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Research paper

Brief Review of Current Research on Electrical Grids

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ABSTRACT

Electrical grids play a crucial role in the global energy transition by providing reliable energy transport. They must accommodate the integration of decentralized renewable energy systems (RESs), which vary in scale, generation rates, and intermittency. Ensuring this integration requires modern grids with enhanced performance and reliability. Today, various types of electrical grids are undergoing modernization, especially with the rise of electric vehicles. Traditional power grids are being equipped with advanced solutions across transmission, sub-transmission, and distribution networks. This modernization also extends to microgrids, high-voltage direct current (HVDC) systems, and wide-area synchronous grids, contributing to the emergence of new concepts such as supergrids and smart grids. This paper reviews rapidly the current state of research on electrical grids development, emphasizing critical concepts related to grids modernization and intellectualization. It aims to serve researchers, academics, and utility engineers interested in the latest advancements in the field. The aim of this work is unique and has not been addressed before, as the topics related to electrical grids are dispersed throughout the literature in large quantity, but they have not been reviewed as a cohesive whole.

1. INTRODUCTION

Line-based electrical power transmission is generally preferred over resonant inductive coupling wireless transmission (Lin et al. 2021) due to its superior efficiency. Utilizing this approach, electrical lines cover various areas, from small to large scales, with the size of the area determining the grid's scope. The term power grid (Pagani & Aiello, 2013) is often used when an entire country or one of its regions is served, while microgrid Zahira et al. 2022) refers to coverage of a smaller area. When multiple

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power grids with the same frequency are interconnected, they form what is called a wide-area synchronous grid (Mayer et al., 2022). A supergrid (Ndlela & Davidson, 2022) refers to an enhanced power grid with substantially increased performance and transmission capacity, designed to support high integration of non-conventional loads and generation sources, such as electric vehicles (Anwar et al. 2022) and renewable energy systems (Djoudi et al. 2014). The type of electrical grid also depends on the current waveform. Most grids operate on alternating current (AC), while direct current (DC) grids—mainly used for high-voltage transmission (HVDC grids) over long distances—offer reduced costs and lower power losses.

A classical power grid functions as an electrical circuit that includes both single-phase and three-phase loads and generators. Its complexity arises from several key factors. First, the network's vast size, with numerous connection points linking a wide variety of consumers and producers, contributes to its complexity. Second, there is significant variation in cable and line lengths, which results in differing parameters across substations and connection points. Third, some integrated loads exhibit nonlinear behavior. Fourth, consumer power demands fluctuate unpredictably. Lastly, the power system must meet stringent operational conditions, such as maintaining grid frequency, voltage, current levels, and waveform integrity. Meeting these conditions is challenging, especially given the system's complexity and the potential for unexpected faults.

To operate that complex power system effectively, a structured methodology is required to ensure continuous power supply with the quality of electrical energy demanded by consumers. This quality is closely related to maintaining appropriate voltage levels and waveform integrity at connection points. The methodology considers the various operational states of the grid and includes a set of rules designed to meet these goals. These guidelines are specified in grid codes (Preda et al. 2012), which often adhere to established standards (Wu et al. 2017) to ensure the secure and efficient operation of grid components. Maintaining a consistent frequency across the grid near its nominal value is essential, as is keeping voltage levels within defined tolerable bounds across all parts of the power system. Frequency and voltage regulation are critical challenges in power system operations, especially in complex, multi-variable networks. Research in this area has reached a mature stage in some aspects, including the development, control, and design of grid components. Additionally, short- and long-term planning methods and optimization techniques are essential for efficient operation.

In many countries, power grids are increasingly incorporating renewable energy systems (decentralized production) across transmission, sub-transmission, and distribution systems. This shift introduces new challenges in addition to those faced by traditional power grids. One significant issue arises from the bidirectional flow of active power in some distribution-connected elements, as consumers now have the capability to integrate renewable energy sources. This change affects grid components and operational methods, making them different from those in conventional power grids. Optimization strategies, planning methods, and target goals also need to be adapted (Ullah et al., 2019). A similar complexity emerges when integrating decentralized renewable energy producers at high penetration levels into sub-transmission and transmission systems (Akeyo et al. 2020; Racz et al. 2018). The intermittent and variable nature of renewable energy introduces challenges for grid components, frequency and voltage regulation, and system stability. To address these, coordinated control across different parts of the grid is essential, achieved through information and communication technology (ICT) and computer systems. This setup forms the foundation of a smart grid, a widely researched concept due to its importance for the energy transition. Similar principles apply to microgrids, HVDC transmission systems, wide-area synchronous grids, and supergrids.

Recently, dispersed and large number of papers have been published in the literature covering topics related to power grids and other types of electrical grids. Among these, studies highlight grid security support, focusing on adjusting the power grid frequency in a steady-state regime through the participation of non-conventional loads and generators (Yang et al. 2024; Olasoji et al. 2024; Li et al. 2023;Ullah et al. 2024). Additionally, there are challenges concerning the integration of renewable energy sources and electric vehicles into the power grid (Verma et al., 2024; Qiyang Li et al., 2022, Jha & Shaik, 2023; Yang et al. 2014). Some research also addresses the integration of storage systems (Rana et al. 2023), resilience in operation under grid faults (Hossein et al. 2024), and various architectures of converter-based renewable energy sources (Wang et al. 2025). Other studies focus on components that improve electrical energy quality (Gandoman et al. 2018) and that function under transient regimes (Rafique et al. 2022). Since a microgrid is considered a small-scale power grid, the challenges related to its development are, in many ways, similar to those faced by larger power grids.

While these papers provide an accurate overview of their respective areas, they have not been compiled into a single comprehensive review that summarizes current research on electrical grids. Such a unified work would serve researchers, academics, and utility engineers, offering a thorough understanding of existing systems and ongoing developments in the field.

This paper addresses the current state of research on the aforementioned electrical grids. It provides an overview of automated, or "smart," grids and power grids, with some detail on their concepts. The rest of the paper is organized into seven sections. Section 2 discusses different categories of electrical grids. Sections 3 and 4 provide more details on smart grids and grid codes, respectively. Sections 5 and 6 focus on grid stability and the requirements for integrating renewable energy systems, as specified in certain grid codes. The paper concludes with a final section summarizing key insights.

2. CATEGORIES OF ELECTRICAL GRIDS

An electrical grid is seen as a network of lines needed to connect two electrical sides. An electrical side is defined as a set of loads, consumers or a set of points of another electrical grid. It permits to transfer of electrical active and reactive powers from one side to another. The manner in which different components of the grid are installed, protected and exploited depends on tolerated amplitudes and frequency of currents and voltages (Dupriez, 2009; Doulet, 1997; Calmet, 2009). It depends also on the waveform (continuous DC or Alternative AC) of the transmitted current (Alassi et al. 2019). The materials used along electrical lines are as consequence chosen mainly basing on that mentioned factors. The type of an electrical grid depends mainly on its voltage and power levels, as well as on the waveform of electrical states (currents and voltages). The notion of smart grid comes to be introduced recently in the literature in order to have a best management, monitoring and supervising of electrical grids using telecommunication and control technologies (Fan et al. 2021). Five types of electrical grids are distinguished as given in the Figure 1. The rest of the paragraph is structured in a way to describe the architecture of different electrical grids types.

2.1 Microgrids

The size of that category of grids is defined by its medium and/or low voltage levels. Mostly, that technology is dedicated to auto-electrification. The possibility of connection to the main grid can be envisaged in some cases (Debouza et al. 2022). Generally, that solution integrates renewable energy conversion systems like PV systems and wind energy conversion systems. Storage systems or diesel groups are mostly envisaged in order to ensure the equality between produced and consumed powers. The extracted power from PV or wind systems is mostly following MPPT algorithms (Majumder et al. 2021). Rectifiers, inverters, DC/DC converters, filters and transformers are utilized for driving and adaptation once required. Instrumentation material like currents/voltages sensors and control system is also used to get well driving. Sizing, protection and installation procedures need to be handled to meet relative standards (IEC, NF). It can require both medium and low-voltage transmission lines and cables depending to the size of the concerned microgrid. That is achieved mostly based on step-up or down-up transformers. The transfer ratio of each transformer is defined based on primary and secondary voltage levels. Three types of microgrids are distinguished, DC (Doostinia et al. 2022), AC or hybrid (Yang et al. 2022) as shown in Figure 2. DC microgrids are chosen because they allow to easily control the target system. The reactive elements do not exist which leads to a reduced cost of the installation. Frequency control is no longer required. However, the supervisor must ensure equality between consumed and generated powers. It permits to reduce the power losses and voltage drops. It permits also to increase the transferred power capacity of the electrical lines.

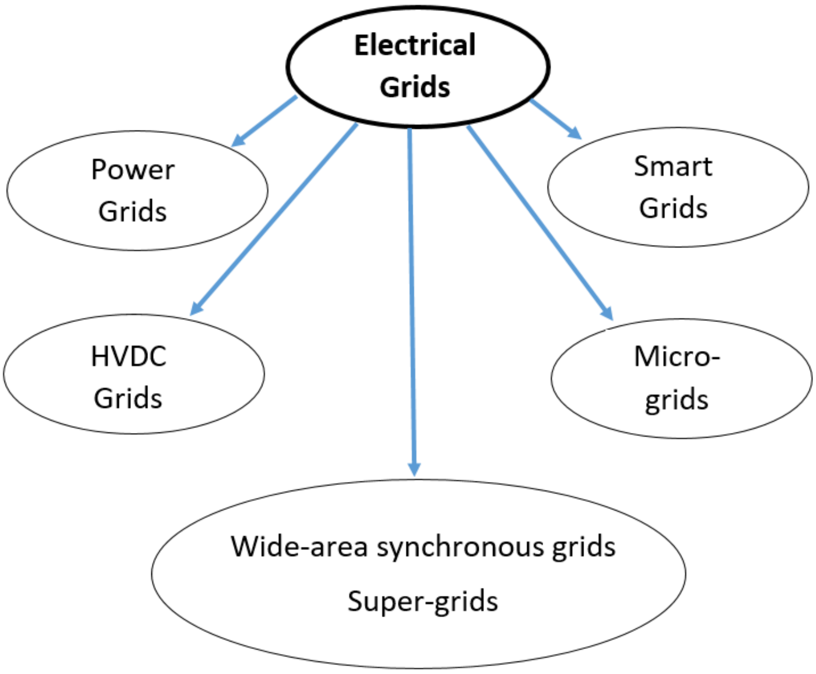

Fig 1. Types of electrical grids

That architecture may need additional components like AC/DC converters or solid-state converters (Mogorovic & Dujic, 2018) as an interface with AC consumers and generators. Recent standards are appeared to judge the quality of DC electrical power (Barros et al. 2019). Hybrid microgrids can use both AC and DC technologies profiting from the advantage of each category (Hosseinzadeh & Salmasi, 2015). DC one is used to profit from its advantages mainly under medium voltages. The advantage of AC microgrids consists in their easy interface with AC loads and generators. For that category, the supervisor needs to ensure continuous regulation of frequency and voltage levels or so-called ancillary services. Limits relative to operating conditions of a microgrid need to be also supervised. Achieving low-cost architecture is among the targets of hybrid microgrids. Its DC part allows the connection between the DC bus of different systems-side converters like DC/DC one in the case of PV systems, and DC/AC in the case of electromechanical energy conversion systems. The AC part of a microgrid is interconnected to DC one through AC/DC converters. It permits possible connection to a power grid once needed or distribution of electrical power to consumers.

Several research works have been dedicated in the literature for efficient operation and performances amelioration of microgrids. This is under autonomous and/or grid-connected modes. It touches on numerous topics like sizing (Rey et al. 2022) and protection (Dagar et al. 2021) of microgrids, and feasibility studies to integrate renewable energy systems (Bouchekara et al. 2021). Design, planning of microgrids and forecasting for different energy resources have been also considered in (Sandelic et al. 2022), (Gao et al. 2022), and (Netsanet et al. 2022) respectively. Alghamdi & Canizares (2022) developed methods for frequency and/or voltage regulation or so-called ancillary services. A concept of dynamic microgrids or so-called flexible boundaries ones being appeared in the literature (Pannala et al. 2020). That is called for microgrids with variable production and configuration. Modern methods have been devoted to supervising such a category (Hakimi et al. 2020). Multi microgrids clustering (Meng et al. 2017) is considered as a set of dynamic microgrids interconnected adaptively between themselves or to a power grid. The objective of that technology consists mainly in increasing renewable energies integration ratio as distributed generations all ensuring electrical power quality provided to consumers. Some works have been devoted to the synchronization phase of a given alone or microgrids set to a power grid (Yu et al. 2020). The topic of detection and/locating or management of defaults is also to be considered (Chen et al. 2022). Operating enhancement of a microgrid can be done through the introduction of new technology of converters like modular multilevel ones (Xiao et al. 2022) and a new topology of DC/DC converters (Prabhakaran & Agarwal, 2019). Modern control methods have been dedicated in literature for preferment driving of microgrids (Ahmethodzic & Music, 2021). Methodologies have been also treated like power flow study and mathematical model elaboration (Garces, 2018), long-term planning (Stevanoni et al. 2018). Fault ride-through methods have been also devoted (Xia & Long, 2020).

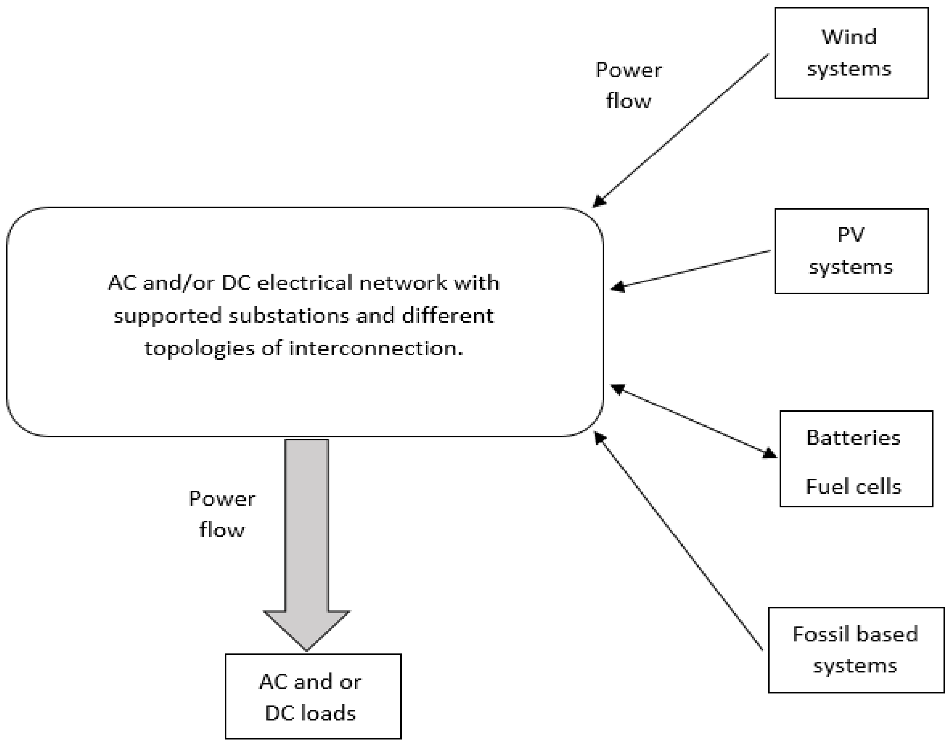

Fig 2. AC and/or DC microgrids.

2.2 HVDC Grid

It’s based on DC high voltage transmission and it is utilized mostly for long-distance due mainly to economic benefits (Alassi et al. 2019). It permits to achieve electrical power transport with lower power losses, deep-less voltages, and best-transferred power rating compared to those based on AC technology. This scheme is needed mostly to ensure high power transmission between two or more distant AC/DC electrical areas as shown in the example in Figure 3. Indeed, that is a solution for the integration of isolated high power producers from renewable sources like wind farms (Darabian et al. 2020), CSP farms (Zhang et al. 2013) to a power grid. It can be used for networks interconnections (Li et al. 2016). Each end of DC lines is connected to AC circuit via transformer and AC/DC converter. Voltage source converters (VSCs) and line commuted converters (LCCs) are used for AC/DC conversion. LCCs are based generally on power thyristors and diodes. VSC are based on power controllable components like IGBT. Modular multi-level topology-based VSCs seem to be the better solution (Debnath et al., 2014a).

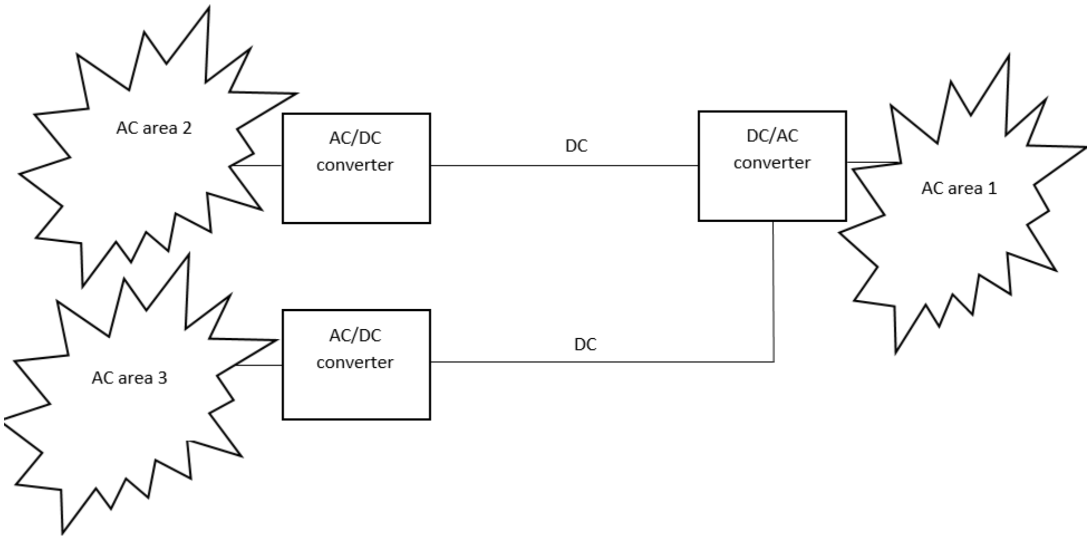

Fig 3. HVDC system example.

There exist three main configurations for HVDC transmission. The first one consists on a monopole with both metallic and earth electrodes return options. The second one is based on a symmetrical monopole. The third one is bipolar with return options. Numerous research works have been devoted to operation and improvement of the HVDC systems including multi-terminal ones. Faults issues have been treated widely in the literature (Muniappan, 2021). Among these faults, it is quoted commutation failures of the interfaced converter which are mostly due to AC voltage deeps. Failures can also be due to converter devices faults (Li et al. 2022). Faults can occur on electrical transmission DC lines like a misfire or short circuits (Li et al. 2022).

Fault isolating and equipment protection concepts have gained recently considerable importance in research works. This is by developing novel equipment like DC breakers (Mohammadi et al. 2021), current default limiters [67], distance and differential protections (Safei et al. 2020; Wang et al. 2022; Qin et al. 2022). Faults ride through control methods (Liu et al. 2020) have been also developed.

Driving methods of HVDC system-based power grid have been also studied like control of sending-end and receiving-end converters under different circumstances of AC voltages (Wang et al. 2019), starting-up procedures (Chanzigian et al. 2022). The control is mostly done by MMCs for participation in quality improvement of electrical energy of a power system like frequency regulation (Liu et al. 2022) and voltage fluctuation suppression (Zhao et al., 2020a). Dispatching (Montoya et al. 2022) and planning (Moradi-Sepahvand & Amraee, 2020) concepts of HVDC systems have been also considered. Novel material has been also developed like DC lines and DC cable joints (Lagrotteria et al. 2019; Park & Lee, 2021). Studying articles has been also devoted to phenomena linked to HVDC grounding electrodes (Cao & Zhang, 2022), and the impact of lightning on HVDC systems (Han et al. 2015).

2.3 Wide Area Synchronous Grid, Super Grid

The term wide-area synchronous grid is given when electrical grids of several countries are interconnected all with the same frequency (*Wikipedia, Wide-area synchronous grid*). Its aim consists in increasing the frequency stability margin of the whole synchronous system. This is due to the participation and cooperation of reserves of all synchronous interconnected grids once frequency deviation occurs. This minimizes the impact of power unbalances compared to the case when a power grid operates alone. It means that frequency deviations, frequency regulating time and blackout cases number are all minimized. It allows also for reducing the utilization of tertiary reserves by starting other production units, especially under consumption picks. It permits also to encourage the integration of renewable energy systems of a given synchronous system which present intermittency and fluctuation characteristics. In fact, introducing fossil energy-based units or storage systems to synchronous grids in order to compensate for the cited undesirable characteristics all minimizing the injected CO2 quantity is very interesting. A wide area synchronous grid allows the existence of electrical energy business between deferent covered countries. The configuration of interconnected networks leads to improved reliability and performance. The synchronous grids of Europe and North Africa are examples of wide-area synchronous grids.

Exploiting the benefits of both wide-area synchronous grid configuration and HVDC transmission systems (Itiki et al. 2020), a novel configuration so-called super-grid or mega-grid is under study. It has an objective to trade high electrical power between long distant areas. It can be considered an essential mean for the energy transition. It is considered an international and intercontinental wide area synchronous power system. The driving of that super-structured system is relatively difficult. This is due mainly to the propagation effect of electrical defaults through electrical lines and cables. Driving that mega-system needs smartness supervising means.

2.4 Power Grid

The term power grid is given to an electrical grid covering a country. It's based on AC voltages. It is seen as an electrical network linking a set of loads (consumers) to centralized producers through electrical lines under different voltage levels interconnected by electrical substations. Each part of the lines having the same voltage level distinguishes an electrical system. The voltage level of an electrical system is chosen to ensure safe and low-cost installations used for electricity transportation. The section of an electrical line is defined mainly by the amplitude of the transported current. Electrical losses and installation costs are proportional to the line section. The current rate depends on the transported maximum power and voltage. Related substation set that voltage which defines the current rate. Three main electrical systems are distinguished within the network of a power grid. The set is mastered by following a grid code. This last ensures a safe operation by considering grid stability. It takes into account frequency and voltage levels adjustment. Under the coming of the renewable energy integration era grid codes need to incorporate a set of requirements. Details about grid codes and stability, architecture and requirements for renewable energy system integration are given in the following sections.

2.5 Smart Grid

The appellation of a smart grid is given to an electrical grid when this last incorporates modernized means including performant computers, remote sensors and actuators, information and communication technology. It comes to facilitate the exploitation of the target electrical grid and increases its performances and efficiency. Cited modernized means allow to increase the controllability and observability compared to smart-less concerned grid. The controllability is ensured through the ability to control remote actuators in an electrical grid part depending on measurements and data related to another one. Among actuators, it is cited mainly generators regulators of active and reactive powers, and storage systems regulators of injected/absorbed active power. It is cited also regulators of absorbed/injected reactive power in the case of shunt active filters, and ones of injected harmonic currents for compensation. Actuators to select protection elements states are concerned. It is quoted also regulators of active powers of consumers (controllable loads) or ones related to transfer ratio control of transformer-based substations. The observability is increased due to the introduction of remote sensors relating to currents and voltages measurements, states of protection elements, and online estimation methods. It concerns also switch controllers allowing to connect/disconnect between different lines. Different parts of the target grid are supervised, controlled, scheduled and planned by optimizing a fitness function basing on measured/estimated quantities. Their concern is the stability of voltage levels and frequency in the presence of grid defaults, renewable energy systems integration which have a random characteristic. A smart grid integrates to its functions a trading one. More details about the subject of smart grids are given in section 3.

3. SMART GRID

3.1 Description and functions

The development step of smart grids is underway mainly for the category of power grids. For that last some researchers (Amin et al. 2013) conceived a structural way of developing future smart grids. As depicted in Figure 4, a smart grid has two main parts. Soft and hard ones. The hard part is divided into two ones, power and command-based parts. The first one consists of components of a classical power grid containing renewable energy-based generators, consumers including power-two-senses ones. The second one includes remote-controlled sensors and actuators, regulators of different controlled components of the grid. The last set is linked to computer-based decision makers (CDMs) via information and communication technology means. A smart grid may have one or many CDMs connected between them exchanging information and instructions, covering different portions of a concerned electrical grid. The soft part allows to supervise or implement elaborated algorithms or to configure CDMs for optimization, control, faults detection and prevision, faults-ride through exploitation, scheduling, and short time planning for grid configuration. Supervising tasks is often associated with monitoring which is ensured by necessary means (Aranda et al. 2022). A power grid began to be automated (smart grid) once non-commanded or locally controlled components were replaced by controlled and remote ones. The performances of a smart grid depend mainly on one of the utilized information and communication technology means, CDMs capacity.

3.2 Targets, and related research works

The targets of smart grids development are resumed as follows:

3.2.1 Big data acquisition, saving and treatment

Big data acquisition, saving and treatment is one of the main advantages of smart grids compared to classical ones. This is because it permits the acquisition under a small sample time. Saving of quantities profiles under normal and abnormal situations allows the treatment of the data for accurate planning (Mohtashami et al. 2016) and forecasting (Da Silva et al. 2021), faults localization and detection, and faults prediction.

3.2.2 Optimal control of different parts of the target grid

Cooperative driving is a mandatory task to have optimal control of an electrical system in respect of a predefined fitness function. Optimized parameters taken by this one can be the injected CO2 (Pratt et al. 2010) by favoring power production coming from renewable energy systems. It can also be the price of absorbed or injected power of prosumers (Lu et al. 2020). Optimizing of consumed or injected power is required for that objective. It can concern frequency regulation through controlling power references of absorbed and/or injected powers (Islam et al. 2019). Voltage level adjustment can be considered by fixing reactive power references of different components' participation in its injection and absorption (Antoniadou-Plytaria et al., 2017). It may concern also voltage distortions attenuation or balancing (Owosuhi et al. 2023). This last can be achieved by controlling references of compensating components like series or parallel active filters. Minimizing deviations from the functioning point of a component of the electrical grid for its lifetime increase can also be considered. This last is the case of Debnath et al. (2014b). Minimizing power losses can be also taken into account (Sambaiah & Jayabarathi, 2020). Power transmission capacity can be considered as an objective function. This is under normal or abnormal circumstances (Ghosh et al. 2020a). A smart grid is considered necessary for the energy transition. It supports real-time algorithms-based calculators in order to find the optimal solution of a considered fitness function based on actual or previous values of different inputs all considering different constraints. The solution is defined as algorithms outputs. Algorithms inputs consist of components states, electrical and mechanical states/measurements at different points of the supervised electrical grid. The outputs concern the configuration of electrical grid architecture via regulators references and switches states.

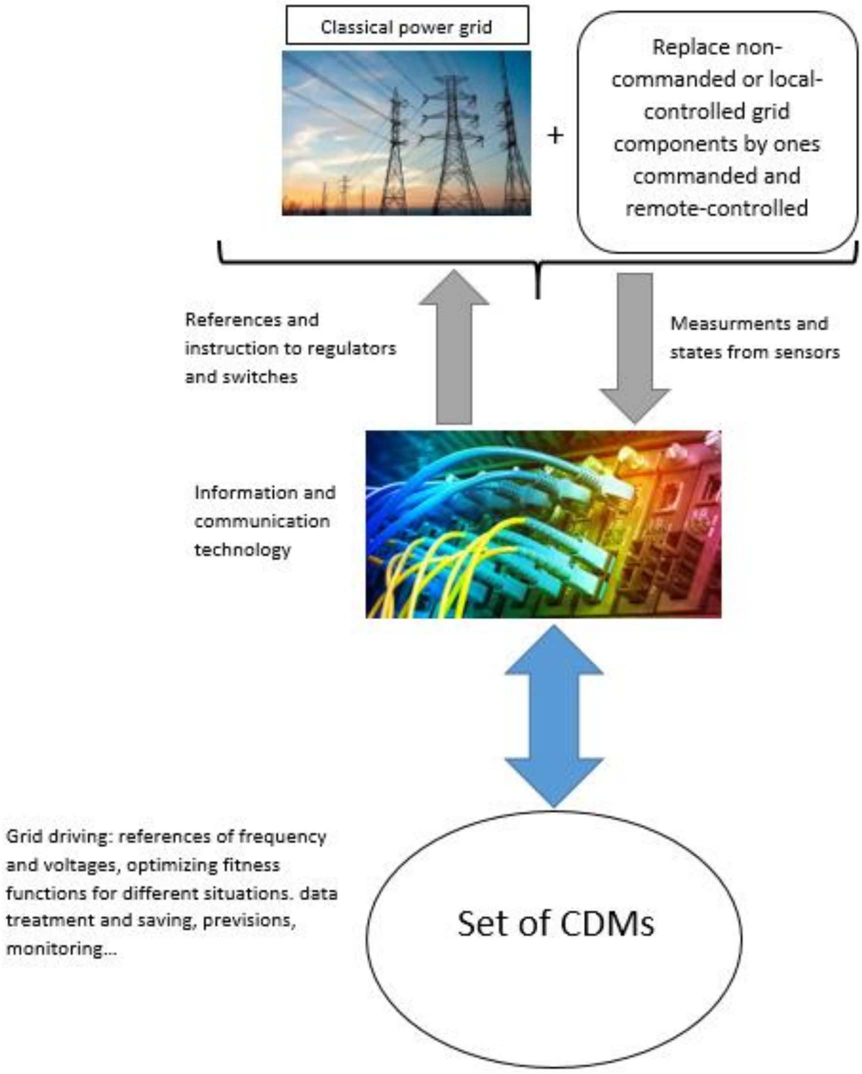

Fig 4. Smart grid description

Adding to cited research works, numerous others have been dedicated to the literature. In (Zhao et al. 2020b) privacy-preserving data aggregation schemes have been developed. Some algorithms have been devoted to energy theft detection (Tehrani et al. 2022) respectively. Methods have been proposed for migration from a traditional power grid to a smart one (Neffati et al. 2021). Applications have been dedicated to smart microgrids (Jiang & Fei, 2014). Methods based decision-making for smart grid mastering have been proposed (Garcia et al. 2018). Tiwari & Pindoriya (2022) gave a review about optimizing methods and communication tasks of smart grids. The smartness option can be utilized for all classes of electrical grids as cited.

4. POWER SYSTEM DESCRIPTION

Figure 5 depicts the global illustration of a power grid. It is seen as four main parts like a production system, transmission system, sub-transmission and distribution systems. Energy conversion systems allow the production of electrical energy using traditional primary resources. These last are considered as a production system and are connected to the transmission one. The produced electrical energy is then transported to the electrical loads via transmission, sub-transmission and distribution systems respectively. Each system is characterized mainly by its voltage level. The interface between the two systems is ensured via electrical substations. Step-up transformer-based substations guarantee the connection of the production system to the transmission one. The last one is connected to the sub-transmission system via step-down transformer based-substations. The interconnection of the sub-transmission system to distribution one is so ensured via step-down transformer based-substations. More details are given in the following subsections. The voltage levels of the production system, transmission, sub-transmission and distribution systems are different. The range of each one depends on the grid code of the concerned country. Electrical substations contain mainly step-up or step-down transformers, electrical buses, active or passive reactive power compensators, and/or electrical equipment for quality energy amelioration. It may contain also the material required for connection or isolation, currents/voltages measurements, and other material needed for the local or remote supervision.

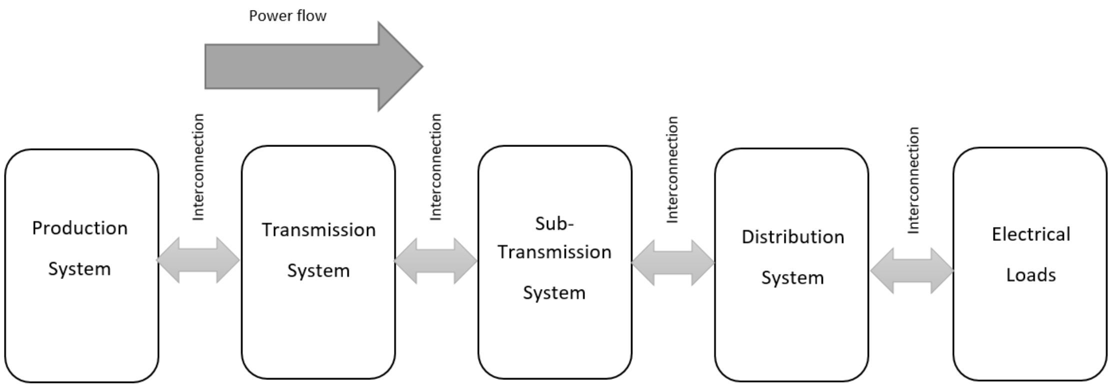

Fig 5. Global illustration of the power system.

4.1 Production system

The energy consumed by electrical loads comes originally from the production system. It’s seen as a set of centralized producers. Each one contains several energy conversion systems (ENCSs) connected to the transmission system in a parallel manner. As shown in Figure 6, each centralized producer is connected to the transmission system through a step-up transformer-based substation.

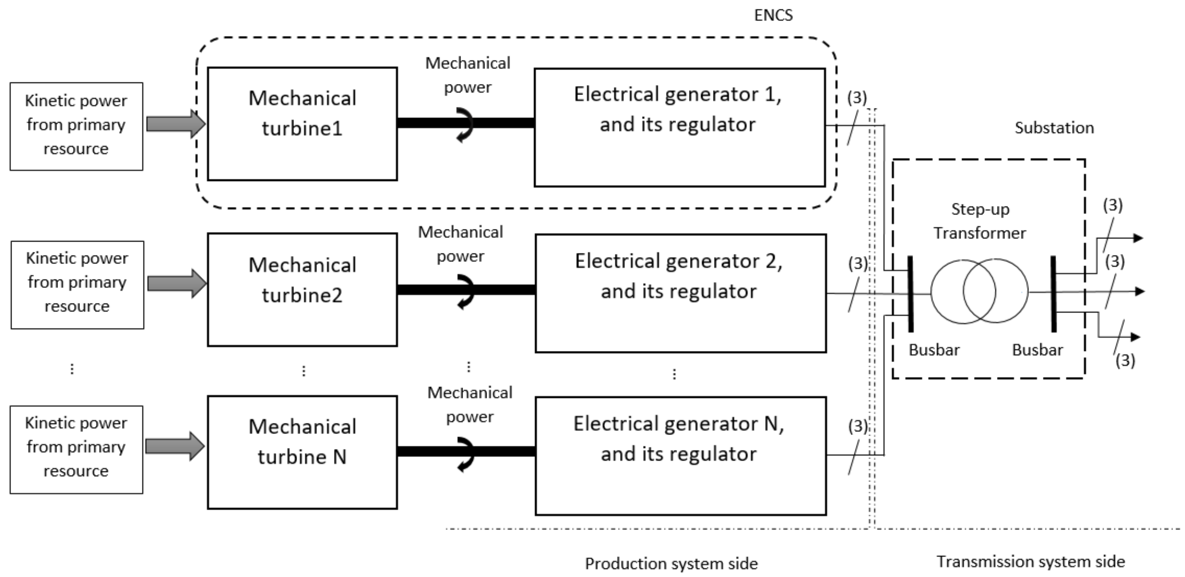

Fig 6. Centralized producer connected to a transmission system with (N) ENCSs.

Each energy conversion system contains two main parts. The first one is the mechanical turbine allowing the conversion of kinetic power available in a fluid into mechanical power as rotating speed and mechanical torque in the rotor shaft (Djoudi, 2016). The second one allows the conversion of the produced mechanical power into electrical power through three phases electrical generator which is generally a synchronous machine with excitation. The power of the last one is commanded in order to respond to the exigencies of the transmission system operator. Historically, the power control is ensured through an analogical regulator of fluid debit and/or excitation voltage of the synchronous machine. Voltage control of the generator can be considered in some cases when this last is considered as a reference or slack generator. Kinetic power available in the fluid comes from the exploitation of potential energy of primary resources like natural gas, oil, barrages (case of hydroelectric systems), and coal. Generally, within a centralized producer, some ENCSs are on utilization and others are on standby.

Recently renewable energy conversion systems are being integrated with large scale (Kebede et al. 2022). This is the case with integrated on-shore and off-shore wind farms. This is the case also for systems based on geothermal resources (Boretti, 2022). Thermal solar and ocean energy-based systems (Kumar et al. 2022) are also being considered for large-size integration. These types of energy are preferable due to the smooth variation of input power. Other renewable energy types can be utilized like wind energy (Tahir et al. 2020) and solar photovoltaic energy (Jawad et al. 2022). Other types of machines utilized as generators on ENCSs are taking considerable part while optimizing the operating efficiency. This is due to the introduction of power converters. Among the machines used are quoted doubly fed induction machine type (Nkosi et al. 2022) and permanent magnet synchronous machine type (Qais et al. 2021).

Centralized producers are often integrated with high size with megawatts order. So the machines and associated converters have to be with high operating performances and service continuity under eventual faults. That can be ensured through multilevel converters (Polanco & Dujic, 2021) and redundant systems. It can be ensured also via control methods (Jahanpour-Dehkordi et al. 2019) with fault tolerance. Power converters-based ENCSs offer two main advantages compared to classical energy system schemes. Indeed, it permits of increase in the power conversion efficiency of the considered system and less effect with free mechanical oscillations under grid disturbances (Djoudi et al. 2017) due to the command-ability of the whole system by grid interfaced converter. It permits also to have a hand on other electrical states like reactive power (Ghosh et al., 2020b). These last have considerable consequences on the target system because it has an impact on the rate and losses of electrical power on the machine, converter and transmission grid. The generators are driven mainly by speed or power control.

Some works have been dedicated in the literature for migration from classical ENCSs to converters-based ENCSs. The frequency regulation profile (Muftau & Fazeli, 2022) is an interesting one in order to imitate the frequency behavior of classical systems. This in order to ensure safety and smooth transition while migrating from analogical control-based synchronous generators with excitation to converters-based generators including DFIGs and permanent synchronous ones.

Frequency versus power deviation response is among the interesting things of production system operating because it acts directly on power system stability and mechanical oscillations of rotor shafts.

4.2 Transmission System

Transmission system permit to transport of the produced electrical power over long distances with considerably high voltage. This is to minimize the ratio of transmitted power per line diameter. The transmission system is usually looped which offers the opportunity for service continuity once a default occurs in a line or in a centralized producer. The interconnection of different centralized producers permits them to share equitably the grid constraints, especially the frequency deviations. As depicted in Figure 7, a transmission system permits also the interconnection of the concerned grid to those of neighboring countries through interconnection substations.

Transmission systems contain reactive components like shunt active and passive filters which contribute mainly to the adjustment of the voltage. The transmission system (or network) could be configurable (selection of active lines via correspondent substations) in order to respond to some constraints: losses minimizing, and voltages deviations minimizing for example.

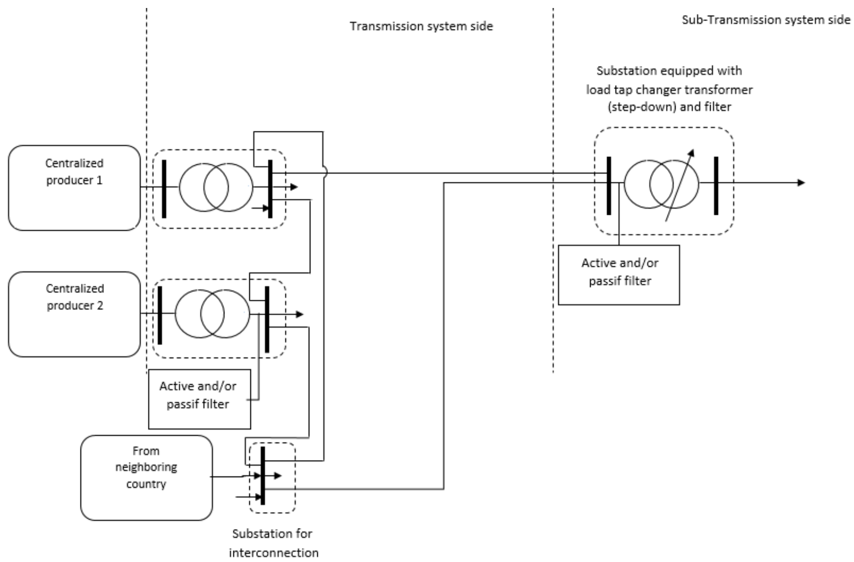

Fig 7. Example of a part of transmission system.

Faults identification and localization (Zeb et al. 2022) methods are still under consideration even with a new era of large-scale renewable energies integration to sub- or transmission systems. Two kinds of faults are distinguished, i.e. physical and operational ones. Physical faults category includes mostly short-circuits. Operational defaults consist of voltage disturbances like distortions, unbalances under- or over-voltages, interruptions or frequency deviations. Those disturbances are related to the currents status of interfaced substations to the distribution system or to unbalance between produced and consumed powers. Interruptions can be resulted from isolating and protecting components under non-tolerable situations. Mitigation strategies for the faults have been developed in (Zeb et al. 2022). Some research works have been devoted to enhance the operating efficiency of FACTs based sub- or transmission systems through developing robust control methods (Chmielewski et al. 2021).

With the emergency requirement for the integration of large-scale renewable energy systems, some concerns need to be addressed as in recent studies works. The issue of transition from traditional sub- or transmission systems to renewable energy systems-based ones are taken into account under planning studies which are widely treated under different scenarios (Watkiss & Tabors, 2022). This is the main target to increase the integration ratio of renewable energy systems (RESs). Types of components to be included on sub- or transmission systems determined by the kind of envisaged RESs. Each RES is distinguished by its time constant, its size and its periodicity. Components associated with a set of RESs could be FACTs or storage systems like pumped storage hydropower systems (Toufani et al. 2022) and flywheel energy storage systems (Zhang et al. 2022). For each long-term planning the following points need to be considered. It's cited firstly feasibility and profitability concepts. It's cited secondly frequency and voltage stability keeping (Yu et al. 2022). The first point is to be decided through techno-economic studies, especially under RESs integration (Ahmad & Zhang, 2021). The second point is ensured by implementing the required components taking into account the type and size of RESs and reactive elements. Short-time planning of these elements determines their operating references as decided through optimal dispatching (Pearre & Swan, 2020). Forecasting (Archer et al. 2017) task of RESs inputs powers is required for that. The reconfiguration of the target network can be proceeded in order to overcome faults, minimize losses, favor integration of RESs, and minimize utilization of storage systems. It can be useful for minimizing imported power. This is all with respect to the constraint of instantaneous adjustment of frequency and voltage levels. Modern methods have been developed for operating enhancement of FACT systems for participation in voltage regulation or to improve the transmission capacity of electrical lines. It can be used for distortion mitigation or voltages balancing.

4.3 Sub-transmission system

It permits the repartition of electrical power to different regions of the covered country. It's looped like the transmission network. This is mainly to offer a service continuity option once faults happen. Reactive components and load tap changer transformers are inserted into the system for voltage adjustment. Reactive components are linear and non-linear filters like analog and power electronics-based ones respectively. Figure 8 depicts an example of a sub-transmission system. Its configuration can be changed following working constraints as cited in paragraph 2.2. Storage systems can be inserted into a sub-transmission system. This in order to ensure service continuity once defaults occur. The places, sizes and types of inserted ones are decided after a long-term planning process.

4.4 Distribution system

It ensures the distribution of electrical power to the consumers (or loads) (Yang et al. 2014) which are generally divided into two categories. The first one concerns low-power consumers like houses, hospitals, schools, etc. The second class of consumers are with medium power like tramway, metro, manufacturers, etc. The power ranges of the cited categories can be specified in the concerned grid code. The totality of the distribution network is arterial. Some parts are looped this in order to ensure redundancy feeding with service continuity of consumers with high priority. Figure 9 shows an example of a part of a distribution system. Generally, consumer's side substations are equipped with load tape changer transformers. Electrical consumers are three phases' loads or dipolar loads (one phase and neuter). Load tap changers transformers can be used for voltages adjustments.

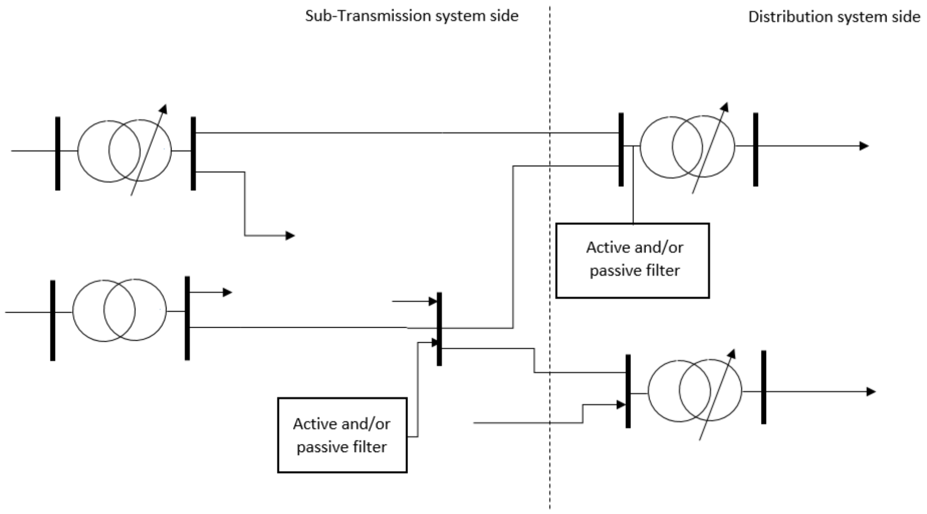

Fig 8. Example of a part of a sub-transmission system.

Storage systems could be integrated into power systems through the distribution system. It allows twin directions of active power, absorption or injection depending on the requirements of the power grid.

Recently non-conventional loads like electric vehicles are part of the power grid. It offers the possibility to control the flux of absorbed power through power electronics elements. This point can be used by the distribution operator system for the control of grid frequency. It can be used as primary reserves. The concept of decentralized generation systems comes to be widely treated (Madadi et al. 2019). It permits users to inject active power produced principally from renewable energy systems.

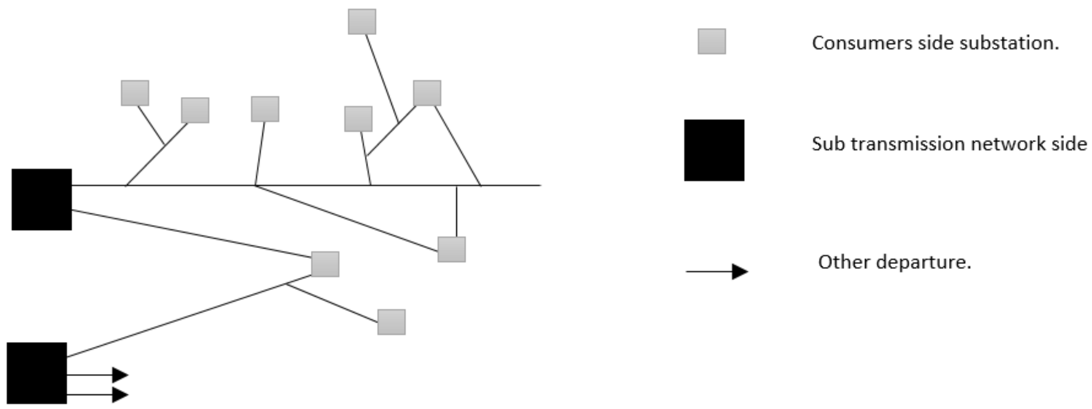

Fig 9. Example of a part of distribution system.

The ambition to introduce renewable energy integration through a disturbed system with an optimal rate motivates associated research works. Flow power has therefore twin senses as shown in Figure 10 in the new paradigm of power grids. This target is still under study due to its complexity and necessary changes to the infrastructure of the distributed system. Planning (Klyapovskiy et al. 2019) of the distribution system is still under study. The main objective is to offer the option of power injection/absorption at any entry point of the target system, all ensuring the quality of electrical power. That means respecting tolerable evolution interval of THD, unbalance factor, frequency and amplitude variations (IEEE standards as an example). Voltages distortions are evaluated by the THD factor and it depends on currents distortions coming from non-linear loads of the system. These voltages distortions could be deleted through shunt active filters. An unbalanced factor represents the severity of voltage unbalances.

This unbalancement could be mitigated via parallel active filters. Voltage amplitude variation could be corrected via transformers tap changer or via regulation of reactive power circulation. Frequency variation can be controlled by utilizing the participation of prosumers to adjust their consumption or production, especially under peak demands (Gao et al. 2016). Planning of the distribution system depends on place, size and characteristics of cited corrective elements. It depends also on marketing considerations. The service continuity option is to be taken into account through novel infrastructure. Short-time planning depends on scheduling (Rotering et al. 2021) and dispatching (Li et al. 2020) of cited components, forecasting of prosumers injected or absorbed active/reactive powers. Feasibility investigations are mostly based on real-time simulations using power flow calculation methods. Optimized results are so dependent on the objective function and the model used for the optimization process. The convergence time depends principally on the optimization method and used constraints. Storage elements are necessary for some situations of prosumers' side market considerations and increasing the self-sufficiency time. For distribution systems storage elements, one could consist of chemical batteries like lithium-ion-based ones (Stai et al. 2020), hydrogen fuel cells (Sun et al. 2021). Several works have been devoted to frequency and voltage level control participation. This case is described in the articles (Sepehrzad et al. 2022).

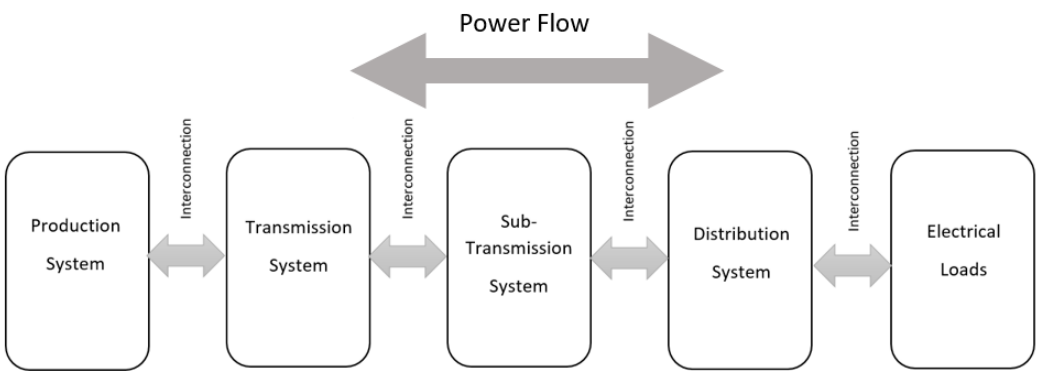

Fig 10. New paradigm of power grids.

5. GRID CODES

The term grid code is designed for an electrical grid covering a country (power grid). As known, the power grid is seen as a set of producers and consumers interconnected via electrical lines with different equipment and materials. Such a number of elements need to be exploited respecting structured rules like grid code in order to ensure the safety and operating functions of the power grid. It depends heavily on the size of the power grid and its infrastructure. Its articles come from experts via expertise, publications and patents. It comes also from grid standards. It treats day-to-day tasks on power grid elements and operators. Its main objective is to increase economical and functional efficiency. Parts of the grid code depend on the country from which the grid code is coming. All parts of the power system are taken into account with different circumstances, normal and exceptional ones. It contains three main chapters. One concerns the planning and development of the power grid. Another part concerns connection conditions. The third part is dedicated to procedures covering the operating stage.

The feature of a power grid depends on the electrical energy quality delivered to consumers which is related directly to the characteristics of the voltages. It needs to be balanced, sinusoidal, and uninterruptible with magnitude and frequency as given in the concerned grid code. That is the primary requirement of a power grid. The voltages at a given point of the grid depend on the operating way and state of different components of a power system including electrical loads. Application of technical requirements is ensured by the transmission system operator and distribution system operator. The duties of each one are listed on concerned grid code (*National Grid Web site)*. Figure 11 resumes grid code principles.

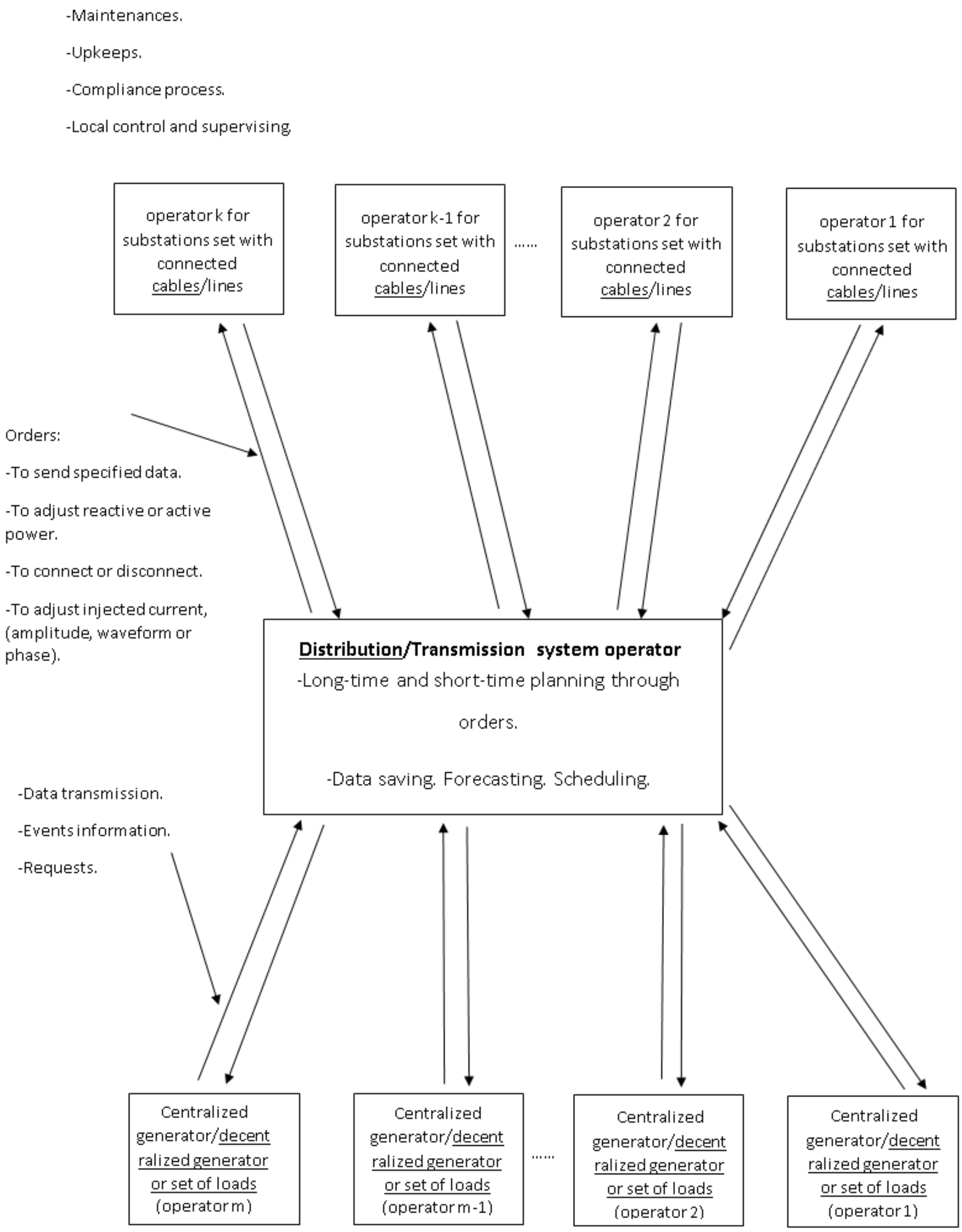

Fig 11. Brief description of a grid code.

5.1 Planning and development

It consists mainly of rules covering data provision and development criteria of power grid elements. It concerns generally reinforcement or extension, the introduction of the new element to the grid. It’s taken as an example introduction of new connection points via electrical substations. Reinforcement by adding new electrical lines in order to augment transmitted power to electrical substations or offering redundancy capability. Quoting also the introduction of new centralized or decentralized producers. Extension of existing producers or substations. Grid frequency regulation ensures the balance between the consumed and produced powers. The connection of new high/medium power consumers. Installation of reactive power compensators in order to increase the transportation capacity of electrical lines or to enhance the magnitude of a given voltage. Another point is relative to the installation of series or parallel electrical filters allowing the amelioration of the electrical energy quality. Other installations can be envisaged in order to ride through grid defaults like short-circuits or over voltages.

The planning chapter treats also the type of required information data and transfers time period. Three types of data are distinguished: characteristics essential elements of the grid, current and forecast data. It may concern data of selected centralized or decentralized producers following power margin. It concerns also data of selected consumers, data of electrical substations, and data of active power demand or reactive power.

Usually, planning data are based mainly on electrical measurements, historical data and states of the concerned part of the grid. The electrical quantities concerned by the planning data can be the frequency, the voltages, and the currents, instantaneous/nominal active and reactive powers, the maximum and the minimum of the cited quantities. Other measured, estimated or forecasted quantities can be considered all depending on the taken target.

5.2 Connection conditions

This part of the grid code fixes a set of rules and procedures related to different elements connected or seeking to be connected to the power grid. The concerned elements are energy conversion systems based on centralized producers, selected power range of consumers, interconnecting substations, synchronous and static compensators. Part of these rules takes into account safety purposes and procedures which must be considered. Safety considerations for sizing and design of these elements are also taken into account like short circuit ratio and neutral earth. Citing also short circuit current and other safety considerations. Operating capability of active and reactive power resources versus frequency and voltage variations respectively to be considered. Citing also maintenance responsibilities, verification compliance methods, exigences of installed equipment, active and reactive power capability under some operating conditions. It takes also into account requirements of protection material like response time and other parameters depending on defaults characteristics. The connection depends also on the quality of the grid voltage profile like waveforms, voltages balance, and amplitude, frequency, fluctuations. Requirements might touch the selected power range of consumers concerning current waveform and reactive power. Procedures relating to start-up and grid synchronization are considered.

5.3 Directives for operating step

That section of the grid code defines precisely the duties of all operators of different elements of the grid. All essential elements are supervised. That is mastered through human or machine-based operators. Two types of operators are distinguished, distribution side operators and transmission side operators. These two ones are supervised by the distribution system operator and transmission system operator respectively.

Directives for the operating phase of the power grid consist of data and orders transfer between different operators. This in order to organize the function of grid operators. Estimated, forecast and instantaneous data are distinguished. The sense of orders is taken into account. The manner of data and orders transfer are considered under both normal and abnormal situations. It concerns also service systems like frequency and voltage regulations.

It concerns the forecasting of the active power demand of the consumers, and short-term planning in order to achieve an optimal configuration of the power grid all respecting the existing constraints and scheduling which consumers or producers have to be isolated or connected in the case of power unbalance. This last is interpreted via grid frequency deviation from its tolerable bounds. It covers also the operations of reparation, testing and maintenance. It is quoted also the needed procedures once grid defaults or urgencies occur.

6. GRID STABILITY

6.1 Frequency regulation

This task is for the transmission system operator. The fundamental frequency f is the same at all points of the power grid. For excited synchronous generators, the most utilized type historically for centralized electrical power generation, the frequency is proportional to the rotating speed because the stator circuit is directly connected to the grid. The rotating speed is proportional to the debit of the fluid actuated on the turbine. This last depends on the injected power and fundamental grid frequency. The debit is commanded by an automatic valve, as depicted in Figure 12.

The reference of frequency control is defined as a nominal one f_0 and is set as given in the concerned grid code. Activities on frequency regulation depend on its deviation compared to the nominal one. This is due to the natural law of power conservation. Total produced power P_t equal to consumed one P_c by consumers and electrical lines (Power losses) as given in relation (1). Two cases of unbalance or difference ΔP between the produced power from primary resources P_u and consumed one are distinguished. The quantity ΔP is defined as given in relation (2).

$$P_t = P_u \tag{1}$$

$$\Delta P = P_u - P_c \tag{2}$$

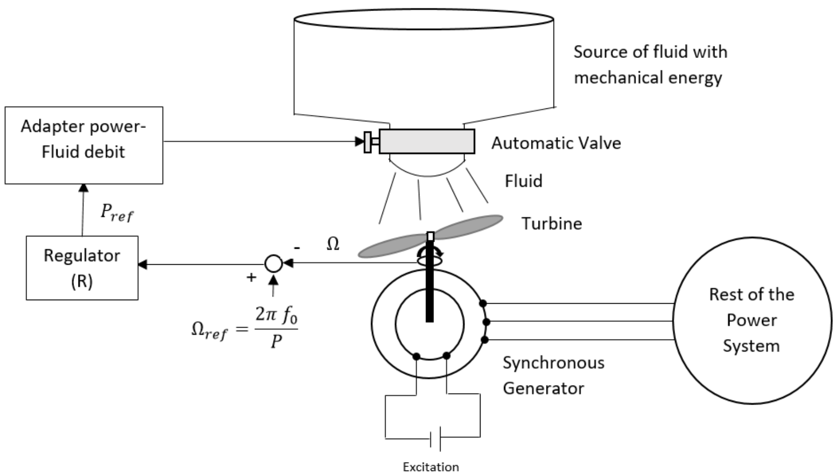

Fig 12. Description of the frequency control process of excited synchronous generator based on centralized producers.

The first one is once ΔP is negative. In this situation, the frequency deviates below its nominal one because the difference in power is compensated by kinetic energy stored on generators shafts. Generator's speed and frequency decrease for this reason. The second one is once ΔP is positive. The speed and frequency increase because the surplus of power is stored by kinetic energy on generators shafts. The regulation is made therefore through adjustment of produced power from primary resources by an automatic valve. This last controls the fluid debit. The reference for produced power P_{ref} is set by the speed regulator R. The control error of the rotating speed Ω is given by the relation (3). Ω_{ref} represents the reference of the rotating speed. It's given in relation (4). P represents the number of poles pairs.

$$e = \Omega_{ref} - \Omega \tag{3}$$

$$\Omega_{ref} = \frac{2\,\pi\, f_0}{P} \tag{4}$$

The main fact favoring frequency deviation concerning unscheduled fluctuations of total power consumption and sudden disconnection of large-scale producers or consumers due to electrical defaults. Usually, three phases are distinguished for frequency regulation. The first phase is primary regulation which is automatic. It is activated once speed or frequency control errors deviate from their limits L_Ω and L_f respectively, as given in relations (5), (6) and (7).

$$\left|\Omega_{ref} - \Omega\right| > L_\Omega \tag{5}$$

$$|f_0 - f| > L_f \tag{6}$$

$$L_\Omega = \frac{2\pi\, L_f}{P} \tag{7}$$

For this step, the regulator consists of a proportional part of the PI controller. The values of L_Ω or L_f are also specified on the grid code.

The second phase is secondary regulation with the target to eliminate static error caused by primary regulation. Also, establish the conventional exchange powers with other interconnected power systems as proceed before the frequency deviation event. This is because generally all interconnected countries participate in secondary regulation once frequency disturbance appears. An example of this phase is explained in (*RTE website*). Tertiary regulation is engaged if secondary reserves are not sufficient to ensure attended targets. Requirements on primary, secondary and tertiary reserves eligible for participation in primary, secondary and tertiary regulation are specified on the concerned grid code. It can be made also by disconnecting some parts of the grid if the reserves are not sufficient.

Mostly for primary regulation, all generator units of interconnected systems participate in frequency control. Secondary regulation is ensured only by generator units of the system where frequency disturbance appears. Tertiary frequency control is guaranteed manually by the transmission system operator. The main steps of frequency control are resumed in Figure 13.

6.2 Voltages level control

The sizing and characteristics of composed components of different parts of the power grid impose the voltage level of each part. This is to ensure the operational efficiency and security of that components. The voltage level of the transmission system is depending mainly on the slack bus which connects centralized producers containing reference ENCS. The voltage level of this one is controlled through an excitation circuit. It is not the same as other buses of the transmission system. Voltage drop appears likewise for other power system parts. This is due to the existence of active and reactive elements (R_L and X_L respectively) of power lines which transmit active and reactive powers P_{ac}, Q_{re} respectively. The difference between composed voltages (ΔU) of given line extremities is related to P_{ac}, Q_{re}, R_L and X_L. This is modeled by the relation (8). U represents the composed voltage at an extremity of a power line.

$$\Delta U \cong \frac{R_L\, P_{ac} + X_L\, Q_{re}}{U} \tag{8}$$

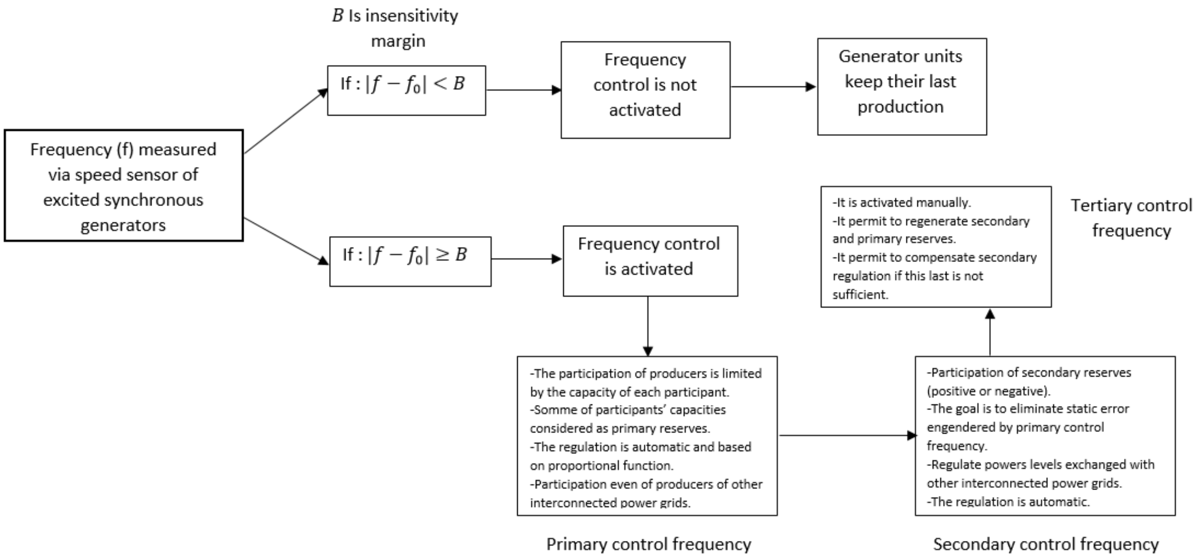

Fig 13. Main steps of frequency control

Based on this relation, the voltage difference is controllable mainly by circulated reactive power. The last can be adjusted through absorbed, injected reactive power of connected components like active and passive filters. Centralized producers based on an excited synchronous generator can be also used for the contribution to the exchanged reactive power control. The control is done by the excitation voltage. Load changer tap transformers are also used as shown in Figure 14. Coordinate control of these elements may be a solution to minimizing voltage differences.

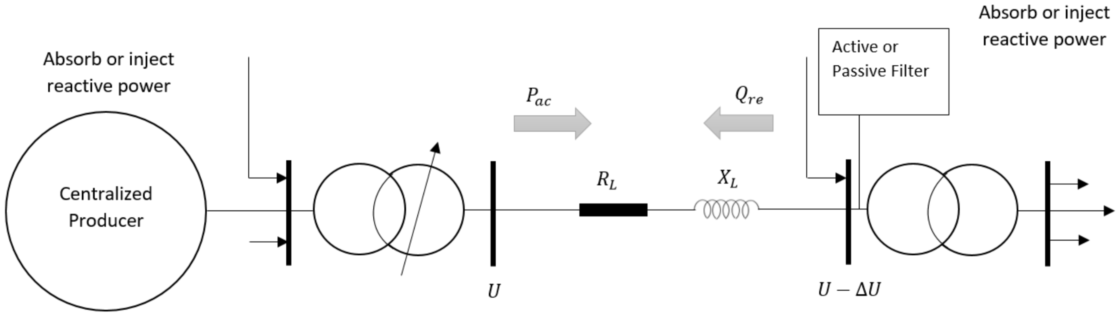

Fig 14. Main components for different voltage regulations.

6.3 Frequency and voltage levels control under integration of RESs

With the arrival of the renewable energy systems integration era with different scales to both sub- and transmission and distribution systems, some considerations come to be added to some grid codes. They concern mainly requirements of envisaged RESs for integration (as given in section VI). Others can touch the operating rules of grid components other than RESs. Several approaches have been developed for voltage level and frequency control for different parts of a power grid under several types and sizes of integrated RESs. Brief state-of-arts is already given in the previous sections. Grid stability has been studied sufficiently for several parts of the grid and under the integration of different types of renewable energy systems with different sizes (Hookoom et al. 2022). Grid stability depends mainly on compensation reserves availability for frequency and voltage level regulation. Compensation reserves are reactive and active powers available for grid control. Active power reserves are of global influence and are responsible for frequency regulation. Reactive power ones are with local influence and are responsible for voltage regulation. Assessment models have been proposed for frequency control with the participation of different scales of decentralized generators (Marinelli et al. 2021). Assessment methods have been also developed for voltage stability under RESs different scales integration in transmission grids and distribution ones (Moradi & Davarani, 2022).

The stability can be related to the balance and waveform states of three-phase voltages at different points of the grid. Unbalance and voltage distortions have different causes. Mainly loads unbalanced and currents harmonics are the origin of that situation. To overcome that, specified components like UPFCs (Unified Power Flow Controller) and participation of RESs interfaced converters.

7. REQUIREMENTS FOR INTEGRATION OF RENEWABLE ENERGY SYSTEMS

The integration of renewable energy systems into a power grid is an issue of great interest. This is due to several considerations like economic and environmental ones. In order to augment the integration ratio and minimize undesirable effects on the grid, requirements for renewable energy systems integration are introduced in some grid codes or standards (Wu et al. 2019; Buraimoh & Davidson, 2020; Wu et al. 2017). Specifications of each requirement depend on some parameters like size and types of integrated RESs. It depends also on the nature and state of the system in which renewable energy systems are interconnected (Basso & Deblasio, 2012; Mahmud et al. 2020). These undesirable effects are interpreted through frequency deviation (power unbalance), voltages disturbances. This is mainly due to random variation of produced power under the MPPT regime, the integration of dipolar generators based on decentralized renewable energy systems. It is quoted also as waveforms of currents issued from renewable energy systems. This last impacts the voltage due to the effect of electrical cables and lines. The integration of renewable energy systems can be done through either distribution systems or sub-transmission, transmission ones. This is depicted in Figure 15. These all depend on the power size of the integrated system.

It is quoted among the requirements for renewable energy system integration, and is shown in Figure 16.

Tolerance for frequency and voltage deviation

It is required for integrated renewable energy systems to operate continuously if frequency and voltage amplitude deviates from their nominal ones with percentage as defined in grid codes and standards. Under that bound, renewable energy systems need to be operational without intervening protective material. If the deviation is superior to the defined limit it becomes the default. The concept of tolerance is generalized sometimes for other deviations like distortion, unbalance, and fluctuations.

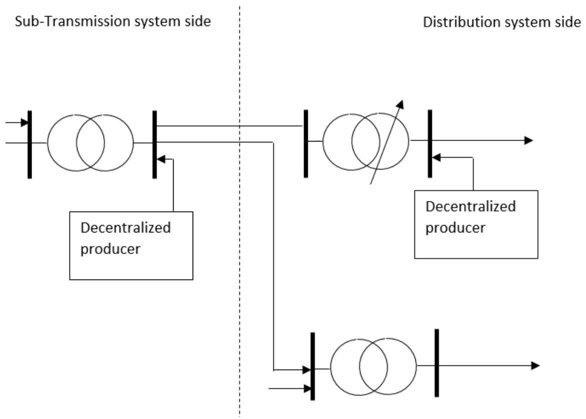

Fig 15. Example of integration of decentralized producers.

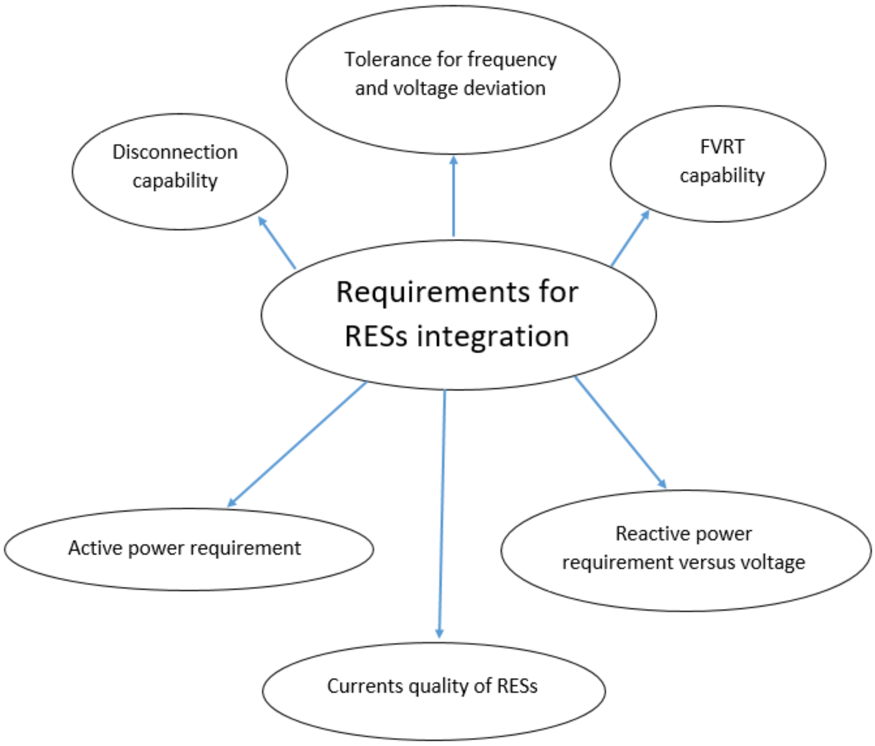

Fig 16. Requirements for RESs integration.

Faults voltage right through (FVRT) Capability

Some standards and grid codes require for integration of a specified power range of renewable power systems with the capability to right through some faults voltages. Voltage deep and overvoltage are the two main types of fault voltages that are considered. That is taken into account through adequate methods, hard or soft. The size and nature of the material used for that need depend on the variation range of renewable power system side voltage and transmitted current. This is all in order to ensure the operating continuity of the whole system although cited defaults. The range of voltage variation is considered in the grid code or standards.

Disconnection under some defaults

Connected renewable power systems are required to have disconnection capability from the grid if tolerable deviation bounds of different parameters characterizing voltages deviations are exceeded.

Among them, it is quoted the total distortion harmonic for the case of fluctuations and distortion, the frequency for the case of frequency deregulation, the unbalance ratio for the case of voltage unbalance. The disconnection might be involved once the injected current characteristics are out of tolerable bounds. It might concern injection/absorbed reactive power level.

Reactive power requirement under overvoltage and voltage deeps

Depending on the disturbance nature of voltage amplitude, the connected renewable energy system can inject or absorb reactive power. The response of reactive power of the concerned system is versus the value of overvoltage or deep. The objective of that requirement is the participation of connected systems for voltage regulation. More details are to find in the concerned grid code and standard.

Active power requirement for frequency regulation

It could be required in grid codes or standards a correlation between produced active power of a connected renewable energy system and frequency. The relation is dependent on the function regime of the system. This is to ensure participation in frequency regulation. MPPT regime is applied once the frequency is around its nominal one. In other cases, the regime of the service system is applied.

Quality of currents issue from the connected system

The quality of the three-phase currents of the connected centralized renewable energy system is considered in some cases. The total harmonic distortion that interprets the waveform of three-phase currents requires to be limited as required in a concerned standard or grid code.

8. CONCLUSION

This paper has an objective to present the current state of research on electrical grids as unique overview. These are AC/AC or hybrid microgrids, smart grids, HVDC systems, wide-area synchronous systems and super grids. A brief resume dedicated to each category covered the latest research activities. The same process is applied to power grids or so-called power systems where their architecture and management procedures come to be changed compared to classical ones, especially under the integration of smart non-conventional loads and generators like electrical vehicles and renewable energy conversion systems. A part of this paper is devoted to other interesting concepts which are related to a power grid like grid codes and grid stability. A section is devoted to requirements of some grid codes under the case of renewable energy systems integration in order to increase the integration ratio all respecting delivered electrical energy quality.

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