Improved Virtual Inertia Emulation for Frequency Stability Enhancement in Microgrid System

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Abstract-The increased integration of inverter-based renewable energy sources (RESs) in today's microgrids leads to many problems associated with the low inertia nature of power electronic devices that degrades the frequency response and might lead to system instability. However, virtual inertia control (VIC) is considered as one of the suitable control schemes used for controlling microgrids and maintaining the frequency stability in isolated electrical systems. This paper presents an improved technique for VIC for the battery energy storage system to enhance the frequency stability in microgrid systems under large penetration levels for RESs. The amount of emulated inertia is proportional to the rate of frequency change and the value of the VIC. Thus, in this study the developed VIC scheme uses two types of controllers, which are: the PI controller which is used for controlling the ROCOF signal and the fuzzy logic controller which is used for selecting the appropriate value of the inerta constant. Simulation and system modelling are performed using the MATLAB/Simulink software environment. The proposed scheme was tested under various operating conditions including changes in system parameters and changes in penetration levels of renewable energy resources. Further, the proposed scheme was compared with three available schemes in the literature, namely; conventional VIC, enhanced VIC with damping properties, and self-adaptive VIC, the proposed scheme shows a good improvement in the overall frequency response.

Keywords Microgrid, Frequency Stability, Virtual inertia, Renewable energy source, Fuzzy-logic controller.

1. Introduction

Renewable energy sources (RESs) are widely integrated today into bulk power systems due to economic growth, population increase, and addressing environmental problems that include air pollution problems and increased greenhouse gas emissions from the conventional fuels usage [1]. Nowadays, RESs are integrated into the distribution system through a new power system concept known as microgrid which provides a sufficient infrastructure to seamlessly integrate the wind, solar and other types of RESs easily with the main grid [2]. Stability of the microgrid under high penetration of RESs is an important issue. In order to allow more application of RESs, microgrid's stability and dynamics should be robust. In modern power systems and microgrids, where the power converter-based systems have been integrated to these systems, the control modes and control parameters play a vital role in shaping the dynamics of inverter-based system and its contribution to the overall system operation and stability [3, 4, 5]. In [6], an energy management system for controlling microgrid components with hybrid energy storage systems was proposed. A methodological approach for optimal sizing and location of the mixed energy sources in a microgrid interconnecting several villages was analsysied in [7]. Stability analysis of a microgrid was analysed in [8]. The effect of adding of the electric vehicles in microgrid system was studied in [9]. An optimal protection coordination scheme of over current relays in microgrid System was proposed in [10]. The scheme is using nonstandard tripping characteristics and two optimization algorithms, Particle swap optimization and Kalman Particle swap optimization. In [11] the impact of a large-scale microgrid on the power quality of the grid network was investigated. In [12] a survey for the provision of smooth transition between operation modes of PV-BESS (photovoltaic and battery energy storage system) microgrid was provided. A circuit modelling of a microgrid with a solar power system incorporate with maximum power point tracking and a battery energy system was studied in [13]. In [14], a robust coordinated control technique based on frequency superimposed for the power sharing among for multiple energy storage systems is proposed. As RESs are based on power electronic inverters to exchange power with microgrids and due to the low inertia nature of power electronics compared with the conventional synchronous generators, high fluctuations in voltage and frequency are generated in the microgrid. Therefore, the increasing penetration levels of RES resulting in decreasing microgrids inertia and making difficulties in stabilizing the microgrids voltage and frequency [15].

A new inertia control method, known as virtual synchronous generator (VSG), was proposed in [16]. This method mimics the behavior of converter-based RERs to that of conventional synchronous machines to provide virtual inertia power in the aim of raising the stability and improve the performance level of the microgrid system. Recently, several studies have shed a light on the virtual inertia scheme for controlling system frequency such as the study in [17]. where a VIC scheme is proposed based on VSG behavior through the use of a power electronic inverter together with storage devices of short-term energy to improve microgrid system performance and increase frequency stability. The robustness of VIC control is ensured to provide a stable operation of the micro-grid in both grid-connected and island operating mode [18]. In [19] an alternating inertia control scheme is applied to multiple virtual synchronous generators unites to enhance frequency stability and system performance. The VIC scheme of ultra-capacitor for the islanded microgrid is implemented in [20] for improving frequency stability by imitating the inertia response of synchronous generators. In [21] the VIC scheme is developed in doubly-fed induction generator (DFIG) wind turbine where both supercapacitors and the rotating mass of DFIG are used as virtual inertia sources. The virtual synchronous power strategy is applied in [22] to participate in frequency stability of multiple high voltage direct transmission current (HVDC). Enhanced virtual inertia-based derivative control for battery energy storage is provided in [23]. The inertia emulation can be developed in a proportional manner through coupling the converter's active power signal and the frequency derivative signal. However, in all the above VIC-based references, the value of the virtual inertia constant is fixed irrespective of the penetration levels of RERs. The selection of inappropriate value of virtual inertia constant for various penetration levels for the RERs or multiple load disturbances may result in system instability due to having high-frequency oscillation which occurs after these contingencies. For resolving the problems that are associated with the fixed value of virtual inertia constant under different operating conditions, some researchers developed self-adaptive VIC schemes. For example, in [24] an alternating inertia approach for stabilization of electrical systems is applied through employing the virtual synchronous generator. A virtual self-adaptive inertia control considering the damping impact for improving frequency stability is proposed in [25]. Other VIC schemes have been proposed in [35]-[37]. However, based on the above-published research work the effect of high integration of RERs in Microgrids is not fully investigated. The uncertainties associated with high levels of RERs penetrations may lead different virtual control schemes to fail in their tasks of maintaining system stability under a variety of operating conditions. To fill that gap and to ensure a stable operation of microgrids with low system inertia due to high RERs penetration, this paper proposes an improved virtual inertia control scheme that is based on derivative and PI control schemes to enhance the microgrid system robustness and increase frequency stability under a variety of operating conditions. To verify the effectiveness of the proposed control scheme in improving microgrid system stability and decreasing frequency fluctuations, results are compared with some available methods in the literature mainly, the conventional inertia virtual control [26], the improved inertia virtual control with additional damping properties [27], and the VIC that is self-adaptive [28].

The paper is organized as follows: After the introduction, the remainder of the manuscript is arranged as section II contains an introduction to the conventional VIC with the basic concept and modeling. Section III includes the studied microgrid system with the dynamic modeling. Section IV is about the improved VIC scheme that is based on fuzzy logic controllers and IP for frequency stability improvement. Section V displays the simulation results and discussions for different case studies. Lastly, the main results are summarized in section VI.

2. Modelling and Concept of the Virtual Inertia Conventional Control Scheme

As known, the synchronous conventional generators got replaced by RESs in today's microgrids. That is because REs are considered clean and sustainable. However, the low inertia nature of these systems decreasing the overall system inertia (H) because they don’t have rotating masses. Therefore, they are not participating in microgrids frequency regulation. In the contrast, the thermal power plant can provide two control loops (primary and secondary), which help in stabilizing the microgrid performance and recovering system frequency. Figure 1 shows the time intervals for inertia, primary, secondary responding to frequency response during a contingency. The primary control loop takes place within a time interval btween10-30s after the frequency drop due to a disturbance. The governors of the turbines take place in primary frequency response.

Following the control deemed primary and the inertia compensation timescales, the secondary frequency control is activated, which is used for returning the system frequency back to its nominal value within 30 seconds to 30 minutes. The generation control deemed automatic is abbreviated as (AGC). It’s one of the control schemes used the most for secondary frequency control. In case the system frequency drops in a rapid manner and reaches a value that’s critical during any disturbance or critical event, the emergency and tertiary controls shall be deemed essential for restoring the frequency [29]. However, during the interval 1-10s or during severe cases of low system inertia resulting from high penetration levels of RESs, the primary and secondary controls may not be sufficient to provide the suitable frequency control degree, which helps in keeping the system performance stable. Therefore, the concept of VIC is developed to provide the system of microgrid with a control response that is fast based on the principle of inertia control provided by traditional synchronous generators.

In synchronous-based power systems, it is possible to regulate the frequency under any contingency (i.e. increasing RESs penetration or variation in loads). That's attributed to the inertia properties supported from the rotor part of the synchronous machines. Frequency issues resulting from replacing conventional synchronous generators with different penetration levels of RESs can be solved using a VIC scheme which can imitate the action of the prime mover of traditional synchronous machines to improve the overall system inertia and stabilizing the microgrid system frequency. VIC-based frequency derivative technique is offered by [16]. It's used to calculate the rate of changes of frequency (ROCOF) during different RESs penetrations or load variations and therefore adjusting the additional active power added to the setpoint power of the microgrid. Figure 2 shows the dynamic model of the virtual inertia through the use of the derivative technique which consists of the derivative block used for determining the rate of frequency change (df/dt), the low pass filter which reduces the noise, and the limiter block which restricts output power taken from the ESS. The power delivered by ESS based on VIC during any frequency deviation is given by [15]:

$$\Delta P_{inertia} = \frac{J_F}{1+sT_{VI}} \left(\frac{d(\Delta f)}{dt}\right) \tag{1}$$

Where J_F represents the VIC, T_{VI} indicates the time constant virtual inertia to imitate the dynamic control of ESS and Δf is the system frequency deviation.

3. Modelling of the studied Microgrid system

The studied microgrid system contains various types of generation systems with two types of loads as shown in Fig .3. The capacity of the main thermal power plant is 12 MW. The generated power is consumed by the industrial loads with a capacity of 10 MW and 5 MW capacity of the commercial loads. The system has 15.0 MW installed capacity of renewable energies; as 7.0 MW and 6 MW for wind power plant and PV solar farm respectively. The system base used is 15 MW. To resolve the problems associated with the high integration of RESs such as decreasing overall system inertia and increasing frequency fluctuations, a 4.5 MW capacity of an energy storage system (ESS) equipped with an improved VIC scheme was added to the microgrid system. The power lines (black solid lines) are used to deliver the electric power to the loads. The red dotted lines represent the communication link used to exchange the information and control instructions relating to inertia, primary and secondary control loops and the green solid green lines represent the frequency control lines. The microgrid system in this study is assumed to work in stand-alone mode without any connection with the main power utility

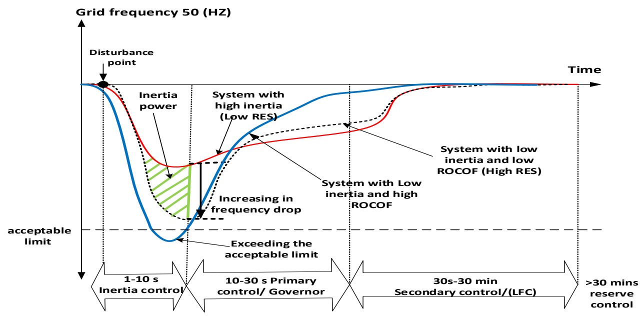


Fig. 1. Time intervals for inertia, primary, secondary responding to frequency response during a contingency.

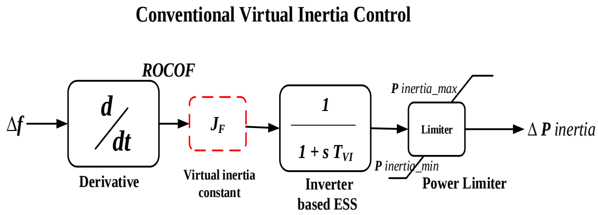


Fig. 2. The dynamic model of virtual inertia control.

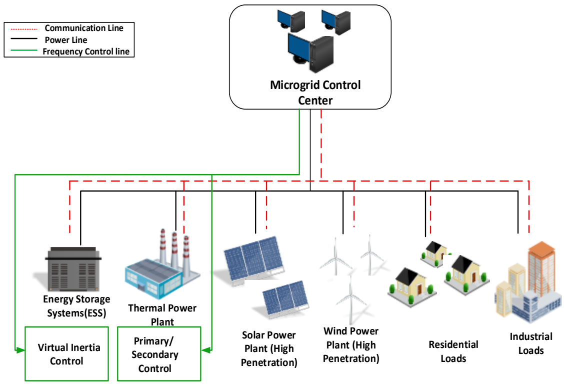


Fig. 3. The studied Microgrid system (simplified model represnsation).

The examined microgrid dynamic model is constructed as shown in Fig .4 for frequency stability studies. The block diagram describes the microgrid area with a thermal power plant, wind, and solar generation units. The nonlinear features such as the generation rate constraint (GRC) for the steam turbine and the governor dead band is also considered to make the closer to the practical system and to obtain the physical dynamics of the microgrid system [29]. In this study, the GRC for the main system of thermal power is identified as 12% pu. By comparing the responses of both simplified and detailed model, it is found that the simplified microgrid model used in Fig .4 is sufficient and has good accuracy for frequency stability analysis. The parameters system and control of studied Microgrids are shown in Table 1.

Table 1. The microgrid control and dynamic parameters [28].

Parameter	Value
Frequency Bias factor, β (p.u.MW/Hz)	1
Secondary frequency controller, *Ki*(s)	0.1
Governor Time constant, *Tg*(s)	0.1
Turbine Time constant, *Tt*(s)	0.4
Droop characteristics, *R*(Hz/p.u.MW)	2.4
System damping parameter (p.u.MW/Hz)	0.016
System inertia, *H*(p.u. MW s)	0.082
Time constant of virtual inertia, *T VI* (s)	10
Time constant of wind system, *T W (s)*	1.5
Time constant of solar system, *T PV* (s)	1.85
Maximum limit of valve gate speed, *VU*	0.5
Minimum limit of valve gate speed, *VL*	-0.5
Maximum ESS capacity , *P inertia max*	0.3
Minimum ESS capacity , *P inertia min*	-0.3

In any conventional power system, the rotating masses of synchronous generators can absorb the kinetic energy or release it during the imbalances between the power generated and consumed. This property of such rotating masses to oppose the change in frequency during any contingency known as the moment of inertia. To understand the concept of inertia control deeply, this part presents the frequency control dynamic structure concentrating on inertia response. In the traditional systems of power, that is based on synchronous generators, the system dynamic behavior can be expressed using the swing equations as follows [31]:

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

Js denotes the moment of inertia, ω is the angular velocity, Tm and Te denote the rotor's mechanical and electrical torques, respectively, and Pe and Pm denote the synchronous generator's electrical and mechanical power, respectively.

As previously stated, the relationship existing between the kinetic energy and the system power rating is represented by the stored kinetic energy in the rotating masses producing the inertia power response and the system inertia.

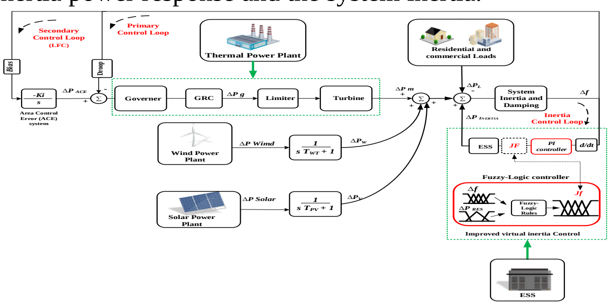


Fig. 4. Model of the studied microgrid for frequency analysis.

Therefore, the kinetic energy of the rotating masses (E kinetic) and the system inertia (H) could be expressed as follows

$$E_{kinetic} = \frac{1}{2}\ Js\omega^2 \tag{3}$$

$$H = \frac{E_{kinetic}}{S} \tag{4}$$

S represents the power ratings of the system-based-synchronous generator.

The derivative technique that is based on inertia control is used for calculating the ROCOF, and adjusting the ESS' reference of active power for emulating inertia after any contingency. Thus, the ROCOF which defined as the frequency's time derivative can be expressed by:

$$ROCOF = \frac{d(\Delta f)}{dt} = \frac{f_0\,(P_m - P_e)}{2HS} \tag{5}$$

Where f_0 represents the system nominal frequency.

Focusing on the dynamic effect of each component of the studied microgrid including the impact of inertia, primary, and secondary frequency control loops, the frequency deviation can be expressed as follows:

$$\Delta f = \frac{1}{2H\,s + D}\ (\Delta P_m + \Delta P_{RES} + \Delta P_{inertia} - \Delta P_L) \tag{6}$$

Where:

$$\Delta P_m = \frac{1}{1 + s\,T_t}\ (\Delta P_g) \tag{7}$$

$$\Delta P_g = \frac{1}{1 + s\,T_g}\ (\Delta P_{ACE} - \frac{1}{R}\ \Delta f) \tag{8}$$

$$\Delta P_{ACE} = \frac{K_i}{s}\ (\beta . \Delta f) \tag{9}$$

$$\Delta P_{RES} = \Delta P_W + \Delta P_{PV} \tag{10}$$

$$\Delta P_W = \frac{1}{1 + s\,T_W}\ (\Delta P_{wind}) \tag{11}$$

$$\Delta P_{PV} = \frac{1}{1 + s\,T_{PV}}\ (\Delta P_{solar}) \tag{12}$$

$$\Delta P_L = \Delta P_{SL} + \Delta P_{BL} \tag{13}$$

Where H represents the microgrid system inertia, D represents the equivalent damping parameter of the microgrid system, ΔP_m is the change of the power that was generated by the plant,ΔP_{RES} of thermal power is the adjustment that occurred to the total power generated by RESs, $\Delta P_{inertia}$ is the change of the virtual inertia power generated by ESS, ΔP_L is the change of the total load, ΔP_g is the adjustment that occurred to the total power that is generated by the governor unit based –thermal power plant,ΔP_{ACE} is the change of the signal of secondary control, ΔP_W is the change of the wind farm generated power, ΔP_{PV} is the change of the solar power plant generated power,ΔP_{wind} is the initial change to power from the wind,ΔP_{solar} is the initial change to solar power, $\Delta P_{SL}$and ΔP_{BL} are the changes in the residential and industrial areas load powers respectively.

4. Improved Virtual Inertia Based Fuzzy-PI Controller

Fuzzy logic can be defined as "a heuristic approach that uses human knowledge or the way of human thinking in the design of controllers". Fuzzy logic is widely used in different engineering fields due to its robustness, simplicity, and reliability [29]. It has the potential to be extremely useful in power systems. control and operation, for its capability of solving problems associating with uncertainty or non-linearity and helping in solving the problems related to the complex behavior of the un-modeled systems.

As mentioned earlier, the VIC technique is widely used nowadays for providing the inertia response instead of synchronous generators especially with the high integration of RES. However, the conventional VIC with a VIC fixed value can't handle the problem of low inertia resulting from high RESs penetrations levels. The amount of inertia power emulated is proportional to the rate of frequency change and the value of the VIC. Thus, in this study developed VIC scheme using two types of controllers, which are: the PI controller used for controlling the ROCOF signal and the fuzzy logic controller used for selecting the appropriate value of the VIC. The structure of the developed inertia control scheme is presented in Fig.5

Based on results shown in Fig. 5, the derivative block is employed to obtain the rate of frequency change or the frequency derivative which is employed by the improved virtual inertia scheme as an input signal to the PI controller. For area j the control equation of the PI controller can be represented as follows:

$$\Delta P_{cj} = K_{Pj} ROCOF_j + K_{Ij} \int ROCOF_j \tag{14}$$

K_P and K_P refer to the proportional and integral gains, respectively.

The wrong selection of the virtual inertia constant could lead to having a long recovery time, and higher frequency oscillation. It may sometimes result in having system instability. To avoid these problems, the fuzzy logic controller is added to the VIC scheme to adjust the level of the VIC with various load disturbances and penetration levels of RESs

The controller of fuzzy logic used in this article is based on that in [25]. The frequency deviation (Δf) and the change in the real power of the RESs (ΔP RES) are used as inputs to the fuzzy which then converted to the fuzzy rules using the fuzzification process. Figures 6 and 7 shows the fuzzy logic membership functions and the fuzzy logic controller's schematic diagram.

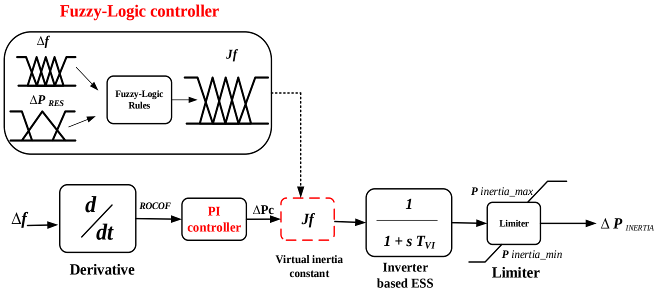


Fig. 5. The proposed virtual Inertia Scheme based on PI and Fuzzy logic controller

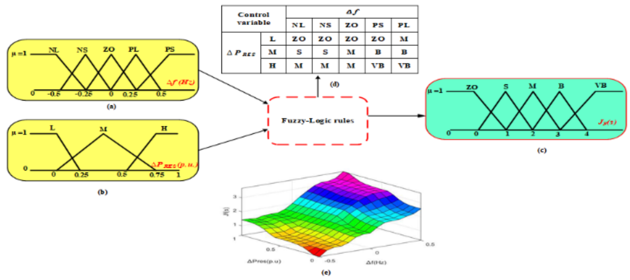


Fig. 6. Fuzzy logic membership functions. (a) The membership function for frequency deviation (b) the membership function for RES power penetration (c) the membership function for the inertia constant (d) The fuzzy rules for the fuzzy logic controller for a linguistic variable (e) effect of frequency deviation and RES penetration on virtual inertia constant.

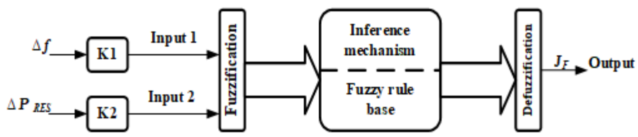


Fig. 7. The fuzzy logic scheme for calculating the value of virtual inertia constant.

5. Simulation Results, Discussion, and Analysis

For examining the robustness of the developed VIC scheme in enhancing the frequency response, the simulation results are displayed in this part where the microgrid system is tested under various operating conditions of changing the RESs penetration levels and varying the industrial/ residential load consumptions. Since the proposed inertia control is dependent on derivative technique, the results have been compared with other VIC schemes based on derivative including the conventional virtual inertia [23], enhanced virtual inertia with damping [24], virtual inertia based fuzzy-logic [25], and with the case where no VIC is used. The MATLAB/Simulink software has been used to carry out the simulation results. based on [31], the acceptable limits of frequency deviation are defined as ±1 (49 to 51 Hz) for any contingency relating to generation or load and as ± 0.5 (49.5 to 50.5 Hz) for a normal condition.

5.1. Scenario 1: The Effect of VIC Values on System Frequency Stability

As mentioned in previously, the VIC can offer a higher system performance level than the conventional synchronous machines especially under the critical conditions, such as of low system inertia and damping values that result from having high integration of RESs. Contrary to the conventional synchronous machines, the VIC parameters can be altered to enhance the dynamic frequency response of the system. In order to understand this concept, the microgrid system's response is tested under 0.1 step load change (increase) at t=2.0s with different values of inertia constant. Figure 8 depicts the frequency deviation under six value of inertia constant.

It is observed that by increasing the virtual inertia constant, the frequency overshoot drops (the overshoot point is known as Frequency Nadir). That shall lead to showing a higher performance and improved system stability. However, if the virtual inertia constant value increases too high, a longer time is needed to settle the system frequency. Thus, choosing the suitable value of virtual inertia constant plays a vital role in stabilizing system frequency. In the proposed VIC, a fuzzy logic controller is used to adjust the value of the virtual inertia constant, hence increase the amount of virtual inertia power emulated in the system.

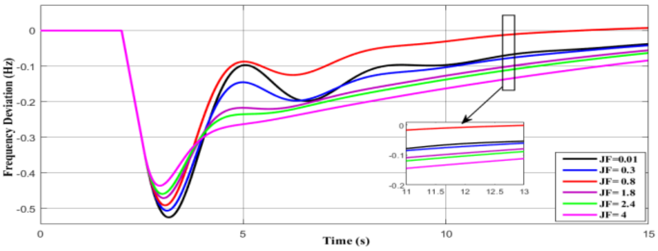


Fig. 8. System frequency response under the varation of virtual inerta constant vaule (JF)

5.2. Scenario 2: Normal and 50% Inertia and Damping Reduction with Sudden Load Increase

In this scenario, the improved virtual inertia is tested under load increase ($\Delta PL = 0.1$ p.u) at t = 5 s without considering the power fluctuations of wind and solar systems with normal and 50 % reduction of damping and system inertia. The reached results were compared with other VIC scheme for verifying the effectiveness of the control system that was proposed. The simulation results are shown in Fig. 9 and Fig.10, respectively. Based on the results, for a system with 50% reduction of damping and system inertia, a higher frequency deviation was found when compared with a system of normal values of damping and system inertia. For example, the frequency deviation for the system without inertia control is about-0.6 Hz (normal values of damping and system inertia) compared with -0.82 Hz frequency deviation (half values of damping and system inertia).

In addition, the frequency response of conventional, enhanced, and self-adaptive VIC schemes shows a higher frequency deviation with 50% reduction values of inertia and damping. However, it can be noticed that the performance of the proposed VIC shows a small frequency deviation compared with other virtual inertia-based derivative techniques in particular under the critical conditions of low damping and system inertia (50% reduction). During the transient state, the improved VIC could produce further power, resulting in a lower level of frequency nadir and ROCOF. That indicates that the robustness of the proposed control scheme can maintain frequency stability under low damping and system inertia values.

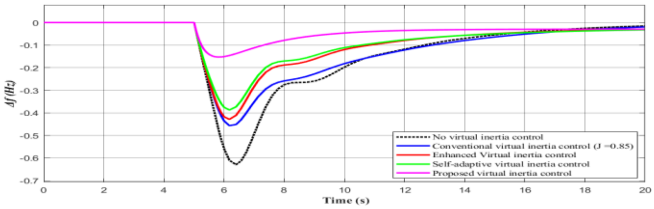


Fig. 9. Frequency deviation with 0.1 step load increase and normal system inertia and damping.

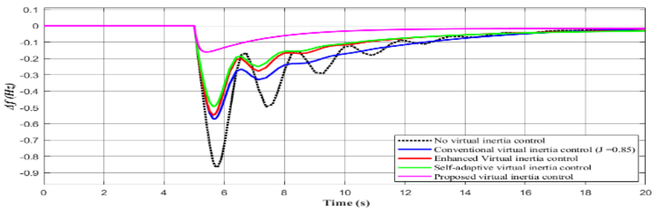
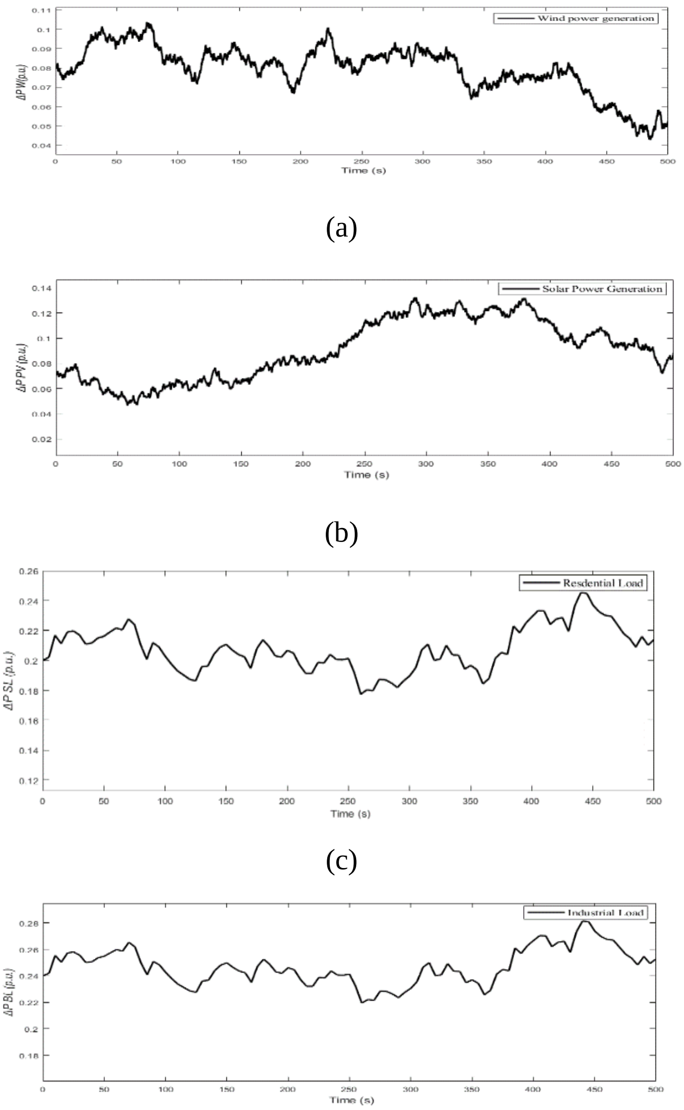


Fig. 10. Frequency deviation with 0.1 step load increase and 50% inertia and damping reduction.

5.3. Scenario 3: Impacts of Low RESs Penetrations on Frequency Stability with Normal Inertia and Damping Values

For this scenario, the microgrid is tested under normal operating conditions (small reduction in damping and system inertia values), with low solar and wind power penetrations levels and high level of consumption of power from both residential loads and industrial ones (see Fig.11). The power fluctuations of RESs due to the change in wind speed and solar irradiation or due to having changes to the load demand are also considered in this scenario.

Figure 12 shows the system frequency under low penetration of RES. Low penetration of wind power connected at 150 s result in frequency overshoots to about +0.06 for the proposed virtual inertia controller, whereas the frequency deviations for other VIC schemes rise to about +0.18 Hz,+0.13 Hz, +0.12 Hz, and +0.09 Hz for no VIC, conventional virtual inertia, the enhanced VIC with damping properties and the virtual inertia based fuzzy logic, respectively. For the time interval between 150 and 350 s, both RESs (wind and solar) are connected, and the proposed virtual inertia scheme provides the best frequency response compared with other virtual inertia-based derivative schemes.



(a)

(b)

(c)

(d)

Fig. 11. Power disturbances for Scenario 3: (a) Low penetration of wind power (b) low penetration of solar power (c) residential load pattern (d) industrial load pattern.

At t = 350 s 0.08 p.u of solar power generation is disconnected and the frequency drops to about -0.1 Hz, -0.085 Hz, -0.078 Hz, and -0.067 Hz for the cases of no VIC , conventional VIC , enhanced VIC , and the virtual inertia with fuzzy logic control respectively whereas the frequency drops to about -0.05 Hz for the case of the proposed virtual inertia scheme. Thus, the improved virtual inertia-based fuzzy-PI controller contributes to having a better system performance level through reducing the frequency deviation and improving the system robustness and resiliency.

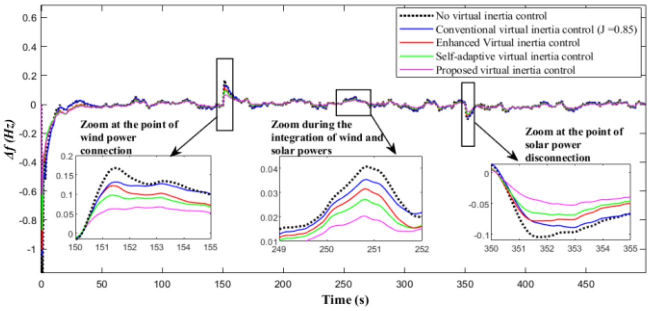


Fig. 12. Microgrid Frequency response under low RESs penetrations and high values of inertia and damping (scenario 3).

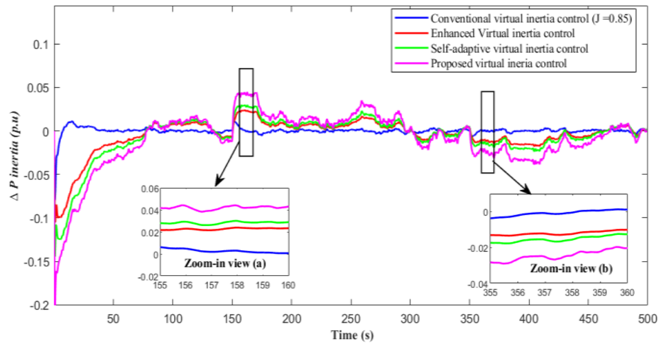


Fig. 13. Virtual inertia power for conventional and enhanced inertia control schemes.

Fig. 13 shows the inertia power extracted from ESS for all virtual inertia schemes mentioned above. It is clear that the microgrid with the improved virtual inertia extracted more inertia power from ESS, during the disconnection of the solar farm and absorbed more power during the connection of wind farm compared with other VIC schemes this shows the effectiveness of the proposed control scheme in tracking the changes of RESs penetrations. Figure 14 shows the response of thermal power generation under different VIC schemes, as it observed with the proposed VIC the stresses on thermal power plants is reduced as the required contribution from the thermal power generation is minimum.

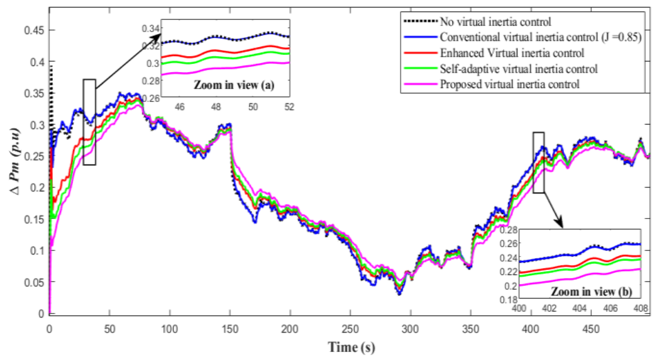


Fig.14 Thermal power generation response with different VIC schems. (Scenario 3)

5.4. Scenario 4: Impacts of High RESs Penetrations on Frequency Stability with Low Inertia and Damping Values

In this scenario, the microgrid system is tested under high levels of solar and wind power penetrations (see Fig. 15). It's presumed that the system has low inertia and low damping values (i.e. 80% reduction from their initial values) and with the same load patterns used in the case study 1 which is shown in Fig 11. the frequency response of all the other virtual inertia that's based derivative control schemes.

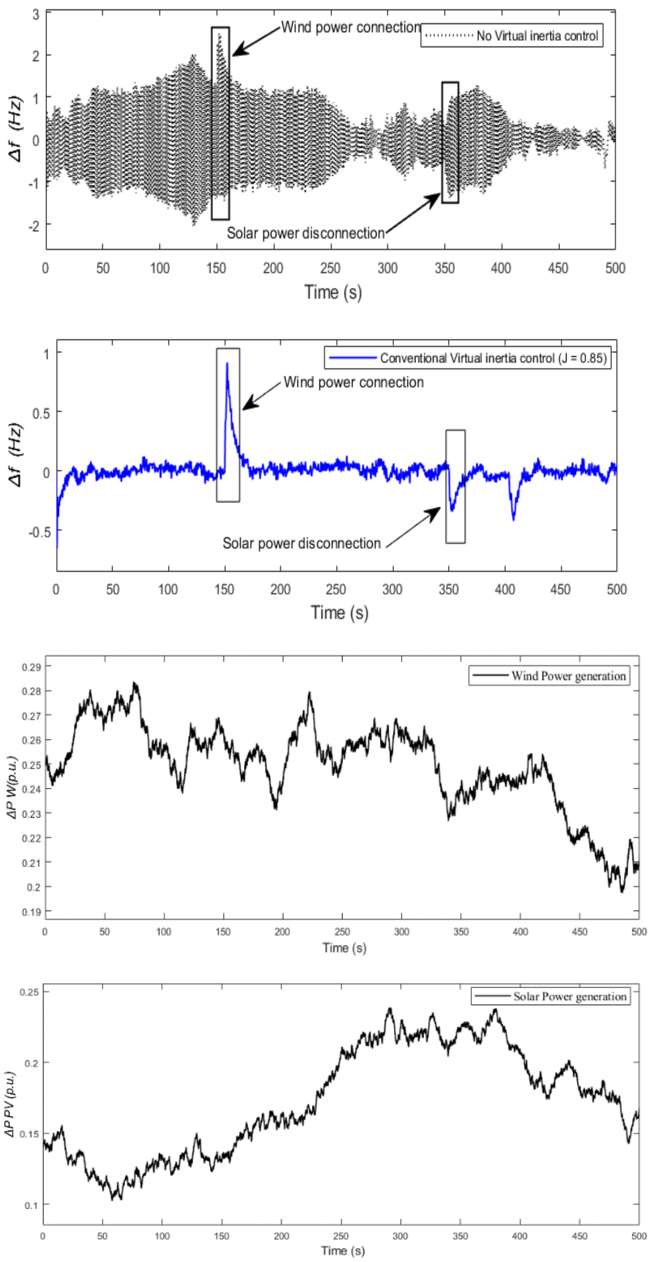


Fig. 15. High penetration levels of wind and solar energy for scenario 3

Figure 16 shows the frequency response of the system. It is understood that the proposed scheme has the capability to maintain frequency stability under high levels of wind power connection and solar power disconnection compared with other virtual inertia schemes. As shown in figure 16 the frequency response for the case of no VIC shows a high-frequency rise of about +2.5Hz at the point of wind power connection, which exceeds the acceptable frequency limits. From the figure it is observed that for the case for conventional inertia frequency rise to about +0.93 Hz, for enhanced inertia with damping control frequency rise to about +0.79Hz, for self-adaptive frequency rise to +0.4 Hz whereas the frequency rises to only +0.2 Hz for the case of improved VIC . During the connection of both wind and solar plants (150 to 350 s), the proposed virtual-based fuzzy-PI controller could regulate the frequency deviation with the lowest value. Following the disconnection of 0.2 p.u from the solar power generation at 350 s, the frequency drops and the proposed virtual inertia scheme can keep the same frequency deviation to about -0.15 Hz which is better than the frequency response of all other virtual inertia based derivative control schemes.

Based on Fig. 17, during the connection and disconnection of wind and solar farms, the inertia power taken from ESS is greatly charged and discharged in the case of an improved virtual inertia-based fuzzy-PI control scheme compared with the conventional and enhanced control schemes. Thus, the developed VIC can provide the best frequency response. It has the capability of maintaining the system performance stable under various operating conditions. Such conditions include: having changes to the power generation or consumption levels.

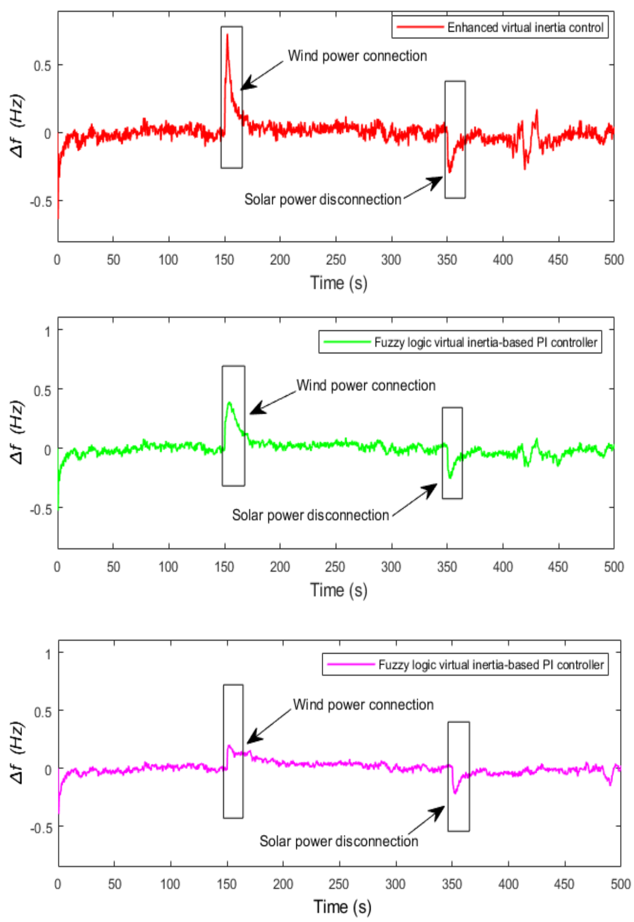


Fig. 16. System frequency response under high RESs penetrations and low values of inertia.

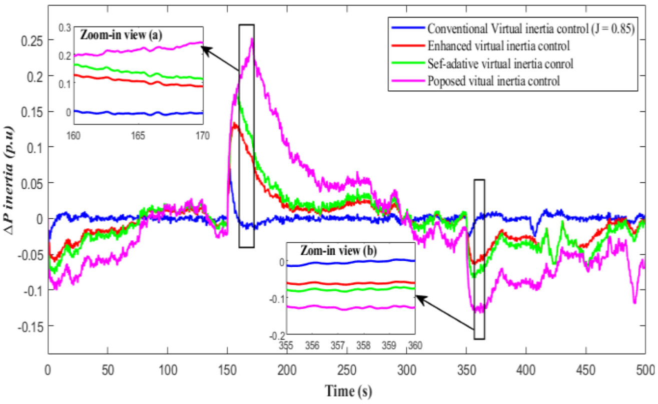


Fig. 17. Active Power changes under different VIC scheme. Scenario 4

5.5. Scenario 5: Mismatch System Parameters with Multiple Disturbances

In practical microgrids, the inaccuracy of the system parameters estimated in designing the microgrid or the variation of the system parameters with time can affect the system performance and may deteriorate the system stability. Therefore, in this part, the microgrid is tested under wide variations in system parameters such as the mismatch of the primary and secondary control parameters (see table 2) with multiple disturbances including high penetration levels of RESs, low system inertia, and damping similar to scenario 2 and multiple load events. For this scenario, the high wind power is connected at t= 100s, an industrial load is disconnected at second 200, part of solar power is disconnected at t =300s, and an additional residential load is connected at t = 400 s.

The frequency response of the system of microgrid for this scenario is presented in Fig. 18. For the case without VIC, the frequency response in a severe manner fluctuates (exceeding the acceptable frequency limits), which may widespread to create Cascading failures. It may lead to the degradation of microgrid system stability. The simulation results indicate that the use of conventional VIC results in high-frequency deviation, oscillation, and overshoots at the points of connection and disconnection of the wind, solar farms, residential and commercial loads which means that the VIC with a fixed virtual constant value is not robust enough for the case of high penetration level of RESs and low system inertia and damping, whereas the enhanced and the VIC schemes that are self-adaptive may be responsible for providing the system stability under the mismatch of microgrid system parameters or the mismatch of primary control parameters or secondary ones. However, the frequency deviation of the improved VIC is less than other VIC schemes. That means that the proposed control scheme is more reliable for providing system stability either under emergency conditions.

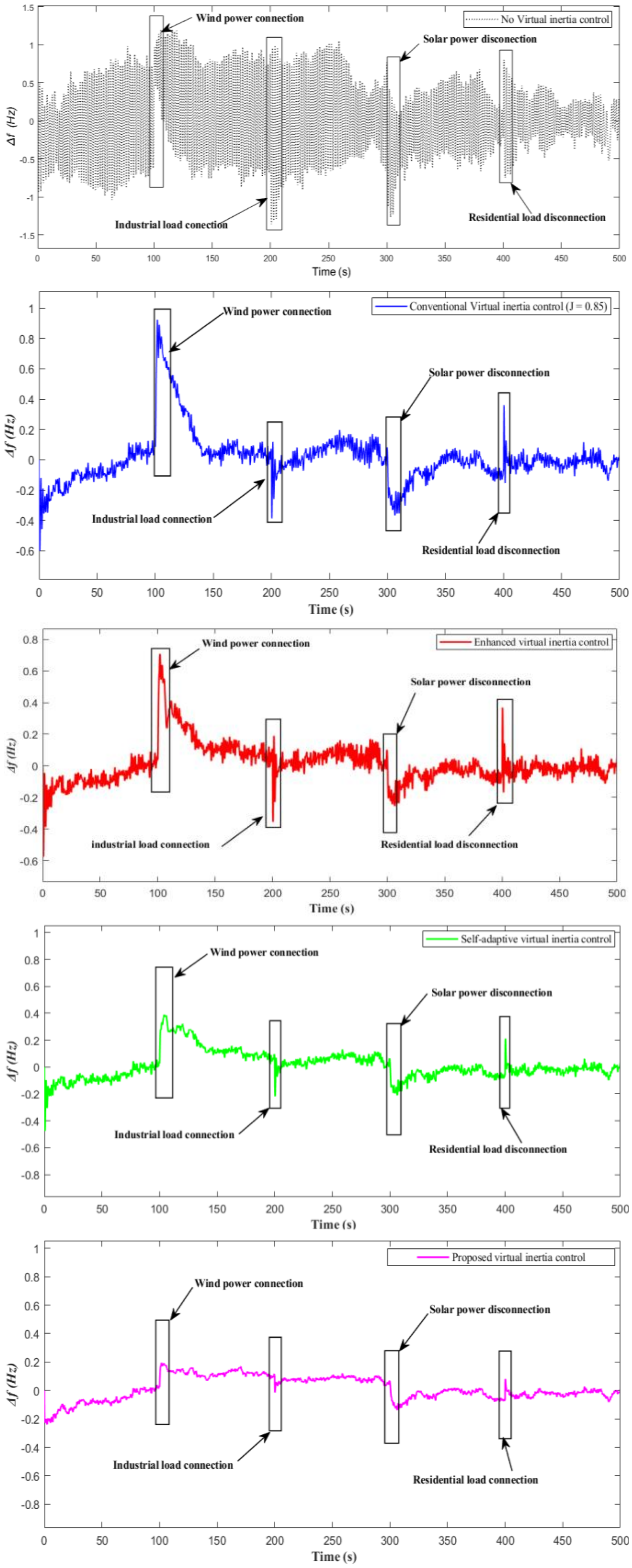


Fig. 18. Frequency response of the microgrid under mismatch system parameters and multiple load disturbances (Scenario 5).

6. Conclusion

The high integration of inverter-based renewable energy resources in today's and future microgrids leads to the low inertia system and frequency instability challenges. In this paper, an improved virtual inertia scheme for the battery energy storage system has been proposed. The amount of emulated inertia is proportional to the rate of frequency change and the value of the VIC. The proposed scheme is based on combination of derivative technique and PI controller with the help of fuzzy-logic controller. Simulation and system modelling are performed using the MATLAB/Simulink software environment

The proposed scheme has been tested under various operating conditions and different system parameters including; high penetration levels of RESs, low system inertia, low system damping, and the high loads consumptions. The results indicate that the ability and robustness of the proposed control scheme to maintain frequency stability in microgrids in a wide range of system operation and parameters variation.

Further, the proposed scheme was compared with three available schemes in the literature, namely; conventional VIC, enhanced VIC with damping properties, and self-adaptive VIC, the proposed scheme shows a good improvement in the overall frequency response compared with these schemes.

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