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Optimal Power and Frequency Control of Microgrid Cluster With Mixed Loads

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ABSTRACT In recent years, voltage and frequency regulation issues have been extensively discussed for the microgrid clusters (MGCs), as the high penetration of renewable energy resources (RES) might affect the continuous operation of the microgrid (MG). Furthermore, to enhance the MGC's operation reliability, stability concerns need to be addressed. In this study, a residential MGC connected to a commercial MGC has been considered. A novel control scheme that combines both droop control and virtual inertia control is proposed. This control strategy relies on online measurements, and it can be adapted to different situations. At each iteration, the damping coefficient and droop coefficient are calculated this allows the system to switch as needed between the droop and the virtual inertia controller. This dynamic coefficient calculation allows plug and play capability, which provides the MGC with major flexibility in terms of the MGs operation and flexibility.

INDEX TERMS Parallel inverters, microgrid cluster, virtual inertia, droop control.

NOMENCLATURE

δ	Power angle.
θ	Line Impedance angle.
Z	Line Impedance.
$\emptyset$	Current angle.
P	Active power.
Q	Reactive power.
Q_0	Reactive power reference.
H	Inertia coefficient.
K_d	Damping coefficient.
P_0	Active power reference.
ω	Output frequency of the inverter.
ω_0	Frequency reference.
ω_g	Grid frequency.
ω_c	Cut off frequency.
D_ω	Droop coefficient.
D_P	Slope of the power-frequency droop.
f_l	Load frequency measurement.
f_d	Delayed frequency.
Δf	Frequency difference.
Δt	Time delay.
f'	Frequency deviation.
V_r	Rated voltage.
f_r	Rated frequency.
V_0	Reference voltage of droop.
f_0	Reference frequency of droop.
E	Generation bus voltage.
K_q	Voltage-frequency droop gain.
K_p	Power-frequency droop gain.

I. INTRODUCTION

MICROGRIDS (MGs) play an important role in reducing the Levelized Cost of Energy (LCOE), ensuring stability, and further, increasing the probability of supplying the load consistently. Furthermore, the integration of renewable energy sources (RES) faces various challenges largely due to their intermittency and stochastic existence. Reliability represents a significant challenge to integrate RES into the power grid, and as such, battery storage has been utilized to provide ancillary service operations support (e.g., peak shaving, increasing inertia, and preventing frequency destabilization). During a microgrid power interruption, a battery energy storage system (BESS) may be used as a power resource to serve local loads. This characteristic plays an important role in accomplishing grid requirements and meeting load demands to secure the voltage and frequency stability. Multiple interconnected MGs located in the same vicinity are referred to as microgrid clusters (MGCs). A recent study on MGCs [1] presented a hierarchical cooperative control strategy for AC MGCs such as three distinct layers of control that are cooperating. This control strategy is a multi-objective control that achieves several optimization objectives: minimizing operation cost, minimizing voltage fluctuation, and reducing frequency fluctuations. Even though this control approach presents important results, its implementation may be extremely complicated as it requires large computational capabilities, and heavily relies on communication links, which increases the voltage and frequency instability probability in case of an outage. In [2], the sensitivity of different components and parameters in a PV microgrid system is studied. Based on this study, the power system's inertia can be achieved by adjusting the power output of the PV and selecting a larger size DC link capacitor; the latter is a cost-prohibitive endeavor. Therefore, a cost-effective way to achieve inertia can be done by implementing an inverter control system. In [3], a DC-DC bidirectional converter link among DC MGs is proposed to supply power from a MG to another unit by utilizing the RES available on the generating MGs. Despite the off-grid energy supply approach effectiveness, the controller proposed in [3] considers only DC MG interconnections. The concept of community MGs in AC/DC microgrid systems was proposed in [4], [5] to manage the operation of nearby MGs in the same neighborhood to enhance the reliability and efficiency of the local power system.

Several studies have focused on developing inertia control models to increase the grid's stability [6]–[9]. In [6], the authors proposed a virtual synchronous generator (VSG) controller to emulate inertia by simulating a governor speed control and load frequency control loops simultaneously to decrease the frequency deviation of inverter-based MGs in grid-connected mode. VSG are used as a mechanism to improve the microgrid's inertia response. In [7], the authors proposed a VSG controller in which the converter dynamical features are considered to demonstrate that the relationship between the damping factor and the virtual inertia should be lesser than the crossover frequency to stabilize the grid. In [8], a virtual inertia control strategy is proposed linking with the potential inertia advantages of VSG technology, the authors improve the weak compatibility among the virtual inertia principle and the energy storage control algorithm. Additionally, the virtual inertia method is used instead of VSG methods. In this way the inverter's controller will do all the tasks of controlling the voltage and frequency in MGs. In [9], following the principle of the synchronous generator, inertia is derived from the total kinetic spinning energy available in the system and dictates the variability of the frequency in response to imbalances in supply and demand.

Different methods are focused on developing control models not only to enhance the MGs frequency response but also to take advantage of the available RES to reduce operational costs and increase the life cycle of the MGs power assets. For instance, in [10], a bi-level control algorithm is used to define an optimized operation strategy for MGC. The first layer of control has the objective of reducing the cost of system operation, while the second layer of control minimizes the risk of the operation of each MG. In [11], the authors address the system instability by developing a dynamic virtual inertia model as an optimization problem, minimizing the costs, and improving the life cycle of BESS.

In [12], the authors introduced an optimization algorithm to tackle the frequency instability by optimizing the parameters and location of grid-following and grid-forming inverters. In [13], the authors propose an optimization algorithm to minimize the power mismatch. In [14], an energy management system was developed as a multi-objective optimization problem, in which the cost of the multi-MG and dependence on the grid are considered. The authors propose an independent performance index as a function of the flexible loads, where the energy injected from the grid to the multi-MG and the operational costs are reduced.

Other studies have focused on increasing inertia by developing virtual inertia-related control methods. In [15], it is shown that a virtual inertia control may introduce instability as it boosts voltage sensitivity to the converter current change. In [16], the authors compare the grid forming and following converter operation modes by utilizing active power droop control (APDC) and virtual inertia emulation (VIE), the effect of both types of controllers in frequency response is analyzed. To improve the frequency response and reduce the MG sensitivity to high-frequency noises, a variable virtual inertia control to compensate for frequency variations on AC MGs in both, grid-connected and islanded modes, is proposed in [17]. The fixed gains in [16] and [17] that is set for the controller limits the controller's application.

From the inverter control standpoint, droop and virtual inertia control combined can improve the grid's stability. In [18], droop and virtual inertia controls are implemented for a single MG with constant droop coefficients to control the frequency response of the system subject to sudden frequency changes in a single microgrid. It is possible to have a better control of the frequency response by adjusting the virtual inertia and the droop control coefficients at each iteration.

By removing physical components such as external communication links along with a combination of droop control and virtual inertial control, the systems' failure probability may be decreased. It may also reduce the cost of the inverter system. Both methodologies combined provide the MGC with plug-and-play features, and thus, improving its autonomy. The plug-and-play feature is introduced in this paper as a step forward to enhance the reliability of a MG by removing the vulnerable components.

From the system standpoint, a microgrid may satisfy its emergency loads during a blackout. In this study we propose a cluster of combined residential and commercial MGs, since their load profile are different and most of the time

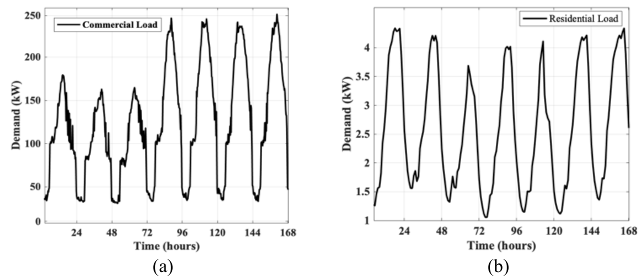

FIGURE 1. a) commercial load demand, b) residential load demand for 1 house (starting from Saturday to Friday).

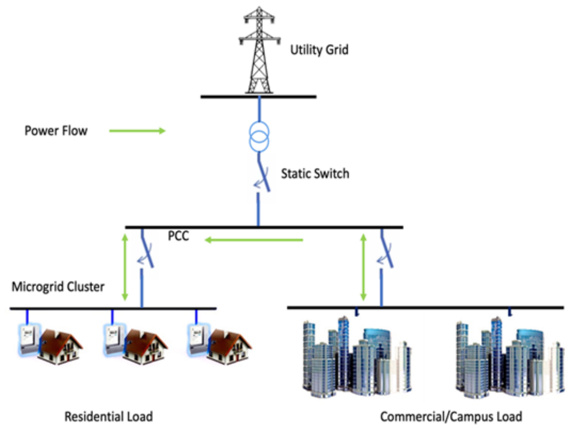

FIGURE 2. MGC system topology.

complementing each other. By taking advantage of their load profile difference, we will show that this will improve the power grid's stability and maintain the voltage and frequency.

The proposed work deals with the aforementioned issues in the form of the following contributions: 1- A control scheme that combines droop control and virtual inertia to keep the voltage and frequency stable. Contrary to previous studies their coefficients are calculated online while preserving the system stability. 2- The proposed control strategy can take advantage from diversity of load profile and low inertia therefore long-term load forecasting is not required. 3- Communication links and DC links are not required hence a more cost-effective strategy.

The remainder of the paper is organized as follows. In section II, the microgrid structure is described in detail. In section III, the energy management scheme used in the proposed system is discussed. In section IV, the results and analysis are presented. In the final section, conclusions are provided.

II. STRUCTURE OF MICROGRID

A. SYSTEM DESCRIPTION

As previously mentioned, a microgrid may satisfy its emergency loads during a blackout. To enhance the stability of the defined system and control the voltage and frequency, a MGC with a combined residential and commercial is considered using the data provided by NREL (National Renewable Energy Laboratory) [19]. Fig. 1 demonstrates what typical commercial and residential power consumption during a week (Saturday – Friday) looks like. Commercial peak load happens during the week, while residential peak load occurs during weekends. Furthermore, the residential load follows a duck curve whereas commercial load varies between a minimum and a maximum value. By utilizing the difference in power demand between residential and commercial load, excessive power from the commercial MGC may be used to satisfy the residential load. This allows power to flow from the commercial side of the system to the residential side during weekend peak demand hours, and thereby, enhancing the reliability of the system.

In Fig. 2, each MGC and grid connection is equipped with a static switch and can operate in both operation modes: grid-connected and islanded modes. Each switch can connect or disconnect a part of the system from the MGC or disconnect the MGC from the electrical grid in case of fault or emergency load situations such as natural disasters. In the case of islanded mode operation, each MG is locally connected, and control signals are sent among them to connect or disconnect them from the MGC.

As previously mentioned, systems with higher inertia are more capable of managing instabilities and variations in frequency compared to a lower inertia system. However, there are certain strategies, such as virtual inertia control, that make a system with PV less vulnerable to failures. The present study emulates the operations of the heavy spinning rotors and incorporates inertia emulation algorithms into the inverter. The virtual inertia control can compensate for the lack of synchronous generators or the main power grid by emulating the virtual inertia using the swing equation.

B. POWER MANAGEMENT STRATEGY OF THE MULTI-MG

To function independently, a MG must balance its demand and supply to handle the voltage and frequency fluctuations; the same strategy applies to a multi-MG. To achieve a stable voltage and frequency in a power system, generation should match the demand. To address issues related to the power imbalance in MGs, a combination of droop and virtual inertia can be considered. Multiple solutions have been proposed to increase the inertia of the power system such as VSG and virtual impedance [9]. For instance, in [9], following the principle of the synchronous generator, inertia is derived from the total kinetic spinning energy available in the system and dictates the variability of the frequency in response to imbalances in supply and demand.

In a MG where the key source of energy is the PV systems, the MG may not be able to balance its power as traditional power systems. Due to the lack of inertia and sudden changes in voltage and current, it is difficult to design the control mechanisms for an autonomous MG under a high-level PV generation. Since the MG gets its power from RES, there is also a need to actively augment the inertia of the MG to achieve a controllable unit. In [18], the lack of

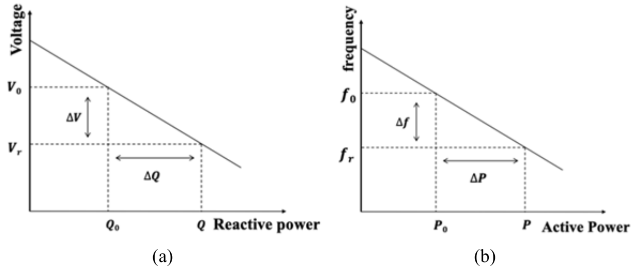

FIGURE 3. **(a) P-f droop control, (b) Q-V droop control.**

sufficient inertia due to the PV generation was overcome by applying the emulated inertia and damping coefficient to the inverter's droop control unit. The controller defined in [18], can restore and sustain the frequency within the target range. Using a bidirectional converter, excess power is sent to the BESS. The inverter of the BESS provides the supplementary energy needed in case PV alone cannot serve the total energy demand. The controller proposed in [18], combined two different types of control mechanisms. The first is the droop control typically used in MGs to regulate the frequency and voltage, the second control mechanism adds virtual inertia to the droop control.

Conventional grids have high X/R. However, this might not be the case for all microgrids. First, to apply the conventional droop control, high X/R is needed [20]. The microgrid can be assumed inductive if the X/R ratio is high [21]. Usually, an inverter is attached to the microgrid, which makes the X/R very high, making the whole microgrid highly inductive [22]. Hence the conventional power frequency droop can be applied in highly inductive microgrids.

By assuming that the MG system is highly inductive based on a system that has a very low ratio of resistance over reactance (R/X) and a small power angle difference, the power angle (δ) can be controlled by regulating the active power (P), while the inverter voltage is controllable through reactive power (Q). Control of the real power flow dynamically controls the power angle as well as the frequency. Therefore, by adjusting P and Q independently, the frequency and amplitude of the grid voltage are determined. These results form the basis for the well-known frequency and voltage droop regulation through both active and reactive power, respectively. By tracking the droop characteristics as illustrated in Fig. 3, the active and reactive outputs of the inverter are controlled to regulate grid voltage amplitude and frequency to preset values.

The control rules are described by (1)-(2) and relates load frequency and grid voltage, respectively, and are the transient set point for the inverter's reactive and active power. Droop equations can be defined as [23]:

$$V_r = V_0 - k_q(Q - Q_0) \tag{1}$$

$$f_r = f_0 - k_p(P - P_0) \tag{2}$$

In (1) and (2) P_0 and Q_0 are the set points for active and reactive power of the inverter. In (1) and (2), P is the active power, and Q is the reactive power. f_r and V_r are the rated frequency and voltage consecutively. f_0 and V_0 defined as the referenced frequency and voltage, consecutively.

The second control mechanism used in [18] is the inertia emulation method. In traditional power systems, power is produced by the generator's spinning rotors, and thus, the traditional power system frequency does not get significantly disturbed in the event of sudden load changes or a temporary fault. However, for the controller of the MGs, it can be a challenging task to control the voltage and frequency of MGs because of the increasing penetration of RES, particularly PV due to the zero inertia [24].

C. METHODOLOGY

The control strategy proposed in this paper is an extension to the work discussed in [16] and [18] In this modified control strategy, the algorithm can reduce the uncertainty and fluctuations of the grid operating conditions. The influence of droop and inertia emulation control is calculated online at each iteration.

The coefficients of inertia and damping of a Synchronous Generator (SG) can be emulated using a modified swing equation as defined in [16], [18], [25] to obtain (3).

$$2\frac{\dot{\omega}}{\omega_c D_p} = \frac{P_0 - P}{\omega} - D_\omega(\omega - \omega_0) - \frac{1}{D_p}\left(\omega - \omega_g\right) \tag{3}$$

In (3), H is the inertia constant, k_d is he damping coefficient, P_0 is the active power reference, ω is the frequency output of the inverter, ω_0 is the frequency reference, ω_g is the grid frequency, ω_c is the cut off frequency and D_ω is the droop coefficient. Depending on the upcoming operating conditions, D_ω and $\mathrm{K_d}$ will get adjusted online to improve the transient and steady state response of the system. We can rearrange (3) and obtain (4):

$$2H\dot{\omega} = \frac{P_0 - P}{\omega} - D_\omega(\omega - \omega_0) - K_d(\omega - \omega_g) \tag{4}$$

By defining the inertia H and the damping k_d coefficients as shown in the equations (5) and (6) [25]:

$$H = \frac{1}{2\omega_c D_p} \tag{5}$$

$$K_d = \frac{1}{D_p} \tag{6}$$

The damping coefficient is inversely linked to the droop coefficient and, the cut off frequency and the droop gain are inversely linked to the Inertia.

In this study, compared to the previous work [18], the proposed algorithm can reduce the uncertainty and fluctuations of the grid operating conditions. Therefore, depending on the operating conditions, coefficients for the droop and virtual inertia controllers are computed online. The damping coefficient may contribute to reducing the transient effect of the system. This equation has two different sections: $D_\omega(\omega - \omega_0)$ for the droop control, and $k_d(\omega - \omega_g)$ for the inertia control. The coefficients computed online to enhance the frequency response of the system during transient situation.

Any sudden change of frequency forces the controller to increase the impact of inertia emulation control. The controller assigns more weight to inertia emulation control compared to droop control. If the frequency extensively varies, then the controller must add major virtual inertia to improve the transient response to frequency variation. On the other hand, the system would avoid excessively high inertia (the system's inertia should be low enough to allow the MG to recover its normal operation after a transient event such as shift load or a fault), otherwise, the MG may experience instability as the power systems may have issues to come back to the frequency setpoint due to the high inertia.

In [18], the lack of sufficient inertia due to the PV generation was overcome by applying the emulated inertia and damping coefficients however K_d and D_ω were constant and calculated once. To improve the transient response and remove the steady-state error K_d and D_ω, are calculated online in each iteration in the method proposed in this paper. The first step towards calculating these coefficients online is to detect the frequency's difference (Δf). To find the Δf, measured data from the past is used to compare it with the current frequency. This way, we can see if the system is in a steady-state or not. For calculating delayed frequency (f_d), a time delay (Δt) is defined. Then, the current load frequency measurement (f_l) is compared to the f_d to get the frequency deviation (f') by dividing Δf over the fixed time step. If f' is close to zero (depending on the sensitivity of the controller), the system is in a steady state. If f' is negative and $f_d, f_l < f_0$ the K_d needs to be increased and D_ω needs to be decreased, if f' is positive and $f_d, f_l < f_0$ the K_d needs to be decreased. If f' is positive and $f_d, f_l > f_0$ the K_d needs to be increased and D_ω needs to be decreased, if f' is positive and $f_d, f_l > f_0$ the K_d needs to be decreased. This way, the frequency response can be improved compared to the fixed gain method in [18] as it is shown in the result section.

III. ENERGY MANAGEMENT SCHEME

For the energy management system (EMS), a control strategy based on matching the load with demand is introduced. Protection is one of the most crucial and challenging problems for microgrid systems. Conventional microgrids include converter-interfaced distributed energy resources (DER), loads, and conventional electric machinery. In the case of different faults within these structures, the converters interfacing the DER produce limited fault current corresponding to the response of the conventional electric machinery [26]–[28]. The primary challenge of microgrid protection is that voltage and current levels solely cannot be used to recognize system faults. Therefore, a method based on the intrinsic dynamics of the microgrid is developed. Besides, relying on communication is not desirable in protection systems because it deteriorates the reliability, slows protection operation, and adds cost to the system.

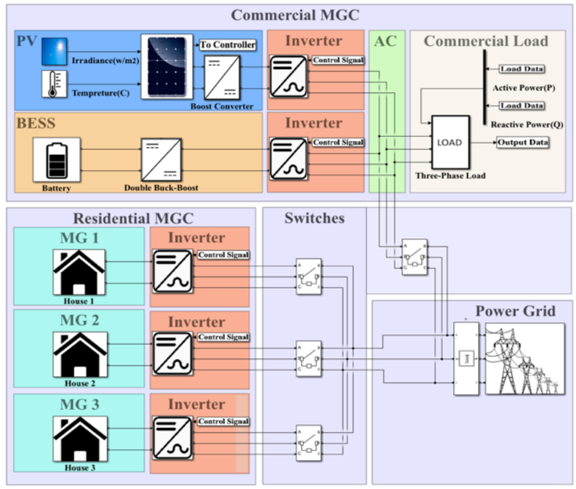

FIGURE 4. **MGC model in MATLAB/Simulink.**

Furthermore, protecting the microgrid without communication channels could lead to blinding (circuit breakers not tripping for faults) or nuisance tripping (tripping incorrectly) [29]. According to [29], a communication-less control system is defined as detecting the faulty MG in a MGC and disconnecting it from the rest of the system. Therefore, such a system can prevent its impact on MGC.

The model used for this study and simulated in Simulink (Fig. 4) contains a utility power grid and a cluster of commercial and residential MGs. In this model, a control unit that calculate K_d and D_ω at each iteration helps to improve the response. In the proposed MG, the system has a control unit that obtains the coefficients simultaneously based on the deviation of the frequency. The system has a PV equipped with a modified maximum power point tracking (MPPT) controller, in which the maximum power point can be adjusted and become load following. This controller keeps the reactive power to the minimum level and extracts the maximum real power to inject it into a MG.

An inverter control system is designed for this type of MGC. BESS and PV systems are utilized for both types of MGC. MGs in this model can operate in both grid-connected and islanded modes. To further enhance the frequency response of the MGC to faults or disturbances, each inverter is implemented with a virtual inertia control system. In this study, the proposed controller has the objective to minimize frequency fluctuation. The proposed controller is a combination of virtual inertia and droop control. The proposed control strategy is an extension of the work discussed in [18]. This controller can automatically adjust the coefficients between virtual inertia and droop control to improve the responsiveness of the system during the transient time and fluctuations. This proposed control strategy is expected to minimize steady-state error. Also, during voltage and frequency sudden changes, virtual inertia control may take effect.

The objective of this study is as follows: 1) balancing power between generation and demand of the proposed system, 2) enhancing the flexibility and reliability of the MGC by removing the communication link and adding plug-and-play capabilities, 3) minimizing the power and frequency fluctuations. The proposed MGC is tested under different situations: load changes, fault occurrence, grid connection/disconnection, and the energy flow from the commercial to the residential loads. The fluctuations will be limited to the IEEE-defined standard and regulations. BESS is equipped with a bi-directional DC/DC converter to either charge or discharge the battery based on the flow of the current. By adding the proposed control unit to [18], the responses will be improved in challenging situations such as load changes or system initialization. Droop and inertia emulation controllers are unified in a single system presented in Fig. 4. The system is built and simulated to examine the proposed control technique for reliable MG operation.

IV. SIMULATION RESULTS

The model is simulated with MATLAB/Simulink. This includes PV, BESS, power grid, and variable loads. In the islanded mode, an active and reactive power control strategy has been used for the inverter interface. A bidirectional buck-boost converter is connected to the BESS, and it controls both the charging and discharging of the battery in Fig. 4. In the grid-connected mode, a PQ control is utilized. The prototype is simulated under the islanded mode of operation.

In this section, a combination of residential and commercial MGC represented by the model described in Section II.C is considered and simulated in MATLAB/Simulink. This simulation is used to examine the performance of the EMS. It compares the performance of the proposed control strategy to the previous model developed in [18]. A commercial MG is connected to the cluster of residential MGs. Among the components of the commercial MG, the PV and BESS are identified as the power generation source of the MG. The results of the simulation are explained below.

The results obtained from the comparison between the proposed model and the previous work [18] in the islanded mode for different scenarios (e.g., load following and frequency response to fluctuations) are compared. The parameters of the model can be seen in Table 1.

To compare the performance of the proposed controller for the same MG, droop control, the unified controller from [18], and the proposed controller are compared. Fig. 5 shows the simulation results. To compare their performances, the load is increased at t = 2sec, and reduced t = 3sec. The effect of this sudden load change on each type of controller is demonstrated in Fig. 5. Droop control and unified controller have a 6.1 Hz and 3.2 Hz deviation from the reference frequency, consecutively. However, the proposed controller deviation is less than 2.1 Hz from 60 Hz.

Fig. 6 shows the frequency response of several controllers under a fault scenario. The test was performed by applying a single line to ground unsymmetrical fault with $R_f = 0.01\Omega$ to the MGC between t = 2sec and t = 2.07sec. The proposed controller shifts the values for both, droop and virtual inertia control coefficients, according to dynamic coefficient calculator described before to find the best inertial response to the simulated fault. As it can be seen from Fig. 6, the fault was cleared after 70 ms, and although all the controllers reached the reference frequency at some point, it can be noticed that the proposed controller displays a more gradual change compared to the other two controllers.

In Fig. 7 the frequency response of the controllers comparing the frequency responses of the three different types of controllers under a sudden 20% irradiance change from t = 2sec to t = 3sec. The droop and virtual inertia control is more vulnerable to the change in the PV generation. Fig. 7 shows that the proposed controller out performs both droop and droop and virtual inertia controllers.

TABLE 1. Parameters for MGC.

Object	Value
Grid Voltage	120 V
Battery Voltage	350 V
Commercial Load Peak	249 kW
Residential Load Peak	34.7 kW
BESS Capacity	3200 kWh

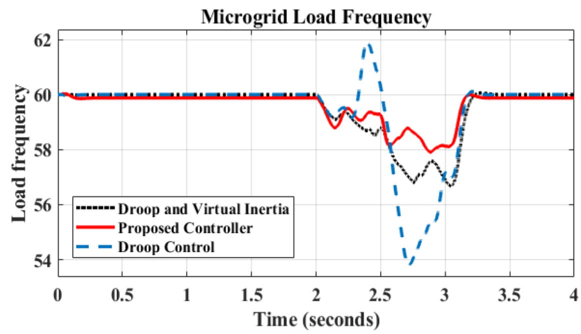

FIGURE 5. Frequency response comparison in different control systems.

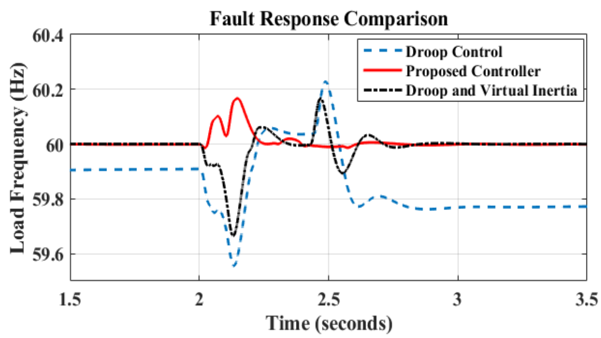

FIGURE 6. Frequency response comparison between controllers.

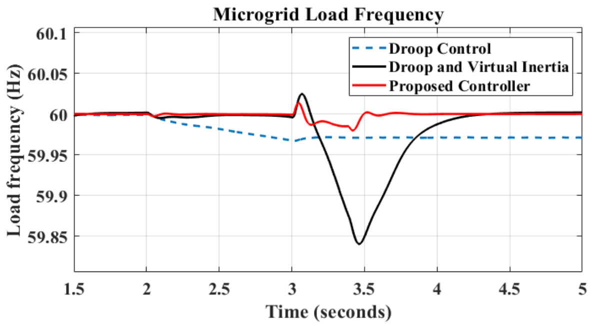

FIGURE 7. Frequency response comparison between controller's sudden change in irradiance.

V. CONCLUSION

In this paper, a MGC with commercial and residential loads is introduced. A resilient electrical grid community model incorporating a proposed inverter control system for each MG is developed. This control scheme has been compared to two other controllers. In all previously proposed methods, the coefficients are fixed and the MG model does not include the energy storage system. In this study online coefficients calculation is faster than previous methods elucidated in published literature since our method dynamically calculates the coefficients based on the changes in the frequency which is explained in detail in §III energy management scheme. The use of commercial MGs as a source of power in a multi-MG system is a viable solution to the problem of providing reliable power, where the main power grid is disconnected. The controller adjusts the impact of the inertia emulation and droop control simultaneously based on the frequency signal for each MG. The improvements in EMS and frequency responses that the controller has offered in different scenarios such as fluctuation, initialization of the system, reaction to load change, and irradiance changes, can be observed. Furthermore, this study demonstrates that the combination of commercial and residential load in a MGC can be utilized as an all-around system to maintain voltage and frequency for all the MGs.

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