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Inertia Effects on Power Systems

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Abstract - Inertia plays a vital role in maintaining the frequency stability of power systems. However, the increase of power electronics-based renewable generation can dramatically reduce the inertia levels of modern power systems. This issue has already challenged the control and stability of small-scale power systems. It will soon be faced by larger power systems as the trend of large-scale renewable integration continues. In view of the urgent demand for addressing the inertia concern, this paper presents a comprehensive review of inertia enhancement methods covering both proven techniques and emerging ones and also studies the effect of inertia on frequency control. Among those proven techniques, the inertia emulation by wind turbines has successfully demonstrated its effectiveness and will receive widespread adoptions. For the emerging techniques, the virtual inertia generated by the dc-link capacitors of power converters has a great potential due to its low cost. The same concept of inertia emulation can also be applied to ultra capacitors. In addition, batteries will serve as an alternative inertia supplier, and the relevant technical challenges as well as the solutions are discussed in this paper. In future power systems where most of the generators and loads are connected via power electronics, virtual synchronous machines will gradually take over the responsibility of inertia support. In general, it is concluded that advances in semiconductors and control promise to make power electronics an enabling technology for inertia control in future power systems.

Index Terms—Batteries, control, energy storage, inertia, power electronics, power systems, renewable energy sources (RESs), ultra capacitors, virtual synchronous machines (VSMs).

INTRODUCTION

Technical factors contributing to the eventual adoption of alternating current over direct current in the 1890s comprise a marriage of the developments of practical transformers & poly phase systems. Transformers play a vital role as they enable ac power to be easily transformed and transmitted at high-voltage levels. Power systems in majority of the world share a standard frequency of 50 HZ, except for the American and parts of Asia, Where the nominal frequency is 60HZ.The complete worldwide standardization seems economically unattractive, and there is no great technical reason to prefer one over the other. Frequencies as high as 400HZ are used in small-scale weight-sensitive systems, such as aircraft, submarine, and computer power supply systems, mainly for reducing the size of transformers and filters. Frequency control, i.e., the balance of generation and demand, is of great importance and has been identified as a high priority area by many power system operators. Ideally, the grid frequency should always stay at its nominal value. Unfortunately, ever-changing load and generation profiles will cause frequency deviations the operation of generating units at a low frequency may Impose vibratory stresses on the turbine blades and reduces the outputs of boiler feed pumps or fans .To guard against low-frequency operations, under-frequency protective relays are nominally involved so that generators will be tripped off when the frequency decline is excessive. Therefore, tripping of generation, cascading outages, or even isolation of areas and formation of electrical islands may happen as the results of an ineffective frequency control. Inertia is an inherent property of synchronous generators (SGs). When the frequency drops, SGs autonomously turn slower and release the kinetic energy stored in their rotors to slow down frequency deviations, thus helping to mitigate the frequency nadir. As the penetration levels of renewable energy sources (RESs) grow, inertia decreases. This is because RESs are normally coupled to the power grid through static power electronics devices, which do not possess any inertia. The decreased inertia deteriorates the frequency nadir & threatens the system stability and reliability. Therefore, great efforts should be attached to the improvement of inertia. The reduction of inertia in future in future power systems will challenge the regulation of the time derivative of frequency, i.e., the rate of change of frequency (RoCoF). When exposed to high-RoCoF events, generating units are subject to the risk of pole slipping & catastrophic failure. High –RoCoF events may cause the protective tripping of generating units. The capability of mitigating RoCoF levels is another benefit of inertia. For future power systems with high inertia the grid frequency changes slowly, and this, it can be easily stabilized. However, the over-decreasing inertia brings in concern of high-RoCoF levels, particularly for small-scale power systems without any ac interconnections [1]. Many projects aiming to overcome the above mentioned challenges were initiated. In the view of the urgent demand for improving the inertia in future more-electronics power systems. This paper provides a comprehensive review of the inertia enhancement methods.

EFFECT OF INERTIA ON FREQUENCY CONTROL

A standard frequency control frame work of single-area power systems is shown in figure. Where R is referred to as the speed regulation or droop, which, together with Kg(s), can model the speed governor and turbine of thermal, hydraulic, and nuclear power plants. D with a typical value of 1-2 denotes the load –damping constant. Physically, it means the change in the absorbed power of motor loads with the frequency due to the change in motor speeds. $\Delta p_{m}\_p_{u}$ and $\Delta P_{t}\_P_{u}$ stand for the mechanical power change and non-frequency- sensitive load change, respectively, where subscript P_u& prefix Δ are per unit and perturbed notations. ΔPu_p_u&Kc(s) are related to inertia control. As the penetration levels of RESs grow, SGs are gradually being phased out by renewable generators. However, renewable generators are essentially power electronic converters without any direct inertia contribution. In consequence, RoCoF levels may become excessively high. This issue has already challenged the control and stability of small-scale power systems and will soon be faced by larger inter connected power systems. One straightforward solution to the RoCoF concern is enhancing the RoCoF capabilities of generators, including both conventional & renewable generators. Many power system operators put more stringent requirements on RoCoF withstand capabilities through their rule change proposals to prevent generation tripping during frequency events [2].

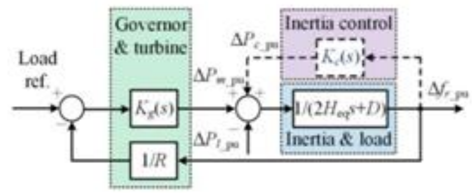

Fig.1 Frequency control framework of single area power and system

I. PROVEN TECHNIQUES FOR INERTIA ENHANCEMENT

For clarity, this paper categorizes inertia enhancement techniques into two groups, i.e., the proven techniques that are already used in practice and the emerging techniques with active research efforts under way.

A. Inertia Enhancement by Synchronous Condensers

Synchronous condensers are essentially SGs running without prime movers or loads. Normally, they are used for reactive power compensation and voltage control. Apart from this, synchronous condensers may also be employed to reap the benefit of their inertia. In addition, synchronous condensers may be modified to improve their inertia contributions by adding additional rotating masses. Although the adoption of synchronous condensers eases the RoCoF issue, high capital and operating costs have deterred their widespread applications for inertia enhancement.

B. Inertia Emulation/Frequency Support by Wind Turbines

With the increasing penetration of wind power in power systems, it is desirable for wind turbines to have similar characteristics as conventional synchronous generators. Conventional generators provide frequency support to the grid through the methods of inertial response, primary and secondary frequency regulation, whereas variable speed wind turbine generators (WTGs) do not have those desired abilities because they are integrated into the power grid via power electronic converters. The wind energy has been regarded as one of the most promising RESs, and the inertia emulated by

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wind turbines provides added incentives for the use of wind energy.

For wind generation system configuration, doubly fed induction generators (DFIGs) with partial -scale power converters are dominating on the market by far. A schematic of DFIG- based wind generation systems, where the stator of the DFIG is directly connected to the grid while the rotor is tied to the grid through a back-to-back converter consisting of a grid side converter. The grid side converter is intended to regulate the dc-link voltage and reactive power. In contrast the generator side converter seeks to control the active power and rotor speed, and it may also be regulate the reactive power. DFIG enables wind turbines to operate with various range of speeds. For the diagram i_s stator current, $v_{s.}$ stator voltage, i_c capacitor current, v_c capacitor voltage, vg grid voltage, ig grid current.

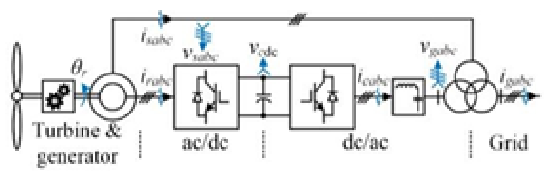

Fig 2 Schematic of DFIG-based wind generation systems.

The trend of using SGs with full-scale power electronics is appearing. The diagram of permanent magnet SG (PMSG) - based wind generation systems. As noticed, a back-to-back converter interconnects the stator windings of the wind turbine to the power grid. Although this solution necessitates high power converters, it allows the elimination of slip rings, simplified or even eliminated gear box, and enhanced power & speed controllability. PMSG is used for low power, low cost, synchronous generator, and low speed direct drive wind turbine generator. The rotor windings replaced with permanent magnets. They have slip rings & contact brushes. It should be recognized that the inertia emulation by DFIG and PMSG – based wind turbines are both achieved by changing the grid injected power Pc or the electromagnet torque Tc.

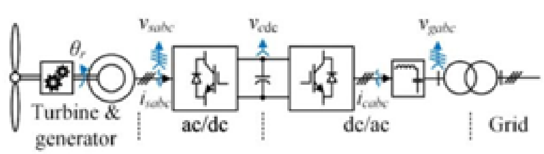

Fig 3 Schematic of PMSG-based wind generation systems

As evidenced, the inertia contributed by the wind turbine is different from the synchronous inertia. This can be understandable, as the wind turbine does not output the power exactly the same as SGs do during the frequency event. In this sense, the term "inertia emulation"may more precisely be replaced by "frequency support ". In practice, grid codes normally specify the performance metrics including the minimum boost time, boost power, maximum actuation time, drop power, recovery time, and dead band. The emulated inertia can be expected from wind turbines even without the supplementary inertia control if the torque Tc is controlled slowly enough. However, this is achieved at the expense of torque tracking performances. As pointed out by, speed recovery processes will greatly change the inertial responses of wind turbines and may even cause the rotor stall and system instability. It is revealed that the maximum power point tracking (MPPT) controller in wind turbines facilitates the speed recovery but deteriorates the effects of inertia emulation. When wind speeds exceed their rated value, the additional power required by inertia emulation comes from wind instead of rotors by overloading wind turbines for a short period. In this case, wind turbines should be regulated through the pitch or active stall control, and therefore, speed recovery process are no longer necessary. It is desirable to incorporate this function into new wind plants during the design and commission stage. Otherwise, retrofitting could be considerably more expensive

EMERGING TECHNIQUES IN INERTIA EMULATION

As the progress along the trajectory of renewable integration continues, there will be a growing penetration of emerging and evolving inertia enhancement techniques into the market. On the one hand, these techniques will create new opportunities for service providers to actively participate in the market. On the other hand, the recognition of these opportunities will enable system operators to improve the stability and reliability of future more-electronics power systems.

Inertia Emulation by Various Energy Storage Units

In order to emulate inertia, energy storage units should be employed and properly regulated to release or absorb energy in the same way as the rotors of SGs do. In this section, the emerging inertia emulation techniques are classified according to their energy storage units.

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dc-Link Capacitors: Dc-link capacitors are inherently necessary in nearly all types of grid-connected power converters for dc link voltage support, harmonic filtering, and reactive power compensation. Recently these capacitors are also showing great premise for relaxing the stresses due to high-RoCoF levels and low-frequency nadir through inertia emulation. The mechanism of inertia emulation can well be explained by the mapping between SGs and dc-link capacitors. Where Hcap denotes the inertia constant of capacitors. In this figure the similarities between generators and capacitors clearly be identified.

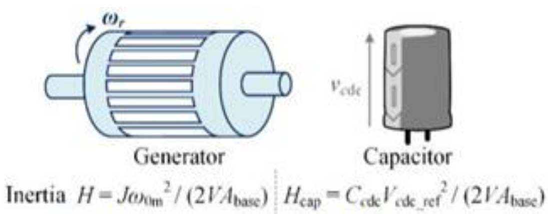

Fig 4 Mapping between SGs and dc-link capacitors

Specifically, the dc-link voltage V_{cdc} (V_{cdc_ref} denotes its rated value) and capacitance C_{cdc} play similar roles as the frequency Ꞷ and moment of inertia J respectively. The interesting observation results in the proposal of one simple frequency controller, which proportionally relates the grid frequency to the dc-link voltages of grid-connected power converters for generating the emulated inertia or known as the virtual inertia.

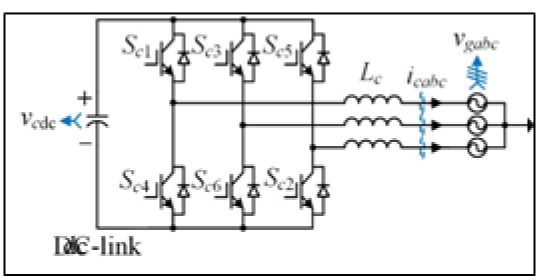

Fig 5 schematic of grid-connected power converters

L_C is inductor filters can be replaced by higher order passive filters to achieve better harmonic filtering and cost saving. He candidate applications of grid-connected power converters include wind generation, energy storage systems (ESSs), active power filters, static VAR compensators (STATCOMs), variable speed drives, high-voltage direct current (HVdc) transmissions, and power supplies for data centers [3].To experimentally validate the effectiveness of emerging techniques in inertia emulation and improvement, a stand-alone more-electronics power system has been constructed and used as the test system. The schematic diagram of the test system, which consists of a virtual synchronous machine (VSM), a PV generation system, and an ESS. The VSM is employed here to regulate the grid frequency and provide the grid voltages in a similar way as conventional SGs do so that the inertia improvement can be validated. The dc-links of the interfaced power converters for the VSM, PV generation, and ESS can flexibly be connected to various components or circuits, e.g. capacitors, ultra capacitors, or dc-dc converters, depending on specific applications. The photo graph of the test system, where the Dspacecontroller (Microlabbox) serves to control all the power converters. It should be mentioned that power converters only generate the virtual inertia and help frequency control rather than providing the grid frequency in this case.

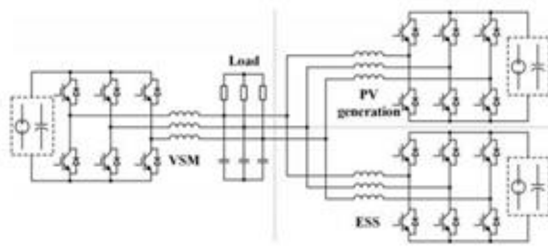

Fig 6 schematic of the test system

Fig 7 photograph of test system

2) Ultra capacitors when the inertia emulated by dc-link capacitors is insufficient and/or other frequency support functions are required, ESSs can further be employed. In ESSs, power converters serve interface between power grid and energy storage units and can be provide a tight control of their charging states. Among the candidates of energy storage units in ESSs, ultra capacitors have the benefits of high-power density and long lifetime. The figure shows the schematic of a typical ultra capacitor storage system, Where V_{uc} denotes the

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voltage across the ultra capacitor. Through a dc-dc converter, V_{uc} can be boosted into higher dc-link voltage V_{cdc}, making possible the exploitation of a conventional two-level three phase inverter for grid synchronization. As compared with dc-link capacitors, ultra capacitors Feature large capacitance, hence, higher capabilities for inertia emulation. Moreover, the additional dc-dc converter can decouple the ultra capacitor from the dc-link, thus allowing a wide range of voltage variations and further inertia enhancement. The continued progress in ultra capacitors will make this technique more economically attractive.

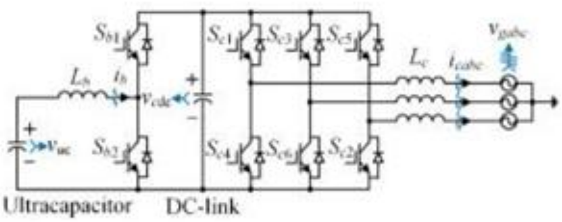

Fig 8 Schematic ultra capacitor storage systems

3) Batteries

Characteristics such as higher energy density, fast response and moderate cost make batteries stand out among all the energy units when applied to frequency control [4]. Although batteries being used to emulate inertia have so far not been reported in the industry, this technique has a great potential for providing a degree of inertia control in the future. However, unlike capacitors or ultra capacitors, batteries feature almost fixed voltages in normal charging states, which cannot easily be regulated for inertia emulation. Alternatively, it is possible to tightly regulate battery output power. The figure shows battery storage systems in one possible implementation of inertia emulation is achieved by proportionally linking the active power reference and RoCoF.

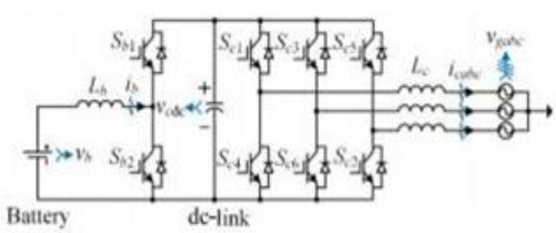

Fig 9 Scmematic of battery storage system

It is concluded that a slow virtual inertia control can address the instability concern. The relevant analysis and conclusion are of imporatance and can provide usefule guidelines for the virtual inertia design.

Frequency Control by Virtual Synchronous Machines

Presently, the objective of grid frequency provision and regulation are mainly by power electronic-interfaced renewable generators. Fortunately, the concept of VSMs, i.e. VISMAs or virtual SGs (VSGs) has been proposed. It is reported that VSMs are essentially power converters emulating the operation of SGs, providing not only the power system inertia but also grid forming functions [5]. Various VSM model and control schemes have been introduced. First, the complete mathematical model of SGs covering both mechanical part and electrical part is constructed to make VSMs operate in the same way as SGs. Where VSMs are implemented as current - controlled inverters. Furthermore, the same research group proposes to implement VSMs based on a simplified model including the major mechanical part and electrical part.

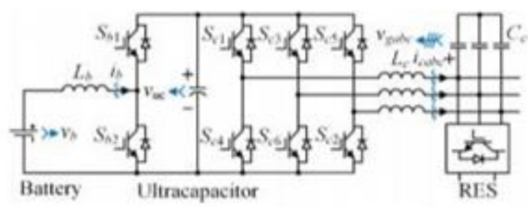

Fig 10 schematic of VSMs with hybrid energy storage systems

The figure visualizes one VSM implementation following this idea, where a hybrid ESS consisting of a battery and an ultra capacitor is connected in parallel with the RES generation system operated in the MPPT mode. The ultra capacitor is interposed between-dc converter and inverter. Such a VSM implementation is to reduce the fluctuations and changing rates of battery power in order to extend the battery life time and system efficiency.

OTHER TECHNICAL ISSUES

Time Delays

Ideally, power converters should immediately output power following its references for frequency support. However, in practice, the time delays introduced by communications and converter control are inevitable, which will degrade frequency

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control and may even destabilize the entire power system. The time delays due to communications, e.g., the transport time delay from center control stations to individual power converters (up to several seconds), can be minimized through the decentralized control [6]. Specifically, the decentralized control establishes a rule for individual power converters to follow without communications, e.g., the frequency droop control. Through this approach, a global objective, e.g., the active power sharing can automatically be achieved by all the participators. However, the tradeoff between the benefits introduced by the decentralized control and those due to the centralized control, e.g., the mitigation.

Adaptive Inertia

The fast-responding feature of power converters enables inertia suppliers to change their inertia contributions during frequency events, and hence, the further improvement of frequency control can be expected. However, the nonlinear nature of adaptive inertia control may negatively influence the stability of power systems. This issue should be carefully investigated in future research.

Placement of Inertia

For large power systems, both the time-varying inertia profiles and locations of inertia may greatly influence the effectiveness of inertia emulation [107]. For the inertia emulation by energy storage units, e.g., ultra capacitors and batteries, one special issue is where to optimally place energy storage unit. The results may provide insightful guidance on the day-ahead planning of inertia. Note that, the fluctuations of inertia caused by RES variability and limitations of inertia suppliers must be considered before performing the day-ahead inertia scheduling.

Market Design for Inertia Service

For Inertia Service a well-functioning market for the inertia service should clearly be designed before the emerging inertia emulation techniques can successfully be deployed. Currently, inertia is considered to be an inherent property in most power systems, thus being excluded from ancillary services markets.

CONCLUSION

This paper has presented a comprehensive review of inertia enhancement techniques allowing the improvements of frequency nadir and RoCoF in future more-electronics power systems. Among these techniques, the inertia emulation by wind turbines has already demonstrated its cost effectiveness in practice and will be pursued by more power system operators. Although being proposed recently, the concept of the inertia emulation by dc-link capacitors featuring the minimized or even no hardware change shows great promise due to its low cost. As compared with dc-link capacitors, ultra capacitors have larger capacitances and higher flexibility for inertia emulation. In addition, batteries will become another important inertia supplier after the successful development of fast and accurate RoCoF measurement schemes. As the trend of renewable integration continues, VSMs will eventually serve as the enabling components for inertia provision and frequency control in replacement of SGs in the future.

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