Review: Frequency Regulation of Electrical Power system

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***Abstract* - The increasing penetration of Distributed Energy Resources (DERs), such as solar photovoltaic and wind power, is fundamentally transforming large-scale power systems. While DERs offer environmental and economic benefits, their intermittent nature and inverter-based operation significantly reduce system inertia and traditional frequency control reserves, leading to greater volatility and potential instability in the grid frequency. This project addresses the critical challenge of maintaining system reliability and stability in high-DER scenarios through advanced frequency management techniques. The research proposes a comprehensive framework for enhanced frequency control, focusing on leveraging the inherent capabilities of inverter-based DERs to actively participate in frequency regulation. Key methodologies explored include the design and implementation of Synthetic Inertia (SI) and Fast Frequency Response (FFR) schemes, which can be dynamically injected by DERs during grid disturbances. The study utilizes detailed dynamic modeling of a large power system benchmark (e.g., IEEE 39-bus or a realistic regional model) to simulate various DER penetration levels and operational contingencies.**

I. INTRODUCTION

The global shift towards sustainable energy sources has accelerated the integration of Distributed Energy Resources (DERs), primarily solar and wind generation, into existing large-scale power systems. Traditionally, frequency stability was inherently maintained by large, synchronous generators which possess significant rotational mass, providing system inertia. This inertia acts as a natural buffer, slowing down the Rate of Change of Frequency (RoCoF) following a sudden power imbalance (e.g., a generator trip or a large load change).

However, DERs are predominantly connected to the grid via power electronic inverters and, unlike synchronous machines, they do not inherently contribute to system inertia. As the penetration level of DERs rises and displaces conventional generation, the overall system inertia decreases dramatically. This reduction in inertia makes the grid more susceptible to rapid frequency deviations, leading to higher RoCoF and potentially lower frequency nadirs (minimum frequency reached), which can trigger load shedding and cascaded outages. Therefore, the reliable operation of large power systems hinges upon developing sophisticated control strategies to manage grid frequency in this low-inertia environment.

Problem Statement The core problem addressed by this research is the deterioration of grid frequency stability in large power systems due to high penetration of inverter-based DERs.
Specifically, the challenges are:
Increased RoCoF: Reduced inertia causes faster frequency decline, challenging the response time of conventional frequency controls.
Lower Frequency Nadir: Increased stress on the system leads to greater maximum frequency deviation, risking system collapse.
Lack of Control from DERs: Conventional DER control strategies are often passive, failing to utilize the fast response capability of inverters to contribute actively to frequency regulation.
Research Objectives and Scope This project aims to enhance the frequency stability of large power systems by actively engaging DERs in grid frequency management.

The primary objectives of this research are:Modeling and Analysis: To establish detailed dynamic models of a reference large power system with varying levels of DER penetration to accurately quantify the impact of reduced system inertia on grid frequency dynamics.

Development of Control Techniques: To design and implement advanced inverter control algorithms for DERs, specifically focusing on providing:

Synthetic Inertia (SI): Mimicking the inertial response of synchronous generators.

Fast Frequency Response (FFR): Providing rapid, short-duration active power injection/absorption to arrest frequency decline/rise.

Performance Validation: To rigorously evaluate the effectiveness of the proposed SI and FFR schemes in mitigating frequency excursions (R.C.F.) and nadir) under critical contingencies, ensuring compliance with relevant grid code requirements. The scope of this work is limited to the design and simulation-based validation of the control strategies using industry-standard power system simulation software (e.g., MATLAB/Simulink or Dig SILENT Power Factory), focusing on the active power control loop of the DER inverters.

	GB	CE	NE	IRE
Standard frequency range	±0.2 Hz	±0.05 Hz	±0.1 Hz	±0.2 Hz
Maximum instantaneous frequency deviation	0.8 Hz	0.8 Hz	1.0 Hz	1.0 Hz
Maximum steady-state frequency deviation	0.5 Hz	0.2 Hz	0.5 Hz	0.5 Hz
Frequency recovery range	±0.5 Hz	not used	not used	±0.5 Hz
Time to recover frequency	60 sec	not used	not used	60 sec
Frequency restoration range	±0.2 Hz	not used	±0.1 Hz	±0.2 Hz
Time to restore frequency	600 sec	900 sec	900 sec	1200 sec

The main challenges in exploiting the ESSs for FR services are understanding mathematical models, dimensioning, and operation and control. In this review, the state-of-the-art is synthesized into three major sections: i) review of mathematical models, ii) FR using single storage technology (BES, FES, SMES, SCES), and iii) FR using hybrid energy storage system (HESS) (BES-SCES, BES-SMES, and BES-FES). The categories (ii) and (iii) are further divided into two sub categories: control and operation, and sizing. The contribution of this work lies in the fact that it comprehensively reviews all the aspects that are required to understand the FR services provided by ESSs. Moreover, it highlights the research gaps, limitations, and gives future directions.

II. TRANSMISSION AND DISTRIBUTION SYSTEM

The Kundur's two-Area system with parameters taken from [21] which is comprised of four synchronous generators(two in each area) that are boosting up with transformers and connected through transmission lines, form generation and transmission parts in this example. The areas are connected to each other through a tie line. IEEE 13 node test feeder [22] is used as distribution system. The DGs such as PV and battery energy storage unit (BES) are connected to distribution system using a voltage source inverter (VSI). PV system includes PV arrays and a unidirectional boost DC-DC converter which is working under perturb and observe (P&O) maximum power point tracking (MPPT) control . BES includes batteries and a bidirectional boost DC-DC converter controlled by multi-loop voltage and current control. The outer loop controls voltage and inner loop controls current through

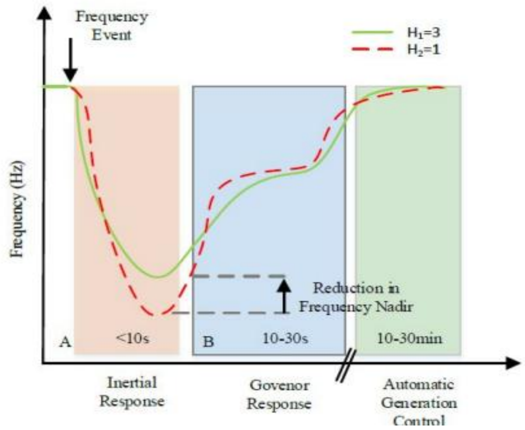

Figure 1: Multiple time-frame frequency response in a power system following a frequency event.

III. IMPACT OF DER ON FREQUENCY

Since the power electronic interfaces used in DGs have no rotating mass and damping, the inertial constant in the microgrid is reduced which results in increasing the rate of change of frequency (RoCoF) of the grid and may lead to the load shedding even under small disturbances in the system. Fig. 1 shows the frequency curve of system with different amount of inertia in presence of a contingency. For the control and stability of these small scale power grids, a hierarchical algorithm including primary, secondary and tertiary control is introduced, similar to conventional grids. Droop control for voltage source inverters as an example for primary frequency control is discussed in [23], provide barely any inertia/damping support for the grid.

IV. FREQUENCY REGULATION IN POWER SYSTEM

In power systems, frequency is the continuously changing variable which is influenced by the power generation and demand. A generation deficit results in frequency reduction while surplus generation causes an increase in the frequency. The frequency is kept in permissible limits for the stable operation of power systems. Different system operators have defined different set of frequency operating standards for normal and abnormal operations. The frequency operating standards set by European network of transmission system operators for electricity (ENTSOE) are given in Table 1. The data given in Table 1 can be found in chapter 18, on page 1140 of [11]. There are four synchronous areas in Europe. 1) Great Britain (GB): alone forms synchronous area. 2) The continental Europe (CE): includes part or all of Austria, Bulgaria, Belgium, Bosnia, Herzegovina, Czech Republic, Croatia, western Denmark, France, Germany, Greece, Hungary, Luxembourg, Italy, Macedonia, Net- -herlands, Montenegro, Poland, Romania, Portugal, Slovakia, Serbia, Spain, Slovenia, and Switzerland. 3) The inter-Nordic system (NE): constitutes transmission grids of Norway, Sweden, Denmark (eastern part), and Finland. 4) The all-island Irish system (IRE): includes Republic of Ireland and Northern Ireland is another synchronous area. The frequency operation standards set by Australian Electricity Market Operator (AEMO) are given in Table 2 [16]. It can be observed form the Table 2 that the most of the time frequency is required to be kept within ±0.15.

Table 2: Frequency operating standards in Australia [16]

Condition	Containment	Stabilisation	Recovery
No contingency or load event	49.75-50.25 Hz 49.85-50.15 Hz*	49.85-50.15 Hz within 5 min	49.85-50.15 Hz within 5 min
Generation event or load event	49.50-50.50 Hz	49.85-50.15 Hz within 5 min	49.85-50.15 Hz within 5 min
Network event	49.00-51.00 Hz	49.50-50.50 Hz within 1 min	49.50-50.50 Hz within 5 min
Separation event	49.00-51.00 Hz	49.50-50.50 Hz within 2 min	49.50-50.50 Hz within 10 min

*: 99% of the time, load event: 50 MW, generation event: 50 MW

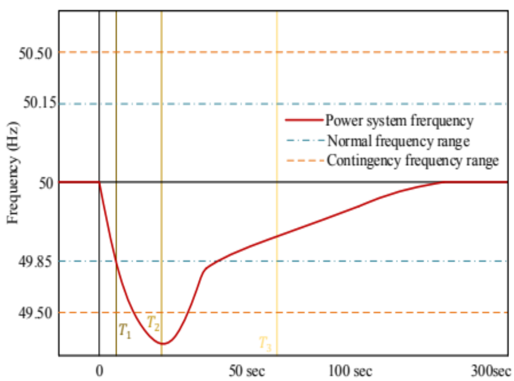

Figure 2: Contingency FCAS stages by AMEO

Hz. The complete definitions of load, generation, network, and separation events can be found in the reference provided in [16]. Power systems need to be operated within the defined operating frequency standards. A deviation in frequency from the standard operating limits leads to disconnection of generators and demand which result in poor reliability and economic loss. In AEMO contingency frequency control ancillary services (FCAS) are used to suppress large frequency variations caused by a sudden loss of large load or generation [17]. The contingency FCAS have six stages: 6 second raise (R6) and lower (L6), 60 second raise (R60) and lower (L60), and 5 minute raise (R5) and lower (L5). The Fig. 1, shows an example of the variation in frequency after loss of large generation and different stages of contingency FCAS. The generation loss event occurs at 0 sec resulting in rapid decline in frequency. The R6 contingency FCAS gets activated at T1 when the frequency leaves the normal frequency operating range. The R6 contingency FCAS supports the system for 6 sec and then at T2 (T1+6) the R60 contingency get activated. The R60 contingency brings back the frequency within the normal frequency operating range. At T3 (T1+60) R5 contingency FCAS activates and restore the frequency to 50 Hz [17]. Fig. 2 shows a power system, with conventional generations, renewable power generation systems, energy storage systems, and controllable and uncontrollable loads. In modern power system, the system operators have multiple resources that can be procured for FR services, i.e., conventional synchronous machines based generation, ESS, demand side management (DSM), electric vehicles, and RESs. Active power of these resources is controlled to support grid frequency. Conventional power generation systems employ synchronous machines with heavy rotating masses. In event of any difference in generation and demand the synchronous machines instantaneously slow-down/speed-up by injecting/absorbing the kinetic energy in/from the power system [18]. This instantaneous response is called IR which is the inherent characteristic of synchronous machine, requires no control. Controlled FR services can be obtained from conventional generation plants using the governor control which increases the power output of generator as per control signal [19, 20, 21]. The typical variation in frequency after the occurrence of an event and the necessary control actions taken to ameliorate its impact are shown in

Fig. 3. The first stage is the inherent response of synchronous machines (i.e. IR) in which the synchronous machines oppose the reduction in frequency by releasing the kinetic energy stored in rotating masses. This stage is followed by the primary frequency.

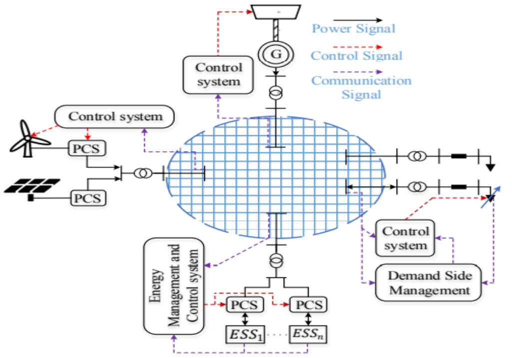

Figure 3: Power system with various FR resources

V. CONCLUSION

DERs have multiple negative impacts on the bulk power system which have been addressed in the paper. In between, lower or zero inertia is one of their major aspects that will affect the stability of the whole power grid and may lead into unwanted load shedding. The solution for adding inertia to DERs by mimicking synchronous generation behavior is introduced. By using the proposed seamless control framework, a simple control strategy is implemented to operate under normal and faulty grid conditions. Several experiments have been conducted to verify the performance of the proposed system.

REFERENCES

[1] R. Karki and R. Billinton, "Reliability/cost implications of pv and wind energy utilization in small isolated power systems," IEEE Transactions on Energy Conversion, vol. 16, no. 4, pp. 368–373, 2001.
[2] H. Nikkhajoei and R. Iravani, "Steady-state model and power flow analysis of electronically-coupled distributed resource units," IEEE Transactions on Power Delivery, vol. 22, no. 1, pp. 721–728, 2006.
[3] H. Chen, J. Chen, D. Shi, and X. Duan, "Power flow study and voltage stability analysis for distribution systems with distributed generation," in 2006 IEEE Power Engineering Society General Meeting. IEEE, 2006, pp. 8–pp.
[4] J. Slootweg and W. Kling, "The impact of large scale wind power generation on power system oscillations," Electric Power Systems Research, vol. 67, no. 1, pp. 9–20, 2003.
[5] S. Dierkes, F. Bennewitz, M. Maercks, L. Verheggen, and A. Moser, "Impact of distributed reactive power control of renewable energy sources in smart grids on voltage stability of the power system," in 2014 Electric Power Quality and Supply Reliability Conference (PQ). IEEE, 2014, pp. 119–126.
[6] U. Tamrakar, D. Shrestha, M. Maharjan, B. Bhattarai, T. Hansen, and R. Tonkoski, "Virtual inertia: Current trends and future directions," Applied Sciences, vol. 7, no. 7, p. 654, 2017.
[7] H. Bevrani, T. Ise, and Y. Miura, "Virtual synchronous generators: A survey and new perspectives," International Journal of Electrical Power & Energy Systems, vol. 54, pp. 244–254, 2014.
[8] A. Vassilakis, P. Kotsampopoulos, N. Hatziargyriou, and V. Karapanos, "A battery energy storage based virtual synchronous generator," in 2013 IREP Symposium Bulk Power System Dynamics and Control-IX Optimization, Security and Control of the Emerging Power Grid. IEEE, 2013, pp. 1–6.
[9] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," IEEE Transactions on industrial electronics, vol. 58, no. 4, pp. 1259–1267, 2010.
[10] Q.-C. Zhong, "Virtual synchronous machines: A unified interface for grid integration," IEEE Power Electronics Magazine, vol. 3, no. 4, pp. 18–27, 2016.
[11] K. Sakimoto, Y. Miura, and T. Ise, "Stabilization of a power system with a distributed generator by a virtual synchronous generator function," in 8th International Conference on Power Electronics-ECCE Asia. IEEE, 2011, pp. 1498–1505.
[12] J. Liu, Y. Miura, H. Bevrani, and T. Ise, "Enhanced virtual synchronous generator control for parallel inverters in microgrids," IEEE Transactions on Smart Grid, vol. 8, no. 5, pp. 2268–2277, 2016.
[13] J. Liu, Y. Miura, and T. Ise, "Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverterbased distributed generators," IEEE Transactions on Power Electronics, vol. 31, no. 5, pp. 3600–3611, 2015.

[14] J. Alipoor, Y. Miura, and T. Ise, "Stability assessment and optimization methods for microgrid with multiple vsg units," IEEE Transactions on Smart Grid, vol. 9, no. 2, pp. 1462–1471, 2016.
[15] H. Wu, X. Ruan, D. Yang, X. Chen, W. Zhao, Z. Lv, and Q.-C. Zhong, "Small-signal modeling and parameters design for virtual synchronous generators," IEEE Transactions on Industrial Electronics, vol. 63, no. 7, pp. 4292–4303, 2016.
[16] W. Wu, Y. Chen, A. Luo, L. Zhou, X. Zhou, L. Yang, Y. Dong, and J. M. Guerrero, "A virtual inertia control strategy for dc microgrids analogized with virtual synchronous machines," IEEE Transactions on Industrial Electronics, vol. 64, no. 7, pp. 6005–6016, 2016.
[17] C. Andalib-Bin-Karim, X. Liang, and H. Zhang, "Fuzzy-secondarycontroller-based virtual synchronous generator control scheme for interfacing inverters of renewable distributed generation in microgrids," IEEE Transactions on Industry Applications, vol. 54, no. 2, pp. 1047– 1061, 2018.
[18] K. Shi, W. Song, P. Xu, R. Liu, Z. Fang, and Y. Ji, "Low-voltage ridethrough control strategy for a virtual synchronous generator based on smooth switching," IEEE Access, vol. 6, pp. 2703–2711, 2017.
[19] T. Zheng, L. Chen, Y. Guo, and S. Mei, "Comprehensive control strategy of virtual synchronous generator under unbalanced voltage conditions," IET Generation, Transmission & Distribution, vol. 12, no. 7, pp. 1621– 1630, 2017.
[20] H. Zhao, Q. Yang, and H. Zeng, "Multi-loop virtual synchronous generator control of inverter-based dgs under microgrid dynamics," IET Generation, Transmission & Distribution, vol. 11, no. 3, pp. 795–803, 2017.
[21] P. Kundur, N. J. Balu, and M. G. Lauby, Power system stability and control. McGraw-hill New York, 1994, vol. 7.
[22] W. H. Kersting, "Radial distribution test feeders," IEEE Transactions on Power Systems, vol. 6, no. 3, pp. 975–985, 1991.
[23] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodriguez, "Control of power converters in ac microgrids," IEEE transactions on power electronics, vol. 27, no. 11, pp. 4734–4749, 2012.
[24] J. Alipoor, Y. Miura, and T. Ise, "Distributed generation grid integration using virtual synchronous generator with adoptive virtual inertia," in 2013 IEEE Energy Conversion Congress and Exposition. IEEE, 2013, pp. 4546–4552.
[25] T. Shintai, Y. Miura, and T. Ise, "Oscillation damping of a distributed generator using a virtual synchronous generator," IEEE transactions on power delivery, vol. 29, no. 2, pp. 668–676, 2014.
[26] A. Fathi, Q. Shafiee, and H. Bevrani, "Robust frequency control of microgrids using an extended virtual synchronous generator," IEEE Transactions on Power Systems, vol. 33, no. 6, pp. 6289–6297, 2018.
[27] K. Sakimoto, Y. Miura, and T. Ise, "Stabilization of a power system including inverter type distributed generators by the virtual synchronous generator," IEEJ Transactions on Power and Energy, vol. 132, pp. 341– 349, 2012.
[28] X. Zhang, D.-b. ZHU, and H.-z. XU, "Review of virtual synchronous generator technology in distributed generation," Journal of Power Supply, vol. 3, pp. 1–6, 2012.
[29] Y. Du, J. M. Guerrero, L. Chang, J. Su, and M. Mao, "Modeling, analysis, and design of a frequency-droop-based virtual synchronous generator for microgrid applications," in 2013 IEEE ECCE Asia Downunder. IEEE, 2013, pp. 643–649.
[30] Z. Zeng, W. Shao, L. Ran, Z. Lyu, and R. Li, "Mathematical model and strategic energy storage selection of virtual synchronous generators," Automation of Electric Power Systems, vol. 39, no. 13, pp. 22–31, 2015.
[31] Y. Hirase, K. Sugimoto, K. Sakimoto, and T. Ise, "Analysis of resonance in microgrids and effects of system frequency stabilization using a virtual synchronous generator," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 4, pp. 1287–1298, 2016.
[32] C. Li, J. Xu, and C. Zhao, "A coherency-based equivalence method for mmc inverters using virtual synchronous generator control," IEEE Transactions on Power Delivery, vol. 31, no. 3, pp. 1369–1378, 2015.