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Secondary Controller for Parallel Operated Inverters in Islanded Microgrid Using Variable Structure Control Strategy

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Abstract
This paper presents a novel linear variable structure secondary controller for islanded Microgrid driven by voltage source inverters. The main control stretchy depends on a low pass filter based frequency restoration. The proposed control strategy solves the problem of trade of between accurate frequency restoration and active power sharing accuracy by using variable structure controller. A bank of low pass filters with different parameter values are used instead of single fixed parameter controller. An efficient algorithm is designed to switch between the compensators in the bank to achieve the two objectives, namely accurate frequency restoration and fast power sharing. The switching algorithm uses event driven protocol to trigger its activation until reaching steady state and then staying stand by for the next event where the event is active power change. Simulation results shows an excellent result.

Keywords
Microgrid, Distributed Generators, Secondary Controller, Event Driven, Power Sharing, Frequency Restoration.

I. INTRODUCTION

Renewable energy sources (RES) are increasingly being included into the electrical grid as a result of growing concern over environmental deterioration brought on by the use of fossil fuels [1–3]. Numerous difficulties in managing and controlling the local electricity grid were brought about by this integration [4–6]. A Microgrid (MG) is one of the main building blocks of the new electrical power system or smart grid. The Microgrid is a small and complete efficient power system consisting of all electrical power systems components such as sources or distributed generators (DGs), transformers, circuit breakers and loads [7–9]. Being a complete electrical system means that MG can be operated as a standalone (islanded) or by cooperating with main utility or other MGs in second mode (connected mode). All sources incorporated into the electrical grid by MG are referred to as distributed generators (DGs) [10–13]. Synchronization, power quality, stability, and power sharing are some of the many issues that result from these DGs operating in parallel [14, 15]. Control and energy management become more difficult when MG is operated independently or in islanded mode, which is when it is not connected to the utility grid. Since the utility grid functions as an infinite grid-forming and supporting source, power quality is guaranteed when MG is connected to it in connected mode [14, 16]. In islanded mode, the control and management system is in charge of keeping the frequency and voltage magnitude within reasonable bounds in order to satisfy power quality standards and provide a steady supply of load. MG is connected to RESs and storage devices using inverters or AC/DC electrical converters. These inverters can be configured to function as grid feeding or current sources, or as grid forming or voltage sources [17–20]. The inverter is controlled to deliver a certain amount of electricity in a grid feeding control scheme, regardless of frequency or voltage magnitude. Grid forming inverters are managed to track a voltage reference signal in order to function as voltage source inverters (VSI) [14]. Having at least one grid-forming inverter is the only way to preserve electricity quality when operating in islanded mode. Then, in islanded mode, grid forming inverters function similarly to utility grids, providing the necessary power that grid feeding inverters are unable to provide and preserving power quality by keeping the MG voltage's frequency and magnitude within reasonable bounds [20–25]. The control system is in charge of distributing the load evenly among the grid-forming inverters when MG has multiple of them operating concurrently [14, 26]. For this, a variety of methods can be employed, such as the droop approach, which is distinguished by its unnecessary communication and ease of design and implementation [27–32]. In power networks supplied by synchronous generators with transmission lines with a high inductive to resistive ratio, the droop technique replicates the well-known link between active power/frequency and reactive power/voltage magnitude, which is the reality in vast area utility grids [27, 28, 33]. Instead of adding physical components, it is usual practice in MG, where the inductive/resistive ratio is actually quite low, to raise it by virtual impedance [14, 34]. Because of the complexity and the multi-objective nature of the control system of DG, it is very often to organize the control system of DGs in islanded mode as a three-layer hierarchical system [35–37]. The first layer, known as the primary layer, is responsible for maintaining frequency and voltage stability and achieving power sharing to prevent overloading some DGs. The second layer, known as the secondary layer, is responsible for restoring nominal frequency and voltage magnitude where the primary control system uses droop strategy to achieve communication free power sharing which introduce deviation in frequency as a result of active power sharing and a deviation in voltage magnitude as a result for reactive power sharing. The third layer, known as the tertiary layer, is responsible for optimizing power dispatch of DGs and other power management tasks to ensure optimum operation [38–44]. The droop based primary layer is a local or communication free control system, while tertiary layer is communication based system where centralized communication is mainly used where a central controller calculates optimum power set point for DGs and other management tasks. Also, techniques based on distributed communication strategies have been used. Power sharing between many DGs has been accomplished by the widespread application of the droop control technique. Using droop control will inevitably cause the output voltage's frequency and magnitude to deviate from their nominal values. This issue is resolved by restoring nominal values using the secondary control. A PI regulator is the fundamental control technique used as a secondary control to account for frequency and magnitude errors by computing a correction term that is added to the drop equation [45–50]. Secondary control can be implemented using centralized communication, where the compensation term for the deviation caused by primary control is calculated by center control and distributed to all DGs [14]. Both situations have a number of disadvantages. A number of PI controllers will operate in parallel when using a PI controller to locally calculate the secondary compensation term, putting the system at risk of instability due to clock drifts or the hunting phenomenon. On the other hand, the hunting phenomena issue can be resolved by utilizing a centralized IP compensator to determine the restoration period and distributing it to all DGs. However, this control structure is not desirable due to the associated issues, such as single point failure, and the financial cost of communication complexity. There are now other, more effective centralized controllers [51–53]. Even though these controllers function well, their single point failure and communication delay issues make them undesirable methods for secondary control design. The distributed-based approaches are the other communication-based secondary control alternatives. In order to achieve excellent improvements, a number of distributed controllers have been created employing various strategies, such as averaging [54–58] and the so-called consensus technique based [59, 60]. With additional improvements, other distributed-based secondary controllers have been developed [61, 62]. With the distributed-based secondary control design, each DG determines its restoration term based on local measurements and the data that is communicated between DGs. Thus, the single point failure issue has been resolved. Notwithstanding the benefits of employing dispersed techniques, the necessity of communication in these methods remains a drawback because of communication-related issues such as delay and failure. These factors make a secondary control based on decentralized, local, or communication-free solutions desirable because they are easy to implement and solve the communication issues outlined above. A number of improved methods have been put up as substitutes for traditional PI local secondary control. Enhancement of PID based [63–65], controller based on control theory [66, 67], filter based [68, 69], and event driven strategy based [70], [70] are some of these methods. The variable in event-driven secondary controllers has an adaptive value; it takes a fixed value while the power distribution is steady and a different value or values when the MG's power fluctuates. For example, in [70], a secondary control based on a low pass filter was established, and by varying the filter gain, which is triggered by events, an adaptive aspect was added to the controller. These modifications have been triggered by the active power. The objective of parameter adaptation is to set the droop parameter to a large value only during active power transients and to return it to a modest value during active power steady state. Even though these controllers work well, they have a number of issues, such as complicated design and implementation, non-smooth changing behavior, and a non-smooth response to frequency and power transients. This paper presents a novel linear variable structure secondary controller for islanded mg driven by voltage sources inverters. The main control strategy depends on decentralized low pass filter based frequency restoration. The proposed control strategy solves the problem of trade-off between the accuracy of restoration of frequency and power sharing by using variable structure controller where a bank of parallel filters is used to achieve the two objectives. An efficient even driven algorithm is used to switch between to these filters to achieve the two objectives namely accurate frequency restoration and accurate power sharing.

II. PROBLEM FORMULATION

In islanded mode of MG, grid forming inverters are used to share load. The droop method is mainly used for this purpose. In this paper, the focus is on frequency/active power (f/p) droop and voltage/reactive power (V/Q) is not discussed. The basic idea of the droop method is to mimic the linear relationship between frequency and active power and voltage magnitude with reactive power in network having dominant inductance impedance transmission line. The basic f/p droop equation is [14]:

$$\omega_i = \omega^* - m_i P_i \tag{1}$$

Where ω_i is the DGi frequency and ω^* is the nominal frequency. p_i is the filtered signal of the instantaneous active power of DGi, which can be described by the following equation [70]:

$$P_i = \frac{\omega_c}{s+\omega_c} P_i \tag{2}$$

In which, p_i is the instantaneous active power and ω_c is the cut of frequency of the low pas filter. m_i is the droop parameter which mainly determine system behavior, here with large m a good power sharing can be obtained at the cost of high frequency deviation and increasingly risk of instability, and with small m, a small deviation of frequency but with poor power sharing. From (1), it is clear that droop method introduces some deviation into DG frequency. The secondary controller is responsible for compensating this deviation by adding restoring term to droop equation [69]:

$$\omega_i = \omega^* - m_i P_i + \delta \tag{3}$$

Where δ is the restoration term which should be generated by secondary controller. This term should be generated by dynamical control system with suitable bandwidth to avoid interference between the primary control action which target achieving active power sharing and secondary controller which aims restoring frequency nominal value. The simplest compensator suitable for this task is certainly the PI controller which can be easily tuned for good performance. But as it well known that distributed integrals operated in parallel suffer from many drawbacks where clocks drift or hunting phenomenon can lead to instability and also different initial conditions can lead to incorrect active power sharing. For this reasons, a first order low pass filter control which can be regarded as a proportional control with simple dynamics behavior represented by single pool is proposed in literature instead of PI controller to overcome the drawbacks associated with PI compensator. Eq. (4) represents the basic equation of this controller.

$$\delta = \frac{k_g}{s+k_g k_w} e_\omega \tag{4}$$

Where k_g and k_w are design parameters and e_ω is error of radian frequency (ω-ω^*).This equation clearly shows that the static and dynamic properties of this controller are related to two different control objectives. And to clarify this dependency, (3) is rearranged after substituting (4) and the following equation is obtained:

$$\omega_i = \omega^* - \frac{s+k_g k_w}{s+k_g(k_w+1)} m_i p_i \tag{5}$$

This equation clarify that the low pass filter controller maintains droop equation structure but with dynamical droop parameter instead of fixed value parameter where the new droop parameter now is:

$$m_i(s) = \frac{s+k_g k_w}{s+k_g(k_w+1)} m_i \tag{6}$$

Then, the new droop parameter will pass through two different operating conditions depending on active power states, these are transient and steady state. In steady state where active power balance takes place, the droop parameter takes the fixed value:

$$\frac{k_w}{(k_w+1)} m_i \tag{7}$$

This equation shows that the steady state of droop parameter in (5) is $m_i$as a maximum value and frequency deviation will be $\frac{k_w}{(k_w+1)} m_i p_i$, then it is clear that for small frequency deviation, k_w should be small. At the other side, the band width of dynamical droop control represented by (6) which determines the response for changes in active power should be high enough to ensure fast response and efficient active power sharing in acceptance time period. This band width and as it is clear from (6) is also depends on k_w. So, k_w is a design parameter with relation to two different control objectives with two different requirements and a trade of between these two objectives should be made according to some specified requirements priority for the two objectives. And the requirements of the two control objectives cannot be optimally achieved with fixed design value for k_w. The possible solution for obtaining optimal performance for the two control objective is by isolating design problem into two control regions. The first is at the transient where fast response is required to ensure fast and accurate power sharing. This behavior of controller should be triggered when an active power change or imbalance between load and generation is detected. In this operating condition and as concluded previously, a high value for k_w should be used. The second region of operation is at the steady state where active power is balanced in generation and consumption. In this operation condition where the dynamical droop parameter reaches its static gain as described by (7), the value of k_w should be selected as minimum as possible taken into account the design consideration.

III. Proposed Controller

In this work and to isolate the controller operating regions, we suggest a low bass filter based secondary controller with a bank of identical filters as described by (4) with different values for k_w parameter. These values are designed to ensure achieving the two objectives where the minimum value is designed to ensure minimum frequency deviation and maximum value is designed to ensure fast and accurate power sharing. The filters in controller bank with values in between the maximum and minimum is used to achieve smooth change from state to state. The switching between filter bank components is the responsibility of an event driven control circuit. Active power or frequency can be used as a variable for event driven system. After detecting any event, a designed time protocol is used by switching system to switch between filters. Fig. 1 shows the basic block diagram for the proposed control system.

Fig. 1 shows that the proposed controller consists of four filters having four different k_w values. k_{w1} represents the designed value for fast and accurate power sharing which should be used in operating transient response for active power imbalance, while k_{w4} represents the designed value to obtain the desired frequency deviation and as stated before this value is used in steady state where a balance between active power generation and have been reached. The other two filters with kw_2 and kw_3 are used to smoothen change from transient response to steady state. The switching circuit uses event driven timing protocol where the circuit uses active power

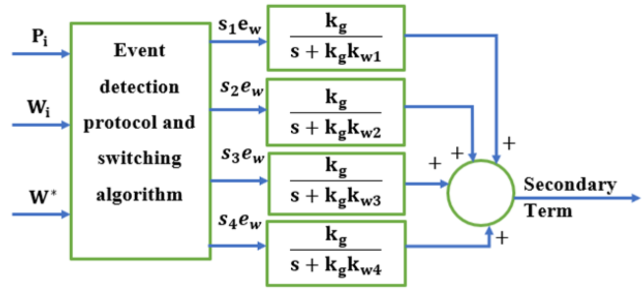

Fig. 1. The basic block diagram for the proposed control system.

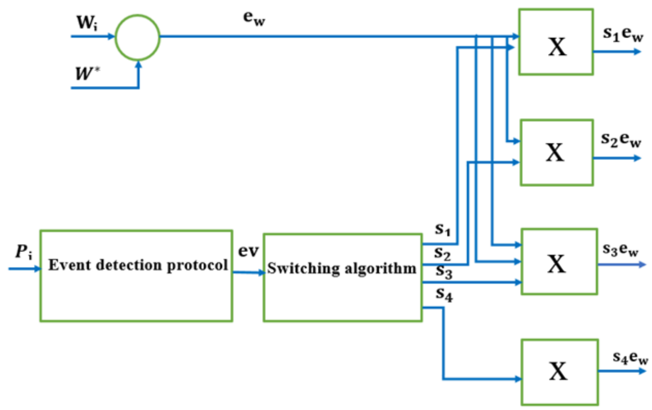

Fig. 2. The timing protocol of the proposed controller.

events or changes to initiate its timing protocol. The timing protocol is simply a sequence of binary signals used to drive multipliers as shown by Fig. 2.

1) Controller Design

In this subsection, the various controller component will be designed.

A. Parameters Design

The maximum value for k_w is designed based on the fact that the maximum possible frequency deviation can be happened when maximum power is delivered by a DG and the dynamical system response for a change happened in active power is just finshed. This deviation is easy to be concluded and it is as described by the following equation:

$$e_m = \frac{k_{w1} m_i P_m}{(k_{w1}+1)} \tag{8}$$

Where e_m is the maximum allowed deviation and P_m is the maximum possible active power. From this equation, the maximum value for the parameter k_w can be obtained. It is also worth mentioning that (8)indicates that the maximum value for droop parameter in the proposed controller can be stated as in (9):

$$m_{max} = \frac{k_{w1} m_i}{(k_{w1}+1)} \tag{9}$$

And it is clear from this equation that the maximum value taken by dynamical droop parameter described by (5) is less than the droop parameter of the main controller (m_i). This result is advantageous for the proposed controller since limiting the value of droop parameter within specified value is required to ensure system stability. The minimum value k_{w4} can be designed by noticing that this value determines the desired deviation in steady state which can be described by the following equation:

$$e_d = \frac{k_{w4} m_i p_m}{(k_{w4}+1)} \tag{10}$$

From this equation, the minimum value of the design parameter k_w can be calculated. The other values k_{w2},k_{w3} are selected to smoothen the transition from transient where high bandwidth is to steady state where smaller bandwidth for filter is used. Linear spacing between k_{w1} and k_{w4} can be used to calculate k_{w2},k_{w3}.

B. Switching Stretchy

The stretchy used to switch between controller bank of filters is simple and depends on event trigger starting followed by timing protocol. In steady state where a balance between generation and load takes place in MG, the filter with minimum value of k_w (k_{w4}) is used as a secondary controller to have the desired frequency deviation. Once a balance in active power is detected as a result of load or generation changes, the switching mechanism switches the secondary controller filters bank filter with maximum k_w value (kw_1) to ensure fast response for droop controller to ensure fast and accurate power sharing which ensure fast getting back to the balance state. This switching represents the starting of timing protocol where the rest of the switching protocol is a switching driven by time to ensure smooth transition from transient where the secondary term is generated by Fig. 11 to steady state where Fig. 14 is used. Fig. 3 shows the timing sequence after event detection and the value of k_w for each time.

C. Event detection protocol

The first stage of the proposed controller is the event detection which is the part responsible for detecting changes in active power. And since the change of active power leads to changes in frequency, then frequency and active power can be used to design event detection protocol. In our work, active power is used as input to event detection protocol. Different event detection protocols have been used in literature. In our work,

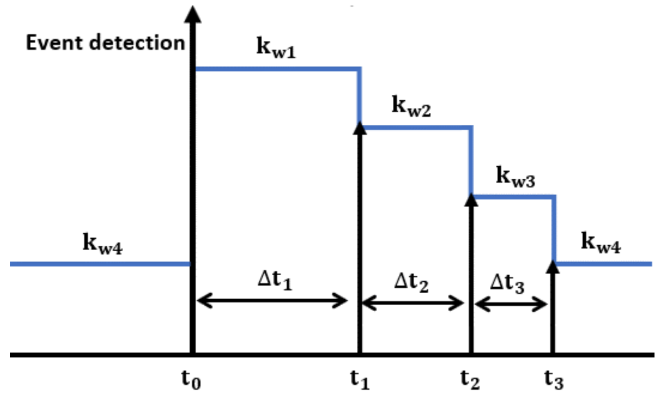

Fig. 3. Timing sequence of timing protocol.

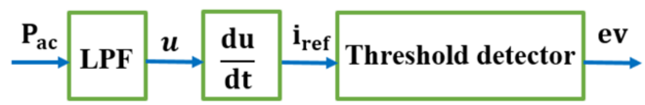

Fig. 4. event detection protocol.

the active power which is used as input is first filtered by a low pass filter to eliminate the high frequency oscillation of active power. The protocol then uses derivative action to detect changes in active power. The third stage is a threshold detector which is used to detect a certain value to make sure that a real change has occurred. Fig. 4 shows a block diagram for the described protocol.

D. Switching algorithm

The input to switching algorithm is the output signal of event detection protocol (ev). The algorithm simply conducts a timing sequence once a logic one is detected for ev signal. Simple flow chart is shown by Fig. 5.

This figure shows that when there is no event, then s4 only is 1 and filter with the gain k4 is selected. When event is detected, then the timing sequence protocol is initiated as described by figure.

IV. Simulation Study

A comprehensive simulation research has been done to examine the performance of the suggested controller and confirm its validity. Three DGs operating as grid forming in a low voltage islanded MG make up the simulated system. Four loads are supplied by the DGs via transmission lines, and the DGs' virtual impedances and overall transmission lines are made to be sufficiently inductive to guarantee that the droop method condition is satisfied. Table I shows the values of the simulated MG's primary components, and Fig. 6 displays the single line diagram. Using Clark transformation, the primary controller of inverters was constructed based on $\alpha\beta$ channels.

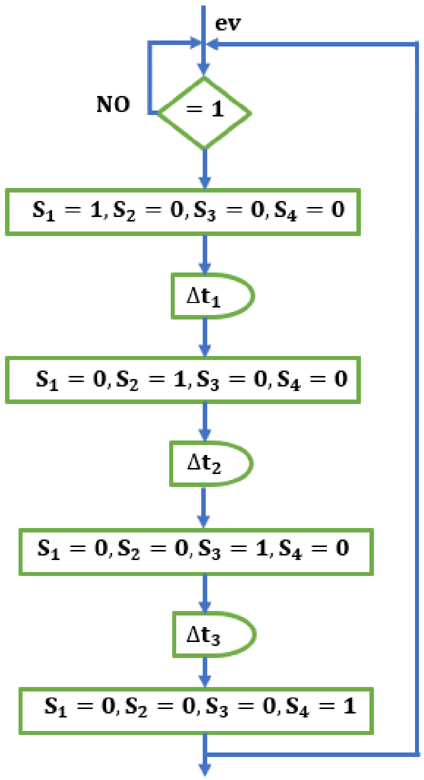

Fig. 5. flowchart of switching algorithm.

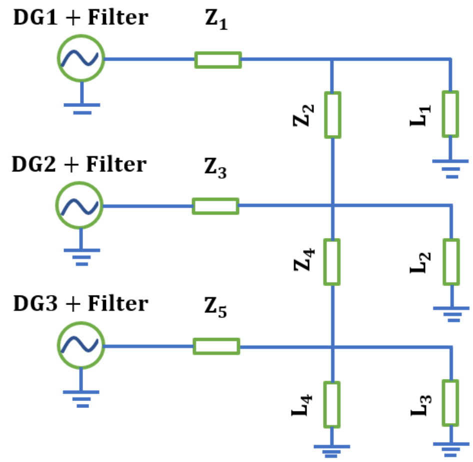

Fig. 6. MG of the simulation study.

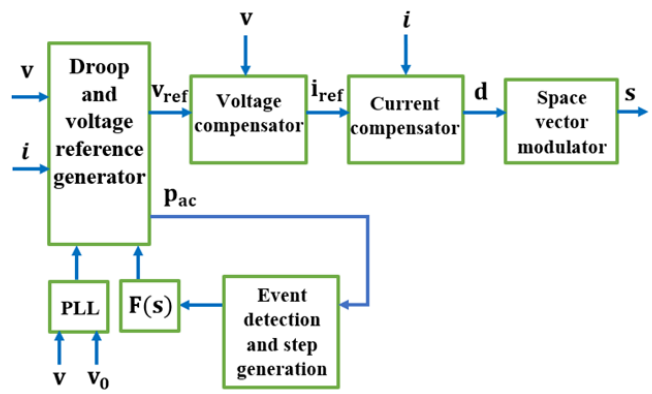

Fig. 7. The general block diagram of the simulated MG.

The general integral or proportional plus damped resonance (PR) has been employed as a compensation for the controller's voltage and current loops. The general block diagram for the designed controller is displayed in Fig. 7, the symbols used are explained in Table II. The values of primary parameters controller loops are listed in Table. III where the design of these loops depended on the controller design in [14]. Table IV shows the suggested secondary controller parameters depending on the proposed design procedure. To avoid a large transient response, DGs have been synchronized using a phase-locked loop (PLL) right before connecting.

The following were included in the simulation study: Black start test The following order is chosen for the black start test: DG1 and L1 are connected at second 0. DG2 and L2 are joined at t=10 sec. DG3 and L3 are joined simultaneously at t=20 sec. At t=27sec, L4 is finally linked. The frequency and active power of the three DGs are displayed in Fig. 8. Selected scenarios Numerous scenarios have been used to thoroughly test the developed control system. Two carefully chosen, potentially challenging-to-manage active power changing scenarios are provided as an example for this comprehensive test in this subsection. They are as follows: Scenario 1 (instantaneous multiple events): This scenario examines the system's capability to handle several events concurrently. The following sequence was chosen to examine this ability: DG1 and L1 are initially linked. Dg2, DG3, and L2 are connected at t=5 seconds, and at t=10 seconds, L3 and L4 are connected but Dg2 and L2 are detached. While DG3 and L2 are connected at t=15 seconds, DG2 and L3 are disconnected. While DG3 and L4 are disconnected at t=20 seconds, DG2 and L3 are connected. L3 disconnects at t=25 seconds, L4 connects, and L4 is eventually shut off at t=30 seconds. Frequencies and active power for this situation are displayed in Fig. 9. Scenario 2 (line to line fault): This scenario tests the planned controller's capacity to handle line-to-line faults. The scenario where a line-to-line fault develops at various times and periods is depicted in Fig. 10. The black start test describes the primary operating scenario. The following is the fault sequence: the first fault happened at second 5 and lasted for 0.3 seconds, followed by the second fault at second 15 and lasting for 0.4 seconds. Lastly, the third fault, which lasted for 0.5 seconds, happened at 25. It can be inferred from the frequency and active power responses of these scenarios as well as the black start that the system has a very high response

TABLE I.
MG MAIN COMPONENTS AND THEIR VALUES

Parameter name and symbol	Value
Nominal line voltage V_n	$220\sqrt{3}$ V
Nominal radian frequency ω_n	$2\pi \cdot 50$ rad/s
Line impedance z_1	$(0.2 + j1.7)\ \Omega$
Line impedance z_2	$(0.08 + j0.38)\ \Omega$
Line impedance z_3	$(0.06 + j1.7)\ \Omega$
Line impedance z_4	$(0.08 + j0.38)\ \Omega$
Line impedance z_5	$(0.06 + j1.7)\ \Omega$
Load L_1	7.85 kW
Load L_2	5 kW
Load L_3	5 kW
Load L_4	5 kW
Cut-off freq. of active power filter ω_c	10 rad/s

TABLE II.
MG SYMBOLS AND THEIR DEFINITION

Symbol	Definition
v	Inverter output voltage
i	Inverter output current
v_o	Bus voltage
v_{ref}	Reference voltage to be tracked
i_{ref}	Reference current to be tracked
d	Duty cycle of switching modulation
s	Switching signal for inverter switches
P_{ac}	Filtered active power

with very little frequency variation and no overshooting.

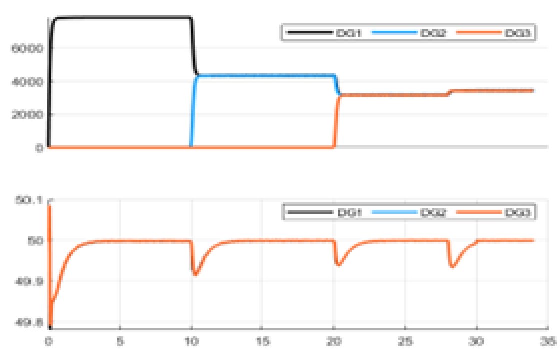

Fig. 8. The frequency and active power of the three DGs in black start.

A. Comparison study

In this subsection, the suggested controller is contrasted with controllers that rely on communication. A consensus

TABLE III.
PRIMARY PARAMETER VALUES

Control loop	Parameters
Voltage compensator	
$G(s) = K_{pv} + \dfrac{K_v \cdot 2\xi\omega_n s}{s^2 + 2\xi\omega_n s + \omega_n^2}$	$K_{pv} = 0.1\ \Omega^{-1}$ $K_v = 0.1\ \Omega^{-1}$ $\xi = 0.01$ $\omega_n = 2\pi \cdot 50$
Current compensator	
$G(s) = K_p + \dfrac{K_i \cdot 2\xi\omega_n s}{s^2 + 2\xi\omega_n s + \omega_n^2}$	$K_p = 12\ \Omega$ $K_i = 200\ \Omega$ $\xi = 0.1$ $\omega_n = 2\pi \cdot 50$
Droop parameter $\hat{m}_i$	$100\ \mu$rad/Ws

TABLE IV.
SECONDARY PARAMETER VALUES

Parameter	Value
K_g	70
K_{w1}	0.9
K_{w2}	0.5
K_{w3}	0.2
K_{w4}	0.03

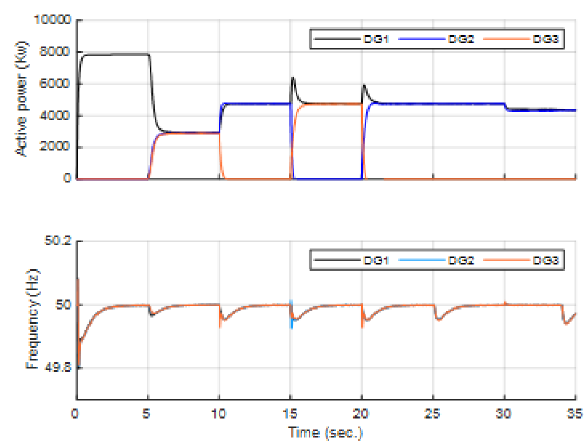

Fig. 9. The frequency and active power of the three DGs in scenario 1.

technique-based controller [58] is chosen as an example for distributed-based controllers, while a centralized PI secondary controller [14] is chosen as an example for centralized-based controllers. Fig. 11 and Fig. 12 show the controllers' reactions for our system's identical black start sequence, while Fig.13 and Fig. 14 show the controllers' responses for scenario 2. With its superiority as a communication necessary controller, it is evident from these data that the suggested

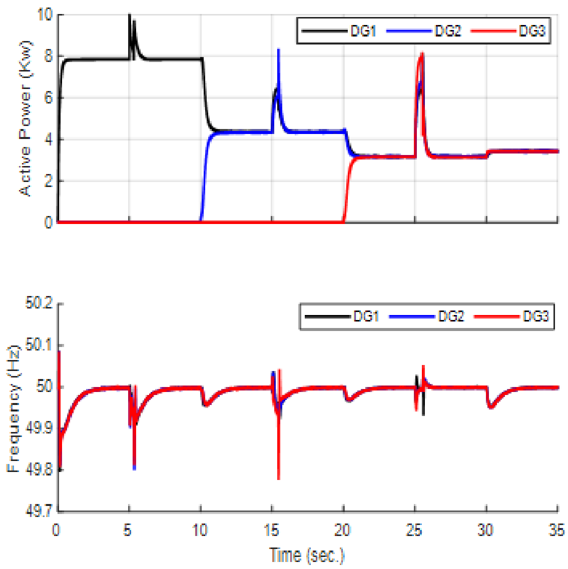

Fig. 10. The frequency and active power of the three DGs in scenario 2.

system performs comparably to these controllers.

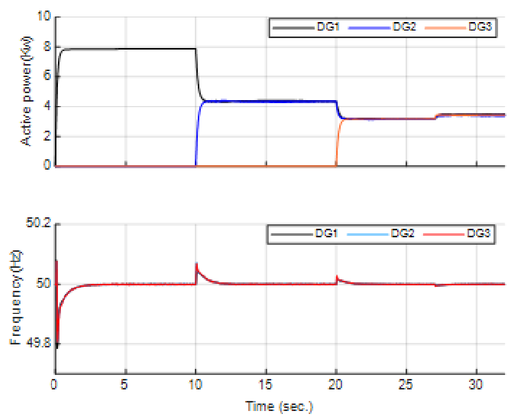

Fig. 11. The frequency and active power of the three DGs in centralized controller black start test.

V. Conclusion

For parallel-operated DGs that use droop controllers to share power in islanded MGs, this work suggests an efficient local frequency restoration controller. A new linear variable structure secondary controller for islanded MG powered by voltage source inverters is presented in this paper. The secondary control method relies on frequency restoration via a decentralized low pass filter. By employing a variable structure controller

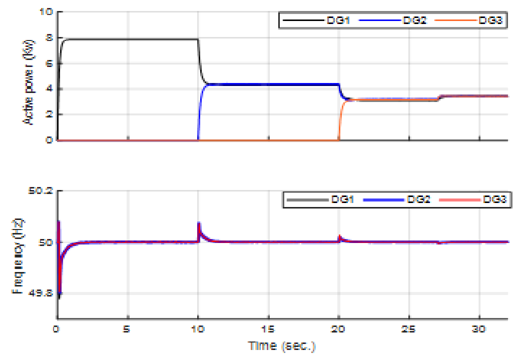

Fig. 12. The frequency and active power of the three DGs in distributed consensus black start test.

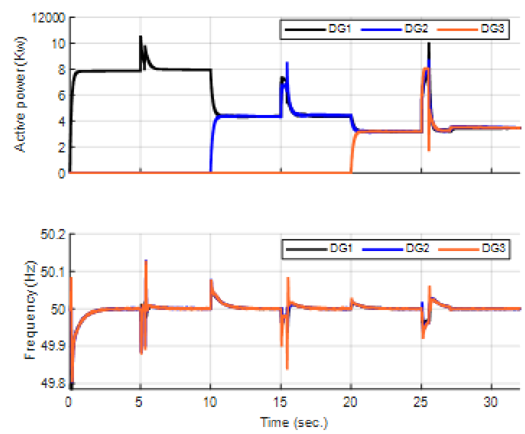

Fig. 13. The frequency and active power of the three DGs for centralized controller in scenario 2.

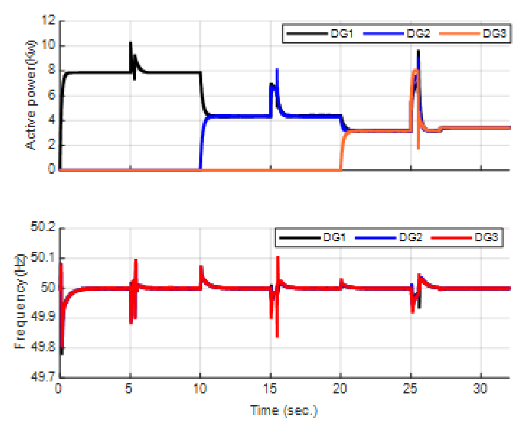

Fig. 14. The frequency and active power of the three DGs for distributed consensus controller in scenario 2.

and a bank of parallel filters to accomplish both goals, the suggested control technique resolves the issue of the trade-off between power sharing and frequency restoration precision. To accomplish the dual goals of precise frequency restoration and precise power sharing, an effective event-driven algorithm is employed to alternate between these filters. The simulation analysis, which also included a comparison with other well-known controllers, proved the validity and superior performance of the proposed controller. Stability studies and an experimental implementation of the proposed controller are probably going to be the main topics of future research.

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

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