load; lower load limit 5% ca.	50 s - 5 min	90-95	4000-6000	5-40
PAFCs	quasi steady efficiency for 50% load; lower load limit 25% ca.	50 min - 4 h	88-96	3000-5000	5-40
Photovoltaics	Limited (depending on weather and control system)	0 s - 1 min*	100*	3000-7000	1-4
Wind turbines	Limited (depending on weather and control system)	0 s - 1 min*	95-99*	800-3000	10-20

*In case of optimal wind/solar radiation availability and depending on control system

The following notions of power generation can be identified as indicators for the assessment of the performance of various DG technologies:

- Continuous power: operation for at least 6000 hours per year
- Combined Heat and Power: cogeneration of electricity and heat
- Peak power: capability of operation for 200-3000 hours per year during periods of high electricity price or high site demand
- Green power: operation with zero or very low emissions
- Premium power: provision of electricity of a higher quality and reliability than the one available from the grid

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[20] The availability of a DG technology is a measure of its reliability and takes account of the yearly hours (in percentage) of DG operation availability.

[21] The costs range includes the costs for CHP application.

A qualitative comparative assessment of the aforementioned performance indicators for the main DG technologies is shown in Table 4.3 [20] [24]-[29] [38] [60]-[61].

Table 4.3 - Qualitative comparison of performance of main DG technologies.

Technologies	Continuous	CHP	Peak	Green	Premium
Spark ignition ICEs	Good fit	Moderate fit	Good fit	Poor fit	Moderate fit
Diesel ICEs	Good fit	Moderate fit	Good fit	Poor fit	Moderate fit
Microturbines	Moderate fit	Good fit	Moderate fit	Poor fit	Moderate fit
Industrial gas turbines	Moderate fit	Good fit	Moderate fit	Poor fit	Moderate fit
PEMFCs	Good fit	Poor fit	Poor fit	Good fit	Good fit
PAFCs	Good fit	Good fit	Poor fit	Good fit	Good fit
Photovoltaics	Moderate fit	Poor fit	Poor fit	Good fit	Poor fit
Wind turbines	Poor fit	Poor fit	Poor fit	Good fit	Poor fit

Key:
- (black) : Good fit
- (dark grey) : Moderate fit
- (light grey) : Poor fit

FOR FURTHER READING ON THIS CHAPTER

[34] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, W. D'haeseleer, Distributed generation: definition, benefits and issues, Energy Policy, Vol. 33, 2005, pp. 787-798.

[35] H. Nehrir, W. Caisheng, S.R. Shaw, Fuel cells: promising devices for distributed generation, Power and Energy Magazine, IEEE Vol. 4, Issue 1, 2006, pp. 47 – 53.

[36] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac, Embedded Generation, Power and Energy Series, IEE, 2000.

[38] California Energy Commission, Distributed Energy Resources Guide. Website: http://www.energy.ca.gov/distgen/index.html

[41] U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy. Website: www.eere.energy.gov

5 Grid integration of DG

The simple connection of a DG unit to an electricity network does not necessarily imply that the actual operation of the distributed generator and the power system are well-coordinated. A new generator may be physically connected to the grid with all the needed equipment, but without a preliminary in-depth assessment of the electricity system requirements and a proper design of the grid-generator interface features, the new DG component and the whole system could face several problems. For instance, the DG unit may not be able to supply continuously its rated power or it could easily get disconnected from the network, even in case of minor disturbances. On the other side, the whole system or part of it may suffer the new entrant DG unit in terms of out-of-range electricity parameters (like frequency and voltage) or more serious and persistent network disturbances.

In essence, there is a need to move from the 'fit and forget' way used in the past to connect a generator to the distribution grid to a more integrated approach when planning the connection of a new DG unit to the distribution system [42].

With reference to the access and the full integration of a new DG resource into the distribution network, in some technical documents [19][43] the term "interconnection" is preferred to "connection", thus implying a deeper assessment of the interactions of the several system's components with the new generator to be connected. However, since "interconnection" is also an expression commonly used to describe a transmission line connecting two different countries or control areas, the term "integration" is preferred and generally adopted in this document.

The present Chapter aims at describing the main technical requirements that must be taken into account at the planning stage when connecting a new DG resource to an existing distribution network. The focus is hence on the short-term issues faced by the present distribution systems and the corresponding possible solutions towards DG integration. Long-term evolving issues that may be coped with in future fully-fledged DG architectures (see also Chapter 6) are not considered into detail in this Report.

5.1 Interaction of DG with the network

5.1.1 Electrical interfaces between the DG unit and the network

Three main categories of electrical interface exist between a DG technology unit and the distribution system for DG power supply. These are: synchronous generators, induction (or asynchronous) generators, converter systems. These interfaces may in some cases require a coupling transformer.

- *Synchronous Generators*

The synchronous generator (see also 2.1, 2.3) is the most widely used AC generator. A feature of it is that the average rotational speed of the rotor in normal operation is exactly proportional to the system frequency.

With medium-large size (above 0.5 MW ca.) generators the shaft speed is sufficiently low, at either 1500 or 3000 rpm, for the generator to be of the synchronous type. That is, equipped with four magnetic poles if the speed of the output shaft is 1500 rpm, or two poles if it is 3000 rpm, the generator will produce an alternating current at a frequency of 50 Hz[22]. This is the case with the generator mechanically coupled with natural gas internal combustion or diesel engines, or gas or steam turbines. Such engines and turbines are so designed that at this speed they are operating at optimum efficiency. Among other factors, synchronous machines are suited for contributing to stabilise grid frequency and voltage and can also supply reactive power.

The restriction on output speed has significant effects on the design of the engine and, for any given type of machine, may result in poor efficiency levels at reduced power output. Bigger engines running at low speed will require a multipole generator. For high speed machines the tendency was, in the past, to use a step-down gearbox, which has the result of reducing the speed of the generator down to 3000 rpm.

- *Induction Generators*

The induction or asynchronous generator is an AC generator in which the average rotational speed of the rotor in normal operation is not proportional to the system frequency.

This generator is essentially an induction motor that is driven slightly faster than its design speed (see also 2.1). The induction generator needs an external supply of alternating current from the grid because it has no internal means to produce power. Hence, if the external grid supply fails, so does the unit. This feature may be attractive from the safety point of view, since there is no risk to maintenance staff or consumers by back feeding from a small unit.

In principle, as the cause of this characteristic is the electro-magnetic induction within the generators, capacitors can be added to the system to reduce the inductive effects. In certain circumstances, however, this can result in the local distribution systems staying energised even when it has been disconnected from the main supplier.

Induction generators are utilised to connect wind turbines and also Stirling engines to the grid.

- *Converter Systems*

Nowadays power electronics is playing an important role in the operation both of the power system and of some end-use devices.

A converter is a unit which uses a combination of solid state electronics, inductors and capacitors to convert an electrical input of (in principle) any form into another form (either direct or alternating current) with the required frequency (if AC) and voltage level at grid connection point. This is done by using the capacitors and inductors to store electricity in the form of electrical charges or as magnetism. This energy is released in a controlled way using the solid state circuitry to build up the needed current form.

To convert alternating current (AC) to direct current (DC), AC/DC power electronics-based converters are used and they are also known as rectifiers. Analogously, DC/AC power electronics-based converters are used to convert DC to AC and are also known as inverters. In the same way, AC/AC converters are useful to convert AC to AC for systems having different AC parameters (voltage amplitude, frequency), and similarly DC/DC for systems having different DC parameters (voltage amplitude). Depending on the application at AC level, converters can be also equipped with transformers.

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[22] The frequency (in Hz) can be calculated by multiplying the rotation speed (in rounds per minute, rpm) by the number of polar pair divided by 60.

In the past the main concern has been that, since the sine curve is built by the converter using repeated very short duration injections of power, this can give rise to a "noisy" sine curve (with high harmonic content) with consequent power quality issues, but as solid state electronics systems have improved, this seems to be less of a problem.

Converter systems are therefore much more flexible than either synchronous or induction generators and place few restrictions on the machine or equipment that produces the power. However, converters cannot produce electricity; they convert one form into another. For fuel cells and photovoltaic systems they convert direct current into alternating current. Where rotating machines are concerned, such as micro gas turbines, Stirling engines or internal combustion engines, a synchronous generator or an induction generator would be used to produce the electricity. The alternating current from such a generator coupled to AC/AC converter could be at any reasonable voltage and speed.

The converter has made practical the use of micro-turbines which operate at speeds up to 200000 rpm. The resulting frequency would be over 3000 Hz. The converter takes this current as input and changes it to normal frequencies. In addition, a micro-turbine can be allowed to drop its power output by reducing its speed, greatly simplifying the design.

5.1.2 DG technical requirements

To guarantee the correct operation of a DG unit in all possible situations when connected to the grid, some technical requirements have to be met by the DG system.

- *DG unit protection*

  The DG unit has to be equipped with timely and well-coordinated protection systems which include:

  - Voltage and frequency protection. The DG unit shall automatically disconnect from the network when the local voltage at the connection point and the system frequency are out of a predefined range. The DG installation can reconnect to the grid when these electric parameters are again stable and within the agreed limits.

  - Fault current protection. The circuit breakers at the point of connection to the distribution network must be capable of interrupting the maximum expected fault current.

  - Synchronization protection. The DG unit protection must be additionally equipped with synchronizing devices for parallel operation (or synchronization) with the utility system (see also below).

- *Synchronization*

  In general, disconnection/connection (parallel) operations of generation units from/to the distribution networks can lead to system oscillations of active and reactive power, and consequently of frequency and voltage. These variations may produce high fault currents with possible safety risks, damages to equipment and consequent further disconnections. This is particularly true in case of DG connection via rotating (synchronous/asynchronous) machines. Then, the DG unit must be equipped with devices that prevent parallel operation with the utility system unless the voltage, phase and frequency are within the normal limits [18].

  The principal features of this additional protection may include: automatic synchronizing equipment of the generator output with the utility; relays to open the circuit breaker to the utility system on faults (e.g. loss of power, ground fault) in the distribution system; relay to control the distributed generator circuit breaker to provide generator overcurrent protection, phase current balance protection, reverse power protection, under- and over-frequency protection, and under and overvoltage protection; control of speed governor, generator phase match, and generator load.

The possible electrical connections and set of protection systems for a DG unit are shown in the one-line diagram in Figure 5.1.

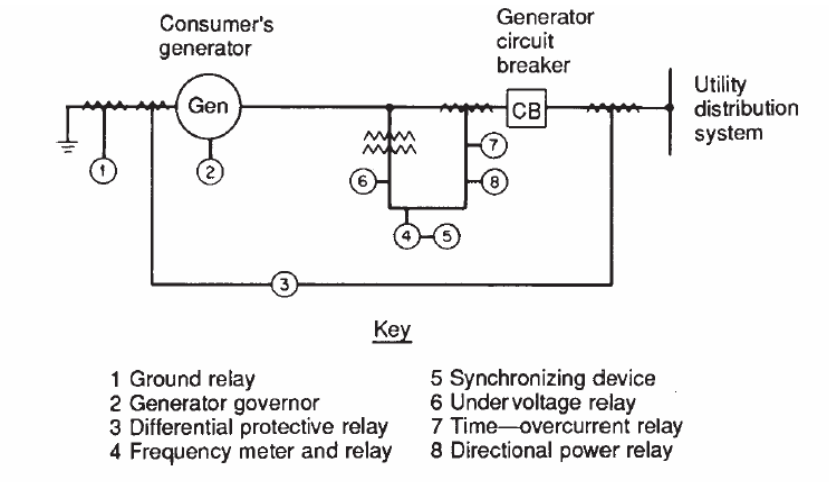

Figure 5.1 – DG protection and synchronization equipment [18].

5.1.3 Impact of DG on distribution systems

Traditionally, distribution networks have mainly been designed and operated to passively distribute power from the upstream generation and transmission system to the final customers. In this situation, with power flows mainly going mono-directionally from the substations to the consumers (see Figure 3.2), the DSOs do not have the possibility and the need to actively control the power flows. For this reason the distribution systems are mostly passive [12].

When increasing numbers of generators are connected to the distribution network, power can be also transferred reversely, from the distributed units to the distribution and the upstream transmission (see Figure 3.3). This would be a new situation.

Such bi-directional power flows pose some issues on the distribution networks, which at the outset have not been designed to account for power input from generators and reverse power flows [12].

In this new situation, the distribution may be subject to change control properties and become more similar to the transmission, that is, have more 'active' control features (see also Chapter 6).

In the following, several issues and aspects regarding the impact of DG on distribution networks are analysed.

- *Network capacity and congestions*

  The availability of carrying capacity, that is the absence of line congestions, in the network portion where DG is inserted, may play a primary role on DG integration. Transmission networks generally have a meshed design offering multiple pathways to the power, whereas distribution networks are looped or have a radial structure, thus allowing only few directions for the power flow. Therefore, considering the lower number of interconnections and also the lower voltage levels adopted in the distribution, the capability to carry power is significantly inferior for the distribution compared to the transmission networks. The connection of generation capacity to transmission systems is then generally less constrained by thermal ratings than connection to distribution systems.

  It is also worth noting that a proper DG insertion close to loads does not generally lead to an increase of distribution congestions, but possibly to their reduction. Then, the choice of the DG connection location assumes a strategic importance for this issue [44].

- *Losses*

  The DG deployment may contribute to the reduction or increase of distribution network losses: this issue heavily depends on the DG location and type, and the network structure and configuration. It is then essential that those elements are thoroughly considered while assessing the DG impact on distribution losses [44]. According to [12], a low DG penetration would decrease energy losses; on the contrary, if more DG penetrates the network, energy losses will rise. Within distribution networks actively managing bidirectional power flows, the growth of energy losses may be controlled and reduced, minimising its effects.

- *Short circuit currents*

  The connection of DG to the distribution system, especially via synchronous or asynchronous machines, generally determines an increase in the level of short circuit currents. This rise can then create problems to the operation of distribution components like line conductors, breakers and switches, if they have been dimensioned to withstand lower short circuit currents. These components, when carrying persisting fault currents, are subject to thermal and mechanical stress. For this reason, it is crucial to verify the level of short circuit currents against the components limits before physically connecting the DG unit to the grid. For line conductors, depending on conductor's characteristics (size, material, insulation), and fault type and duration, the maximum overcurrent safely transportable for the time needed to extinguish the fault can be determined. It is also important to check that the injection of current by the DG unit does not lead to the inappropriate/untimely intervention of overcurrent relays used for distribution line protection.

  In case these checks are not satisfactory, other solutions might be found. One possibility would be the connection of the DG unit to the distribution grid via opportune reactance(s) to limit the level of short circuit currents. Other alternatives are the reinforcement/upgrade of network infrastructure/components or ultimately the change of the DG connection point.

  The most critical locations for DG connection are those where the short circuit currents reach their maximum values, that is, at the lines derived from the primary substation and protected by overcurrent relays.

  Fewer problems with short circuit currents may arise when DG is connected via converter systems, since such devices are capable to better control the DG fault current injections.

- *Protection selectivity*

  A further influence of DG penetration on the distribution concerns the selectivity of the protection system. The dimensioning of the overcurrent relays protecting the lines derived from the primary substation may need a revision/upgrade due to DG presence. In fact, overcurrent relays, which do not distinguish the direction of currents, may unnecessarily intervene and disconnect the line with DG for a fault occurring on another close branch (e.g. parallel line). In this case, the selectivity of protection, which is essential for the correct operation of the system, would be affected and the DG disconnected from the network without any need. Protection selectivity must then be checked.

- *Network robustness*

  Strictly related to the short circuit current levels, the robustness of the network at the proposed connection point is an important element to be analysed when planning DG connection to the grid. The robustness of a network may vary from 'strong' to 'weak'. Dispersed generation and large consumers can cause relatively large changes in the voltage levels on a weak network. A strong network, on the other hand, will be less affected by changes in generation and demand.

A weak electrical system has a low fault (or short circuit) level, which is normally measured in MVA. The strength of a point in the network is determined by the impedance between that point and the main generators on the system: the lower this impedance, the stronger that point. In another way, a weak point in the network is one which is further away from large amounts of generation. The strength of a network also determines the current that will flow in the event of a fault.

- *Voltage profile*

  The connection of DG to the distribution system leads to a modification of the voltage profiles on the distribution network with a possible increase of the voltage along the connection line. This voltage modification depends on the DG unit power rating and location as well as on the power factor and the local structure of the network: the higher the resistances of the lines near the DG connection point, the higher the local voltage.

  As seen in 2.4.3, voltage control at distribution level is carried out by voltage regulators on distribution lines. These devices may also equilibrate voltage profiles altered by DG connection. However, there might be situations, in which in presence of DG the voltage regulators cannot bring the voltage profiles in the due range. For these cases, a solution may be the direct involvement of the DG units interfaced via synchronous machines and converter systems in the line voltage and reactive power control. To avoid unacceptable voltage rises due to converter connections, such device controllers can be set by a ramping algorithm control instead of an on/off control [45].

- *System stability*

  The system stability is related to the interaction of generators and other rotating devices in the network immediately following a fault. In particular, a DG unit shall be able to remain connected to the grid following a fault within the system. In case of tripping, there should be little room for disturbances due to the failure of the generator to remain in synchronism.

  The DG system is: 'steady state stable' if following a small disturbance, such as load or circuit switching, it returns to a steady state operating condition; 'transiently stable' if, following a large system disturbance, it remains synchronised and returns to a new steady state operating position following the removal of the disturbance.

- *Islanding*

  Islanding occurs when a portion of the distribution system gets electrically isolated from the rest of the system, yet continues to be energised by the distributed generators embedded in this subsystem. The so-called 'intentional islanding' considers a set of DG units providing backup power to the system where they are installed and not interfering with the utility electricity system. In case of external power outages, the intentional islanding is a very promising application for DG (see also 6.2), which can guarantee an uninterrupted power supply to portions of the distribution system.

  Problems may arise in case of 'unintentional islanding': it occurs when DG units continue to supply power to a portion of the distribution network which has been islanded (e.g. to clear a fault).

  In an unintentional island, protection systems may be uncoordinated, due to drastic change in short circuit current availability. Moreover, the procedures concerning the search for faulted lines at distribution level may be altered by the DG supply to the island. In addition, utility breakers may try to reconnect the island to the upstream network system when out of phase, failing in presence of DG power supply to the island. Also, the power quality (in terms of voltage and frequency) supplied to the island may be inadequate. Furthermore, unintentional islanding can harm operators of the distribution utility by electrical shock hazard when mistakenly considering the island de-energised.

For all the above described reasons, it is of primary importance to set out disconnection procedures and modes to prevent unintentional islanding. In this sense, the protection system has to be designed with the possibility of selecting the faults which may require the disconnection of the distributed generators from the system. The scope of this requirement is to avoid that slight disturbances like voltage fluctuations lead to the complete disconnection of the generating units.

- *System balancing and reserve*

  For a smooth and reliable power system operation, both active and reactive power must be in balance. In this way, the power produced must instantaneously equal the sum of the power consumed and the power lost. The power output intermittency of some RES (especially wind) makes it difficult to instantaneously balance energy production and consumption. As a consequence, larger reserve capacities are needed to mitigate the fluctuation of energy production. Beside the active power deviations, also uncontrolled reactive power may represent an issue as it may heavily affect voltage levels, especially in emergency conditions.

- *Power quality*

  As seen in 5.1.1, DG connection via interfaces like power electronic converters may cause power quality issues like voltage fluctuations (flickers) and distortions (harmonics) endangering the correct operation of electric devices. Modern, solid state electronics-based filters are a feasible option nowadays to mitigate such disturbances and may then help to resolve these power quality issues.

5.1.4 Impact of DG on the transmission system

DG integration into electric power systems depends on the effects that DG installation may bring about not only on the distribution networks, but also on the upstream transmission system [24][42][45]. In this respect, different aspects have to be considered as in the following.

- *Steady-state effects*

  \- Voltage levels: DG connection may lead to the change or distortion of the profiles of voltage at transmission nodes. This may occur especially if the transmission network is generally 'weak' and does not have enough large generating capacity to control voltages. Vice versa, the effects of DG connection on transmission voltage profiles are negligible in a 'strong' system with a sufficient large generation needed for voltage control.

  \- Losses: the impact that DG may have on transmission losses is strongly influenced by the DG location, but also depends on network topology as well as on DG size and type. DG deployment is expected with more probability to generally lead to transmission losses reduction, than distribution losses decrease.

  \- Congestions: the impact of DG on transmission congestions also depends on DG location. Strategically located DG units, serving customers connected to the distribution system or on-site, may utilise less the upstream transmission system and then help relieving overloaded branches in the transmission network.

- *Contingency analysis effects*

  The application of the (n-1) criterion[23] may result particularly severe and not absolutely appropriate to analyse the system in post-fault situations in case of extensive deployment of DG intermittent technologies. In fact, the results of this contingency analysis based on deterministic approaches may lead to the conclusion that DG operation produces more negative effects than actually in the real operation. This might occur considering the extreme cases, for example with all the wind units producing their maximum power output at the same time and causing overloads on the system as a post-fault result. In these cases, a sensitivity analysis based on probabilistic methods would be required to get a more realistic evaluation of the DG effects in the contingency analysis. Then, in case of occurrence of overloads caused by DG, a temporary DG curtailment can represent a solution to avoid post-fault congestions.

- *Protection effects*

  As seen in 5.1.2, 5.1.3, protection equipment is needed both on the DG unit and on the distribution network at the point of DG connection. This is also to allow safe and secure synchronisation and islanding procedures.

  Especially in case of large DG penetration in a confined area, a failure of DG protection devices may lead to several system operation problems. In fact, in case of a fault on the upstream transmission system, there might be a propagation of its effects on the downstream distribution. Then, the DG may be disconnected from the network with the resulting sudden increases of power flows from upstream in such restricted grid portion. These overloads may lead to the cascading activation of overcurrent relays on distribution and transmission systems. Possible negative effects may also occur on voltage levels in the area of disconnected DG with collapse phenomena. To avoid these problems, it is essential to coordinate the operation of the protection schemes of transmission, distribution and DG connection systems. This can be done through an appropriate strategy of protection time delays, considering however the local conditions and not altering the protections selectivity.

- *Dynamic effects*

  The effects of DG insertion on the dynamic system behaviour depend on the DG type, location and connection interface (synchronous, asynchronous or converter) as well as on the critical disturbances.

  It is important to highlight that DG units connected via power electronic converters may react very quickly to changes in the system. This is due to a very low inertia of these devices and there might be stability issues when they interact with the power system (which is stiff and has a high inertia to changes).

  Results presented in [42] show that DG may have an influence on the system dynamics, depending on the situations. The case of penetration of DG concentrated in a specific area is considered in presence of fault (short circuit) on the transmission leading to a partial disconnection of DG. In this situation, test results depict a post-disturbance stabilisation of system frequency to a level other than the nominal one (50 Hz). This example demonstrates that

[23] The (n-1) criterion, for the system contingency analysis, consists in checking whether the system can be operationally secure (with all parameters in the due ranges) in case of outage on a device (line, generator or transformer). This analysis is carried out by system operators.

the dynamic behaviour of the system can be affected by the DG penetration, and every system condition needs to be carefully analysed vis-à-vis the various elements.

5.2 Ancillary services by DG

Power units connected to the electricity network need to perform - alongside their primary role of power generation – some other tasks to guarantee their full integration into the local power system. These tasks, below reported, are also known as ancillary services [25][28].

- *Frequency control*

  The European electricity system operates at 50 Hz frequency and all electricity customers (users and producers) rely on the fact that the system frequency is kept very close to this level. When the grid is heavily loaded, the frequency (and the voltage) may fall significantly below the standard values. In fact, the frequency varies with load and/or generation changes in the system and also depending on the location of these changes. Any distributed power system will need to deal with these variations and if possible help bring the grid back to the defined operational limits.

  This is achieved by scheduling generation to match demand, and by means of deliberate control actions on most of the generators connected to the grid.

- *Voltage control (reactive power control)*

  The control of voltage levels in distribution networks is an important issue, due to the need to maintain consistent supply to electricity users. Whilst the frequency reference value (50 Hz) is uniform all over Europe, the voltage levels and limits vary in accordance with network types and different national provisions (see also 2.2, 3.2.1, 3.2.2). Although system operators try to keep system voltages close to their nominal levels, the actual voltage varies from point to point around the system, and also with time as the load changes. Voltage levels tend to drop when customers increase their demand of electricity and they are often lower at the ends of long distribution lines.

  The reactive power supplied by synchronous generators of DG units helps in increasing the local voltage levels. DG units may support in improving voltage profiles, however this often makes the centralised process of voltage control more complex. The amount of reactive power of small-distributed generators interfaced with electronic converters can be continuously adjustable on a short time basis.

- *Load following ability*

  The DG may be able to target a particular load - a real one or a fictitious reference value - so that it can adjust its output on the basis of the changing demand. In this way the variation in targeted load has minimal effect on the rest of the system, since it is almost instantaneously balanced by the DG unit's production.

- *Overload capacity*

  The DG unit may be able to operate at reduced load, possibly without large drops in efficiency. In this way, it may be ready to pick up additional load in case of sudden increase in demand (e.g. caused by the outage of other generators in the same area).

- *Fault current generation and withstand*

  DG units, as all the components of the network, feature a fault rating which defines the ability to withstand the mechanical forces and the overheating effects triggered by the peak fault current.

  Connecting a generator to a distribution network generally has the effect of increasing the fault levels in the network close to the point of connection. The additional fault level at the point of connection due to the presence of the generator is referred to as the fault contribution of the generator.

- *'Fault-ride-through' capability*

  Some DG units (e.g. the first type of wind turbines) are particularly sensitive to temporary disturbances. Then, they can disconnect from the network in case of faults happening in surrounding areas, due to the severe voltage dips generated by the same fault currents. The fault-ride-through capability represents the ability of the DG unit to continue to operate ('ride-through') remaining connected to the network during and after the system faults until fault clearance. In this mode, support to the network is insured just when the system needs it more.

- *'Black-start' capability*

  In case of large supply disruption, a number of dedicated DG units must be able to feed local loads forming a small grid. Eventually these DG units must be able to re-synchronize this part of the system with the main grid, contributing to the whole system restoration. This feature is known as 'black-start' capability and is strictly linked with the intentional islanding (see 5.1.3).

Not all the DG technologies at the present stage are able to perform these tasks. Nevertheless, the installation of power electronic devices and control systems coupled with the DG unit can partially increase their electrical performances.

The provision of ancillary services by DG will be needed and might be a requirement for the further deployment and full grid integration of such technologies. The reasons for that are both technical (DG can take the place of large generation if providing flexibility and reliability as well) and economic (DG may access the ancillary services market) [42].

5.3 DG integration planning

5.3.1 DG integration process

This Section summarises the steps (as seen in 5.1.3) needed for planning the technical integration of a DG unit into a distribution network.

These steps are part of the technical process started by the DG proponent/operator to connect and integrate its DG unit into the distribution network operated by a DSO. This process is schematically depicted in Figure 5.2 (DG integration decision tree) on the basis of general, currently applied procedures upon request of DG connection by the DG proponent/operator. It results in a constant interaction between the DG operator and the DSO.

The DG unit, which is equipped with its all needed protection systems, has to meet several technical criteria set by the DSO for connecting and integrating generation to DSO's distribution network.

The DG impact on the distribution network is estimated against a series of deterministic and probabilistic assessment criteria, which specify ranges to be met by some electrical parameters and indexes. The depth of these analyses increases with the complexity of the network structure (meshed rather than radial).

First, the DG proponent/operator is requested by the DSO to check whether all the basic DG unit features comply with the characteristics of the chosen connection point in the distribution grid. These DG unit features include parameters like the power rating, the voltage level, the geographical location of DG connection. In case this evaluation gives a negative result (i.e. one or more parameters do not fit with the grid connection point), there are different options. The connection application may be then diverted either to another DSO or to the competent TSO or even denied.

In case of positive outcome of the first step, the DG unit connection layout has to be assessed by the DSO based on the communications received from the DG proponent/operator. The knowledge of type of DG unit with its electrical DG interface with the grid (synchronous, asynchronous, or converter) and the connection requirements lets the DSO select the different insertion options. These may require a new busbar/substation in an existing line or a new line connected to an existing substation/busbar or also a new line connected to an existing line.

After this step, the DSO needs to evaluate the distribution system with the DG inserted assessing the adequacy[24], the short circuit and voltage levels, the stability and power quality issues (see also 5.1.3). After each of these assessments, the process continues further in case the assessment gives a positive outcome. In case of negative feedback on one or more evaluations, at every step the DSO may consider the feasibility of opportune solutions like network components upgrades/ reinforcements to meet the specific criteria. If this analysis does not give a positive outcome to meet the specific criteria at every step, the DG proponent/operator has to look for a connection alternative. This may be either in the same point with different DG features and connection layout or diverting the original connection request to another zone.

In case all the previous evaluations have been positively addressed by the DG connection request, the DSO submits the proposed connection solution to the DG proponent/operator. In case of agreement on the solution between the DSO and the DG proponent/operator, further technical requirements for the DG side can be considered. In case of final agreement, the project to connect and integrate the DG unit can be authorised and implemented. Instead, in case of disagreement, the DG proponent/operator may search for an alternative connection solution (as in the previous steps) and in the worst scenario change or divert the plan.

5.3.2 Network development issues

At network level, some grid development issues exist which may, directly or indirectly, play their role in the DG connection and integration procedure. These network development issues may concern the border between the transmission and the distribution systems, especially in those EU countries where such border is somewhat fuzzy (see also 2.4.1, 3.2.1, 3.2.2). Some issues faced in the coordinated development of transmission and distribution interoperating networks are described in the following points [46].

- *New connections between transmission and distribution networks.* The main consequence of such connections is an alteration of the power flows registered on both the systems. Several typologies of link can be distinguished: transmission substations or lines connected to

[24] The adequacy evaluation consists in the application of the contingency analysis at distribution and also transmission level ((n-1) criterion) (see also 5.1.4).

distribution lines or substations, distribution substations or lines connected to transmission lines or substations.

- *Intertwined development of transmission and distribution networks.* In certain rationalization activities, in case of new substations construction and in particular network reinforcements implementation, it may be necessary to involve also other bordering interoperating networks. The scope of this would be to effectively relieve network constraints and manage operational issues. As the involved systems are tightly interconnected, it is often unclear how to share the investment costs and how to coordinate construction activities.

  The change in power flow pattern is not the only consequence stemming from a mixed development of interoperating network. Even the short circuit level increase is another aspect to be duly taken into account so as to evaluate the need to upgrade electrical equipment.

- *New transforming substations.* Some transforming substations are planned to supply both high voltage transmission and distribution networks. In some cases, building new substations allows to avoid generally more substantial (from the economic and environmental point of view) reinforcement of surrounding high voltage network.

- *Network restructuring to mitigate territorial/environmental impact.* Rationalization activities carried out to reduce environmental impact are a recurring and sensitive issue attached to the interoperating transmission and distribution network development. Rationalization activities stem from: initiatives from the network operator, when new plants construction implies dismantling/modifying existing facilities for operational/environmental/authorization needs; initiatives from third parties such as local administrations, distributors and power producers.

FOR FURTHER READING ON THIS CHAPTER

[42] J.A. Pecas Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, N. Jenkins, Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities, Electric Power Systems Research, Vol. 77, 2007, pp. 1189–1203.

[43] SOLID-DER European project. Website: www.solid-der.org

[44] R.C. Dugan, S.K. Price, Issues for Distributed Generation in the US, Proc. of IEEE PES Winter Meeting 2002, New York (USA), 27-31 January 2002, Vol. 1, pp. 121-126.

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

[46] M. Rebolini, G. Fulli, A. Ferrante, GRTN's experience in developing the electricity transmission network in the framework of the European energy sector restructuring, Première Conférence sur le transport d'électricité, Alger (Algeria), 19-20 September 2005.

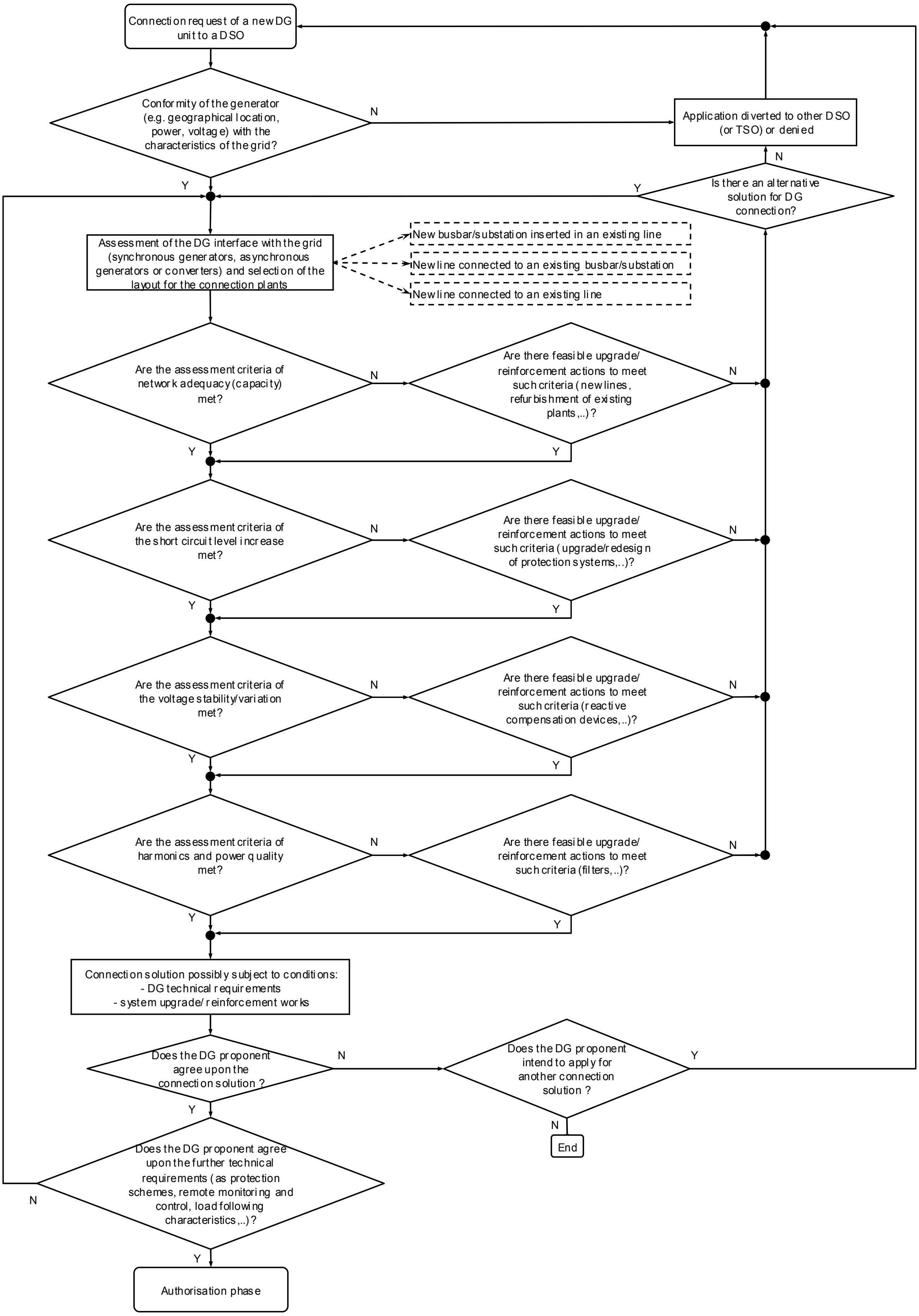

Figure 5.2 – Schematic decision tree for planning DG connection and integration.

6 Development of the distribution system

As seen in Chapter 5, the integration of DG into today's distribution grids is technically possible, provided that all the needed requirements set by the DSO are met. This integration process is applicable for the short-term needs.

Extrapolating data from [28][47][48], in a short-term timeframe the European distribution systems may generally be able to accommodate the DG up to an average penetration level of 15% (in terms of installed capacity). The further growth is capped by a combination of the issues and barriers described in 3.5.

However, in a mid-long term, the distribution systems are those likely to be subject to the most profound changes in terms of system development design and network operation philosophy. Such evolution is foreseen to be gradual and unevenly progressing in the several European electricity distribution grids.

The more DG devices penetrate the distribution networks, the more the distribution systems are expected to evolve towards transmission-like architectures. The reasons for these evolutions have been previously described (see 2.2, 2.4.1, 2.4.2, 3.5). Basically, differently from transmission grids, the distribution networks have been not generally designed at the outset to operate in presence of power injections. These differences mainly rely on the different structure and role, and consequent planning and operation philosophies, between the transmission and the distribution. Figure 6.1 graphically summarises the options in terms of network structure and operation. With an increasing DG penetration the situation is changing resulting in possibly bidirectional power flows (unidirectional power flows without DG).

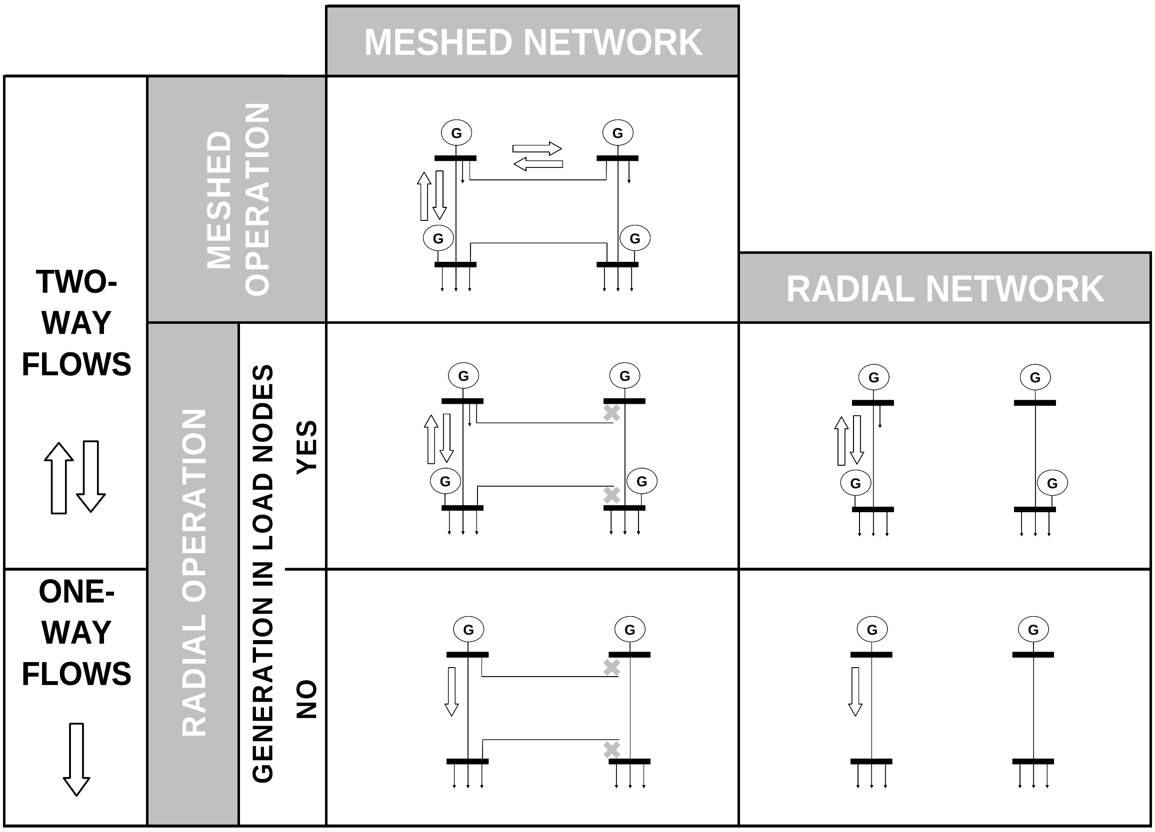

Figure 6.1 – Structure and management options for electricity networks.

The structure and operation of the distribution systems, as displayed in Figure 6.2, tend then to become more similar to the current ones of transmission grids. In a mid-long term these evolutions are first concerning the high and medium voltage distribution systems.

However, this transition process is generally gradual and may require several intermediate steps.

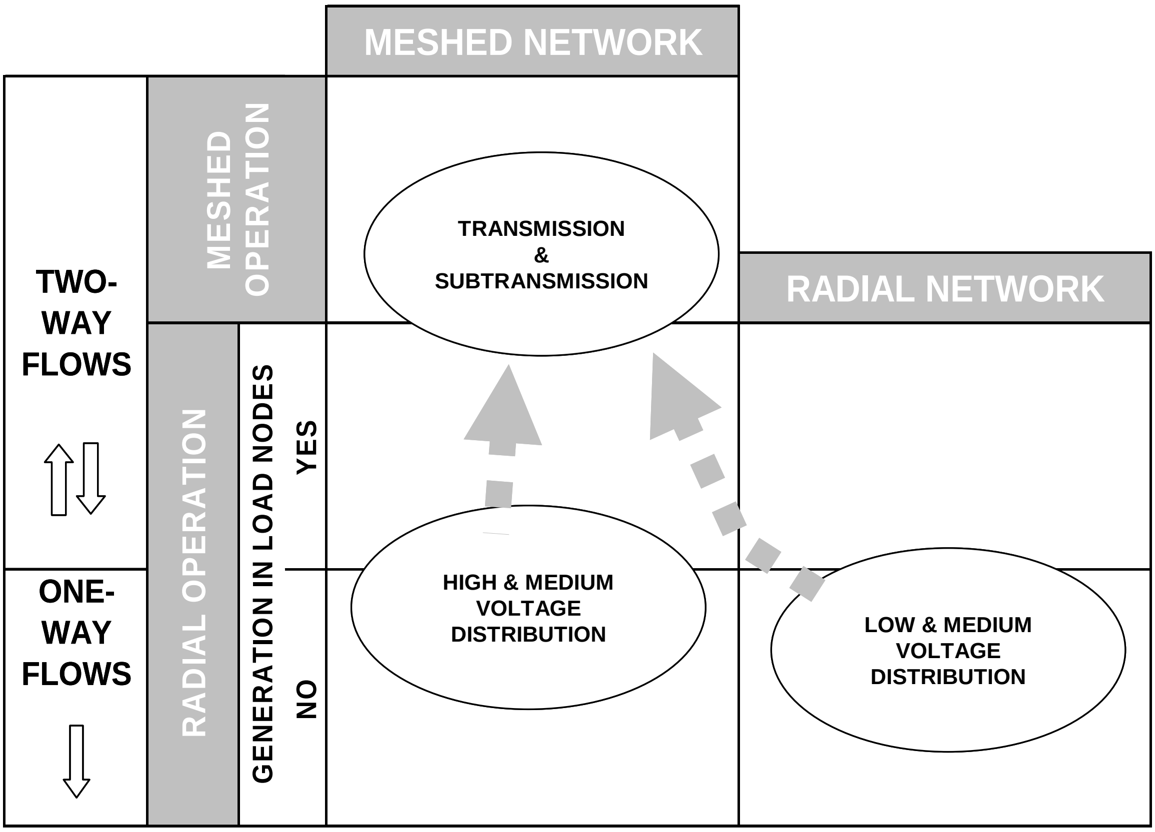

Figure 6.2 – Expected evolution of distribution systems.

The present Chapter introduces some possible developments of the distribution system in the near future as intermediate steps of the above described evolution process. In particular, focus here is on Active Networks, Microgrids, and Virtual Power Plants. All of these three new systems may represent a possibility towards which the today's distribution systems might evolve in presence of DG. Also a hybrid combination of these might result. The scope of these developments is related to the need for ensuring adequate levels of reliability and security of supply in presence of increased DG penetration.

In all three system developments, modern control technologies may result to be very useful. Particularly, soft controllers based on ICT (Information & Communication Technology) and hard controllers based on power electronic devices like FACTS (Flexible AC Transmission System) may support the DSO controlling the system. These technologies may prove helpful for the TSO too. The ICT-based technologies can be used to improve the communication between a DSO and a TSO and provide the DSO with more advanced monitoring tools (like SCADA). Power electronics-based devices like FACTS are able to control electrical parameters like the real and reactive power flows and the voltage amplitude at network nodes in a very smooth, fast way. FACTS devices are proven technologies for a flexible transmission system control. At distribution level the equivalent devices are known as D-FACTS[25] and may be useful for a better control of power flows, voltage level, power quality issues in distribution grids [47][50].

Other advanced network controllers are given by WAMS (Wide Area Measurement System). These technologies include soft (ICT) and hard (PMU, Phasor Measurement Unit) tools. PMUs are devices able to remotely monitor phase voltages and currents and the corresponding angles at network nodes. Each phasor is measured and coupled with a very precise time stamp derived from a GPS (Global Positioning System) satellite. These time stamps allow to wireless obtain voltage phasor angle differences across long distances and establish a power system monitoring tool. In fact, from the phasor angle differences, it is possible to assess the state of the system and its proximity to instability. WAMS systems are already utilised to control transmission systems.

This Chapter finally presents an interesting pilot project ongoing in Denmark: the Cell Controller Pilot Project. The Cell, which is a type of Microgrid, may become a new paradigm of how to handle the distribution (and the transmission) system in presence of a large DG penetration [51][52].

6.1 Active Networks

Active Networks are foreseen as probable evolution of today's distribution networks [53] (see Figure 6.3 for the traditional structure of distribution systems). These systems, which, as seen in 2.4.1, 3.5, are passive[26], can evolve to be structured and operated similarly as the transmission systems, which are active managing bidirectional power flows. This change of the distribution design may be triggered by the connection of an increased amount of small generating units.

This evolution shall be accompanied by an opportune upgrade of the protection schemes, along with the introduction of new (soft and hard) technologies for a more flexible system control. The distribution network will then be more meshed (currently it has a radial structure or it is operated mainly as radial) and more controllable by means of ICT and power electronics-based devices. The active distribution network may then deliver power to users and/or transfer it to the transmission system as well. Figure 6.4 depicts an example of the architecture of active distribution networks.

This first big transformation is already ongoing in some European countries.

[25] D-FACTS controllers are also known as Custom Power devices.

[26] As seen in 2.4.1, 3.5, the today's distribution systems are passive as they are not able to control power which is unidirectionally flowing from transmission substations to the users through distribution.

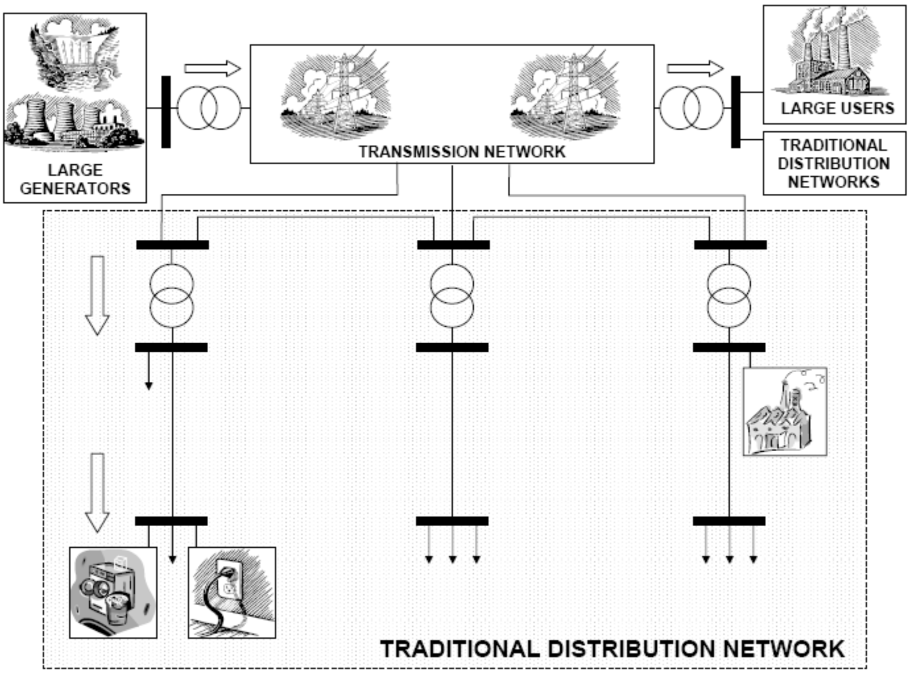

Figure 6.3 – Structure of a traditional distribution system.

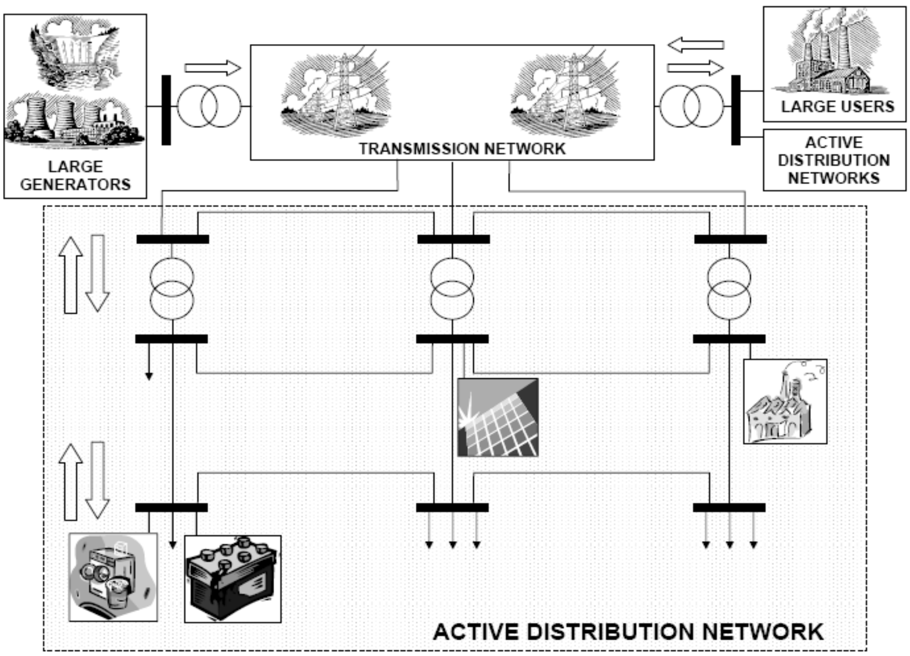

Figure 6.4 – Structure of an active distribution system.

6.2 Microgrids

The European SmartGrids Technology Platform [53] defines Microgrids as low voltage networks with DG sources, together with local storage devices and controllable loads (e.g. water heaters and air conditioning). The unique feature of Microgrids is that, although they operate mostly connected to the distribution network, they can be automatically transferred to islanded mode in case of faults in the upstream network. After a fault has been resolved and the upstream network operation restored, they can be resynchronised to the rest of the system. As explained in 5.1.3, intentional islanding mechanisms can protect clusters of customers against power outages occurring on bordering and/or upstream networks. In case of disruptions affecting a nearby network, by disconnecting a Microgrid (having sufficient generation and storage resources) from the faulted network, power supply to local customers can be maintained. Additionally, the islanding procedure could be implemented at a less sophisticated level, more simply allowing that a Microgrid is able to 'black start' in case of a widespread system outage. In the case of large disruption, a number of dedicated DG units may be able to feed local loads and eventually to re-synchronize this part of the grid with the main system. In this way, a Microgrid would contribute to the restoration of normal operation conditions for the whole system.

Within the system, a Microgrid can be regarded as a controlled entity which can be operated as a single aggregated load or generator, eventually as power source providing network support and services [54]. Figure 6.5 shows the structure of a Microgrid. Microgrids generally have a total installed capacity in the range of between a few hundred kW and tens of MW.

Pilot projects of Microgrids are present in Greece [55][56][57], Germany, Netherlands, Italy, Portugal, Spain [57], and in Denmark [51][52] (see also 6.4 for more details on the Danish experience).

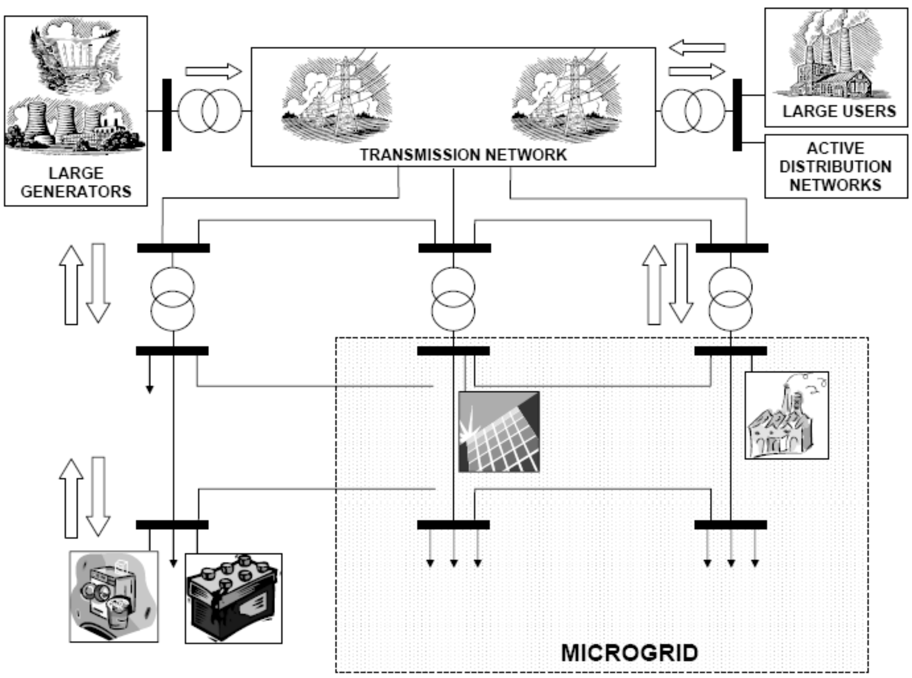

Figure 6.5 – Structure of a Microgrid.

6.3 Virtual Power Plants

The Virtual Power Plant (VPP) is a decentralised energy management system tasked to aggregate different small generators either for the purpose of energy trading or to provide system support services. The VPP concept is not itself a new technology but a scheme to combine decentralised generation and storage and exploit the technical and economic synergies between system's components. This aggregation is not pursued by physically connecting the plants but by interlinking them via soft technologies (ICT). For this reason the result is a virtual power plant, which may then be a multi-fuel, multi-location and multi-owned power station. A virtual power station balances required and available power in identified areas, based on off-line schedules for distributed energy sources, storage, demand side management capabilities and contractual power exchanges. For a grid operator or energy trader, buying energy or ancillary services from a VPP is equivalent to purchasing from a conventional station. Virtual power stations using DG, RES and energy storage can potentially and gradually replace conventional power stations [25][53][58]. Figure 6.6 illustrates the concept of VPP.

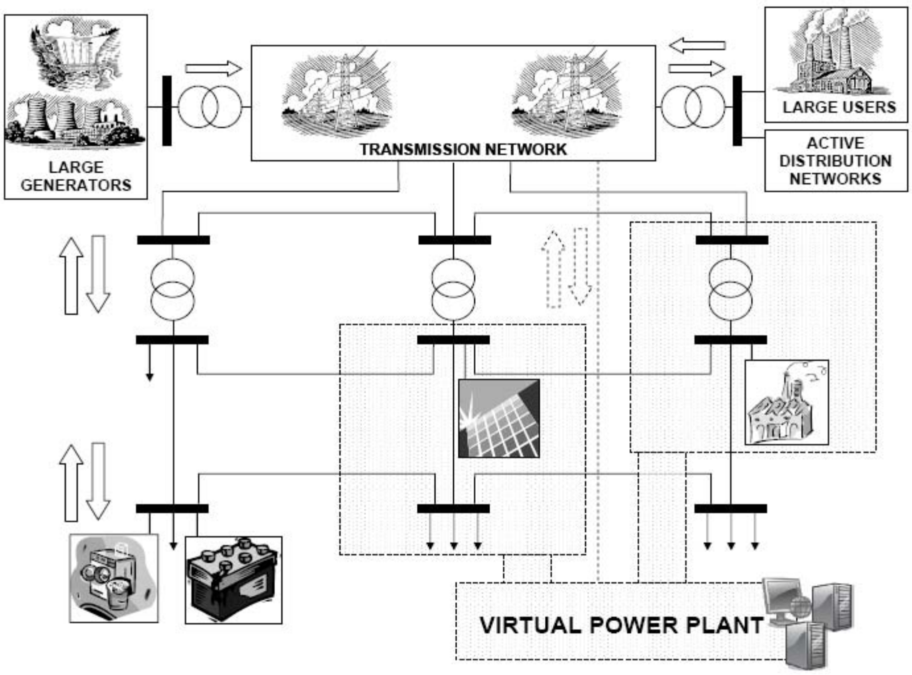

Figure 6.6 – Configuration of a Virtual Power Plant.

6.4 The Danish experience with DG integration

The present Section provides an overview about the Danish experience with the DG integration: particular attention is paid to the Cell concept and the related pilot project. Nowadays Denmark has the highest DG share in Europe (over 40% (2004) of DG penetration respect to power installed capacity) [12][51][52].

6.4.1 The Danish power system

Due to geographical reasons, the bulk power system of Denmark is divided into two AC power system areas, Western Denmark and Eastern Denmark. Eastern Denmark is synchronised with the Nordel system comprising the electricity areas of Finland, Norway and Sweden. Western Denmark is synchronised with the UCTE continental system. Both systems, although not electrically interconnected, are operated by the single Danish TSO, Energinet.dk [12].

At distribution level, many small companies own and operate the Danish distribution networks. There are currently 110 DSOs [16].

The Danish power system is characterised by a large share of DG, comprising small and medium CHP generating stations and wind power plants. This is particularly a feature of the system in Western Denmark, where DG capacity amounts to over 50% of the total. Figure 6.7 shows a basic scheme with the data of the power installed capacity in Western Denmark: data related to installed DG are presented as well. In particular, it is worth noting a capacity totalling 1656 MW of distributed CHP and a capacity of distributed wind amounting to 2214 MW. This DG capacity is installed throughout the distribution systems at voltage levels of 60 kV and below.

Due to this large DG penetration, some problems arise when predicting and controlling the total power generation. In fact, most of this DG is uncontrollable, as CHP units mostly operate on the basis of heat demand, while wind plants produce according to wind presence. There can be hours with a DG production that is larger than consumption. So far the transmission lines to the interconnected neighboring countries have been used to sell the excess production.

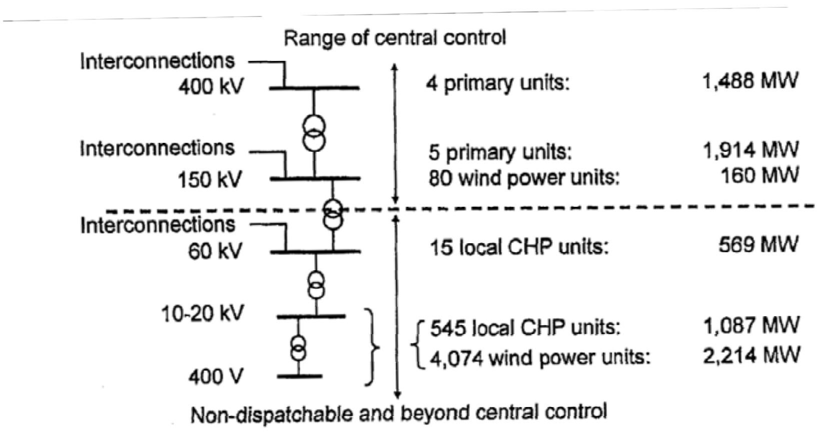

Figure 6.7 – Installed capacity data (2004) in Western Denmark [52].

However, different problems in terms of security (e.g. (n-1) criterion frequently not met, missing information on DG power production) and reliability (e.g. protection systems are often ineffective or not selective in their intervention) are becoming out of the control of the system operators with the increasing DG penetration.

6.4.2 The Cell project

To face the above issues with DG in the Western Denmark system, the TSO Energinet.dk has started developing advanced technical solutions like the 'Cell Architecture'. This is in view of a decentralizing operation of distribution networks containing semi-autonomous cells with specific local functions and possibilities of coordination at system levels. The aim of this system architecture is to streamline and centralise the control of a large number of DG units widespread throughout the distribution systems. The scope is also to exploit DG benefits and counterbalance the DG impact on the grid operation.

A Cell can be characterised as a portion of a distribution system down to a 150/60 kV substation, containing DG capacity locally installed and customers' loads. In the Western Denmark system, the

Cell is based on decentralised CHP and wind plants with an aggregate load typically up to 100 MW. A Cell is structurally like a Microgrid. Figure 6.8 shows a portion of the distribution network in Western Denmark with distributed CHP, wind and loads: this system can be basically considered as a Cell.

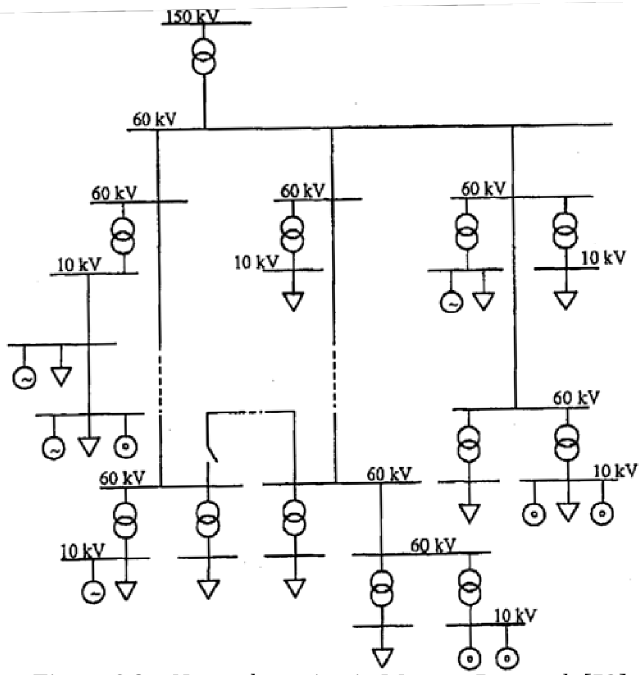

Figure 6.8 – Network portion in Western Denmark [52].

The Cell project, which is ongoing, sees a strong collaboration between the TSO Energinet.dk and a DSO, Sydvest Energi Net A/S, whose distribution network contains the Cell chosen for this pilot project. This interaction between TSO and DSO is an important element which will be essential in the operation and planning of future distribution systems with DG.

By this project the TSO expects to interact with the Cells, centrally controlling them as conventional power plants. In this way, at the end of the project, the TSO shall be able to control the Cells in terms of: power output; ancillary services and network support request; disconnection from the transmission network (intentional islanding) in case of upstream emergencies; black-start capability request for a post-fault restoration operation.

The initial stage of the project focuses on how to intentionally island the Cell from the rest of the upstream system. In normal situations, a Cell depends on the upstream transmission system, exporting the excess production from DG or importing the needed power when DG cannot cover all the load consumption requests at local level. Then, to implement an intentional islanding, communication assumes a crucial role. In fact, a command from the SCADA-based transmission control centre (operated by the TSO) communicates to the Cell controller (operated by the DSO) that the local generation and demand must be quickly balanced. Also, in the islanded mode, voltage and frequency control must then be carried out at Cell level by using the DG resources. Other key issues to be addressed concern the dynamic change of protection, control, and other network parameters from grid-connected mode to islanding and vice versa without any transition problems.

Communication between the DSO and the TSO is also essential for requesting the Cell to provide black-start capability support and restore the service after a fault.

It is evident that by this new distribution system architecture the DSO controlling the Cell will be able to exploit the benefits and the potentials of the locally installed DG. It will be possible for the DSO to control real and reactive power flow from the Cell to the upstream transmission and vice versa, as well as to monitor the DG components and the flows within the Cell.

Figure 6.9 schematically presents how the Cell controller might operate.

The green arrows indicate the flows of measured and monitored information from the components like distributed generators and loads to the Cell controller. These data refer to the load and production. The red arrows indicate the control actions on distributed generators, load feeders and main circuit breakers [51][52].

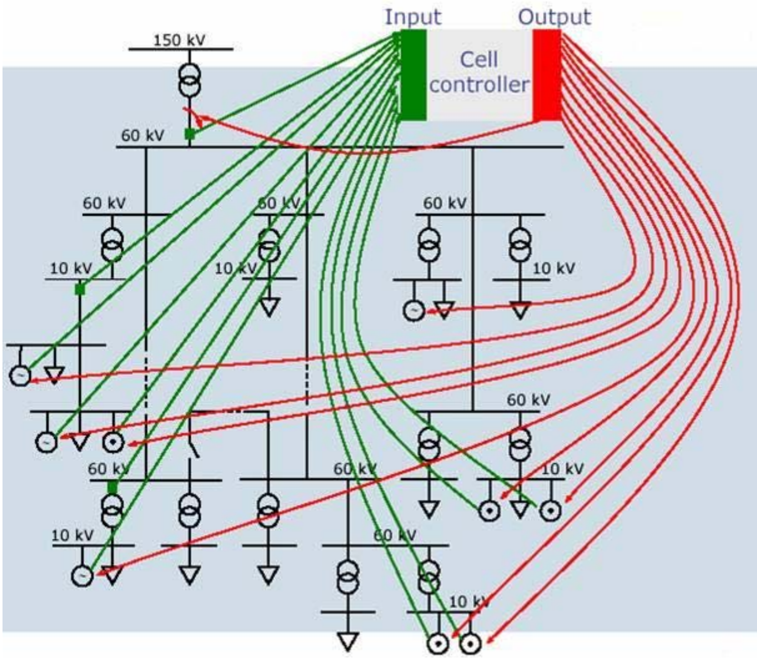

Figure 6.9 – Basic scheme of a Cell controller operation [52].

FOR FURTHER READING ON THIS CHAPTER

[47] DISPOWER European project. Website: http://dispower.org/

[48] G. Fulli, A. L'Abbate, S. D. Peteves, *Challenges for DG integration in Europe,* Cogeneration & On-Site Power Production, PennWell, Vol. 8, Issue 5, September 2007, pp. 59-69 [Online]. Available: http://www.cospp.com/display_article/307887/122/CRTIS/none/none/1/Challenges-for-DG-integration-in-Europe---status-and-potentials-vary-by-country/

[49] DG-FACTS European project. Website: http://dgfacts.labein.es/dgfacts/index.jsp

[50] N.G. Hingorani, L. Gyugyi, Understanding FACTS. Concepts and Technology of Flexible AC Transmission Systems, IEEE Press Inc., 2000.

[51] Eltra - Cell Controller Pilot Project [Online]. Available: http://nu.eltra.dk/dok/NUdok382.pdf

[52] P. Lund, S. Cherian, T. Ackermann, A Cell Controller for Autonomous Operation of a 60 kV Distribution Area, International Journal of Distributed Energy Resources, Vol. 2, No. 2, 2006.

[53] European Commission, European SmartGrids Technology Platform, Vision and Strategy for Europe's Electricity Networks of the Future, 2006 [Online]. Available: http://ec.europa.eu/research/energy/nn/nn_rt/nn_rt_dg/article_1158_en.htm

[54] R. H. Lasseter, MicroGrids, Proc. of IEEE PES Winter Meeting 2002, New York (USA), 27-31 January 2002, Vol. 1, pp. 305-308.

[55] MICROGRIDS European project. Website: http://microgrids.power.ece.ntua.gr/micro/micro2000/index.php?page=index

[56] MORE MICROGRIDS European project. Website: http://microgrids.power.ece.ntua.gr/micro/

[57] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, Microgrids, Power and Energy Magazine, IEEE, Vol. 5, Issue 4, July-Aug. 2007, pp. 78 – 94.

7 Conclusions

The electricity system in Europe is currently facing the challenge of how to simultaneously satisfy a growing electricity demand and meet the three EU energy targets - environmental sustainability, security of supply, and competitiveness. In order to pursue these targets, different evolutions and changes are taking place in the European electric power systems, some of which lead towards a further penetration of Distributed Generation. In fact, many EU countries are already recording a gradual and steady upward trend in deploying DG resources connected to power distribution networks.

This trend is also triggered by drivers like the emerging of new technological solutions for more efficient, environmentally-friendly small-size generating units. Additionally, crucial impediments predominantly affecting the generation and transmission system architecture - namely, social and environmental constraints in building new high capacity infrastructures - may contribute to further DG utilisation. It has also to be remarked that the recent new targets for RES penetration in the EU (globally 20% of energy consumption covered by RES by 2020) will foster a rising DG deployment in the EU countries.

There are, however, major issues concerning the integration of DG technology into the distribution networks. In fact, the existing distribution grids were not generally designed to operate in presence of large quantities DG. Consequently, a sustained increase in the deployment of DG resources may require several adjustments and changes in the electric power system operation and architecture in the near future.

Against this background, the present Report has focused on the potential role of DG. More specifically, this work has considered and assessed the technical issues affecting the system integration of DG technologies in Europe.

After introducing the basic elements of electric power systems and defining DG, this Report has reviewed the state-of-the-art of DG technologies. Then, it has presented today's DG grid integration issues in Europe and their possible technical solutions. Developments and future evolutions of distribution systems such as Active Networks, Microgrids, Virtual Power Plants have been also investigated with particular attention to the Danish experience (Cell project).

The present Chapter first summarizes some key challenges related to technical DG integration issues and their possible corresponding solutions. Then, it proposes a way forward in terms of actions having the potential to overcome existing technical barriers and criticalities.

7.1 Key challenges

As said in Chapter 6, assuming no major network structure change/redesign actions are performed on the current European distribution systems (conservative approach), an average 15% DG penetration (in terms of capacity) is considered feasible in Europe.

However, in case of increasing DG penetration, planning and developing a new architecture for the distribution grids are crucial measures to avoid serious problems occurring on the power system.

It has also to be remarked that the recent new targets for RES penetration in the EU (globally 20% of energy consumption covered by RES by 2020) [11] will foster a fast rising DG deployment in the EU countries.

If the growing DG output is not properly and timely handled, portions of the European distribution systems are naturally exposed to risks of reliability worsening and security of supply deterioration.

In addition, the indirect effects of DG growth at European transmission level cannot be neglected. One reason for that is the lack of clear definition of the borders between electricity transmission and distribution. In fact, in some EU countries the ownership or the management of network assets at the same voltage level - typically high voltage - is shared by the TSO and the DSOs. Furthermore, without properly coordinated system interfaces and flexible controlling devices, the consequences of a power disruption at distribution level may be suffered (if not amplified) at transmission level. Recent disturbance and disruption events in Europe prove this [32].

For all these reasons, developing new approaches and architectures is a vital need to be prepared to securely accommodate rapidly growing DG shares. To get to the final model(s) of the future, a transition process with different temporal stages may be needed. At every stage, the effects of such system and the technological developments have to be carefully monitored in Europe. This approach should permit a smoother coordination and steering over the modifications of the concerned energy systems, thereby reducing the risk of major criticalities and security of supply issues. Figure 7.1 schematically shows the possible stages of this process, linked with the level of DG penetration increase. This process would then move from the traditional approach of simple DG connection ('fit and forget') to different changes/upgrades of system components, starting from the grid protection systems to network reinforcement. The following step would be the introduction of new control means, both soft (ICT) and hard (flexible controlling devices like FACTS [50]), before reaching the final stage: the fully new network architecture.

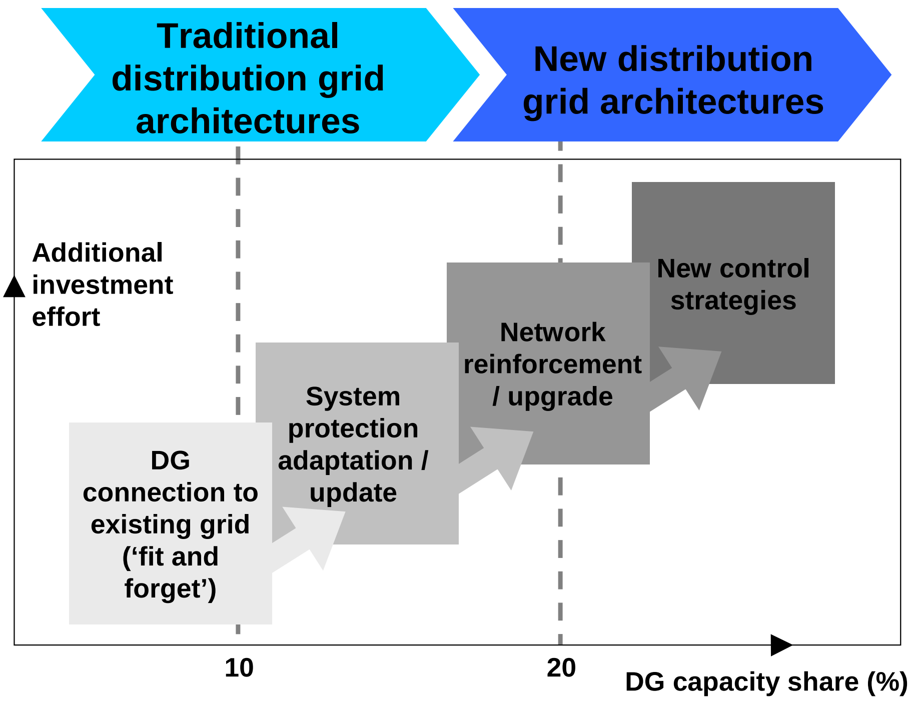

Figure 7.1 – Basic scheme of distribution grid evolution process.

7.2 Technical recommendations for DG integration

Based on the issues presented in the previous Chapters, some technical recommendations for possible actions at DG unit and at transmission/distribution system level are here listed:

- In order to safeguard the governability of the present and future electricity systems, there is a need for a clear definition of the networks borders and the control areas. This is required to delimit roles and accountabilities of the different operators.

- As noted in 3.5, 7.1, there is a need for a better coordination of the transmission and distribution systems, which have to efficiently and safely work together. Both systems need to be further developed, not necessarily only in terms of carrying capacity but also and mostly in terms of ICT infrastructure and communication platforms. In particular, the transmission system strongly needs clear interfaces with the downstream distributed system (see also 5.3.2). This is a matter which the recent electricity power disruption recorded on 4th Nov. 2006 in Germany and in other European countries has made urgent to address. One of the causes of that event was recognised in the lack of structured communication between DSOs and TSOs, as stated in the investigation by ERGEG [32].

- Considering the transmission planning issues brought about by the electricity market liberalisation[27], a cautious approach should be followed before extending the same planning procedure to subtransmission and distribution systems. For certain aspects, at the outset, a more regulated approach might be useful to more effectively plan the power systems before introducing fully competitive elements.

- Distribution planning and operation practices more oriented to active power flow management should be carried out by the DSOs, especially where the DG penetration has reached certain levels and cannot be neglected any more. The distribution system might be subdivided in more subsystems. Each subsystem should be eventually able to balance supply and demand effectively (i.e. be self-sufficient) for different reasons. First, to be able to disconnect from the interconnected system and continue running in case of large and widespread disruptions. Second, to reduce the burden (in terms of control actions and losses) on the upstream systems.

- The provision of ancillary services by DG (see also 5.2), especially by the DG units interfaced via power electronic converter or synchronous machine, is necessary for a truly complete integration of DG into the system. Such requirement is pushed both by technical (DG may take the place of large generation providing flexibility and reliability as well) and economic needs (DG may enter the market of ancillary services).

- The development and improvement of cost-effective and coordinated high-power energy storage systems, based on different technologies, may play a key role in facilitating a larger penetration of DG resources. In some EU countries (as described for the Danish case, see 6.4), short-to-medium term distributed systems are likely to be dominated by small-medium sized CHP plants. Since most of these installations are designed and operated according to the heat needs, local heat storages near the distributed CHP plants may prove helpful in optimising CHP electricity output.

- Innovative network controlling devices like WAMS (Wide Area Measurement Systems) and FACTS (Flexible Alternating Current Transmission System [50]) should be inserted and utilised by TSOs to better and more effectively control their transmission grids.

- Innovative network controlling devices like D-FACTS (FACTS for distribution [47]) might be considered by DSOs for a better control of the distribution grids in terms of power flows, voltage level, power quality issues etc.

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[27] In a liberalised power system the planning of new power plants is decided by power generation companies competing in the market: the transmission planning which follows the new generation planning has consequently to adapt to this situation and cannot rule the process.

In the recent years, several large EU-funded research projects [8],[28]-[30],[47],[55],[58],[59] have investigated different aspects and issues related to DG.
It has to be remarked however that, in spite of this, the above issues concerning transmission and distribution planning and operation have not been widely addressed by these projects.
Finally, apart from technical and technological aspects, the broad introduction of Distributed Generation and the consequent adaptation of the power systems result also in economic, regulatory and environmental issues. These other aspects need also to be accurately investigated, in order to properly manage the transition and identify all the possible attached benefits and drawbacks.

FOR FURTHER READING ON THIS CHAPTER

[58] FENIX European project. Website: www.fenix-project.org/
[59] EU-DEEP European project. Website: www.eudeep.org/

References

[1] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal of the European Communities No. L 027, 30.01.1997 P. 0020-0029.

[2] Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, Official Journal of the European Union No. L 176, 15.07.2003 P. 0037-0055.

[3] European Commission, DG Energy and Transport, *European energy and transport, Trends to 2030 – update 2005*, May 2006 [Online]. Available: http://ec.europa.eu/dgs/energy_transport/figures/trends_2030_update_2005/energy_transport_trends_2030_update_2005_en.pdf

[4] COM(2007) 723 final, Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, *A European Strategic Energy Technology Plan (SET-Plan)*, 22 November 2007 [Online]. Available: http://ec.europa.eu/energy/res/setplan/doc/com_2007/com_2007_0723_en.pdf

[5] EURELECTRIC – Union of the electricity industry, *Statistics and Prospects for the European electricity sector (EURPROG 2005)*, 2005 [Online]. Available: www.eurelectric.org/CatPub/Document.aspx?FolderID=1540&DocumentID=18870

[6] Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC, Official Journal of the European Union No. L 52, 21.02.2004 P. 0050-0060.

[7] Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, Official Journal of the European Communities No. L 283, 27.10.2001 P. 0033-0040.

[8] ELEP European project. Website: www.elep.net

[9] COM(2006) 105 final, Green Paper of the European Commission, *A European Strategy for Sustainable, Competitive and Secure Energy*, 8 March 2006 [Online]. Available: http://ec.europa.eu/energy/green-paper-energy/doc/2006_03_08_gp_document_en.pdf

[10] Directive 2005/89/EC of the European Parliament and of the Council of 18 January 2006 concerning measures to safeguard security of electricity supply and infrastructure investment, Official Journal of the European Union No. L 33, 04.02.2006 P. 0022-0027.

[11] COM(2007) 1 final, Communication from the Commission to the European Council and the European Parliament, *An energy policy for Europe*, 10 January 2007 [Online]. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0001:FIN:EN:PDF

[12] DG-GRID European project. Website: www.dg-grid.org

[13] WADE (World Alliance for Decentralized Energy). Website: www.localpower.org

[14] R. Marconato, *Electric Power Systems*, CEI – Italian Electrotechnical Committee, 2002, Vol. 1-2.

[15] UCTE (Union for the Coordination of Transmission of Electricity). Website: www.ucte.org

[16] ERGEG (European Regulators Group for Electricity and Gas), *Assessment of the Development of the European Energy Market 2006*, December 2006 [Online]. Available: www.ergeg.org/portal/page/portal/ERGEG_HOME/ERGEG_DOCS/NATIONAL_REPORTS/2006

[17] G. Fulli, A. L'Abbate, S.D. Peteves, *Power distribution systems in Europe: present status and challenges towards a further integration of Distributed Generation*, Proc. of Power-Grid Europe 2007 Conference, Madrid (Spain), 26-28 June 2007.

[18] A.J. Pansini, *Guide to Electrical Power Distribution Systems*, 6th Edition, CRC Press, 2005.

[19] Institute of Electrical and Electronics Engineers (IEEE) 1547 Work Group, *P1547 standard series for interconnecting distributed resources with electric power systems*, IEEE Standard, 2003.

[20] Conseil International des Grands Réseaux Electrique (CIGRE) WG 37-23, *Impact of increasing contribution of dispersed generation on the power system*, Final Report, 2003.

[21] International Energy Agency (IEA), *Distributed Generation in Liberalised Electricity Markets*, 2002 [Online]. Available: http://www.iea.org/textbase/nppdf/free/2000/distributed2002.pdf

[22] U.S. Department of Energy (DOE), Distributed Energy Program. Website: http://www.eere.energy.gov/de/

[23] The Electric Power Research Institute (EPRI). Website: www.epri.com

[24] T. Ackermann, G. Andersson, L. Söder, *Distributed generation: a definition*, Electric Power Systems Research, Vol. 57, 2001, pp. 195-204.

[25] A.-M. Borbely, J.F. Kreider (Eds.), *Distributed Generation – The Power Paradigm for the New Millennium*, CRC Press, 2001.

[26] Resource Dynamics Corporation, *Assessment of Distributed Generation Technology Applications*, February 2001 [Online]. Available: http://www.distributed-generation.com/Library/Maine.pdf

[27] H. Zareipour, K. Bhattacharya, C.A. Cañizares, *Distributed Generation: Current Status and Challenges*, Proc. of North American Power Symposium (NAPS) 2004 Conference, Moscow, (USA), 9-10 August 2004, pp. 392-399.

[28] SUSTELNET European project. Website: www.ecn.nl/en/ps/research-programme/energy-markets/sustelnet/

[29] DECENT European project. Website: www.izt.de/decent

[30] ENIR-DGnet European project. Website: www.dgnet.org

[31] International Energy Agency (IEA), *Renewable energy: RD&D priorities*, 2006.

[32] ERGEG (European Regulators Group for Electricity and Gas), Final Report, *The lessons to be learned from the large disturbance in the European power system on the 4th of November 2006*, February 2007 [Online]. Available: http://www.ergeg.org/portal/page/portal/ERGEG_HOME/ERGEG_DOCS/ERGEG_DOCUMENTS_NEW/ELECTRICITY_FOCUS_GROUP/E06-BAG-01-06_Blackout-FinalReport_2007-02-06.pdf

[33] European Commission, Energy Research, *Key Advantages of Distributed Energy Resources* [Online]. Available: http://ec.europa.eu/research/energy/nn/nn_rt/nn_rt_dg/article_1159_en.htm

[34] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, W. D'haeseleer, *Distributed generation: definition, benefits and issues*, Energy Policy, Vol. 33, 2005, pp. 787-798.

[35] H. Nehrir, W. Caisheng, S.R. Shaw, *Fuel cells: promising devices for distributed generation*, Power and Energy Magazine, IEEE Vol. 4, Issue 1, 2006, pp. 47 – 53.

[36] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac, *Embedded Generation*, Power and Energy Series, IEE, 2000.

[37] Hitec Electric. Website: www.hitecelectric.com

[38] California Energy Commission, Distributed Energy Resources Guide. Website: http://www.energy.ca.gov/distgen/index.html

[39] Energieprojecten.com. Website: www.energieprojecten.nl

[40] STM Power Inc. Website: http://www.stmpower.com

[41] U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy. Website: www.eere.energy.gov

[42] J.A. Pecas Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, N. Jenkins, *Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities*, Electric Power Systems Research, Vol. 77, 2007, pp. 1189–1203.

[43] SOLID-DER European project. Website: www.solid-der.org

[44] R.C. Dugan, S.K. Price, *Issues for Distributed Generation in the US*, Proc. of IEEE PES Winter Meeting 2002, New York (USA), 27-31 January 2002, Vol. 1, pp. 121-126.

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

[46] M. Rebolini, G. Fulli, A. Ferrante, *GRTN's experience in developing the electricity transmission network in the framework of the European energy sector restructuring*, Première Conférence sur le transport d'électricité, Alger (Algeria), 19-20 September 2005.

[47] DISPOWER European project. Website: http://dispower.org/

[48] G. Fulli, A. L'Abbate, S. D. Peteves, *Challenges for DG integration in Europe,* Cogeneration & On-Site Power Production, PennWell, Vol. 8, Issue 5, September 2007, pp. 59-69 [Online]. Available: http://www.cospp.com/display_article/307887/122/CRTIS/none/none/1/Challenges-for-DG-integration-in-Europe---status-and-potentials-vary-by-country/

[49] DG-FACTS European project. Website: http://dgfacts.labein.es/dgfacts/index.jsp

[50] N.G. Hingorani, L. Gyugyi, *Understanding FACTS. Concepts and Technology of Flexible AC Transmission Systems*, IEEE Press Inc., 2000.

[51] Eltra - Cell Controller Pilot Project [Online]. Available: http://nu.eltra.dk/dok/NUdok382.pdf

[52] P. Lund, S. Cherian, T. Ackermann, *A Cell Controller for Autonomous Operation of a 60 kV Distribution Area*, International Journal of Distributed Energy Resources, Vol. 2, No. 2, 2006.

[53] European Commission, European SmartGrids Technology Platform, *Vision and Strategy for Europe's Electricity Networks of the Future*, 2006 [Online]. Available: http://ec.europa.eu/research/energy/nn/nn_rt/nn_rt_dg/article_1158_en.htm

[54] R. H. Lasseter, *MicroGrids*, Proc. of IEEE PES Winter Meeting 2002, New York (USA), 27-31 January 2002, Vol. 1, pp. 305-308.

[55] MICROGRIDS European project. Website: http://microgrids.power.ece.ntua.gr/micro/micro2000/index.php?page=index

[56] MORE MICROGRIDS European project. Website: http://microgrids.power.ece.ntua.gr/micro/

[57] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, *Microgrids*, Power and Energy Magazine, IEEE, Vol. 5, Issue 4, 2007, pp. 78 – 94.

[58] FENIX European project. Website: www.fenix-project.org/

[59] EU-DEEP European project. Website: www.eudeep.org/

[60] National Renewable Energy Laboratory (NREL), *Gas-Fired Distributed Energy Resource Technology Characterizations*, 2003 [Online]. Available: http://www.nrel.gov/docs/fy04osti/34783.pdf

[61] U.S. Environmental Protection Agency (EPA), Combined Heat and Power Partnership, *Catalogue of CHP technologies*, 2002 [Online]. Available: http://www.epa.gov/chp/documents/catalog_entire.pdf

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Abstract

The electric power sector in Europe is currently facing different changes and evolutions mainly in response to the three issues at EU level - environmental sustainability, security of supply, and competitiveness. These issues, against a background of growing electricity demand, may represent drivers for facilitating the further deployment of Distributed Power Generation technologies in Europe.
The present Report focuses on the potential role of Distributed Power Generation (or simply Distributed Generation, DG) in a European perspective. More specifically, this work aims to assess the technical issues and developments related to DG technologies and their integration into the European power systems.
As a starting point the concept of Distributed Generation is characterised for the purpose of the study. Distributed Generation, defined as an electric power source connected to the distribution network, serving a customer on-site or providing network support, may offer various benefits to the European electric power systems. DG technologies may consist of small/medium size, modular energy conversion units, which are generally located close to end users and transform primary energy resources into electricity and eventually heat. There are, however, major issues concerning the integration of DG technology into the distribution networks. In fact, the existing distribution networks were not generally designed to operate in presence of DG technologies. Consequently, a sustained increase in the deployment of DG resources may imply several changes in the electric power system architecture in the near future.
The present Report on Distributed Generation in Europe, after an overview of the basic elements of electric power systems, introduces the proposed definition and main features of DG. Then, it reviews the state-of-the-art of DG technologies as well as focuses on current DG grid integration issues. Technical solutions towards DG integration in Europe and developments concerning the future distribution systems are also addressed in the study.

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