Electric Power Systems

Antonello Monti and Ferdinanda Ponci

Abstract The electric power system is one of the largest and most complex infrastructures and it is critical to the operation of society and other infrastructures. The power system is undergoing deep changes which result in new monitoring and control challenges in its own operation, and in unprecedented coupling with other infrastructures, in particular communications and the other energy grids. This Chapter provides an overview of this transformation, starting from the primary causes through the technical challenges, and some perspective solutions.

Keywords Power systems · Smart grid · Renewable energy sources · Monitoring · Control · Distributed resources

1 Introduction

Power systems have been operating for the last about 100 years using the same fundamental principles. Technology has, so far, allowed an improvement of their performance, but it has not revolutionized the basic principles. One fundamental law of physics has been driving the process: because the electrical grid has (nearly) no structural way to store energy, it is necessary that at every instant the amount of power generated to be equal to the power absorbed by the loads. In fact, some energy is naturally stored in the inertia of large generators. This is enough to compensate for small unbalances, which continuously occur and cause small variations of frequency and voltage (remaining within rather restrictive limits). Beyond these, violation of balance leads to voltage perturbation, large frequency variations, and electromechanical oscillations. If corrective measures are not applied in a timely manner, the system may collapse, resulting in widespread blackouts. In this context, automation is the way to determine and actuate these measures via the control of the generators.

A. Monti (✉) · F. Ponci
E.ON ERC, Institute for Automation of Complex Power Systems, RWTH Aachen University, Aachen, Germany
e-mail: AMonti@eonerc.rwth-aachen.de

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The loads are predictable only in a statistical sense, hence the automation is designed following a demand-driven approach. Based on the prediction of the load, the bulk of generation is scheduled. At run-time, unexpected deviations are actively compensated, reaching the due balance of generation and demand. Such a principle works very well under some clear assumptions:

– generation is "perfectly" controllable and predictable, so that the correction in the power balance can always be applied to the generation side of the balance
– generation is concentrated as much as possible in large plants, simplifying the problem of scheduling.

For traditional power systems these assumptions hold perfectly well, and have driven the design and construction of large power plants as we know them today.

The growing attention to the environmental impact and the consequent rise of new policies supporting the penetration of renewable energy sources are, vice versa, real game changers. Two points can immediately make the difference clear:

– generation from renewable energy sources is not perfectly predictable, and furthermore only in a limited sense controllable
– generation from renewable energy sources pushes to a more decentralized approach

While it would be incorrect to claim that power systems were not complex systems in the past, the new scenario is definitely raising the bar, and making complexity an even more tangible concern. In fact, the direct consequence of the new scenario is the creation of a stronger link between the electrical energy system and other infrastructures, such as communications or other energy infrastructures (e.g., gas grid. Furthermore, the new scenario is undermining the foundations of the automation principles, calling for a more decentralized approach to system functions, such as monitoring and control. These are the prime features of the smart grids.

In this chapter the consequence of the rise of complexity is analyzed in detail [1]. A review of the basics of power system automation, as implemented today, is provided. This introduces the final part of the chapter, focusing on cutting edge research and emerging methods for future electrical power systems.

2 The Arising of Complexity in Smart Grids

As introduced in the previous paragraph, one of the main reasons of complexity in energy systems is the growing interdependence among infrastructures. We summarize here the types of the interdependent, heterogeneous infrastructures, the points of coupling, and the arising of complexity.

The presence of intermittent, energy sources, such as renewables, which may not be reliably predicted and dispatched, enforces the presence of energy storage (or of other fast dynamic sources) for balancing load and generation [2]. But massive deployment of new dedicated energy storage units is technically and financially challenging, and at some extent may not be even necessary. Instead, for maximum usage of the existing resources, we need to resume to a broader concept of energy storage, involving the non-electrical energy grids, such as gas and heat, and distributed storage resources, such as plug-in electric vehicles. Gas energy is coupled to electrical energy via thermo-electric devices, such as Combined Heat and Power Units (CHP). Heat grids and heat storage in buildings is coupled to the electrical system through CHP and heat pumps. Plug-in electric vehicles are coupled to the electrical power grid through their batteries. Eventually, the electrical system is coupled with the gas, heat, and traffic systems.

Various business models are under consideration for the joint operation of these interconnected systems, including the creation of new markets for reserves and reactive power, and the establishment of Virtual Power Plants, Virtual Storage Systems, Dual Demand Side Management systems. The economic operation of these businesses and related markets represents yet another type of infrastructure, and another source of interdependence between the aforementioned infrastructures.

The coherent operation of all these infrastructures, and the unprecedented interactions between the generation, transmission and distribution sections of the power system, make the communications critical as never before. The communication infrastructure is coupled with all the aforementioned infrastructures and constitutes their glue (one of the main efforts in this direction are the European projects Finseny [3] and FINESCE [4]).

For interdependent grids, the distribution of control and monitoring functions is a necessity. In fact, the central control is infeasible and undesirable, particularly due to the minute granularity of some of the actors in the smart grid.

The resulting energy system is not only a complicated system made of many parts. It is also a complex system, that is, a system whose global behavior may not be inferred from the behavior of the individual components, and where no single entity may control, monitor and manage the system in real time [5]. The effect of the interdependencies is largely unknown and unforeseeable, in the absence of a clear view of the coupling points, of ways to model it, and of models, data and measurements. Besides, no way to predict the behavior means no way to control the behavior. Let alone more practical issues, such as the interdisciplinary harmonization of the standards, shared knowledge, and more. The vision of the smart grid as the complex system outlined above yields practical effects on the enablers: (1) education and training, (2) tools, (3) methods and design.

2.1 Education

Interdisciplinary study (and research, for that matter) has long been a buzz word in academia. Nonetheless the instruments to make it happen are extensively lacking, as the legal and organizational background is not ready for it. The integration of the disciplines of Electrical Engineering alone, and of closely related fields, is in itself a challenge. The creation of truly interdisciplinary areas, with related official degrees, conflicts with a structure that was developed for very different (and sometimes openly opposite) educational needs. In practice, though, besides the implementation issues, there is a more fundamental question to be addressed, and that is: what is the right curriculum for the smart grid engineers? And in particular, what should the ideal new hire of an energy service company know? What are the topics for her/his life-long education program?

Academic education is not the only competence-building environment affected by these challenges. Professional formation and training at all levels are equally affected. The lack of field experience, of the possibility to train in the field, and of trainers themselves, completes the picture.

2.2 Tools

Tools may mean: (a) the numerical tools to carry out the analysis of the complex smart grids, or (b) the technologies for de-risking new devices and algorithms, supporting the transition from numerical to in-field testing. These tools are primarily numerical simulators, and Hardware in the Loop (HIL) and Power Hardware in the Loop (PHIL) testing platforms. An example of application to interdependent heterogeneous systems that are part of a smart grid can be found in [6].

In a nutshell, these tools should support:

- multi-physics, multi-technology environment, to allow for representing all kinds of dynamic interdependencies
- multidisciplinary environment, fit for diverse users, working at different aspects of the same simulation scenario, with universally understood knowledge
- dynamic and reconfigurable model definition, enabling different users to interact with the simulation schematic focusing though on different levels of detail and obtaining results in a reasonable time
- high-level graphic visualization to support system analysis for the different disciplines, hence providing on one hand the favorite individual visualization options (oscilloscope-like, color-code-like,…) and on the other hand able to synthesize a "system-picture"
- uncertainty propagation, from the sources of uncertainty (e.g., renewable generation, loads, prices) through the discipline borders to the entire system.

2.3 Methods and Design

The lack of methods for representing and analyzing the smart grid as a complex system, and the lack of performance metrics for such a complex system, result in lack of methods for designing holistic controls and for designing components fit for this environment. The complex smart grid must be designed to manage uncertainty and inconsistencies, to be resilient and gracefully degrade when necessary. This implies that all the interdependent systems that the smart grid comprises must have these features, and use them in a coherent way.

We have here briefly described the factors that make the smart grid complex and some consequences. These consequences impact very different worlds, from the education and training, to the manufacturing of components, to development of numerical tools, to the philosophy of design. An enormous innovation in technology and tools is required, together with a deep change of mentality, for the transition to the smart grid to occur. The bright side is that a successful undertaking in the energy sector in the aforementioned directions may then be migrated to other sectors, with widespread benefits for all.

3 Challenges of the Future Grid

3.1 Characteristics of the Present Grid

Most of the existing power systems present common characteristics. The main ones, which are expected to be subject to change, are summarized here and pictorially shown in Fig. 1. Here the power system is shown in its main sections: generation in large power plants; transmission grid to transport the energy at high voltage and for long distances to the location of the demand; and medium and low voltage distribution grid that provides energy to the end users, who may be domestic, commercial or industrial.

Generation is highly concentrated in bulk power plants. These plants can be controlled, in a small signal sense, as briefly outlined in the introduction, to compensate for the variations caused by temporary unbalances of energy supply and demand. However, because of the large inertia of the generators in bulk power plants, and the slow dynamics of non-electrical actuators (e.g., fuel injection), the responsiveness to large variations of demand is very slow. So, while this inertia is beneficial to the overall system, as it constitutes a form of energy storage, on the other hand it makes the control of large, fast variations extremely challenging, if not impossible.

The occurrence of such large imbalances of generation and load, by the way, used to be linked primarily to faults or disruptions. Normally, the system could be considered as quasi-static. This characteristic used to be the underlying assumption of control design. Such an assumption relied on statistically foreseeable, slowly changing load profiles, and most of all, fully controllable generation. The latter assumption based on the prompt availability of the primary source of energy, i.e., some kind of fuel, in most cases. But volatile sources, mainly renewable, do not possess this characteristic, and instead they may be themselves responsible for

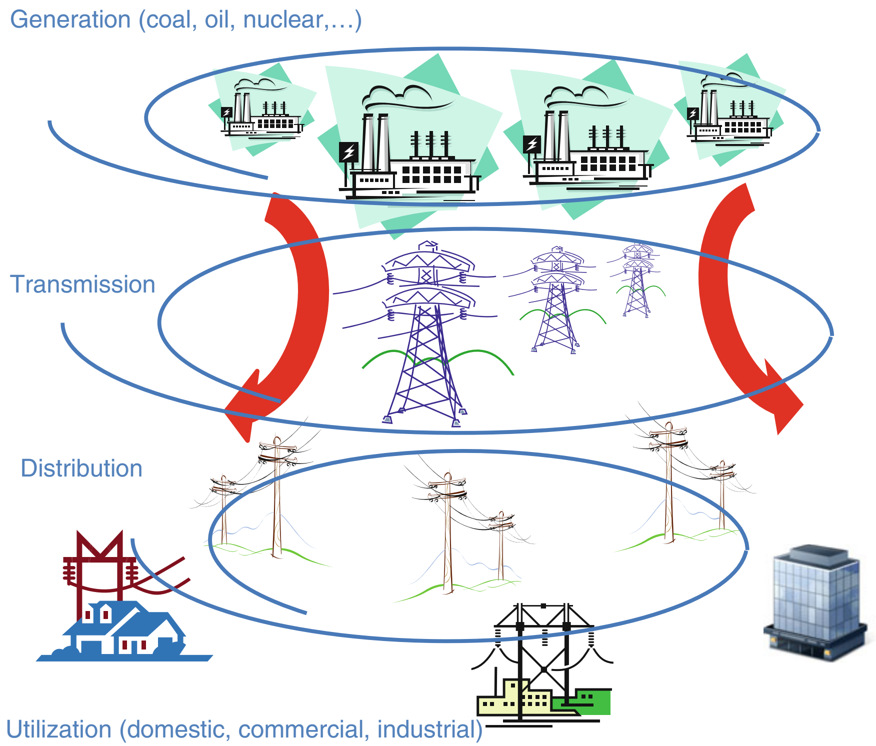

Fig. 1 Scheme of the power system today

large variations, especially in case of high penetration, when they represent a significant fraction of the generation.

From the system viewpoint, the flow of energy in classical systems, is unidirectional, from transmission to distribution and from bulk generators to loads. Generators and loads always preserve their “power injection”, “power absorption” nature with respect to the grid. The distribution systems are assumed to be totally passive.

In Europe, the transmission systems are interconnected as shown in Fig. 2, meaning that power can flow between areas managed by different Transmission System Operators (TSO), and across national borders, and in principle virtually traverse the entire continent. The European system supplies about 500 million people. The Continental Europe Synchronous Area comprises most of continental Europe, and comprises systems locked at the same frequency of 50 Hz (with restrictive tolerance to variation, as mentioned in the introduction). These interconnected synchronous systems operate somehow jointly to address unforeseen situations and major disturbances. The occurrence of disturbances is “sensed” far away from the point where they are originated, through frequency deviations and unexpected changes in the power flows at the interconnections. A true joint

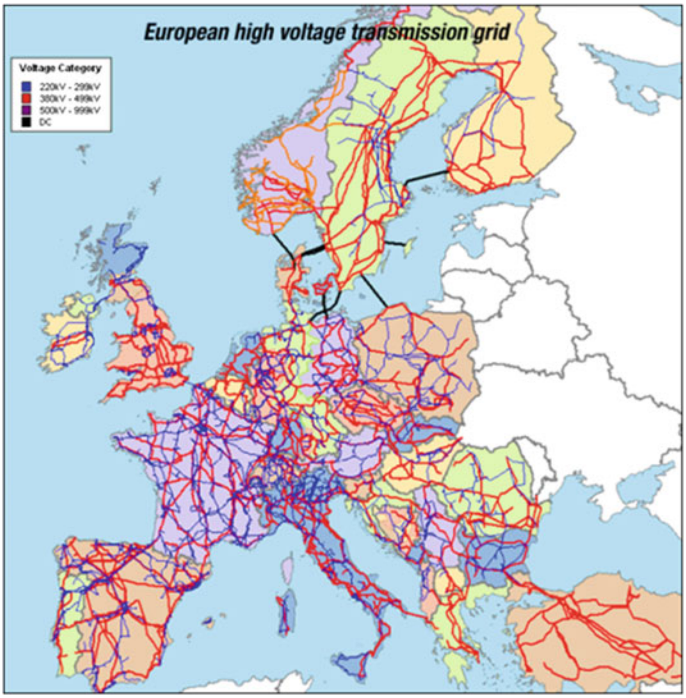

Fig. 2 European high voltage transmission grid from ENTSO-E [10]

operation of such system [7, 8] requires the ability to monitor very wide areas [9], exchange data and information promptly and in a standardized way, to mention just the major needs. More on the planning, regulation and market can be found in [10].

A sample behavior of the power flows within a national transmission grid, the German grid, is visualized in Fig. 3 [10] for the particular case of combined conditions of strong wind, hence large generation from wind farms in the north of the country, and heavy loading. In this scenario, two aspects can be emphasized: the first is the flow from generating areas to loading areas; the second is the consequent “long way” of the power flow, with proportionally large related losses. Furthermore, we point out that in this condition, the status of the grid and of the exchange with the neighboring states depends heavily on a volatile source.

To present the current status of power systems, particularly with reference to penetration of renewables, and provide some coherent quantification, we refer here to the case of Germany, as an exemplary case in Europe.

The German transmission grid comprises the portions at extra-high voltage, 220–380 kV, and at high voltage, 110 kV, with about 350 substations. A high level representation of the German power system is shown in Fig. 4. The distribution grids at medium voltage (MV), 1–50 kV, and low voltage (LV), 0.4 kV, include about 600.000 MV/LV substations. The extra-high voltage transmission system is

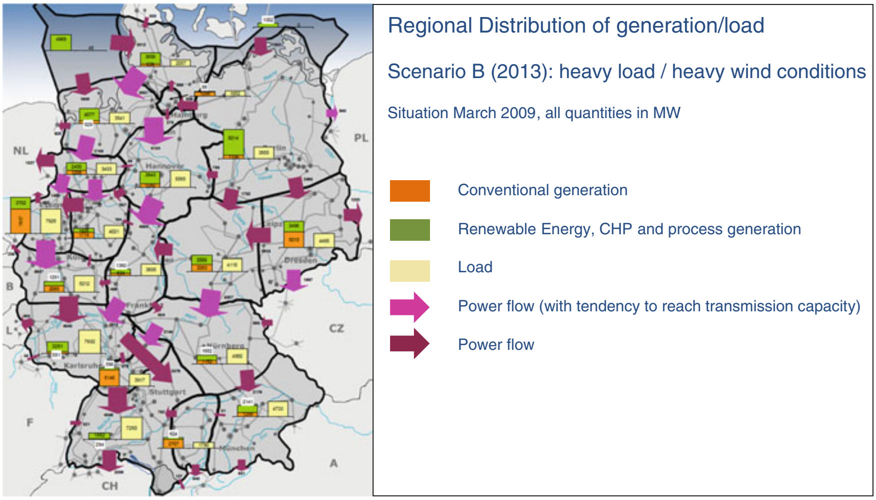

Fig. 3 Scenario of strong-wind combined with heavy load in Germany [10]

part of the European backbone, and it connects the bulk generation. The new generation plants based on renewable sources, together with other minor generation sources (e.g., some industrial plants with generation capacity) are instead connected to the MV. Domestic loads and very small generation are connected to the low voltage distribution systems.

The installed generation capacity amounts to 152.9 GW, as of 2009 (Data from Bundesministerium für Wirtschaft und Technologie), with wind and solar plants representing a fraction of about 27 %. Correspondingly, energy generation in Germany, in 2009, amounted at 593.2 TWh with a consumption of 578.9 TWh. Out of the generated energy, 45.2 TWh came from combined solar and wind sources, thus representing 7.6 % of the total. While, as of now, the penetration of renewables still represents a significant but manageable fluctuating source, things are progressing in the direction of increasing this penetration.

The key to allowing for local fluctuations is the interconnection between systems, such as the case of the European high voltage transmission grid. Thus, in the perspective of increasing the penetration of renewables, the interconnections are to be strengthened further.

A look at the electricity prices provides ground to considerations on the small wiggle room for price variation and for so called grid parity forecasts. The average price in Germany in 2011 is 24.95 c/kWh, of which 45.5 % is taxes.

With reference to the scenario outlined above, the power system of the future is expected to be characterized by: more distributed generation, part of which originating from renewable sources, which are numerous and in part (smaller sizes) not controllable except by the owner, and subject to uncertain fluctuations; active distribution networks; faster dynamics, due to smaller inertia of the sources;

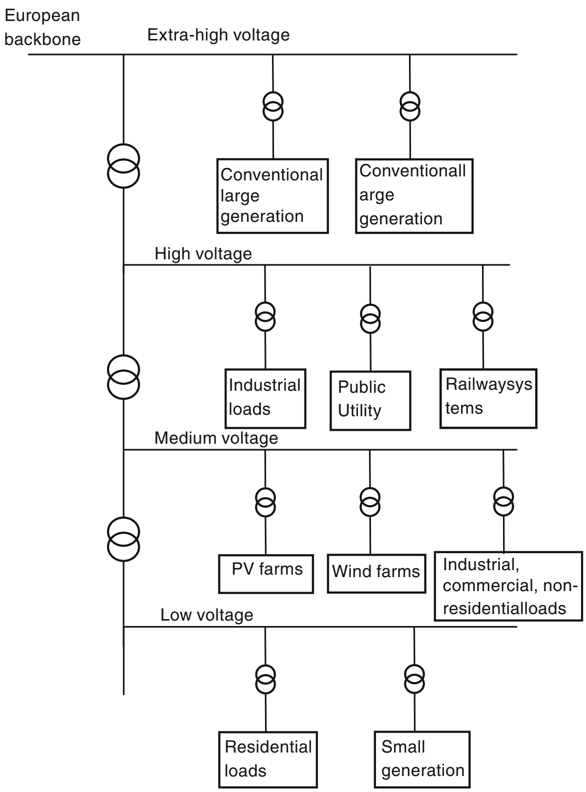

Fig. 4 Notional scheme of the power system in Germany

and potentially sudden source variations (e.g., wind puffs). One additional newly arising characteristic is the interconnectivity between energy systems of different nature, noticeably the connection and coupling between electrical and heat systems, as mentioned with reference to arising complexity. These characteristics give rise to unprecedented challenges.

In the first place, the constant balancing act of the electrical energy system is expected to be more difficult because:

1. if the sources are less predictable the balance is less predictable and
2. if sources are more numerous and decentralized, likely not under the authority of one or very few companies, the balance is more complex

Actually the most developments in the short term are brewing in the distribution system. This is because on one hand that is where the most dramatic changes are occurring, and on the other hand because they may take on more generation and control duties, thus relieving the challenged transmission system. As of now, the distribution systems are in general not ready for automation because of:

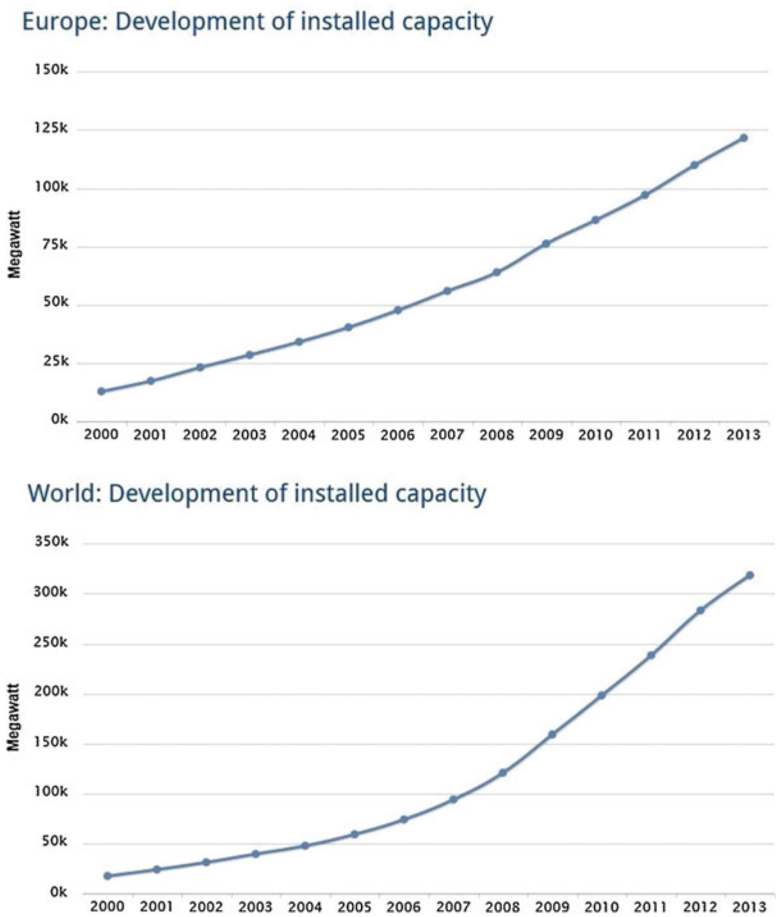

Fig. 5 Installed wind power capacity in Europe and worldwide (© Bundesverband WindEnergie e.V.)

- Very limited monitoring (instrumentation, monitoring functions)
- Majority of resources are not controllable
- Lack of data, information (topology, status, parameters)
- Protection system designed for unidirectional flow of power
- Lack of communication infrastructure
- Scalable methods for monitoring and control in developing phase

The operation of the system is designed under the assumption of slow dynamics and may not accommodate quick variations because of control rooms with human-in-the-loop and insufficient data refresh rates.

To gain an idea of the rate of growth of the phenomena that call for overcoming the limitation of existing power system infrastructure, the following data is provided. The trend in worldwide wind power installation is shown in Fig. 5. Data in Fig. 5 are

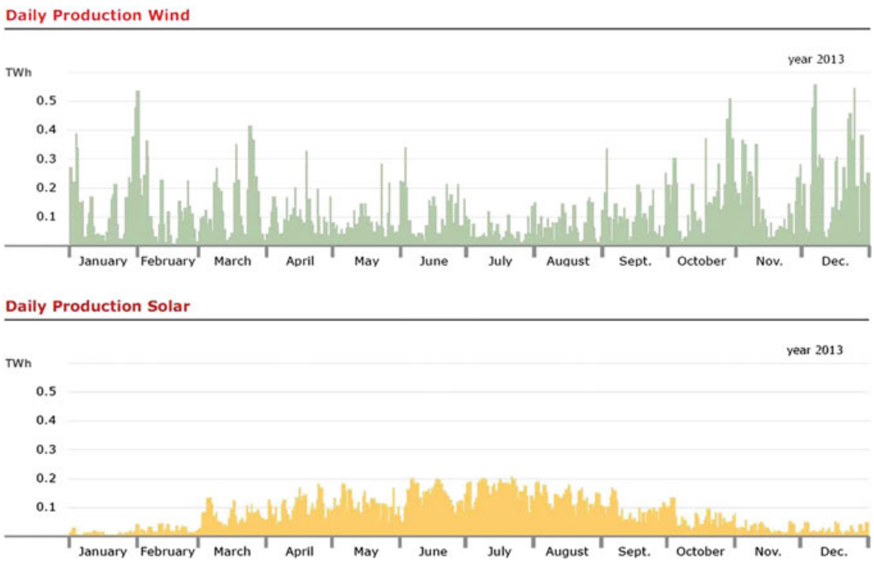

Fig. 6 Wind and solar power daily generation in Germany in 2013 [11]

global, involving power systems in different countries, with very different characteristics and production patterns, so the impact on the operation of the transmission system may not be immediately derived. Instead, to gain a sense of this impact and variations that wind power generation undergoes, a sample case is shown in Fig. 6. Here the 2013 production from wind in Germany is depicted, featuring a maximum peak of 0.56 TWh on 16.12.2013, and a minimum of 0.006 TWh on 17.02.2013, with a power maximum of 26.3 GW on December 5, 2013, at 18:15 (GMT +1:00) and minimum of 0.12 GW on September 4, 2013 at 13:45 (GMT +2:00). Solar production yielded a maximum of 0.20 TWh on 21.07.2013 and a minimum of 0.002 TWh on 18.01.2013. (Data 2013 from Fraunhofer ISE-EXX [11]).

Data in Figs. 5 and 6 point at two main aspects: penetration of renewables is on a steep rise and the volatility is extremely high. Furthermore, volatility affects the other main form of renewable energy, solar energy, as shown in Fig. 7.

The large installed capacity from renewables is generally located where the primary source (e.g., wind or solar irradiation) is maximum, which hardly ever matches the location of maximum load, resulting in a challenge for the transmission system, which was not developed to operate in this way. The volatility adds on the challenge, as it is not a good match for a system that was developed to operate “as planned” rather than “as it comes”, the latter requiring real-time monitoring and control.

The challenges of the renewable scenario extend down into the distribution system. In fact, here, many generation units, some of which non-dispatchable, are installed, making the distribution system an active one. The resulting challenges, linked to load-generation balancing and coordination, do not find a natural solution

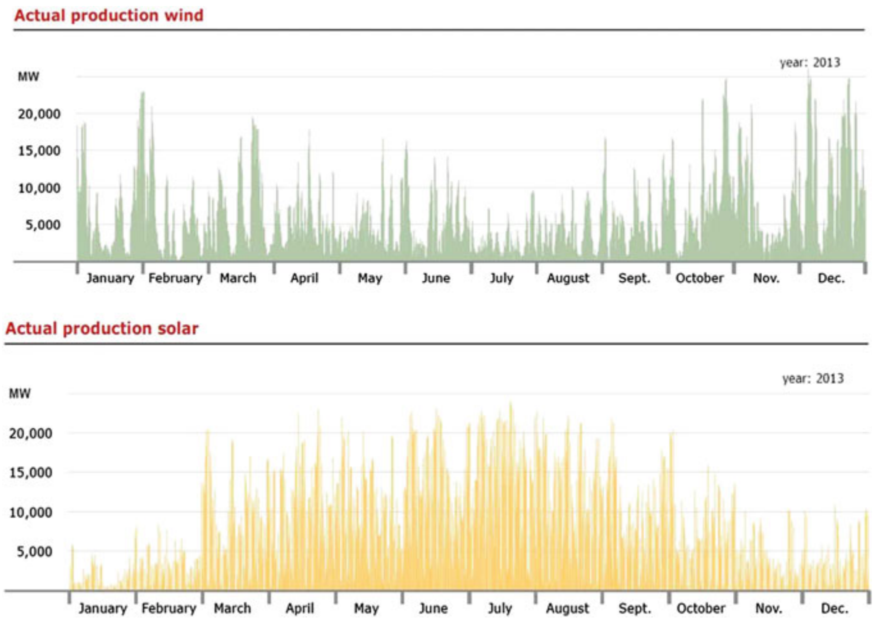

Fig. 7 Actual wind and solar power generation in Germany in 2013 [11]

here, because of the chain of interests of the businesses involved, as they arose after the deregulation, with the Distribution System Operator (DSO), retailer, and possibly other roles, being distinct commercial entities.

In summary, the exemplary case of Germany shows a total installed renewable capacity of 77.36 GW, predicted to rise to 90 GW by 2020, an average load of 60 GW, with peak 70 GW, (2013) [10]. With these numbers, the "100 % renewable mode" is a possibility now, and a likely event after 2020. To guarantee the power quality levels we have today, the most critical factors are going to be energy storage and real-time control, wide-area monitoring and control, and a new architecture for power distribution.

So the new facts influencing the electrical energy scenario and that make it a complex infrastructure interconnected with other complex infrastructures are:

- The storage options (e.g., gas grid, e-vehicles, and thermal capacity of buildings) are heterogeneous; to achieve the amount that is needed, they all must be exploited. As a result, more coupling points would connect the related infrastructures. To quantify the impact of some of these factors, consider for example that 10 million of electrical cars would represent a potential storage in the order of 10–100 GWh.
- The presence of DC technology, in HV and MV, supporting the optimization of energy flows is a realistic option for strengthening the transmission system via

HVDC links. DC is in particular directly applicable in some scenarios, such as an MV DC collector grids for offshore wind farms, so as to easily accommodate connection of renewables.

- Fast, real-time monitoring and control in MV and LV networks.
- Links among energy grids, particularly at district level, where heat, MVDC and LVAC networks may provide a solution that is not invasive at household level but creates the condition of optimal overall use of available energy.

The new interconnections between different infrastructures involve:

- heterogeneous physical forms of energy and related storage capacity (e.g., heat, electrical, gas, environmental)
- heterogeneous forms of each energy type (AC, DC, various voltage levels)
- topological small and large scale (e.g., neighborhood, city, region)
- large and small individual power levels (aggregated small resources, e.g., fleets of e-vehicles, distributed generation, and large wind farms)

In synthesis, the fact that the critical infrastructures are coupled in various combinations of the above list, shows what a challenge is to try to understand the global behavior and model it, test the sensitivity to the occurrence of disruptive events, and design a comprehensive monitoring and control system.

In this framework, what is a Smart Grid? Many definitions are provided, depending on the level of implementation [12–14]. A major common element of these definitions is the presence of two-way flows of energy and information, which enforces new requirements on the measurement/metering infrastructure, and urgently calls for the development of new standards. The pathway to smart grids can be structured according to the natural partition transmission-distribution.

With particular reference to the electrical system, the transmission grid, partly already "smart", may achieve better efficiency via power routing through power electronic devices, such as FACTS (Flexible Alternating Current Transmission Systems). At the distribution level, the full deployment of automation would enable the involvement of the customers in peak shaving, generation (via the Virtual Power Plant VPP), storage, and possibly in grid supporting services.

Several standards address areas that are relevant for Smart Grids, the main ones being

- Automation within the Substations: IEEE 61850 completed and active
- IEC 61970-301 with extension IEC 61968 (in particular part 11)—Common Information Model (CIM)
- Series of IEEE 1547 for Distributed Resources

Gaps in the standards have been identified and reference documents to address them have been published, leveraging on the most recent research work. The USA and EU roadmaps can be found in NIST Special Publication 1108—NIST Framework and Roadmap for Smart Grid Interoperability Standards [15], and the

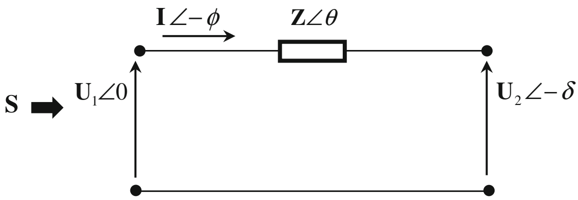

Fig. 8 Model of a line and complex through power

Standardization Mandate (M/490) to European Standardization Organisations (ESOs) to support European Smart Grid deployment [16], respectively. In particular, the Standardization Mandate (M/490) of the European Commission caters to European Standardisation Organisations (ESOs) to support European Smart Grid deployment. These organizations have eventually produced the Final Report of the CEN/CENELEC/ETSI Joint Working Group on Standards for Smart Grids [17].

In the power system infrastructure, the distribution system is expected to undergo the deepest transformation. The presence of power injections at all voltage levels and the presence of controllable resources calls for methods for state estimation, distributed control, and requires new infrastructures (for measurement, computation, communications). Such methods and infrastructures have been, up to now, typical of transmission systems. And the migration of the related transmission system technologies to distribution systems is a challenge [18] in terms of size of the system and characteristics. In fact the distribution system has orders of magnitude more nodes than the transmission system; at present time very limited instrumentation and actuators, especially in the LV section, where it is also poorly known and modeled (in terms of topology and parameters of existing systems) and features different characteristics of the lines.

Consider, for example, the impact of the assumption, commonly accepted for transmission lines, that lines are primarily "reactive", meaning that $R \ll X$, where R is the resistance and X is the reactance of the line. This assumption influences the model of the dependence between active and reactive power flow, and the terminal voltages. Such model is then used in monitoring and control, and so if this assumption does not hold, the related analytical derivations are not applicable, and the same can be said of the derived monitoring and control methods. Hence, for distribution systems, where this assumption usually does not hold, such existing methods developed for transmission are not in general directly applicable.

With reference to Fig. 8, the active and reactive power through a line with impedance Z are given by:

$$\begin{aligned} P &= \frac{U_1^2}{Z}\cos\theta - \frac{U_1 U_2}{Z}\cos(\theta+\delta) \\ Q &= \frac{U_1^2}{Z}\sin\theta - \frac{U_1 U_2}{Z}\sin(\theta+\delta) \end{aligned} \tag{1}$$

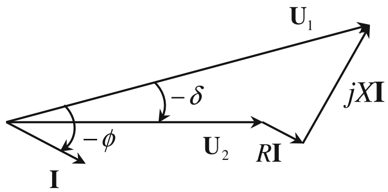

Fig. 9 Terminal voltage and current angles for line in Fig. 8

where

$$Ze^{j\theta} = R + jX$$

The phasor diagram of voltages and currents in this example is shown in Fig. 9. The active and reactive power can also be expressed as:

$$\begin{aligned} P &= \frac{U_1}{R^2 + X^2}[R(U_1 - U_2\cos\delta) + XU_2\sin\delta] \\ Q &= \frac{U_1}{R^2 + X^2}[-RU_2\sin\delta + X(U_1 - U_2\cos\delta)] \end{aligned} \tag{2}$$

The assumption mentioned above, that R ≪ X, allows for the approximation δ ≈ sin(δ), and thus:

$$\begin{aligned} P &\cong \frac{U_1U_2}{X}\delta \quad (\text{hence}\, P \propto \delta) \\ Q &\cong \frac{U_1^2}{X} - \frac{U_1U_2}{X} \quad (\text{hence}\, Q \propto U_1 - U_2) \end{aligned} \tag{3}$$

These simplified relations are the basis for control methods and state estimation decoupling in transmission systems. As the underlying assumption does not hold in distribution systems, where instead R ≈ X, then such control and monitoring methods can not be directly adopted.

4 Overview of Power Systems Control

In a broader perspective the management of the power system can be summarized in market, business management and energy management, as in Fig. 10.

The focus here is the Energy Management System (EMS), which pursues two main goals:

- Production cost minimization
- Loss minimization

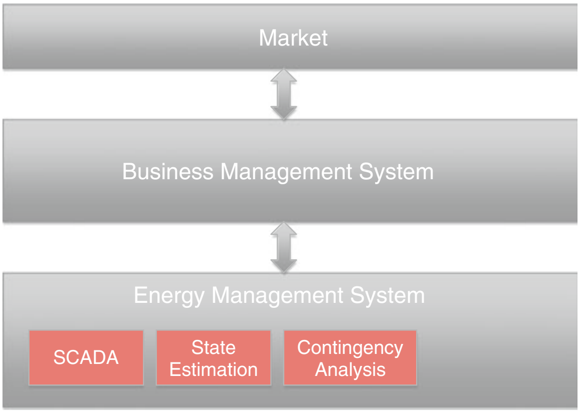

Fig. 10 Power system management

To achieve these goals, the following elements of action are used:

- Generator output control
- Phase shift control (to control voltage phase angle and hence power)

The EMS manages the power system and the power flows. This is done through the central control station and the distributed control centers with delegated control (collecting data and acting on a portion of the system). The management process relies on the Supervisory Control and Data Acquisition system (SCADA) and on the communication links from the control center to primary devices (generators, circuit breakers and tap changers). To realize this link, the devices are equipped with IED (Intelligent Electronic Device) interface actuators, to enable the remote control. Remote Terminal Units (RTU) are computer based interfaces to IEDs and other equipment, capable of local processing and control functions and of maintaining the communication with the SCADA.

The SCADA is a platform, with the basic functionality to classify and handle events, alarm processing, monitoring, and some system level control actions. It comprises the control room system, communication and remote terminal units, and its functions can classified in process database, Man Machine Interface (MMI), and application software. In particular:

- Data acquisition (from the system equipment) and processing
- State estimation (on the basis of the data collected at the substation level) and related ancillary functions
- Control of the transmission system equipment and alarm notifications to operators
- Event and data logging
- MMI
- Voltage control

Considering the layers utility-network-substation-distribution-consumer, the SCADA may be deployed to control different layers in an integrated manner as one system, or as separate systems, passing on data and information to the layer that is hierarchically superior.

The EMS operates through SCADA to achieve the following:

- Generation reserve monitoring and allocation
- Quality and security assessment, and state estimation
- Load management
- Alarm processing
- Automatic generation control (comprising load frequency control (LFC), economic dispatch (ED), and control for limiting the tie line flows to contractual values)
- Inter-control center communications

Reserve monitoring and allocation is needed to guarantee stability by addressing imbalances, as later explained in detail, and requires awareness of resource availability, location and timings. State estimation yields the current state of the system and it is the basis for contingency analysis ("what if" scenarios, to preempt and tackle large disturbances caused by loss of generation or lines) and assessment of the operating conditions, in terms of quality and security. Load management deals with the emergency procedure of balancing load and generation by dropping some of the loads, to rescue the system from potential instability. Alarm processing deals with alarms originating from tripping of protection breakers and violation of thresholds. Automatic generation control dispatches generators according to day ahead set points, but also for real-time regulation in presence of frequency deviations or deviations of tie line flows between areas when exceeding contractual limits. Finally, communication to other control centers guarantees a certain level of coordination in the above actions, that affect the operation of the system over a broad area.

While the functions above are typical of transmission system control centers, the same concept of "automation" applies to the distribution system, covering the entire range of functions, from protection to SCADA operation. The Distribution Automation System is a set of technologies that enables an electric utility to remotely monitor, coordinate and operate distribution system components in a real-time mode from remote locations.

The Distribution Management System (DMS) in the control room coordinates the real-time function with the non-real-time information needed to manage the network. Two basic concepts of distribution automation can be defined:

- Distribution Management System enables the Control Room operation and provides the operator with the best possible view of the network "as operated"
- Distribution Automation System fits hierarchically below the DMS, and it includes all the remote-controlled devices and the communication infrastructure.

The DMS comprises:

- SCADA of substations and feeders
- Substation automation
- Feeder automation

- Distribution system analysis
- Application based on Geographic Information System (GIS)
- Trouble-call analysis management
- Automatic Meter Reading

The SCADA of substations and feeders coupled with RTUs serve as supporting hardware to the DMS in monitoring, providing data collection and event logging, and generating reports on system stations.

The functions of the distribution automation can be summarized as follows, given that not all of them may be active in all distribution control centers:

- Demand-side management
- Voltage/VAr regulation
- Real-time pricing
- Dispersed generation and storage dispatch
- Fault diagnosis and location
- Power quality
- Reconfiguration
- Restoration

5 Control Methods

Existing Primary-Secondary-Tertiary control schemes and state estimation methods are reviewed in this section. Their applicability to distribution systems is under investigation; in fact, active distribution systems are expected to require new controls to limit perturbations. These include propagation of power fluctuations to the transmission system, and internally active and continuous regulation of voltage, regulation of frequency, load and generation balance. Some of these control modes of the distribution systems are rather futuristic, but may help contain the adverse effect of some of the issues caused by the distribution grid transformation mentioned in previous sections.

In the context of frequency control, as reported in Fig. 11, the control levels are so defined and characterized [19]:

- Primary Control (reaction time <30 s) represents the autonomous reaction of generators. Generators exhibit an individual speed-droop characteristic, and their reaction, accordingly, is individual too (independent for each turbine). This control method results in a steady-state frequency deviation different from zero.
- Secondary Control (reaction time 15 s–15 min) consists of enforcing a change or shift of the speed-droop characteristic of the generators. This centralized direction to the turbines enables the return to the nominal frequency of the system, under different loading conditions, preventing undesired power flows within different areas. Eventually, this control eliminates deviations through the Area Control Error.

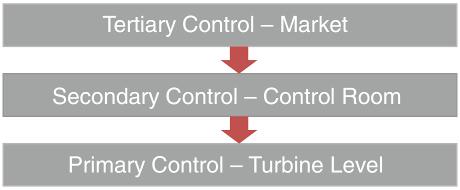

Fig. 11 Power system control scheme

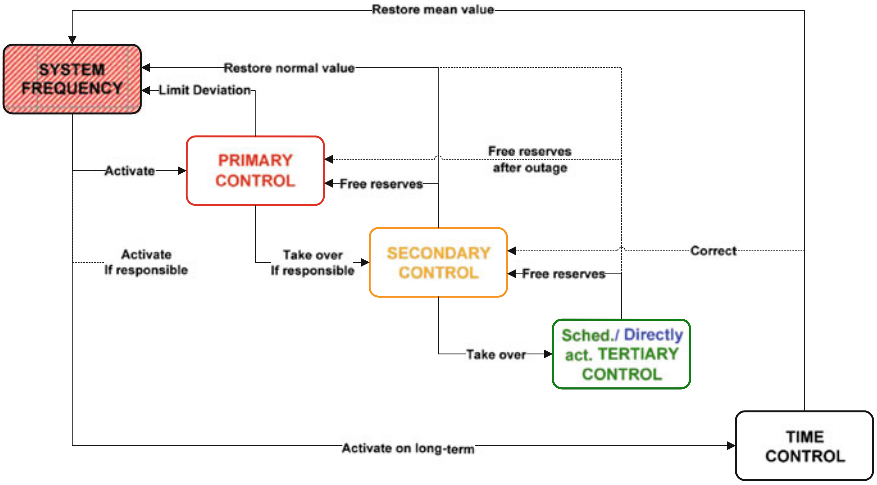

Fig. 12 General scheme of load-frequency control, in UCTE Handbook ENTSO-E [20]

- Tertiary Control (reaction time >15 min) optimizes the overall system operating point (set-points). This is achieved by setting the reference generation for individual generation units so that it is sufficient for secondary control. Reserve is distributed among the available generators in a way that is geographically distributed, and accounts for the various economic factors of each generation unit.

The relation between Primary, Secondary and Tertiary control in response to an outage is shown in Fig. 12.

The generation and load characteristics, resulting in the determination of the operating point are exemplified in Fig. 13 through Fig. 16. Figure 13 shows the characteristic frequency versus active power of the controlled turbine-generator set, which can be written as follows (for the linear portion):

$$\frac{\Delta P_G}{P_{GN}} = -k_G \frac{\Delta f}{f_N} \tag{4}$$

with P_{GN} being the nominal power of the generator, ΔP_G the deviation from nominal of the actual active power of the generator, f_N the nominal system

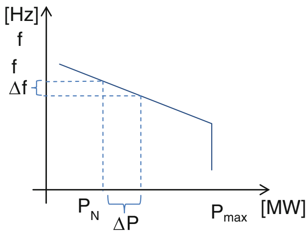

Fig. 13 Generation characteristic of one individual generator

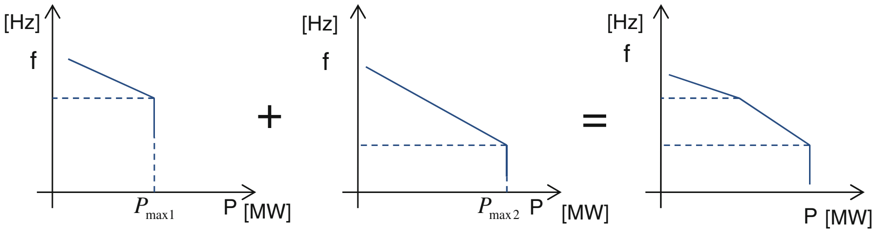

Fig. 14 Combination of two generation characteristics

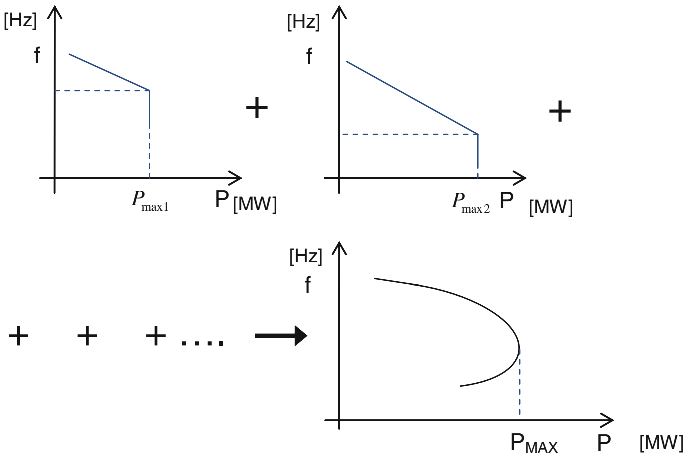

Fig. 15 Combination of generation characteristics

frequency in Hz, Δf the frequency deviation and k_G the characteristic coefficient. Notice that a reasonable assumption is that $k_G \approx 20$, which means that a 5 % frequency deviation corresponds to 100 % deviation power output.

The simplified combination of two such generation characteristics within an interconnected system is graphically shown in Fig. 14. In a system with multiple

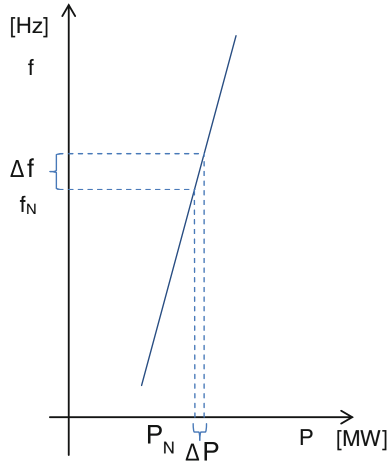

Fig. 16 Load characteristic

generation units, the combination of the characteristics results in the so called droop nose curve, as shown in Fig. 15. This curve shows the capability limits of the primary control, which has a stability limit at power P_{TMAX}.

The active characteristic frequency vs active power of the load is shown in Fig. 16, where ΔP_L is the variation from the nominal load P_{LN}, and k_L is the load coefficient. Notice that the load characteristic shows a weaker dependence than the generation characteristic, in fact, the load coefficient k_L is usually within the range $0.5 \div 3$. This characteristic can be expressed as follows:

$$\frac{\Delta P_L}{P_L} = k_L \frac{\Delta f}{f_N} \tag{5}$$

Given the generation and load characteristics, the operating point is determined by the intersection point, ideally at nominal frequency. Figure 16 shows the effect of the Primary Control, in case of a load increment. The initial operating point is (P_1, f_1) on the characteristic P_L^{old}.

From here, we assume that the load increases by ΔP_{Demand}. In other words, the load characteristic changes to P_L^{new}. The new desired operating point, at frequency f_1, lies on the characteristic P_L^{new}, but cannot be reached with the given generation characteristic. Instead, given the generation characteristic, the new operating point is (P_2, f_2), where the generation provides extra ΔP_G, the load comes short of ΔP_L and the frequency deviates to f_2 from the initial frequency f_1. This is the result of the Primary Control of the turbine. If the new operating point is sustainable, and the frequency within the acceptable limits, the control action has been sufficient and successful. Otherwise, if the new operating point is not sustainable, the secondary control must kick in.

Notice that only generation units that are not already fully loaded can contribute with the behavior exhibited in Fig. 17. The margin ΔP_G was in this case available, implying that at the initial operating point (P_1, f_1) the machine was not fully

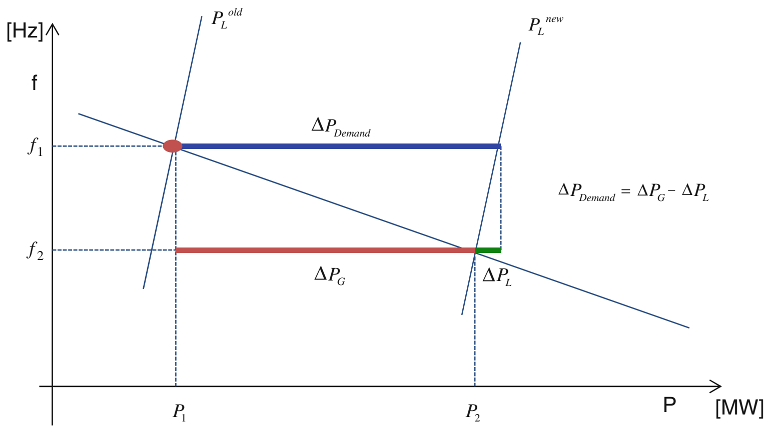

Fig. 17 Generation, load and frequency deviations in response to primary control

loaded, i.e., it had "spinning reserve". Hence it can be seen that the role of the spinning reserve is critical. Furthermore, the spinning reserve must be properly sized, to address most of the normal load variations, and well distributed, to avoid overloading of the lines.

The intervention of the Secondary Control consists of the modification of the characteristic of the individual generators, which results in the modification of the global generation characteristic. The new references are originated centrally with the objective of taking the frequency back to the original value, and are distributed to the generation units.

The effect of this control is shown in Fig. 18. To sustain the new load demand while maintaining frequency f_1, the new operating point should be (P_2', f_1). Hence, the generation characteristic must be different from P_G^{old}, in particular, it must be P_G^{new}. The new operating point eventually is (P_2', f_1), belonging to the characteristics P_G^{new} and P_L^{new}.

The power through the tie lines represents a constraint centrally enforced here. The scheme of a Secondary Control with proportional-integral (PI) structure is shown in Fig. 19, where the Area Control Error (ACE) is obtained in terms of power shortage, combination of power demand inferred from the frequency deviation and deviation from reference power flow through the border of the area. The ACE is then the input to the PI controller which produces the total power deviation to be compensated for by the controlled generators. This quantity is then split among available generators according to indices α_i.

In conclusion, initially, the operating point of each individual power generation unit is set according to the Optimal Power Flow, to minimize global generation cost while satisfying network constraints. Corrections to instantaneous deviations between generation and load are in first place addressed by the Primary Control, hence adequate spinning reserve must be available for units participating in Primary Control. The resulting frequency offset, is corrected by the Secondary

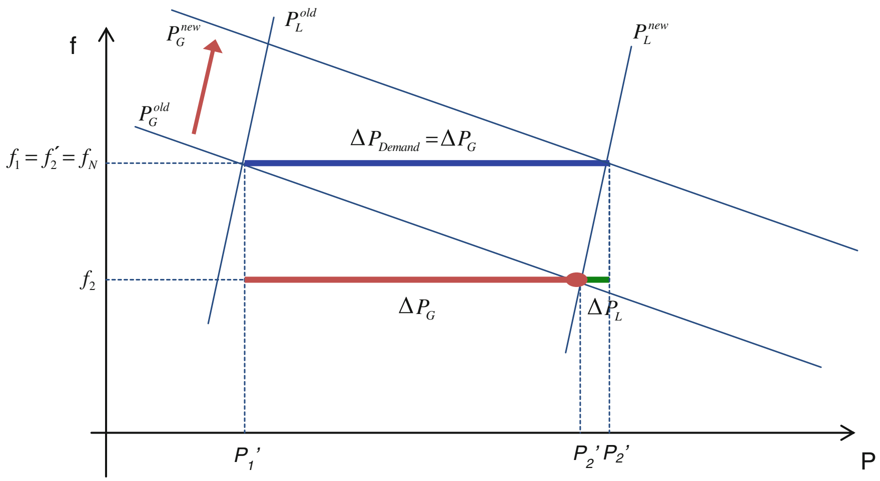

Fig. 18 Generation, load and frequency deviations in response to primary and secondary control

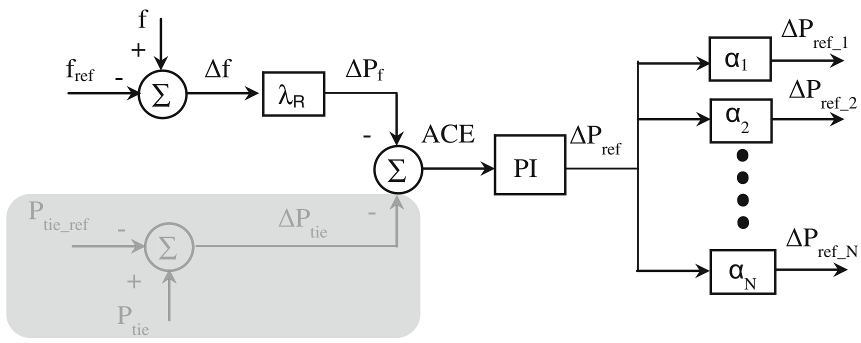

Fig. 19 Secondary PI control

Control that is expected to realize the optimal dispatch of units participating in Secondary Control.

Given the increasing number of generating entities, extending the control concept presented above may be a challenge, because of the large amount of data to be handled in a centralized manner. To increase the survivability of the system, single points of failure, such as the centralized secondary control, should be avoided. Furthermore, future control approaches should support opening the market to new players, for example aggregators of virtual power plants, and should support the Plug and Play concept, especially when extending these control approaches down to the distribution level. Distributed control technologies are under investigation for this purpose.

6 Monitoring of the Future Grid

The most comprehensive monitoring function is the state estimation, yielding the state of the system in terms of voltage phasors at all nodes. This knowledge is used to determine security conditions and as a starting point for contingency analysis. While state estimation is a well established practice in transmission systems, its application to distribution systems is in the developing phase.

The state estimation process is based on the following steps: definition of the current topology of the system, based on breaker and switch status; observability analysis and determination of observable islands; solution of the state estimation problem as determination of the most likely state of the system given the measurements, assumed to be affected by random errors; bad data detection and correction; determination of errors of initially adopted parameters and topology.

In general (although methods to overcome these limits are in full development), some assumptions are made that can be difficult to sustain in certain cases, particularly when applied to distribution networks. These assumptions are:

- The system is balanced, hence it can be represented in terms of direct sequence, and the system evolves slowly.
- Measurements are collected during one scan of the SCADA system, hence a certain time skew is to be expected and tolerated. Usually no dynamic model is included.
- Measurements may originate from the field, but may also consist of statistical information, such as load profiles. These so called pseudo-measurements, are usually affected by large uncertainty, particularly when they refer to grids with pervasive presence of renewable sources, for which historical record over a significant period of time is not yet available.

In distribution systems in particular, measurements from the field are often limited to primary substations, and possibly in the near future secondary substations, and in principle (experimentally used) the measurements from smart meters at the customer premises.

The classic formulation of the state estimation problem, formalized here in terms of measurement equations (where measurements may be active and reactive power flows and injections, rms voltages and currents) with measurements z_i, states x_i, (non-linear) measurement functions h_i and measurement errors e_i. The state of the system consists of voltage rms and phase at all nodes (with respect to a reference bus whose phase is not estimated, but assumed or measured).

$$\begin{bmatrix} z_1 \\ z_2 \\ \\ z_m \end{bmatrix} = \begin{bmatrix} h_1(x_1, x_{2,} \ldots, x_n) \\ h_2(x_1, x_{2,} \ldots, x_n) \\ \\ h_m(x_1, x_{2,} \ldots, x_n) \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \\ e_m \end{bmatrix}$$

Some common assumptions are that the measurement error has an expected value equal to zero, with a normal distribution and a known covariance matrix, often assumed to be diagonal. This over-determined, non-linear problem is then solved recursively according to the maximum likelihood criterion, with a Weighted Least Squares approach. The setup of the numerical problem is to be preceded by an update of the topology of the model of the network, observability analysis, and followed by bad data detection and identification, and verification of topology and parameters, as mentioned above. For details and other possible formulations refer to [21].

In this framework, the synchrophasor measurements, via Phasor Measurement Units (PMUs) [22, 23] are one of the most interesting developments, for transmission grids and, although at some extent futuristic, for the distribution grids. These measurements consist of synchronized rms voltages and currents and phases with a common reference. These measurements can support state estimation by augmenting the classical set of measurements, and find application in advanced monitoring and control applications [24], particularly over wide areas, where the synchronization feature can be well exploited.

A further development in state estimation consists of the implementation of dynamic state estimation. This is increasingly needed in systems that feature rapidly changing conditions, with much smaller inertia than in the past, due to the presence of many power converter interfaced sources, and less large rotating masses. Various approaches to dynamic state estimation and dynamic estimation of the error, have been proposed, many through Kalman filters [25].

While a well-established process for transmission grids, substantial challenges remain in the application to distribution grids. Here, current estimation as opposed to voltage estimation and the use of three-phase estimators to accommodate the presence of imbalances are the two major differences from established transmission state estimators. The primary issue in distribution remains the lack of accurate knowledge of topology and parameters and the lack of measurements. In fact, the "full" state estimation is affected by a lack of actual measurements, which forces an extensive use of pseudo-measurements with poor accuracy. Furthermore, classical state estimation yields phase angles, whose use in applications in distribution systems is at the moment rather limited. And finally, if applied at all nodes in the system, the classical estimation procedure may be cumbersome and at the present time not necessary to the Distribution System Operators.

The potential and performance of the state estimator is heavily dependent on the measurements, in terms of location, type and quality. And such measurements must fulfill other needs besides state estimation, for example metering for billing, as the customer smart meter, or protection. Hence, the decisions on where and how to deploy new measurement equipment, besides satisfying regulatory requirements, is to be seen as a multi-objective optimization. This is an ongoing research topic that accounts for technical issues (of the power and communication system jointly) together with economic issues (accommodating incremental deployment through near optimal "temporary" stages).

Finally, the distribution of the state estimation function may become necessary due to the size of the problem and the amount of measurements to be communicated, for networks with a large number of nodes, for dynamic estimation and in applications where the state estimate is used in time critical functions. A framework to assess state estimation methods, needs, and requirements, particularly in terms of accuracy and dynamics, and particularly for distribution systems is not yet shared knowledge.

7 Advances in Controls for Future Grids

The advances in controls outlined in this section address the increasing complexity of the power system and its dependence on the coordination of distributed resources, thus highlighting the role of communication. The quality of service and stability in generation, transmission and distribution are now linked to one another, while each group is actively controlled for local and global objectives. In general, we can say that dependencies across levels, which once were hierarchically and unidirectionally controlled, are now reconsidered to improve the operation of the system and accommodate new types of sources. However, these same dependencies also create new and easier paths for the propagation of disturbances. This is the scenario that new controls must be designed for.

7.1 Integration of Distributed Energy Resources: The Sample Case of Photovoltaic Systems

The integration and management of distributed energy resources (DERs) is one of the most significant challenges of future grids. In this context, the microgrid concept may facilitate the integration by coordinating the automation of a sub-section of the grid. At present, most of the DERs are not involved in the automation process, hence they do not increase local efficiency and they are not involved in the reactive power management, so they do not support network stability.

The case of photovoltaic (PV) systems in the low voltage (LV) grid is here taken as an example to demonstrate the feature and potential of DERs. From the regulatory standpoint, codes are defined in EN 50438:2007, now superseded by FprEN 50438:2013 in the approval stage. Voltage constraints are set by EN 50160 and result in low voltage being regulated.

In the future, PV sources may likely be asked to provide reactive power for voltage control along the feeder, through one of the following methods:

- $\cos\phi$(P) characteristic
- fixed $\cos\phi$ method
- fixed Q method
- Q(U) droop function

During normal grid operation, the active power flows from sources to loads (grid node S > L). The magnitude and direction of reactive power flow can be influenced by reactive power injection via PV inverters. Due to this reactive power control the voltage magnitude at the Point of Common Coupling (PCC) "L" can be actively influenced.

A voltage violation larger than the acceptable limit can be compensated for by setting the PV inverter to an "inductive angle" equal to $\varphi_{PV} = arctan(Q_{PV}/P_{PV})$, which implies shifting the operating point along the characteristic. This control method requires the ability of the PV inverter to control reactive power injection, which is not currently a common feature. Furthermore, the presence of multiple PV systems connected to the same PCC requires coordination, which may be better realized in a distributed manner, for example as in [26].

7.2 Microgrids

A microgrid is a section of a power grid connected through a main switch (MS) to the main power line as in Fig. 20, with local distributed generation and loads, and characterized by the following properties:

- It is equipped with local generation and it is then able to operate independently from the main grid
- It is equipped with a hierarchical control that can manage two main operating states:
  - Parallel mode
  - Islanding mode
- It is equipped with a central controller, in charge of detecting conditions that require to switch from parallel to islanding mode

In parallel mode the microgrid controller coordinates power dispatch of local sources (economic optimization) so the microgrid operates in parallel to the grid implementing synchronization action. In islanding mode, the local sources operate typically according to a droop control logic for P and Q, while the central controller may implement functionalities similar to secondary control or/and change droop coefficients.

The control structure of a microgrid may be summarized as in Fig. 21, where the central controller (CC) functions are Energy Management and Protection Coordination, while the local controller of the DER realizes the local implementation of the control commands from the central controller.

The control structure is schematically shown in Fig. 22, where the feedback variables have the following meaning with reference to Fig. 23:

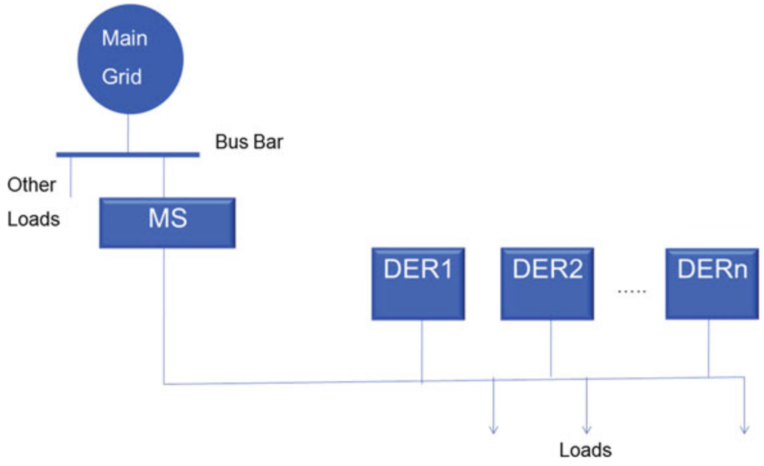

Fig. 20 Generation and load in a microgrid

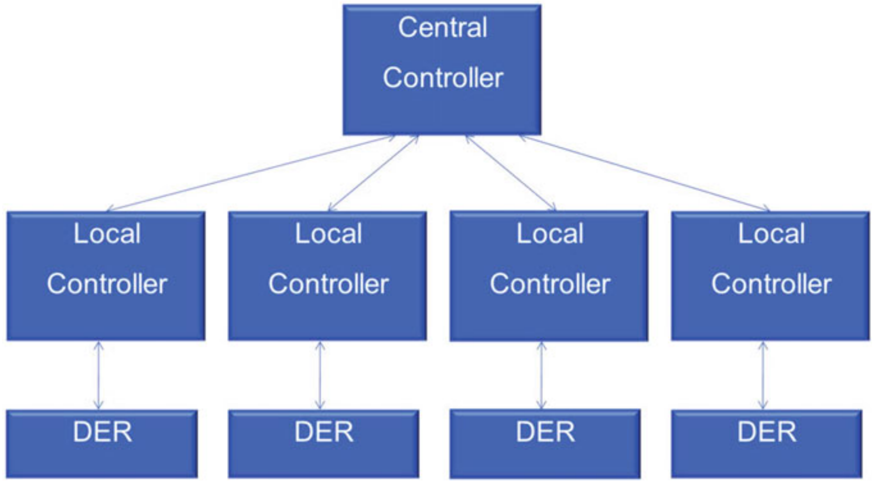

Fig. 21 Microgrid control structure

- i_l: current through L_f
- v_c: voltage across C_f
- i_o: current through L_o
- p, q: active and reactive power reference in the Park domain for the inverter

The more modern state space-based approach can be adopted instead of the nested loop control. In this case Optimal Control and Linear Quadratic Regulator are the typical choices. These control methods are presented next in the more general framework of distributed generation management.

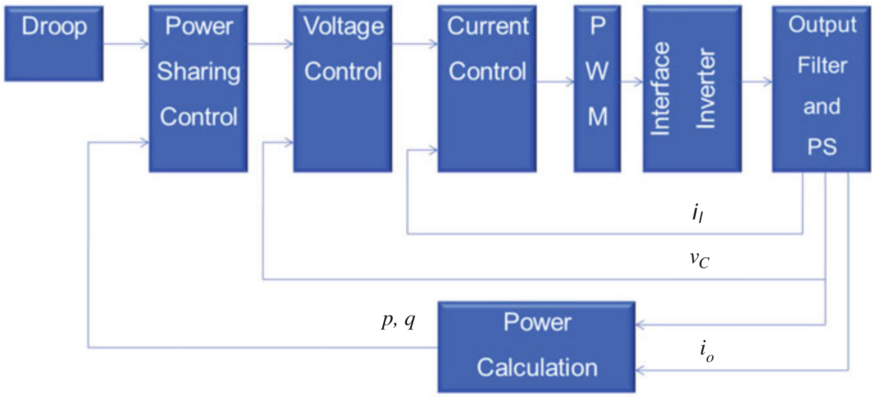

Fig. 22 Control structure of a DER in a microgrid

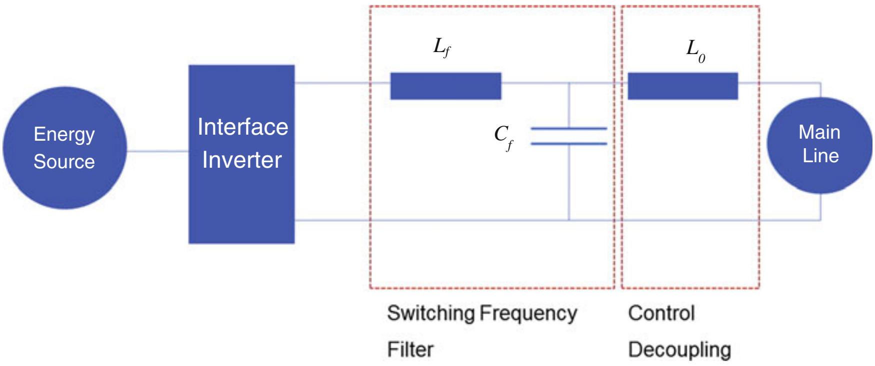

Fig. 23 Interface between each distributed resource and the main line

7.3 Control of Distributed Generation

Distribution of monitoring and control functions in general [27], and control of distributed power generation (DPG) in particular, has been investigated widely regarding stability, grid connection behavior, voltage control and power flow, as for example in [28, 29]. In particular, distributed control methods for parallel power inverters have been investigated in [30–32] where the conventional PI controller is used. Advanced control methodologies, in particular decentralized optimal state feedback [33] and distributed model predictive control (MPC) in [34, 35] have also been proposed. The following section discusses in particular the linear quadratic Gaussian control, based on the theory of optimal linear quadratic regulator (LQR), in its decentralized version.

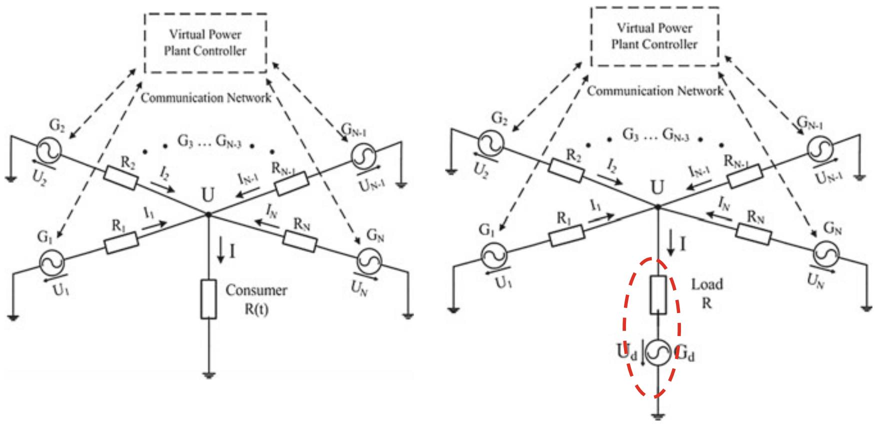

Fig. 24 Simplified model of a DPG network [38]

7.4 Distributed Optimal Control

7.4.1 Decentralized Control Based on Incomplete System Knowledge: Local LQG + Local on-Line Learning of $U_d(t)$ + Local Set-Point Adaptation

Although at present decentralized/distributed controllers are assumed to operate independently, their design is based on a global model of the overall system. In [36] a decentralized linear quadratic Gaussian (LQG) control approach is investigated for droop control of parallel converters through emulation of a Finite-Output Impedance Voltage Source. The design of the decentralized controllers presented in such work is based on local models of the inverters, without communication, and response to disturbance, such as load variation, is not considered. Similarly, in [37] a decentralized LQG control approach is designed, based on local models of a simplified DPG network with incomplete system knowledge. In this approach the local controllers operate individually without knowing and communicating with each other. The control objective is to reject the load variation, modeled as a step disturbance arising in the network. In line with this, each local controller adopts online learning of the disturbance and adapts its own set-point individually. Rejection of the disturbance is achieved after a short transient period, which is also corrected for by the controllers automatically.

The model of a DPG network [38] is shown in Fig. 24 with N linear electrical DC power generators $G_1,\ldots,G_N$. The constant load R can be interpreted as the average of many consumers. The variation of the load is modeled by the generator G_d that produces a time varying voltage U_d.

The power lines are modeled as resistances $R_1, \ldots, R_N$. Due to Kirchhoff's laws, the voltages and currents of all generators are coupled. As opposed to conventional decentralized control synthesis, in which the network is fully known,

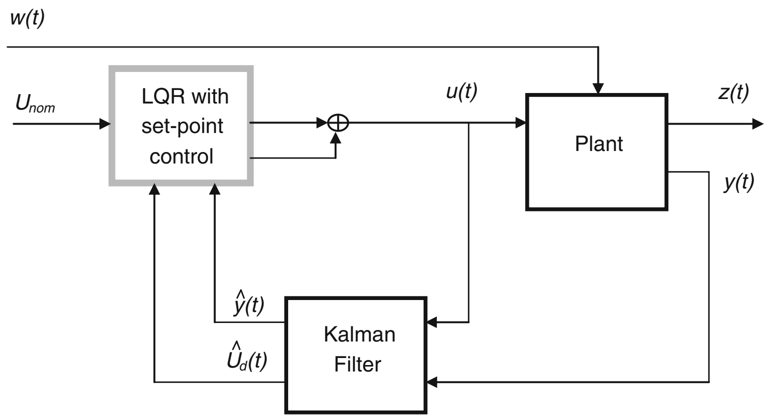

Fig. 25 Structure of the local LQG controller of an individual generator

it is assumed here that each generator is unaware of the presence of any other generator in the network, and it operates as the only generator providing power. In this case, the behavior of each generator is regulated by a local controller based on a local model with incomplete knowledge of the network. The local model from the viewpoint of generator G_i only consists of the elements that are depicted and connected by solid lines, while the rest of the real power grid is invisible to G_i.

The local controller of each generator implements the linear quadratic Gaussian control method, designed with the control objective to reject the influence of the disturbance voltage U_d on the system voltage U, to be kept equal to the constant nominal reference voltage U_{nom}. Each local LQG controller measures the current value of U instantaneously and pursues the objective individually. Thus, each local LQG controller aims at minimizing the squared output error voltage (U-Unom) over the infinite time horizon in the presence of disturbance and measurement noise. Since we model the disturbance *Ud* as a step signal representing on-off switching of loads, the set-points of the LQG controllers have to be adapted. For the set-point adaptation, each local controller estimates the disturbance by regarding it as an additional state in the system dynamics. The structure of the local LQG controller of an individual generator is shown in Fig. 25. Notice that the local model differs from the full model of the power network, which also implies an inherent modeling error of the local model. Hence, the estimation of the disturbance does not lead to the estimation of the actual disturbance U_d, but of a fictitious time-varying disturbance resulting from U_d and from the unknown dynamics of the other generators and their controllers. Nevertheless, it can be shown that this process is fast and it leads to the stable behavior of the system.

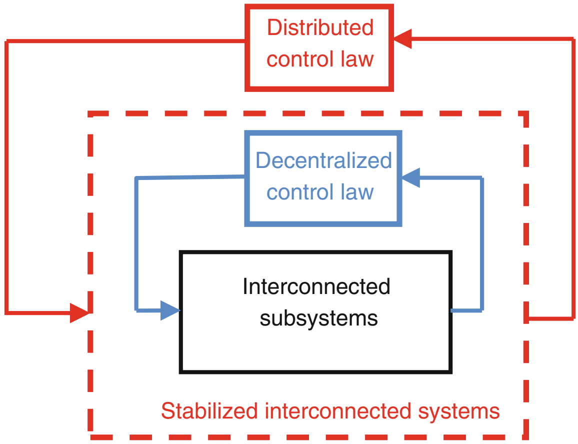

Fig. 26 Two-layer architecture for small signal stabilization

8 Wide Area Monitoring and Control

The small-signal stability of the power system is an important requirement for power system operation. Low-frequency oscillations may possibly cause blackouts or limitations in the power flows. According to the classical control approach, local generator controllers are expected to intervene through the Automatic Voltage Regulator (AVR) and the Power System Stabilizer (PSS). The concept of the Wide Area Measurement and Control System (WAMCS) is to collect accurate information about power system dynamics to support efficient control strategy and enhance the small-signal stability. These information, for example from synchronized phasor measurements or remote signal and information sources are enabled by a wide area communication network.

This points at how the communication network represents an important design parameter, and how it affects the control performance. In fact, adding links may degrade performance [39].

A joint design of controller-communication topology for distributed damping control may be performed and realized via a two-layer architecture for robustness against communication failures, comprising decentralized and distributed control, as shown in Fig. 26. In a first step, the local feedback control law is designed for the *i*-th generator in order to stabilize the overall system only with a local controller and to provide the minimal damping performance. In a second step, the distributed control law that operates on top of the decentralized control for the *i*-th generator, is designed to enhance the damping performance in terms of increasing the decay rate of the system. In this step, communication is accounted for as a cost of available communication links and a cost of new communication links, yielding to a mixed integer optimization problem.

In conclusion, this control architecture achieves:

- Stability, guaranteed by decentralized control
- Damping performance, improved by distributed control
- Robustness to permanent link loss

9 Conclusions

This Chapter presents the evolution of electrical power systems towards a complex system, deeply coupled with other critical infrastructures. New monitoring and control challenges, the consequence of the penetration of renewable sources, and the active behavior of most power system actors are reviewed, together with the basics of current control strategies for power systems.

Some examples of the technologies capable of addressing these challenges are described. Among the underlying commonalities, we identified the distribution of functions and the need to coordinate distributed resources. These features emphasize the dependence on the communication network. Furthermore, the utilization of volatile energy sources require the exploitation of all available flexibility, and the active participation of distributed resources starting from the renewable sources themselves.

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