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Analysis of the Impact of Low Inertia Constant on Power Systems: Cause, Drawbacks, Possible Solutions and Global Trend

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Abstract
Instantaneous power contribution is an intrinsic behavior of conventional electrical power systems. Immediately after a disturbance, the entire set of connected generators and motors deliver their kinetic energy stored in their rotating masses, named inertial response. On the other hand, the increase of renewable energy sources has favored the connection of new non-conventional generation technologies. Many of these technologies are connected to the network by means of power electronics causing, among other problems, reduction of the inertia constant of electrical power systems, to the detriment of frequency stability. Literature regarding this topic is fragmented. Therefore, it is not possible to find an article that encompass the main aspects of this challenge. Considering this, the objective of this work is the assessment and gathering of the most representative articles of this topic. In this sense, the cause and main drawbacks related to the lack of inertia in electrical power systems are exposed. In addition, a bibliographic analysis of existing strategies to mitigate these drawbacks is carried out. Moreover, strategies adopted by different countries to improve frequency stability of electrical power systems, with high penetration levels of electronically connected generation, are analyzed. Finally, conclusions are obtained and global trend is outlined.

Keywords— frequency stability, inertia constant, non-conventional generation.

1. INTRODUCTION

Electrical Power Systems (EPSs) are in charge of converting primary energy from one of its available forms to the electrical form and transporting it to the different points of consumption. In conventional EPSs, electrical energy is generated by big synchronous generators in thermal, hydroelectric or nuclear power plants. Then, as primary natural resources are generally far from demand centers, electrical energy is transported through high voltage lines up to them. Finally, electricity is distributed to customers through medium and low voltage lines [1].

Until now, conventionally used natural resources have been enough to meet the demand with reasonable investments. At present, however, meeting the demand in a conventional way i.e., through large synchronous generation plants, it is becoming more and more expensive. This is due to the continuous growth of demand, depletion of natural resources such as fossil fuels, increased environmental pollution and greenhouse effect, environmental policies, lack of availability of space to install large power plants, congested transportation networks, etc.

Driven by the aforementioned drawbacks, along with scientific and technological advances and the help of government incentives, costs of new power generation technologies have been reduced considerably [2-4]. This has favored the inclusion of a large amount of non-conventional renewable generation, such as photovoltaic and wind generation [5]. In addition, new technologies versatility has allowed their incorporation not only in large generation plants, but also in a decentralized way and even at domestic level [6]. However, this boom only promoted their connection rather than their integration. This leads to problems associated with the correct operation of EPSs protections, violations of voltage limits and current levels, problems related to frequency stability, among others [7, 8].

Maintaining frequency stability is extremely important for guarantying a safe operation of electrical systems. There are several reasons why it is desirable that the frequency remain within a narrow band around the nominal value [9]:

- It ensures the operation of electric motors at a relatively constant speed. This is important in many applications and processes, especially in industrial ones.
- Performance of generators in traditional power plants is highly dependent on the performance of auxiliary electric motors. These motors deliver air and fuel to boilers, oil to bearings, and provide cooling services for all systems. If there is a decrease in speed due to a decrease in frequency, the correct operation of auxiliary motors will be significantly affected. This can cause various problems in generators, activating their protections. This phenomenon can lead to a cascade disconnection of power plants, leading to the EPS collapse.
- In electronic applications, frequency is used as a time base for different processes.
- Transformers are sensitive to frequency variations and they can be overloaded if frequency deviates substantially from its nominal value.

Replacement of conventional generation by unconventional generation causes a decrease in the EPS inertia constant, one of the main causes of frequency instability. This problem has great relevance today, being object of intensive research. However, bibliography related to this topic is extremely fragmented. Consequently, it is not possible to find an article that encompass the main aspects of this challenge. That is, cause, effects, and possible solutions. Hence, the main objective of this work is to evaluate and compile the most

representative articles related with this theme. Therefore, this work includes, classifies and organizes valuable information from articles published in journals, congresses, technical reports and network codes, providing a comprehensive approach to the topic. Thereby, it serves as a theoretical basis to analyze and solve problems related to the decrease in the inertia constant and frequency stability of electrical systems. On the other hand, the review of network codes of different countries serves as basis for those entities that seek to initiate work towards regulating the incorporation of renewable energy sources and preserving the EPS safety and stability.
This article is organized as follows. First, a brief classification of different generation technologies is done, which will help to understand the cause of the problem. Then, the impact of the decrease in the inertia constant on EPSs frequency stability is studied. Subsequently, a bibliographic analysis of existing strategies to mitigate these inconveniences is carried out. In addition, a synthesis of how different countries are addressing the problem is developed. Finally, conclusions are obtained about the global trend regarding strategies to improve the frequency stability of EPSs.

2. GENERATION TECHNOLOGIES

Due to the great diversity of natural resources capable of providing primary energy, there is a great variety of generation technologies. Electric generators are devices that transform primary energy of some kind into electrical energy. However, the generated electricity does not always have the required voltage and frequency characteristics to be directly supplied to the EPS. Hence, in some cases, these characteristics must be adapted. Considering this, generation technologies can be classified into two large groups depending on whether they are directly or indirectly connected to the electrical system.

Direct connection:
These technologies use generators that transform rotational energy into electrical energy. The generated electrical energy is suitable to be supplied directly to the electrical system, i.e. alternating current and nominal frequency of the EPS. Within this group are, for example, large hydroelectric and thermal power plants, which use synchronous generators. Also belonging to this group are those plants that use induction generators, widely used in wind turbines.

Indirect Connection:
When the generated electrical energy is not suitable to be supplied directly to the electrical system, the connection is made by means of power electronics converters. These devices adapt the generator output voltage and frequency, allowing generators to connect to the grid. Technologies belonging to this group are unconventional generation technologies. This group includes, among others, those technologies whose:

- Output voltage is DC, as in photovoltaic generation and fuel cells.
- Voltage frequency is different from the EPS nominal as in the case of microturbines.
- Voltage frequency is variable, like in some types of wind generators.

Most common generation technologies are summarized in Table I [10]. It also indicates the primary source used by each technology and its connection method.

Table 1. Generation technologies and way of connection

Technology	Natural Resource	Connection
Internal combustion machines	Gas, diesel	Direct
Thermal turbines	Gas, diesel, coal, uranium (in nuclear power plants), biomass, heat from the earth (in geothermal power plants), sunlight (in solar thermal power plants)	Direct
Hydraulic turbines and microturbines	Potential and kinetic energy of waterfalls	Direct, Indirect
Wind generation	Wind	Direct, Indirect
Thermal microturbines	Natural Gas, waste gas, propane	Indirect
Fuel cells	Hydrogen	Indirect
Photovoltaic systems	Sunlight	Indirect

As shown in Table 1, great part of the new generation technologies is indirectly connected through power electronics converters. Power electronics allow the use of many intermittent, clean and renewable energy sources, as well as the possibility of incorporating energy storage systems. However, there are certain disadvantages: it increases the EPS complexity and its control, which can cause technical inconveniences and compromise the EPS operational safety [7, 8, 11-13].

3. INERTIAL RESPONSE OF AN ELECTRICAL SYSTEM

The frequency of an EPS depends on the active power balance between generation and demand, including losses. Therefore, frequency stability of a power system can be defined as the ability of the electrical power system to maintain the frequency in an acceptable range around the nominal value, after a severe disturbance that causes an important imbalance of active power. When a power imbalance occurs, the time evolution of the frequency depends mainly on the EPS characteristics, its operating state and the magnitude and type of disturbance. The power imbalance can be both negative and positive, causing decreases or increases in the EPS frequency respectively.
Frequency response during the first moments after the disturbance can be expressed by means of the generator's equations of motion. A frequently used form of the equation

of motion to describe the dynamic behavior of an electrical system is:

$$\frac{2H}{f_n}\frac{df}{dt} = \Delta P \quad (1)$$

Where H [s] is the EPS inertia constant, f_n [Hz] its nominal frequency, df/dt [Hz/s] the rate of change of frequency, and ΔP [p.u.] the active power imbalance [14].

The frequency response of an EPS to a negative power imbalance caused by an increase in load, during the first 20 seconds approximately, is shown in Figure 1. Immediately after the disturbance at t_0 = 2s, the power imbalance is initially compensated by the inertial response, i.e. by the kinetic energy delivered by connected generators and motors rotating masses. This causes a decrease in the rotational speed of such masses and therefore a decrease in the electrical system frequency. When the frequency deviation exceeds the dead band of speed governors, they respond and produce an increase in the output power of generators (Primary Frequency Control PFC). Equilibrium is achieved when the reduction of power consumption by frequency-sensitive loads plus the increase of generated power, equals the power imbalance. At this point, frequency reaches a minimum value f_{nadir}, therefore frequency deviation is maximum $\Delta f_{max} = f_n - f_{nadir}$. The intrinsically stored energy in the rotating masses of connected motors and generators is an instantaneous power reserve available in the EPS. This energy is related to the inertia constant of all connected generators and motors, which constitutes the total inertia constant of the electrical system [14].

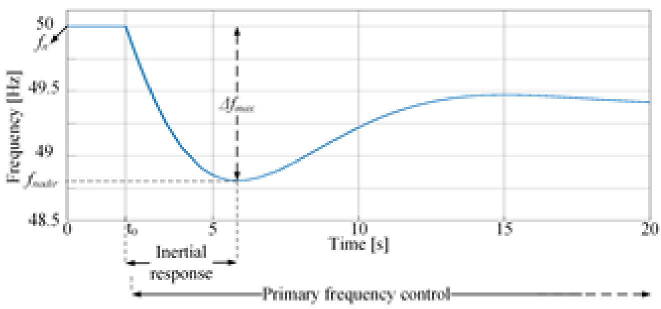

Figure 1: Frequency variation of the EPS after a disturbance, considering primary frequency control but not secondary

However, the connection of generation by means of power electronics converters causes certain inconveniences. One of the main is that the generator is electrically decoupled from the grid by means of the converter, so that regardless of the generation technology, the converter prevents stored kinetic energy from being supplied in the form of electrical energy to the EPS. Therefore, the replacement of conventional generation by electronically connected generation causes a decrease in the EPS inertia constant.

The effect of the inertia constant reduction in an electrical system can be seen in Figure 2. The frequency response of a power system when subjected to a disturbance of the same magnitude (in this case loss of a large generator) with different inertia constants, H_1 and H_2, where $H_1 < H_2$, is shown in this figure.

From (1) it can be deduced that a decrease in H causes an increase in $|df/dt|$, therefore $|df_1/dt| > |df_2/dt|$. As a consequence, the frequency response is faster and its deviation from the nominal value increases. This can be seen in Figure 2, where the maximum deviation of the EPS frequency with less inertia is greater, i.e. $\Delta f_{max1} > \Delta f_{max2}$.

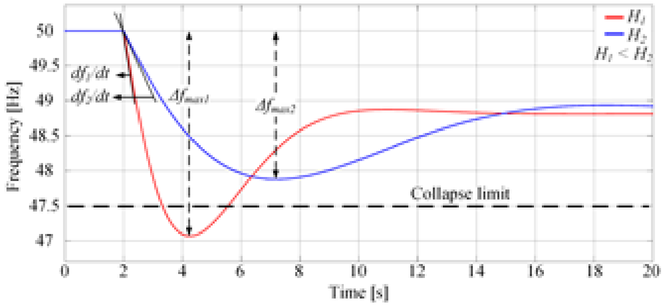

Figure 2: Electrical system frequency response with different inertia constants

The increase of $|df/dt|$ can be considered as one of the main drawbacks when operating an electrical system with low inertia. On one hand, it reduces the time in which generators that perform the PFC must respond, that is, increasing or decreasing their output power before the frequency exceeds the limit for which the load disconnection and/or generation begins. On the other hand, it impacts on protection schemes that act on this variable, both in load relief schemes and in generation. In most of today's electrical systems, distributed generation is connected by df/dt relays to prevent its operation in island mode. In the event of a power imbalance, there may be high frequency oscillations that trigger the relays, disconnecting the generation from the electrical network [15-17]. In this sense, effects of different Fault Ride Through (FRT) methods of offshore connected wind generation are studied in [18]. The article concludes that the electrical system becomes more sensitive to the FRT scheme used as the inertia constant decreases. This can affect angle and frequency stability in weak electrical systems.

On the other hand, if the frequency surpasses the load shedding and/or generation limits, the over or under frequency relays will also activate. Loss of generation due to sub-frequency disconnection increases the power imbalance. This can lead to a cascade effect, leaving much of the demand without energy supply [19, 20].

Furthermore, the decrease in the inertia constant causes overdemanding of generators due to continuous changes in frequency, among other drawbacks. In addition, variations in the generated power due to cloudiness, changes in wind speed, etc., from non-conventional energy sources, makes maintaining the balance of power even more complex, compromising EPSs frequency stability, as indicated in [21].

Although the aforementioned drawbacks are more common in small isolated networks and microgrids, different studies such as the one carried out by the German Energy Agency, conclude that in the near future the European interconnected system could face frequency instability issues due to the lack of inertia [22].

Finally, it can be seen in Figure 1 that the inertial response is overlapped with the primary frequency control, i.e., they complement each other. The instantaneous reserve delivered by the synchronous generators inertial response provides a natural delay until their speed governors respond, activating at that moment the reserve for PFC. At first, the unconventional generation did not participate in the PFC, causing serious stability problems. Today, however, it is common for unconventional generating plants to be required to control active power for PFC [23]. On the other hand, the decrease in the inertia constant causes the EPSs dynamics to be much faster, limiting the natural delay. Therefore, keeping H above a minimum limit is of utmost importance to maintain frequency stability.

4. ALTERNATIVES TO IMPROVE THE INERTIAL RESPONSE OF AN ELECTRICAL SYSTEM

In the event of a severe disturbance, protection devices act in emergency situations to prevent generators damage due to over or under frequency, or to stop the decrease in frequency through demand disconnection. In any situation, the activation of protection devices is considered as a last resort, since disconnection of generation and/or demand is not desirable. Ensuring frequency stability is therefore essential to maintain the EPS safe operation. For this reason, it is essential that the electrical system responds quickly, limiting the frequency variation before protections trip. In this sense, there are different preventive strategies to improve the EPSs inertial response. These strategies can be classified into two large groups, which are presented below.

4.1. Inertia from Synchronous Generation

a) Unit Commitment

An alternative to improve EPSs frequency stability in scenarios of great penetration of electronically connected generation, is to maintain a certain amount of synchronous generation connected to the electrical system, in order to have sufficient instantaneous power reserve. For example, maximum penetration levels of unconventional generation, specifically wind, are studied in [24-26]; to keep the electrical system of Spain, Ireland and Bolivia respectively, within safe operating limits.

On the other hand, an economic dispatch taking into account the minimum synchronous inertia required to maintain the operational safety of the electrical system is proposed in [27]. To do this, a feedback loop is added in the dispatch algorithm. This loop is responsible for evaluating whether the resulting dispatch meets the minimum required inertia or not. Then, an optimal economic dispatch in which restrictions are included in the form of equations that represent the electrical system frequency response is carried out in [28]. These equations are derived from a simplified model of the EPS and then linearized to be included in the mixed integer linear programming optimization problem.

A methodology to determine the amount of operating inertial resources, so as to promote the integration of variable speed wind generation in a weak and/or isolated electrical system is proposed in [29]. This methodology allows identifying which conventional generator can be replaced by wind generation, so that the impact on frequency stability is minimal.

A new paid complementary service is suggested in [30]. It consists of dispatching synchronous generators at their minimum power, with the aim of carrying out voltage control and inertia contribution. However, through this practice efficiency of diesel and gas generators decreases and emissions increase as indicated in [31, 32].

b) Synchronous Condensers

Synchronous condensers are synchronous machines running without a prime mover or a mechanical load [14]. For decades they played an important role in voltage and in reactive power control at both transmission and subtransmission levels [33]. They are capable of providing high fault short-circuit currents. Furthermore, results obtained in [34] show that, in severe faults, they have better dynamic performance than static var compensators. On the other hand, the kinetic energy stored in their rotating masses contributes to the EPS inertia, so that they are also beneficial from the point of view of frequency stability [35, 36]. However, high investment, operation and maintenance costs limit their application [37]. Therefore, installation of new synchronous condensers in an electrical system requires an adequate analysis.

c) Pumped Hydroelectric Storage (PHS)

PHSs are the largest reversible storage systems today. In times of low demand, the plant pumps water from a lower reservoir to an upper reservoir. On the contrary, during periods of high demand, the plant releases the water to the lower reservoir through turbines, operating in generating mode [38]. In addition to operating in pumping or generating mode, pumped hydroelectric plants can operate as synchronous condensers, contributing to the system inertia in all three modes [39, 40]. Its main disadvantage is the geographic requirement. Since an upper and lower reservoir is needed, the feasibility of installing a PHS plant strongly depends on the geography of the place.

d) Compressed Air Energy Storage (CAES) Systems

CAES are a gas turbine-based energy storage technology, which uses electricity to compress air and store it under high pressure in caverns, underground mines, dry wells, gas chambers, etc. The air is then released through the turbine to generate electricity when required [41]. As CAES use synchronous machines, they add inertia to the electrical system, improving frequency stability. They are also capable of controlling voltage, among other services [42]. As in the case of PHS, the main disadvantage of CAES is related to geographic requirements.

4.2. Inertia Emulation

This alternative consists of improving the EPSs inertial response through the contribution or reduction of active power in a similar way as synchronous generators and motors intrinsically do. This is achieved by emulating the inertial response of synchronous generators by controlling power electronics converters, known as synthetic or virtual inertia [43-45]. It is proven that unconventional generation connected by converters that emulate synchronous generators, acts in a more friendly way with the grid, contributing to the electrical system stability [46].

Various algorithms/control topologies developed for contributing with virtual inertia can be found in literature. Among the main ones synchronverters and VISMA topology can be named [47-49]. The basic principle of control implies the contribution or reduction of active power proportional to *df/dt*, as occurs naturally in conventional synchronous motors and generators. Moreover, it has the advantage that virtual inertia constant can be modified online, within certain limits, adapting it to the EPS requirements for a specific operating state [50, 51].

The energy required to synthesize virtual inertia may come from various sources or combinations of them, which are described below.

a) Energy Storage Systems

Electrical and electrochemical storage systems are the most widely used for inertia emulation due to their rapid response. However, flywheels are also presented as a viable alternative for this use. For example, the use of a distributed energy storage system based on ultracapacitors is proposed in [52] to reduce the impact of solar and wind generation on the island of Guadeloupe, France. Results show that the contribution of synthetic inertia from these fast-acting storage systems helps to improve the EPS dynamic response in cases of large generator output. A battery-ultracapacitor hybrid system is proposed in [53]. So that ultracapacitors are in charge of providing the necessary energy for inertia emulation, while the battery is in charge of compensating longer power variations, such as primary frequency control. Then, an adaptive inertia emulation control for high speed flywheels is proposed in [54]. The proposed control combines the advantages of an on/off control and an adaptive one, in order to obtain a fast and proportional response to the frequency disturbance. Off-line and experimental results show that the control strategy significantly reduces the rate of change of frequency, as well as its deviation.

b) Wind Turbines

Inertia emulation in wind turbines is carried out by extracting the kinetic energy stored in the blades masses [55]. However, this causes a decrease in the turbines rotation speed; causing aerodynamic drawbacks and subsequent power deficit that can result in increased power imbalance [56]. Then, this problem is addressed and solved in [57] by means of a centralized and coordinated control of different turbines of the plant, so that speed recovery is not simultaneous for all turbines. A study and comparison between emulating inertia through the energy stored in the blades and through the connection of a supercapacitor in the DC link is carried out in [58]. On the one hand, the first alternative does not require any additional element, but it is highly dependent on the operating state of the turbine at the time of disturbance. On the other hand, the second alternative requires the supercapacitor itself, an additional DC/DC converter and adapting the converter on the grid side. However, it is demonstrated that the supercapacitor outperforms the former alternative; it is independent of wind speed and notably improves the electrical system frequency response. A method to enhance the inertial response of wind plants connected by High Voltage DC (HVDC) link is presented in [59]. Proposed control improves the frequency response, reduces its deviation and performs primary frequency control.

c) Photovoltaic systems

As previously mentioned, a power reserve is needed in order to emulate inertia. In case of photovoltaic systems this is carried out by operating photovoltaic (PV) systems below the point of maximum power (deloading). For example, PV plants operate with a 10% active power reserve in [46]. Results show that, by operating those plants as virtual synchronous machines, they contribute to the power system stability, while PV panels work in the stable region of the curve. Inertial emulation is done in [60] by charging/discharging the DC link capacitor and adjusting the operating point of the PV system. The control is tested on a microgrid, improving its transient response. While a simultaneous control of the DC link voltage and deloading is proposed in [61]. This accomplishes both the contribution of inertia and primary frequency control, effectively mitigating frequency fluctuations.

d) High Voltage DC Links

Inertia emulation from HVDC systems is carried out using the energy stored in the DC link capacitors. In this sense, an inertia emulation strategy that uses the capacitors of a high-voltage DC system based on a voltage source converter VSC-HVDC is proposed in [62]. This strategy does not depend on the *df/dt* measurement, so it is less sensitive to the amplification of measurement noise. Proposed control allows the converter on the grid side to contribute to the inertial response by varying the DC link voltage. It does not require additional hardware and it improves the power system transient response against disturbances. In addition, the control maintains the VSC decoupling characteristic, which is to avoid the propagation of disturbances between connected systems. In this case, between the power system and an offshore wind power plant. An inertia emulation method based on derivative control considering the effects of frequency measurement is developed in [63]. The control is tested on an electrical system consisting of two areas connected by an HVDC system with an added storage system. It is concluded that, although inertia emulation improves the electrical system transient response, delays introduced by the measurement PLL have a negative impact on the control system. A control strategy for an HVDC system based on synchronverter topology is proposed in [64]. In this work, a methodology to configure the synchronverter parameters is presented, managing to improve the EPS dynamic response and its stability.

4.3. Pros and Cons of the Reviewed Alternatives

In the previous titles, different alternatives to improve the inertial response of electrical systems were reviewed. In the first group, those related to contribution of inertia from synchronous generation were studied. Faced with a low inertia electrical system, unit commitment control alternative turns out to be the most direct solution. It helps maintaining instantaneous power reserve in adequate amount and it does not require installation of new generation or storage plants. However, it limits the penetration of non-conventional renewable generation; this goes against environmental and social needs seeking to increase penetration of new non-polluting renewable energy sources. On the other hand, synchronous compensators are capable of increasing short circuit current, contributing to voltage regulation, and inherently providing synchronous inertia. However, high investment, operation and maintenance costs limit its application. Finally, PHSs and CAESs systems use synchronous generators with all the known advantages, but they need a large investment and their application is extremely limited to geographical requirements.

In the second group, alternatives related to inertia emulation were studied. This field of research is still under development. There are a large number of algorithms and strategies of control for supplying virtual inertia. The possibility of adding and/or combining storage systems with other systems makes it a very flexible and scalable alternative. Although inertia can be emulated from DC link capacitors of DC/AC converters, installing fast storage systems increases instantaneous power reserve. As a disadvantage, costs associated with them can be mentioned. However, it should be noted that large amounts of energy are not required, but power. There are a variety of storage technologies suitable for inertia emulation, but they are not the aim of this research.

Without considering additional storage systems, inertia emulation from wind turbines causes a decrease in the rotation speed of turbines and consequently a subsequent power deficit. Therefore, a coordinated control is necessary as indicated above. On the other hand, photovoltaic systems must be operated with a reserve margin, which implies cheap wasted energy. Therefore, the amount of needed reserve must be carefully calculated. Finally, emulated inertia from HVDC systems is obtained from the DC link capacitors, so it does not necessarily require additional hardware. In this sense, its main and probably only disadvantage is related to the existence of an HVDC system in the EPS.

It can be concluded, therefore, that the second group favors the penetration of new unconventional, clean and renewable generation technologies. This is why contribution of virtual inertia is becoming increasingly important. Thus, network codes of different countries around the world consider, among the connection requirements of non-conventional generators, the contribution of virtual inertia.

5. STRATEGIES ADOPTED BY VARIOUS COUNTRIES

5.1. European Union

In 2013 the Irish transmission system operators formally submitted their recommendations to the Single Electricity Market Committee (SEMC) of Ireland. Among those recommendations, it was proposed to redesign the complementary services scheme to meet the technical needs of the electrical system for the year 2020. Taking this into account, the SEMC approved the implementation of a new service called Synchronous Inertial Response (SIR), with its respective market. This service began to be implemented in May 2018 and contemplates the inertial response provided by the synchronous generation dispatched at its minimum power. Within the SIR, synthetic or virtual inertia is also considered as a potential service [30, 65].

Then, in August 2019, virtual inertia contribution became a requirement for non-synchronously connected generator plants throughout the European Union. In particular, Regulation 2016/631 of the European Grid Connection Code, of requirements for connecting generators to the grid, establishes that the Transmission Grid Manager (GRT) will have the right to specify that the aforementioned plants, specifically those with the highest installed power, must emulate inertia during fast frequency variations [66]. On the other hand, Regulation 2016/1447 establishes grid code requirements for connection of HVDC systems and generation modules connected in direct current. The latter specifies that, if indicated by the relevant GRT, an HVDC system must be capable of emulating inertia in response to frequency variations; injecting or rapidly decreasing the active power at the connection point between the DC and AC network, in order to limit the rate of change of frequency [67].

5.2. Canada

In Canada, the public company Hydro Quebec manages the generation, transmission and distribution of electrical power in Quebec. Such electrical system is connected asynchronously, through 15 interconnections, with all neighboring networks. Therefore, the high penetration of wind generation that it is experiencing could compromise the EPS operational safety [68]. For this reason, contribution of virtual inertia from wind generation plants greater than 10 MW, is required by the company. Delivered inertia is done in the same amount as in a conventional synchronous generator, whose inertia constant is approximately 3.5 s.

On the other hand, the Independent Electricity System Operator of Ontario (IESO), dictates that wind generators must have the capacity to provide synthetic inertial response after a disturbance. This response must be activated within one second and held for a minimum of ten seconds [69].

5.3. Brazil

Currently, penetration of wind generation reaches 9.39% of total generation capacity in Brazil. Installed power is about 16.3 GW and new plants under construction will increase that capacity [70]. This increase in wind energy penetration imposes great technical challenges to the operators of the Brazilian electrical system (ONS). For this reason, grid code of minimum technical requirements for the connection of wind power plants was modified by the ONS. Current grid code establishes that wind turbines must provide virtual inertia in order to supply at least 10% of their nominal power to improve the EPS frequency response [71].

5.4. Chile

A flexibility strategy for the national electrical system is outlined by the advisory commission of the Chilean Energy Ministry in [72]. The need to have sufficient inertia in the future is one of the proposed measures. The objective of this measure is to analyze technological solutions and regulatory mechanisms to improve the EPS frequency response. In particular, it is considered necessary to evaluate the incorporation of an inertia emulation service by generation units with a power electronics interface. Thus, when certain levels of inertia are required, said facilities can provide the service and be remunerated through the market.

5.5. Australia

In February 2018 the Australian Energy Market Commission (AEMC) made the decision not to introduce a market mechanism for contributing inertia. Instead, it forced the transmission network service provider to ensure the required levels of inertia, or alternatively an equivalent service [73]. However, several generation and transmission companies such as Delta Electricity, Hydro Tasmania, Infigen Energy and TransGrid have recently made numerous requests for regulatory changes related to the problem of low inertia in the Australian electrical system [74].

6. CONCLUSIONS

In this work an analysis of those main aspects related to the reduction of the EPSs inertia constant is carried out. The cause is studied, the effects are detailed and different alternatives to improve the EPSs inertial response are exposed. In addition, network codes of various countries advancing in the incorporation of non-conventional renewable generation are analyzed. Therefore, it serves, both as a theoretical basis to address the problem, and as a guide for those entities that seek to initiate works towards regulating the incorporation of renewable energy sources.

As conclusions of the research, it can be said that the operation of electrical systems with high penetration of unconventional generation is an increasingly complex task. The decrease in the inertia constant, due to the incorporation of generation connected by power electronics, causes various inconveniences and compromises the EPSs frequency stability. In this sense, there are different alternatives to improve the EPSs inertial response. On the one hand, various studies propose maximum penetration limits of unconventional generation, installation of PHSs, CAESs or synchronous condensers; in order to have an instantaneous power reserve available at all times and to keep the inertia constant above a minimum limit. However, this restricts the penetration of new renewable and clean generation technologies. In addition, high investment, operation and maintenance costs, plus the geographic requirements by PHSs and CAESs, limit its application. On the other hand, active power control in the form of virtual inertia is presented as a promising and feasible alternative to maintain the frequency stability of electrical systems. The inertia emulation contributes to the improvement of the frequency response without limiting the penetration of unconventional generation, while maintaining operational safety. In addition, the ability of adding and/or combining storage systems makes it a scalable and flexible solution. For these reasons, electrical system operators in various countries have adopted this alternative as the main solution, modifying the network codes for connection requirements to non-conventional generation. The latter represents a global trend.

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