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Modified Virtual Inertia Mechanism Based ESS for A real Multi-Source Power System Application: the Egyptian Grid

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Abstract*—Replacement of conventional generation units with a large number of renewable energy sources RESs causes an undesirable influence to the Egyptian power system EPS frequency stability, excessive supply due to full DGs generation due to the lack of system rotating inertia. The EPS consists of several conventional generation units (i.e., non-reheating, reheating, and hydraulic power plants) with inherent nonlinearities, and RESs (i.e., solar and wind energy). In order to solve this challenge, this paper provides a tertiary modified virtual inertia control loop-based energy storage system ESS as an active solution to improve the EPS stability during contingencies, and diminish the frequency deviations and regulate the power flow. In this method, the ability to imitate damping and inertia properties are presented based on the derivative technique. A comparative study between the conventional EPS with/without virtual (inertia + damping) is also presented. The constructed results using Matlab/Simulink software show the superior effectiveness and control effect of the proposed control method in terms of accurate tracking of the reference frequency and attenuating noise over the traditional one. Finally, it was verified that the auxiliary enhanced virtual inertia mechanism assisted the EPS by suppling further power inertia to robust the frequency against RESs and load demand penetrations.

Keywords*— *virtual inertia control, energy storage system, load frequency control, Egyptian power system.

I. INTRODUCTION

Large/Microgrids have received increasing attention as a means of integrating DG's into the electricity grid. These independent grids are usually described as storage devices, clusters of loads, and small generators, and connected as individual entities to the public distribution grid through a point of common coupling (PCC) as shown in Fig. 1. Microgrids (MGs) include a variety of technologies: RESs, such as PV and wind turbines that operated alongside conventional high-inertia synchronous generators (SGs), fuel cells, and batteries. Thus, power is generated near the loads, enabling the use of small-scale generators to increase their reliability and reduce losses over power lines [1].

The system's low inertia occurs as a result of the inverter/converter used to connect RESs to MGs. These devices don't have any inertia or damping characteristics that lead to high deviation in frequency and system instability as stated in [2].

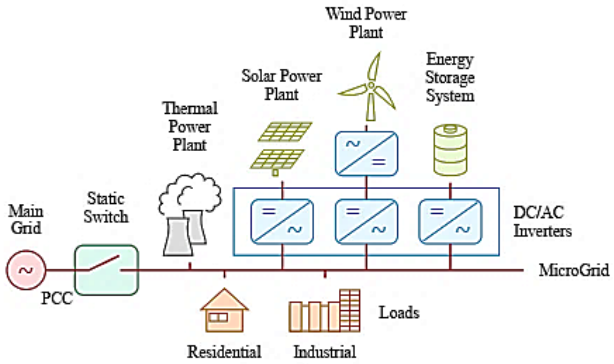


Fig. 1. A typical microgrid with PCC—point of common coupling [1].

To address these issues, several recent survey papers describe various aspects in the context of virtual inertia with a high RESs penetration within power grids. The virtual inertia of DGs/RESs was built using short-term energy storage with a converter/inverter and an appropriate control method. These mechanisms have been known as virtual synchronous generators (VSGs) [3], [4]. The VSG concept is based on replicating the real dynamic properties of SG for DG/ RES units, which relies on power electronics to inherit the merits of SG in enhancing stability.

A comprehensive review of virtual inertia topologies is imitated to form strides within the MGs frequency stability and to suppress voltage oscillation [2], [5]–[8]. In [2], an adaptive control strategy for plug-in electric vehicles PEVs supported by a virtual inertia control loop is proposed for the analysis of the islanded MG frequency stability considering RESs. The impact of PLL and virtual inertia algorithm on AGG system for with parallel AC/HVDC is discussed in [6]. Virtual inertia and frequency regulation for distributed energy sources are mentioned in [9]. In [10], the evolution of inertia estimation in power systems was discussed.

Frequency Control is considered a critical issue in power systems to keep the system frequency and power changes at their standard values. To overcome the instability problem, a lot of control approaches have been implemented to control the system's frequency such as [11]–[14]. A spurious growth can happen in a small-scale dispersed generation due to the large synchronous machine's rotational inertia. This will lead to a continuous decreasing in the system inertia resulting in instability and power outage in the grid due to the mitigation of various disturbances [15].

A promising solution towards the stabilization of MGs is to emulate the behavior of SG virtually to modify the system's inertia, stability, and resiliency. For this purpose, VSG mirrors the prime movers' action (inertia properties) [4], in addition, gives a basis for keeping up the share of DGs within the MGs without sacrificing its stability and adaptability. Therefore, in this paper, we focused on how the presence of virtual inertia and virtual damping control-based ESS can help in solving the frequency regulation issues in large-scale grids (i.e. EPS).

The rest of this paper is arranged as follows: Section II presents a general view of frequency response based on the virtual inertia mechanism. In section III, the dynamic modeling of EPS considering RESs and virtual inertia is presented. An emulation of virtual inertia-based ESS is proposed in Section IV. The simulation results based on time-domain are discussed in section V. Section VI presents the conclusion.

II. FREQUENCY STABILITY BASED ON VIRTUAL INERTIA POWER

In this study, frequency control stability is separated into three major operations; they are primary/secondary/inertia (initial/virtual) controls. No controller is initiated in the inertia control condition, and the kinetic energy fulfilled the required power from VSGs during frequency deviations or contingencies. Later, the primary control will balance the system's frequency to a new steady-state during the contingencies. Finally, secondary control (LFC) will maintain the frequency to an equilibrium state after the contingencies [16].

In conventional power systems or communities, the kinetic energy (initial inertia) of the system rotating mass with spinning loads is determined as [17]:

$$E_{kinetic} = \frac{1}{2}\, J\omega^2 \tag{1}$$

where ω means the speed of a rotor (rad/s) and J indicates the system moment of inertia (kg.m2).

Considering, the rate of change of rotor speed, it is related to torque balance of spinning mass defined as:

$$T_m - T_e = \frac{P_m}{\omega} - \frac{P_e}{\omega} = J * \frac{d\omega}{dt} \tag{2}$$

where P_m means the mechanical power and P_e is the electrical power. T_m and T_e mean the mechanical torque and electrical torque, respectively

Hence, the stored kinetic energy $E_{kinetic}$ can be calculated as proportional to its power rating. It is called the system inertia as:

$$H = \frac{E_{kinetic}}{S} \tag{3}$$

where H is the inertia of the system, S is the system rated apparent power in (VA).

Accordingly, the rate of change of frequency (ROCOF), which is used to evaluate the system inertia is calculated as follows:

$$\frac{d\omega}{dt} = \frac{\omega^2(T_m - T_e)}{2HS} = \frac{\omega(P_m - P_e)}{2HS} \tag{4}$$

III. EGYPTIAN POWER SYSTEM DYNAMIC MODEL

The Egyptian power system (EPS) as mentioned in the abstract includes conventional sources for generation such as (i.e., gas, thermal, and hydraulic power plants), and RESs (i.e., photovoltaics PV and wind turbines WT). These conventional plants are classified into 3 categories; (a) Non-reheat power plants. (b) Reheat power plants. (c) Hydraulic power plants [18]. The total installed capacity for EPS is 58.4 GW and the peak load is 32.4 GW stated by the end of 2019, and the installed capacity comprises basically of combined-cycle plants (55.7%). Moreover, the share of RESs today, including wind turbines and PVs, only represents 3.8% of overall capacity. Egypt aims to raise the power share of RESs to 20% by 2022, and 42% by 2035 [18].

The simplified EPS model with the proposed coordination scheme is shown in Fig. 2, the dynamic EPS model is shown in Fig. 3, and the nominal system parameters are given in Table I [19]. The parameters of PID gains were calculated in the EPS model using Harris hawks algorithm (HHO) as mentioned in [2] considering the penetration of RESs.

In this paper, simulated PV energy and random loads (residential and industrial) are presented. The solar PV plant is modeled as a 1st order transfer function of a unity gain as shown in Fig. 3 with a rated power of 5 GW (assumed according to the Egypt's 2040 target including Benban PV plant and other future projects). In addition, the EPS was validated using random loads of 15 GW power with base power 58.4 GW (full EPS capacity), and finally, 4.5 MW of ESSs are installed in the EPS.

The frequency deviation(Δf) of the studied EPS can be obtained considering the impact of the primary/secondary frequency control loop (i.e. governor action and LFC), and tertiary virtual inertia control loop as follows:

$$\Delta f = \frac{1}{2Hs + D}(\Delta P_M - \Delta P_L \pm \Delta P_{Inertia}) \tag{5}$$

$$\Delta P_M = \Delta P_{m1} + \Delta P_{m2} + \Delta P_{m3} + \Delta P_{PV}) \tag{6}$$

$$\Delta P_{m1} = \frac{P_{n1}}{T_1 s + 1} * (\frac{-1}{R_1} * \Delta f - \Delta P_c) \tag{7}$$

$$\Delta P_{m2} = (m + \frac{m}{T_h s + 1}) * \frac{P_{n2}}{T_2 s + 1} * \left(\frac{-1}{R_2} * \Delta f - \Delta P_c\right) \tag{8}$$

$$\Delta P_{m3} = \left(\frac{-T_w s + 1}{0.5 * T_w s + 1}\right) * \frac{P_{n3} T_d s + P_{n3}}{T_3 s + 1} * \left(\frac{-1}{R_3} * \Delta f\right) \tag{9}$$

$$\Delta P_{PV} = (\frac{1}{T_{PV} s + 1}) * \Delta P_{Solar} \tag{10}$$

$$\Delta P_{inertia} = \frac{J_{VI} s + D_{VI}}{1 + sT_{ESS}} \quad (\Delta f) \tag{11}$$

where $\Delta P_{m,i}, \Delta P_L, \Delta P_{Inertia}, \Delta P_{PV}, and\ \Delta P_c$ mean changes in the mechanical, load, inertia, solar, supplementary control power, respectively. R is the governor speed regulation. T_h is the time constant of reheat thermal plant, T_w is the dashpot time constant of hydro plant, and water, and T_d is the water starting time of the hydro plant. P_{n1}, P_{n2}, P_{n3} are the normal output rated power of non-reheat, reheat, hydropower plants, respectively. J_{VI} means the virtual inertia constant. D_{VI} means the virtual inertia damping constant. T_{ESS} is the inverter-based ESS time constant.

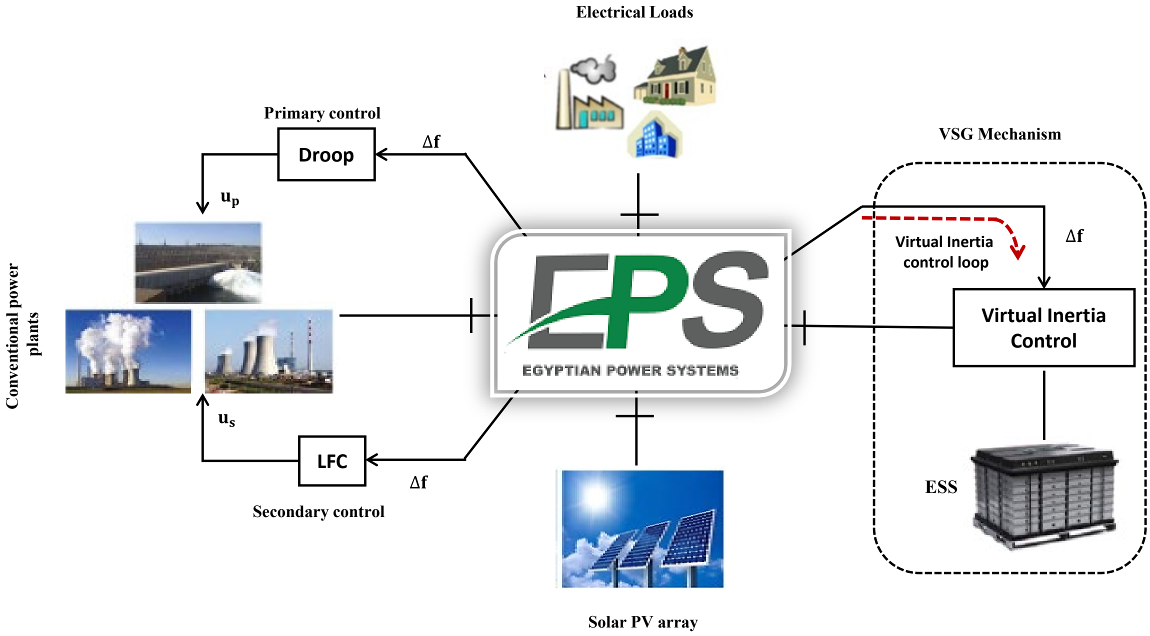


Fig. 2. A simplified model of the EPS considering PV and random loads.

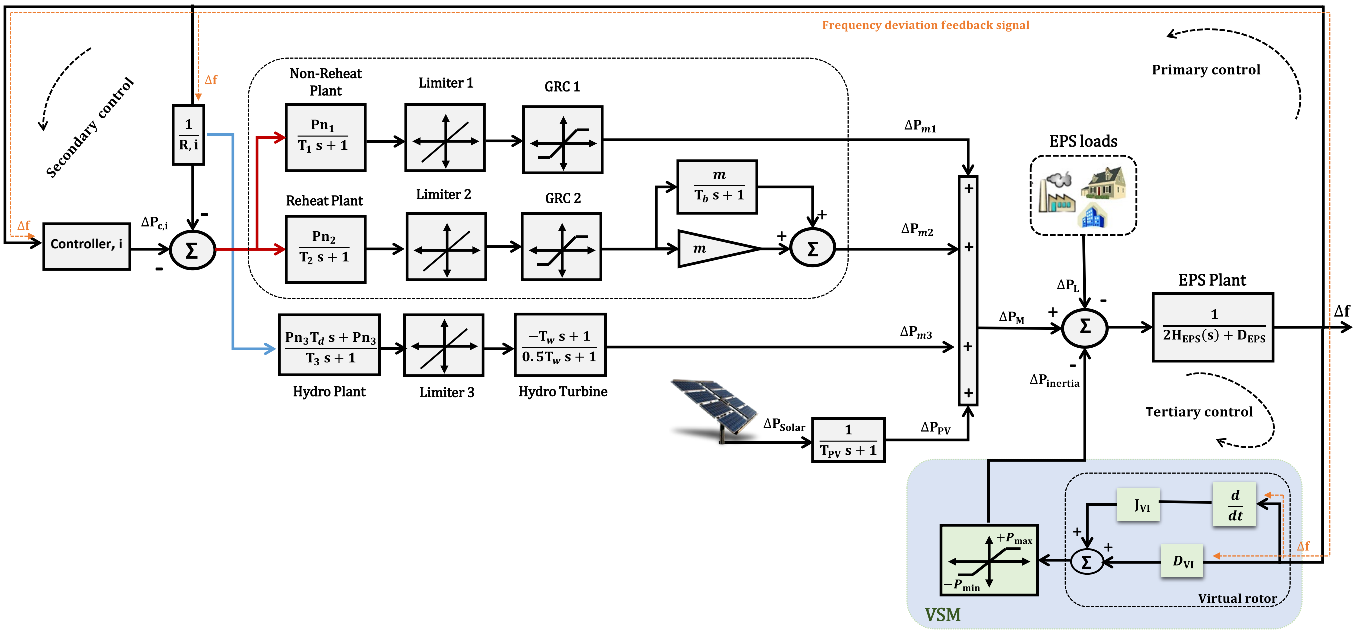


Fig. 3. A dynamic model of the EPS considering RESs with in presence of virtual inertia mechanism.

TABLE I. INITIAL PARAMETERS OF EPS GRID

Parameter	D_{EPS}	H_{EPS}	R_1	R_2	R_3	m	P_{n1}	P_{n2}	P_{n3}	T_1
Value	0.028	5.7096	2.5	2.5	1.0	0.5	0.2529	0.6107	0.1364	0.4
Parameter	T_2	T_3	T_d	T_h	T_w	T_{pv}	T_{ESS}	K_P	K_I	K_D
Value	0.4	90	5.0	6.0	1.0	10	10	26.5370	16.3125	-0.508

IV. PROPOSED VIRTUAL INERTIA AND VIRTUAL DAMPING EMULATION TECHNIQUE

Virtual inertia emulation is a new set of control techniques, ESSs, and power electronics, which can virtually emulate an inertia power based on a conventional power system (i.e., power system-based SG) into the power community-based RESs. Fig. 4 illustrates the concept of emulation virtual inertia using an ESS-based derivative control method. The target is to compute the ROCOF using a derivative technique to add sufficient active power to the community [2]. Therefore, the dynamic structure of the proposed modified virtual inertia can mimic the required inertia and damping characteristics of the community or power system, which improves the overall inertia inside the system (i.e. EPS), frequency stability, and prevents power blackouts.

At last, a control theory for imitating virtual inertia power in the Laplace domain is described in Eq. (11) and calculated using the suggested modified virtual inertia emulation based derivative control technique as mentioned in [7].

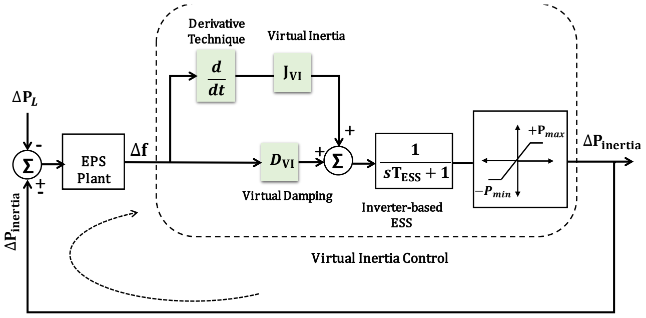


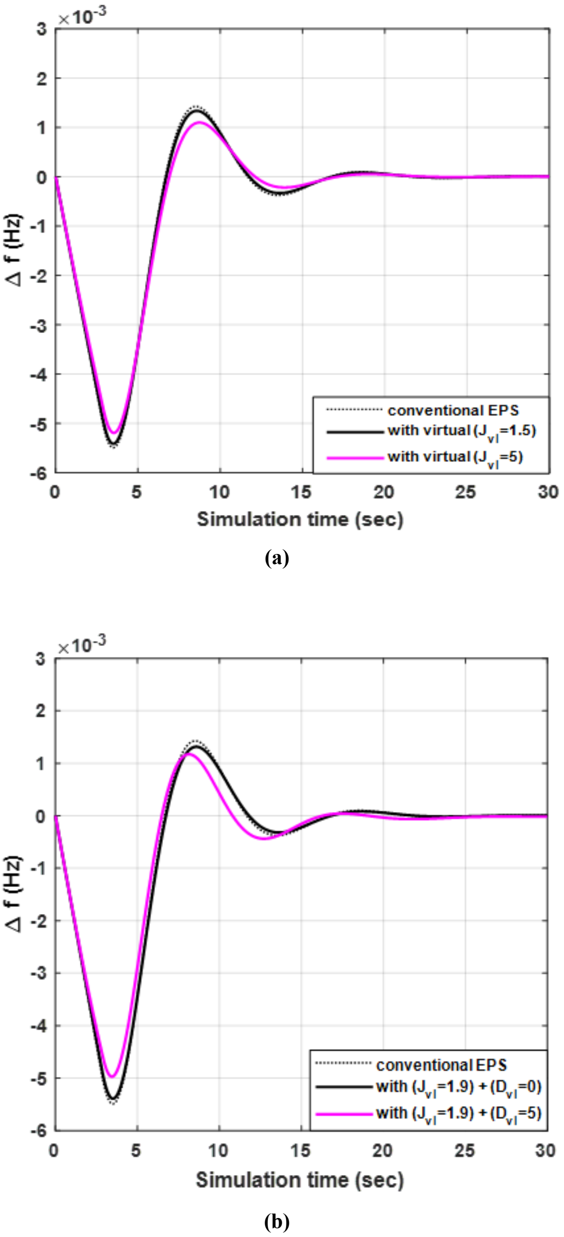
Fig. 4. The dynamic structure of the virtual inertia emulation-based ESS connected to the EPS plant.

V. VALIDATION AND SIMULATION

This section discusses the results of a virtual inertia emulation system compared to the traditional control system (i.e., primary and secondary control) of the EPS. The simulation results are divided into two parts. The first part is concentrated on the impact of virtual inertia and virtual damping on the EPS performance. The second part is focused on the dynamic effects of EPS frequency stability over high renewable integration and random loads fluctuations.

A. Impacts of Virtual Inertia and Virtual Damping on the EPS Performance

In this section, the effect of emulation virtual inertia and virtual damping on EPS performance and stability is investigated. A 20 % of sudden load power change ($\Delta P_L = 0.2$ pu) is applied as a disturbance to the proposed system. For 100% of the initial inertia (normal operation), Fig. 5a demonstrates the results only under the impact of the changes in virtual inertia at ($J_{VI} = 1.5, and\ 5$) for conventional derivative method-based virtual inertia mechanism compared to the conventional system with no virtual inertia. Fig. 5b shows how the proposed modified virtual inertia (virtual inertia + virtual damping) can significantly increase the EPS frequency stability. It's observed by increasing virtual damping ($D_{VI} = 0, and\ 5$) while the effect of virtual inertia is considered fixed at ($J_{VI} = 1.9$), the EPS frequency response becomes less fluctuating and more stable due to the gradual reduction in Max. Overshoot and settling time. The parameters ($J_{VI}\ and\ D_{VI}$) were obtained critically using the Eigenvalue trajectory analysis. Concerning the increasing emulation of virtual inertia and virtual damping, the emulated inertia power $\Delta P_{inertia}$ from the ESS is also increased as shown in Fig. 6. The positive /negative value indicates the charging/discharging power respectively. So it's obvious that the ESS controlled by the suggested technique is highly charged /discharged in response to any abnormal conditions.



(a)

(b)

Fig. 5. EPS frequency deviations due to changes in a) virtual inertia b) virtual damping.

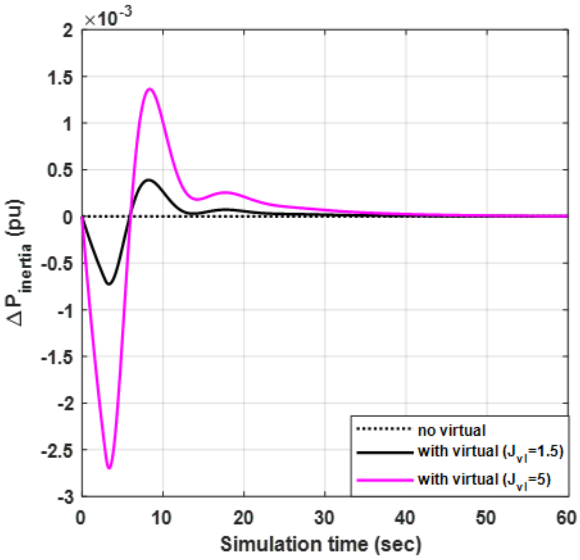


Fig. 6. Changes in power inertia for the EPS.

B. Analysis of Virtual Inertia and Virtual Damping against the Integration of RESs and Random Loads on EPS

In this scenario, the performance of EPS under the effect of the proposed modified virtual inertia control (emulate inertia and damping) on frequency stability concerning the dynamic impacts of power fluctuations produced by PV and load demand is investigated. A suggested scenario is performed to demonstrate the efficacy of the proposed modified virtual inertia control compared to the conventional derivative technique (only emulate virtual inertia), and conventional EPS based SGs; a partial injection of RESs and demand load are described as: (PV connected to EPS from 250 s and switched off at 500s, and demand load is also connected from 100s up to 350s as shown in Fig. 7. The nominal parameters for virtual inertia are fixed $J_{VI} = 1.9$ and virtual damping is D_{VI}=0, 5.

To clearly illustrate the severe impact of RESs penetration to the community, this case applied a penetrated PV power generation and load power demand as shown in Fig. 7.

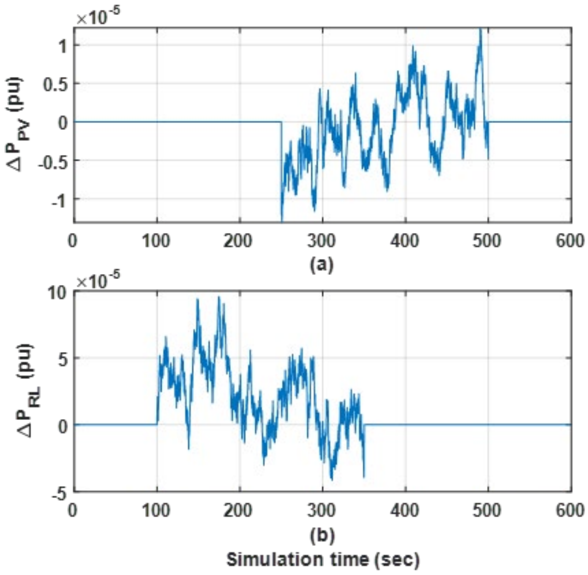


Fig. 7. PV and Load demand power variations.

Due to RESs penetration, the system frequency oscillates significantly with higher transient, deteriorating frequency stability. From Fig. 8, the frequency of the EPS with the conventional control can still be within the standard frequency limit of ± 0.5 Hz as provided by (EETC) [20], but there are higher fluctuations due to penetration of PV/load. In addition, these oscillations are high at the period of connection /disconnection of PV and loads due to the value of virtual damping D_{VI} = 5 which was chosen using Eigenvalue analysis. If the value of virtual damping exceeds a certain limits, the open-loop poles will move towards the unstable region on the S-plane causing instability in the EPS. This may cause instability and power outages for the EPS. It is clear that the system with a modified virtual inertia mechanism can maintain the stability of the EPS within the required standard limit and improving the frequency performance in terms of Max. Overshoot, and steady-state error.

Finally, from Fig. 9, the higher emulation of virtual inertia and virtual damping emulation equal also an increase in, the emulated inertia power($\Delta P_{inertia}$). So it's obvious that the ESS controlled by the suggested technique is highly charged /discharged in response to any abnormal conditions.

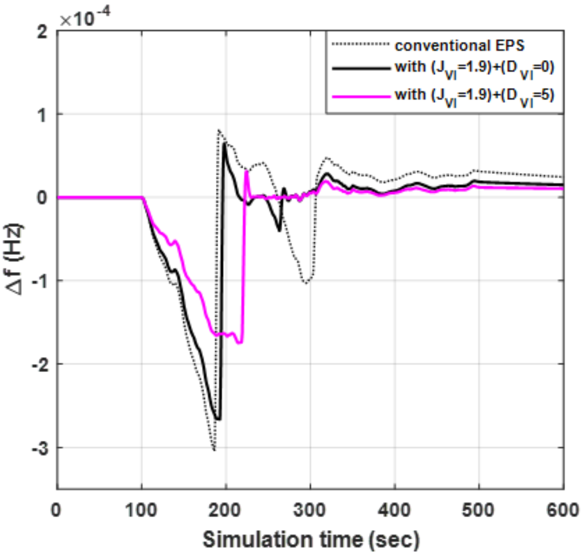


Fig. 8. EPS frequency deviations due to the partial injection of RESs and load demand.

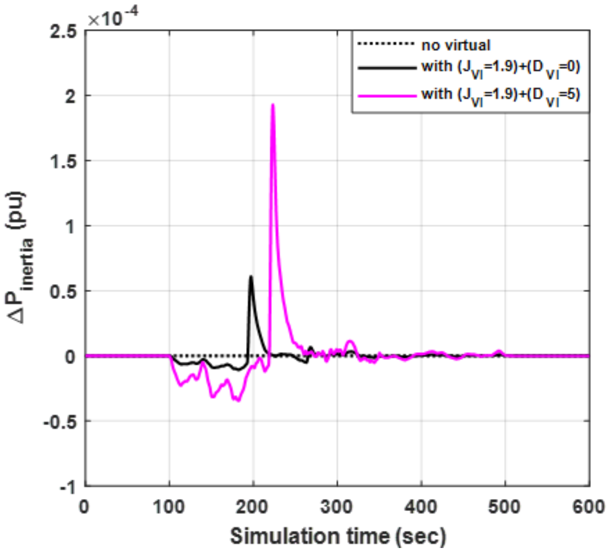


Fig. 9. Changes in power inertia for the EPS.

VI. CONCLUSION

A new challenge is driven by using a large share of RESs penetration for global communities to face the challenges of future energy shortages. However, the irregular nature of RESs and random load variations cause large frequency/voltage fluctuations as well as reducing the system inertia that results from replacing the synchronous generators with RESs. In this paper, the Egyptian power system (EPS) is used as a case study to examine.

The penetrations of RESs will significantly replace the number of traditional generations (i.e., SGs) that provide primary frequency control and inertia response, causing system instability and in the worst case; power outages if there are no trip instruments for protection. To address this issue, an auxiliary modified virtual inertia-based derivative control loop is suggested for the EPS to provide virtual (inertia and damping) that can help in solving the frequency stability issue.

The proposed tertiary derivative control method based ESS is applied for EPS along with primary control used for (governor) and secondary control (LFC) as a supplementary control loop. EPS with modified virtual inertia control is compared with the system only based on the conventional EPS control (i.e. primary, secondary), and conventional derivative technique (without virtual damping consideration). The simulation results confirmed that the tertiary modified virtual inertia control loop can enhance frequency stability, provide robustness and security to the community during RESs and load demand penetrations. Finally, it is strongly recommended to utilize the modified virtual inertia mechanism to allow the RESs to participate in the communities, providing resilient and robust features.

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REFERENCES

[1] V. Skiparev, R. Machlev, N. R. Chowdhury, Y. Levron, E. Petlenkov, and J. Belikov, “Virtual Inertia Control Methods in Islanded Microgrids,” Energies, vol. 14, no. 6, p. 1562, Mar. 2021.

[2] H. Abubakr, T. H. Mohamed, M. M. Hussein, J. M. Guerrero, and G. Agundis-Tinajero, “Adaptive frequency regulation strategy in multi-area microgrids including renewable energy and electric vehicles supported by virtual inertia,” Int. J. Electr. Power Energy Syst., vol. 129, p. 106814, Jul. 2021.

[3] K. M. Cheema, “A comprehensive review of virtual synchronous generator,” Int. J. Electr. Power Energy Syst., vol. 120, p. 106006, Sep. 2020.

[4] H. Bevrani, T. Ise, and Y. Miura, “Virtual synchronous generators: A survey and new perspectives,” Int. J. Electr. Power Energy Syst., vol. 54, pp. 244–254, Jan. 2014.

[5] U. Tamrakar, D. Shrestha, M. Maharjan, B. P. Bhattarai, T. M. Hansen, and R. Tonkoski, “Virtual Inertia: Current Trends and Future Directions,” Appl. Sci., vol. 7, no. 7, p. 654, Jun. 2017.

[6] S. K. Bhagat, L. C. Saikia, N. R. Babu, and D. Saha, “Impact of PLL and Virtual Inertia on Deregulated AGC System Integrated with Parallel AC/HVDC,” IETE J. Res., pp. 1–14, 2021.

[7] T. Kerdphol, F. S. Rahman, M. Watanabe, Y. Mitani, D. Turschner, and H. P. Beck, “Enhanced Virtual Inertia Control Based on Derivative Technique to Emulate Simultaneous Inertia and Damping Properties for Microgrid Frequency Regulation,” IEEE Access, vol. 7, pp. 14422–14433, 2019

[8] G. Lin et al., “A Virtual Inertia and Damping Control to Suppress Voltage Oscillation in Islanded DC Microgrid,” IEEE Trans. Energy Convers., vol. 36, no. 3, pp. 1711–1721, Sep. 2021

[9] D. Singh and K. Seethalekshmi, “A Review on Various Virtual Inertia Techniques for Distributed Generation,” in International Conference on Electrical and Electronics Engineering, ICE3 2020, Feb. 2020, pp. 631–638.

[10] A. Fernández-Guillamón, E. Gómez-Lázaro, E. Muljadi, and Á. Molina-García, “Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time,” Renew. Sustain. Energy Rev., vol. 115, p. 109369, Nov. 2019.

[11] T. H. Mohamed, H. Abubakr, M. M. Hussein, and G. S. Salman, “Adaptive Load Frequency Control in Power Systems Using Optimization Techniques,” in AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 2021.

[12] Y. A. Dahab, H. Abubakr, and T. H. Mohamed, “Adaptive load frequency control of power systems using electro-search optimization supported by the balloon effect,” IEEE Access, vol. 8, pp. 7408–7422, 2020.

[13] H. Abubakr, T. H. Mohamed, M. M. Hussein, and G. Shabib, “Adaptive Frequency Regulation in Interconnected Two Area Microgrid System,” in IEEE Conference on Power Electronics and Renewable Energy, CPERE 2019, Oct. 2019, pp. 284–289.

[14] T. H. Mohamed, H. Abubakr, M. A. M. Alamin, and A. M. Hassan, “Modified WCA-Based Adaptive Control Approach Using Balloon Effect: Electrical Systems Applications,” IEEE Access, vol. 8, pp. 60877–60889, 2020.

[15] L. Wu and D. G. Infield, “Towards an assessment of power system frequency support from wind plant-modeling aggregate inertial response,” IEEE Trans. Power Syst., vol. 28, no. 3, pp. 2283–2291, 2013.

[16] H. Bevrani, Power System Control: An Overview. Springer, Cham, 2014.

[17] P. Kundur, Power System Stability and Control. 1994.

[18] EEHC, “‘Annual report 2018/2019,’” 2019. Available: http://www.moee.gov.eg/english_new/report.aspx.

[19] G. Magdy, G. Shabib, A. A. Elbaset, and Y. Mitani, “Optimized coordinated control of LFC and SMES to enhance frequency stability of a real multi-source power system considering high renewable energy penetration,” Prot. Control Mod. Power Syst., vol. 3, no. 1, pp. 1–15, Dec. 2018.

[20] EETC, “Transmission Grid Code,” Cairo, Egypt. Accessed: Jul. 27, 2021. Available: http://www.eetc.net.eg/grid_code.html.