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Analysis of the cause of power system inertia generation and decline

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Abstract. Variable renewable energy sources (RES) are becoming more and more common, and traditional power generation plants are rapidly being replaced by them. As RES are used more frequently, power electronics are also utilized more frequently, both to connect RES and as drives for electric motors. As a result, the inertia level of the power system is continuously decreasing, and the frequency stability of the power system is facing severe challenges. Traditional power-generating methods such as thermal, hydroelectric, nuclear, and natural gas use generators to produce electric energy. By utilizing the rotational inertia of the steam turbine unit, the frequency fluctuation trend that occurs in the power grid can be delayed. However, photovoltaic power generation lacks rotating machinery and has no rotational inertia, whereas wind turbines operate at a modest speed and have negligible rotational inertia. The response capability is reduced significantly when the power grid's frequency changes. Any electric power system tends to rely on rotational inertia. The relevant factors impacting the inertia level of the power system are introduced based on the concept of inertia of the power system. The power system experiences inertia from the synchronous grid-connected generation side, the load side, and the grid-connected generation side of the converter. These three sources make up the majority of the inertia in the system. From the aspects of the power generating side, grid side, and load side, approaches and strategies to increase the frequency stability of power systems are introduced.

Keywords: power system inertia, renewable energy, inertia control.

1. Introduction

High levels of uncertainty in the grid connection of RES will result in a substantial shortage in the power system's capacity to regulate frequency. The two fundamental RES are photovoltaic and wind power generation, both of which require a power electronic converter to transfer energy. The benefits and drawbacks of distributed generation power, as opposed to conventional generation units, are increasingly evident as the proportion of renewable energy and power electronic equipment rises. Compared with synchronous generators in traditional power systems, power electronic converters are more flexible and controllable. However, the inertia of the system will be reduced by large-scale grid connection of renewable energy-generating units coupled with power electronic converters [1]. If a low inertia power system is disturbed and there is no other frequency support mode available besides the traditional unit, the system's frequency response capability will decline as the inertia level falls. As a result, the system frequency's dynamic response will be more intense, its frequency deviation amplitude will grow, its frequency change rate will accelerate, and its recovery time will steadily lengthen [2]. It is suggested to fully utilize all inertia support resources to increase the inertia level of the power system to lessen the negative effects of low inertia level on the frequency response change of the power system and the safety and stability regulation methods.

With the construction of Ultra High Voltage AC-DC power network, the development of renewable energy, and the deepening of power market reform, the stability analysis becomes more complex. From the perspective of voltage stability, compared with large-capacity rotating equipment, the power electronic devices in the renewable power system lacks reactive power support capacity, and the grid of the renewable energy delivery system is generally weak, resulting in a sharp decrease in the voltage support capacity. From the angle of power stability, the control methods of renewable energy, flexible DC, and other power electronic equipment are diverse, and the synchronization analysis of the system is more complicated under different interference. From the frequency stability perspective, the system's decrease in inertia will directly lead to a decrease in the anti-interference ability of the system frequency. Once the new energy is interlocked off the grid, the system frequency will be directly affected [3]. To improve the problem of insufficient inertia support, converter control methods, such as droop control, virtual inertia control, and virtual synchronous machine, have been proposed in recent years, which can enable renewable energy and energy storage to have the capability of inertia support and frequency adjustment and improve the frequency stability of the system [4, 5].

This paper covers the primary factors that lead to a reduction in the moment of inertia in the power system with a high proportion of renewable energy. Then, methods and strategies to improve the frequency stability of power systems are presented from the perspectives of the power generation side, grid side, and load side.

2. Importance of rotational inertia in power system

2.1. Definition

Rotational inertia in the power system is different from the physical definition of resistance to changes in objects' speed and direction, it describes resistance to the state of motion in the rotating machinery which is connected directly to the power system. In a conventional power system, the turbine and generators, which continuously input kinetic energy, are the main sources of inertia. Contrarily, renewable energy sources have an unsteady kinetic energy input because of erratic weather changes and geographic factors.

The following mathematic expression usually be used to define the relationship between kinetic energy and rotational inertia. The moment of inertia is usually expressed in the form of energy.

Kinetic energy E_k stored in the rotating generator is expressed as

$$E_k = \frac{1}{2}J(2\pi f)^2 \tag{1}$$

J: the moment of inertia of the synchronous machine

f: the rotational frequency of the machine

The kinetic energy of the generator depends on the moment of inertia and rotational speed.

The inertia constant H for a synchronous machine can be defined as

$$H = \frac{E_k}{S} \tag{2}$$

S: rated power of the generator

The inertia constant of the operating generator is only related to the kinetic energy and rated capacity at the rated speed of the generator. H is a frequently used constant in stability analysis.

The classical swing equation for a synchronous generator describes inertia response when power imbalance happens [6]:

$$\dot{E}_K = J(2\pi)^2 f \cdot \dot{f} = \frac{2HS_B}{f} \cdot \dot{f} = P_m - P_e \tag{3}$$

P_m: the mechanical power supplied by the generator

P_e : the electric power demands

When examining the stability of connected generators, this equation is incredibly useful.

2.2. Sources of inertia in power system

Inertia from connected synchronous generation and load, inertia and virtual inertia from converter-connected generation are the three basic causes of system inertia.

2.2.1. Inertia from connected synchronous generation. Firstly, the type, size, and speed of the machine all affect the inertia of large conventional generations. The inertia generated by large conventional generation units is assumed in most studies to be constant, and the inertia constant is inversely related to the rating [7]. Secondly, the type and quantity of connected power plants that currently vary in operation during the day due to priority that are mostly based on the fuel type, will impact the total inertia and lead to generation-side fluctuations.

2.2.2. Inertia from load side. The dynamics and type of the load determine whether it will add to the system's inertia. For example, since the rotational speed of directly coupled motor loads is correlated with the system frequency, they will affect the system's inertial response. Other load types, like resistive loads, are frequency independent.

Various consumer categories also provide synthetic inertia. Thiesen et al. studied a case where a transmission line short circuit to Denmark led to the decoupling of the Flensburg power system and a cascade-like disconnection of districts to maintain power balance [8]. The inertia offered by the four major groups is shown by the figures in Figure 1 as seen in the bars. Each category makes a different contribution to the inertia constant, demonstrating that the portion of the inertia contribution made by the various power consumer groups can be calculated and used to support the application of synthetic inertia in the future.

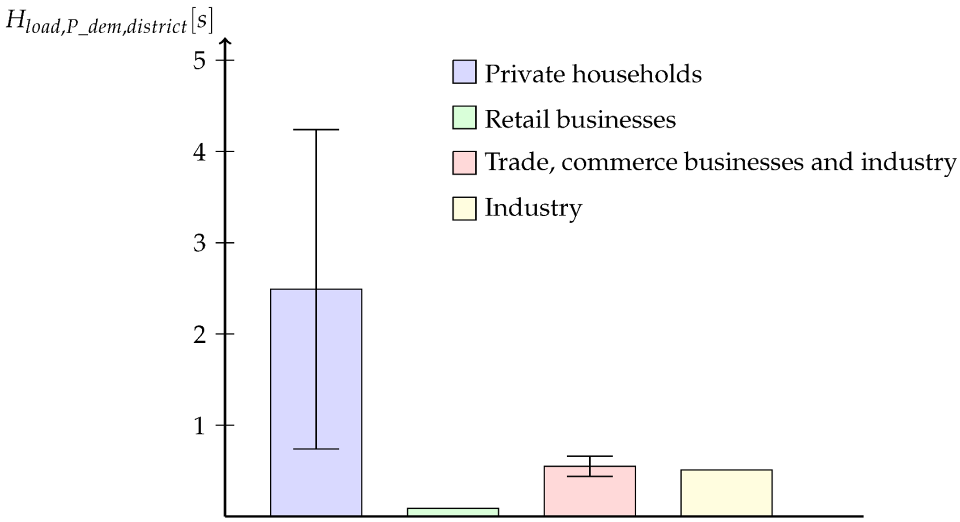

Figure 1. Each bar displays the inertia offered by the particular consumer category [8].

2.2.3. Inertial from converter connected generation. Inverters are used to connect various RESs, such as PV systems and variable wind turbines, to the electrical grid. However, because these RESs have very little or no inertia response, the inertia and frequency stability of the entire system are reduced. Wind power and photovoltaic power accounted for the largest share of converter connection power generation. In the blades, gearboxes, and generators of wind turbines, there is a lot of kinetic energy stored.

However, because there are no rotating components in the PV cell, there is no stored energy present other than the energy in its capacitor.

2.2.4. Virtual inertia from converter connected generation. The short-term stored energy in the DC link of the Distributed Energy Resources (DER) power converters, which should be injected into the AC side following the virtual inertia control target, is the main source of the virtual inertia. For converter-based RES, Ghosh et al. presented an analytical approach to determine the equivalent inertia constant using a dc-link capacitor as the energy storage component to provide virtual inertia for grid frequency regulation [9].

3. Renewable energy sources decrease the inertia in power system

Energy shortages and environmental issues are driving up the percentage of renewable energy sources. Renewable generation units are usually connected by power electronic converters that completely or partially separate the generators from the grid, resulting in inertia power systems. The updated power system's inertial response is reducing as a result of the need for adequate energy buffers and proper control to regulate this energy, just like conventional synchronous machines do.

The thermal power plants and hydropower plants in the conventional power system will gradually reduce the rotor rotation speed and quickly provide a large amount of inertia resource support for the system when the load fluctuation causes an imbalance between the supply and demand of active power. The rapid promotion of renewable energy, however, hastens the removal of conventional power generation units from the system, which causes a sharp decline in the inertia level of the power system and poses a serious threat to its frequency safety and stability [2].

4. Control strategy

To reduce the adverse impact of low inertia levels on frequency response changes of power systems and find stable and safe regulation means, domestic and foreign scholars have studied how to improve the inertia level of power systems and put forward the idea of fully utilizing all inertia to support resources, including the use of renewable energy such as wind and light, load, energy storage, and other inertia resources to participate in inertia response [10, 11]. By proposing converter control methods, such as droop control, virtual inertia control, and virtual synchronizer, renewable energy, and energy storage can be equipped with inertia support and frequency adjustment capabilities [5, 12, 13].

4.1. Frequency support on power generation side

With the integration of a large amount of renewable energy, such as wind and photovoltaic, the proportion of conventional units rapidly diminishes. Renewable energy sources are disconnected from the grid after they are integrated, making it impossible for them to effectively support inertia. To improve the power frequency response ability of the power electronic interface, the converter control strategy can be improved to give the renewable energy generation the same inertia response-ability as the synchronous generator [14].

It can be separated into current source virtual inertia and voltage source virtual inertia based on the response characteristics and control techniques of the inertia sources.

4.1.1. Current source virtual inertia. The core objective of current source inertia control is to adjust the converter's output power in response to the frequency change rate of the power system and to react to the frequency change by supplying the power grid with active power proportional to the frequency change rate, its expression formula is

$$\Delta P = K\frac{df}{dt} \tag{4}$$

K is the virtual inertia coefficient, which is proportional to the rotational inertia of the synchronous machine and its mass. Different from synchronous units, the virtual inertia coefficient of renewable energy can be set independently and is not constrained by physical conditions [15].

The current source virtual inertia is essentially different from the rotational inertia of the synchronous machine. The virtual inertia control is still a power source in essence. It does not have the characteristic of sharing the disturbed power to make the output power change and does not directly provide inertia to the system. Although the current source inertia control design is simple and greatly reduces the construction cost, the current source inertia control in a high proportion of renewable energy power systems has a certain short delay, which will lead to the failure of renewable energy to respond to the frequency change of the power system in time, threatening the safety of the power grid and causing frequency safety accidents [16].

4.1.2. Voltage source virtual inertia. Virtual synchronous generators (VSG) technology is referred to most frequently as voltage source virtual inertia. A virtual synchronous machine, also known as synchronous converter, refers to the introduction of rotor motion and electromagnetic transient equation of a synchronous machine in the converter control process, which can simulate the voltage source characteristics of a synchronous machine. The voltage source virtual synchronous machine has the same external characteristics as the synchronous machine [17]. The desired control quantity for the converter is the output voltage, whereas the uncontrolled quantity is the output power. It is capable of distributing disturbance power like a synchronous machine. When under immediate stress due to input and output power deviations, the inertia storage unit absorbs or releases energy to support the output power and maintain the system power balance. It can instantly supply inertia support power at the time of imbalanced power, and its inertia response characteristics are similar to those of the synchronous machine.

The inertia response of a virtual synchronous machine must have its energy source. According to different frequency modulation principles, VSG technology of wind turbines can be divided into three ways: additional energy storage, utilization of fan rotor kinetic energy, and comprehensive control [18, 15,19]. PV VSG technology can be divided into energy storage control and standby active power according to different energy sources [20-23]. Virtual synchronization technology can be realized through additional energy storage control.

4.2. Grid side frequency support

With the emergence of a large number of microgrids in the distribution network, how to integrate multiple microgrids to improve the flexibility and reliability of the system operation and enhance the regional complementary capability of distributed energy has attracted more and more attention. Flexible High Voltage Direct Current (HVDC) power transmission is one of the best choices to solve the integration and aggregation problem of multiple microgrids. However, under traditional control, DC power transmission will lead to frequency decoupling between microgrids, which makes it impossible to form frequency support between microgrids. A frequency-distributed cooperative control strategy is proposed for a flexible HVDC interconnected island microgrid group to solve the problem of AC-DC hybrid control and frequency decoupling between microgrids caused by DC transmission [24]. In this strategy, the goal of frequency control between micro-networks is realized, and the coordination among distributed units within micro-networks is used to solve the regulation problems such as frequency recovery and accurate allocation of reserve capacity. At present, the more technical and economical DC transmission mode is a multi-terminal flexible HVDC system to realize multi-point interconnection. However, the traditional flexible HVDC converter cannot respond effectively to frequency changes. The converter control strategy must be optimized as a result for the flexible HVDC system to effectively support the system's frequency.

4.3. Load side frequency support

When describing the influence of load on frequency in power systems, static load frequency characteristics are typically utilized. This means that when a system's power imbalance causes the frequency to change, the energy stored in the electromagnetic field and rotational mass of the system load will change to prevent the system frequency deviation. This effect is known as the load inertia effect and is typically expressed by the load frequency regulation effect coefficient. Because the static frequency characteristics of the load in the inertia response stage are mostly caused by the motor load, they can be directly attributed to the motor's inertia response, which can more accurately reflect the dynamic influence of the motor on frequency.

Load inertia response refers to the spontaneous response of grid-connected asynchronous motors to system frequency changes. The rotational kinetic energy of the rotors is used to support the electrical grid's inertia [25]. With the application of high-proportion power electronic devices in power systems, load inertia response is no longer limited to the rotor kinetic energy of asynchronous motors [26]. The load power can be adjusted to react to the frequency deviation in the power grid by enhancing the control of the transformer at the sending end and working with the real-time frequency regulation controller [27]. In addition, relevant researchers also proposed to improve transformer topology and relevant control strategies to enable loads to participate in frequency support promptly [28]. Meanwhile, intelligent buildings and electric vehicles have gradually become the research objects of load-side frequency support strategy [29, 30]. Although the frequency of the load frequency response can also offer support for the system, it can also have a weak and unstable promotion influence on the entire power system.

5. Conclusion

This paper reviews three main sources of inertia in the power system: inertia from synchronous grid-connected generation and load, and inertia from converter grid-connected generation. The objective is to lessen the negative impact of low inertia level on the frequency response variation of the power system and find safe and stable regulation methods from the sources of inertia. Therefore, frequency support method analysis is provided by all three of these factors from the generation side, grid side, and load side.

The main factor causing the power system's inertia to be reduced is the significant amounts of wind and photovoltaic power generation. The converter is required to connect the renewable energy source to the electrical grid. So it is recommended to directly improve the converter control strategy, which can make the renewable energy power generation have the same inertia response-ability as the synchronous generator. The VSG technology, one of the most popular converter control strategies, uses the synchronous machine's rotor motion and electromagnetic transient equation in the converter control process, simulating the synchronous machine's voltage source characteristics and instantly supplying inertia support power in the case of power imbalance.

From the load side, various consumer categories also provide synthetic inertia. Under the condition that the inertia contribution share of diverse power consumption groups is affected by time, geographical location, and other factors, flexible DC transmission integrates multiple microgrids in the distribution network to improve the flexibility and reliability of the system operation. A frequency-distributed cooperative control strategy is proposed for a flexible HVDC interconnected island microgrid group to solve the problem of AC-DC hybrid control and frequency decoupling between microgrids caused by DC transmission.

To reduce the negative effects of low inertia levels on frequency response changes of power systems, the real-time frequency regulation controller and optimized transformer control on the load side of the power grid can be used to modify the load power in response to frequency deviations in the power grid. By utilizing the rotational kinetic energy of the grid-connected motor's rotor, it can also sustain the inertia of the grid. In addition, methods to change the topology of transformers or to use energy-storing loads such as power electric vehicles and buildings as frequency supports are also being studied and improved.

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