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Published in:
Proceedings of the International Conference on Smart Energy Systems and Technologies, SEST 2019

DOI:
10.1109/SEST.2019.8849032

Published: 01/01/2019

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Pournazarian, B., Pouresmaeil, E., Saeedian, M., Lehtonen, M., Chan, R., & Taheri, S. (2019). Microgrid Frequency & Voltage Adjustment Applying Virtual Synchronous Generator. In *Proceedings of the International Conference on Smart Energy Systems and Technologies, SEST 2019* IEEE. https://doi.org/10.1109/SEST.2019.8849032

Microgrid Frequency & Voltage Adjustment Applying Virtual Synchronous Generator

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***Abstract*—The distributed generations (DG) are linked to microgrids (MGs) by power converters regularly and the MG will be in mutual interconnection with conventional power systems. The more the participation level of the converter-based DGs in the MG, the more the stability issues are seen in the MG. Unlike conventional synchronous generators (SGs) which have considerable inertia, the converter-based DG units lack this intrinsic inertia; therefore, they potentially make the MG prone to stability issues. The idea to emulate the behavior of SGs in the control loop of interfaced converters to maintain the MGs stability is a newly-growing idea. This paper tends to propose an improved voltage and frequency control strategy for island MGs consisting several converter-based DGs. The proposed control structure uses an advanced Virtual Synchronous Generator (VSG) model and aimed at implementing the primary frequency and voltage control of MGs. The designed model considers both resistive and inductive parameters of lines in MGs. Since the suggested control structure is a local one, doesn't require communication links between DG units. The simulation results verify the potency of the recommended control structure to preserve the frequency and voltage stability of an island MG even in severe events.**

***Index Terms*—Micro-grids, frequency & voltage control, synchronization, virtual synchronous generator.**

Nomenclature

DG	Distributed Generation
D	Damping coefficient
ESS	Energy Storage System
HVDC	High-Voltage Direct Current
J	Momoent of inertia
MG	Microgrid
PLL	Phase-Locked Loop
PSO	Particle Swarm Optimization
VSG	Virtual Synchronous Generator
SGs	Synchronous Generators
SGES	Synchronous Generator Emulation Strategy
THD	Total Harmonic Distortion
VSG	Virtual Synchronous Generator

I. Introduction

A. Motivation and Background

The worldwide concern over the global warming and energy challenges is accelerating the popularity of green energy resources such as wind, solar, etc. Considering the specific characteristics of the RES like their voltage level, the intermittency of their prime mover and lack of intrinsic inertia, they might cause some stability challenges [1]. A MG is composed of several DGs, storage banks and electrical consumers which can work both connected to the power grid or island. When the grid is available, the distributed generations (DGs) inject their nominal power to the grid and the frequency & voltage are dictated by grid. Once the MG goes to island mode, the individual DGs must adjust the frequency & voltage of the MG. Some researches have proposed various control methods to cope with the frequency & voltage adjustment issue in island MGs, which have been reviewed comprehensively in [2]. One local dispersed control framework, which has been proposed for controlling the DG's interfaced converters is the VSG structure which tends to emulate the behavior of the synchronous machines on the interfacing converters. The main advantage of VSG structure is to add inertia to the converter-based DGs and make the MGs more stable against disturbances. The synchronverters idea was introduced in [3] to mimic the behavior of a synchronous generator by converters. This synchronverter structure can implement the conventional droop sharing mechanism of real & reactive powers. The synchronverters in [4] then were proposed by removing the dedicated synchronization unit (namely PLL).

B. Relevant Literature

The VSG structure in [5] tends to mitigate the real & reactive power low-frequency oscillations and support the stability of the grid under presence of a large degree of

DGs.The synchronous generator emulation strategy (SGES) in [6] was proposed to be implemented on a voltage source converter (VSC) station, which adds an inertia to the active power-frequency characteristic and both primary and secondary frequency regulations were implemented using the proposed SGES strategy. The novel idea of alternating inertia was proposed by [7], which tends to assign different values to the inertia (J) in conventional VSG structures to have a better damping effect and consequently supporting the stability of power system. The frequency & voltage regulation strategy presented in [8] uses consensus algorithm to properly share the active and reactive powers by a local VSG framework. The dynamic characteristics of conventional droop and VSG methodology have been analyzed in [9] through small signal studies. The small signal modeling and parameter design for the VSG has been done in [10]. The virtual impedance was proposed to be added to the VSG structure to have a proper reactive power sharing in [11]. A multi-loop VSG structure have been proposed in [12], which includes a pre-synchronization unit to be activated before connecting the VSG (or VSGs in MG) to have a smooth transition to the mode of grid-connected. Evaluating the stability region for the conventional synchroverters, optimization of parameters of VSG by Particle swarm optimization (PSO) were proposed in [13] and [14], respectively. An adaptive control strategy was proposed in [15] to adjust the inertia and damping coefficient values and consequently having less oscillations in frequency characteristic. Fuzzy secondary controller in the VSG structure in [16] aims to improved dynamic performance with respect to conventional VSG. The local VSG control has been proposed to enable the multi-terminal HVDC systems to attenuate the power oscillations.

C. Contributions and Organization

This paper is going to apply a new VSG structure into the MG voltage and frequency control structure. This VSG structure will keep the voltage and frequency within their standard levels. Considering the inertia (J) and damping factor (D) parameters, thus the frequency response could be controlled in an efficient way. Afterwards, the VSG structure is applied to a MG voltage and frequency structure. Any VSG in the MG will synchronize itself with the common reference frame which is proposed to be rotating in a standard time zone, so the communication links aren't required among individual DGs. The proposed frequency & voltage framework could keep the frequency & voltage within their standard levels, even in rough scenarios. Then, a recent pre-synchronization method is applied to the DGs to have a soft changeover from island to the grid-tied state. The simulation studies as two separate scenarios clarify the performance of the suggested MG control structure. The next parts of this paper are arranged so as; in section II the MG frequency & voltage control framework is introduced. The section III discusses about the simulation studies and demonstrates the corresponding results of two scenarios. The conclusions will be declared in section IV.

II. MGs FREQUENCY & VOLTAGE CONTROL FRAMEWORK

As similar to a conventional power system consisting several generators, in a MG which contains several DGs and ESSs, a power sharing strategy is required to avoid instability and swing between generating units. In [17] it is proposed that, the MG analysis and control should be done on a common reference frame which has been proposed to be the reference frame synchronized with one of the inverters. This assumption requires a communication link between all DGs. Instead of it, it is proposed to consider an identical and well-defined time horizon as a common reference frame. For example, the clock of a city can provide a common time, multiplying this time by a common rotational speed (ω_{com}) will provide a rotational velocity for the common reference frame, which doesn't need a constant communication link between the generating units. All the analysis and control process is implemented on a common d-q rotational frame. Fig.1 describes the proposed reference frame which is rotating at ω_{com}.

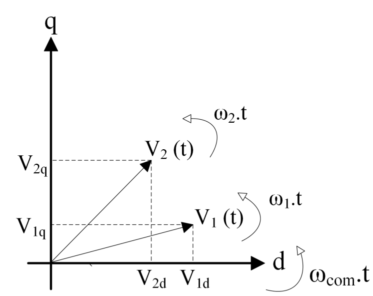

Fig. 1. Voltage vectors in the common d-q frame for two different DGs.

A. Virtual synchronous generator (VSG)

The idea to emulate the behavior of conventional synchronous generators on the interface converters as a local control framework has been proposed in several research papers. Considering the previous VSG structures and also the MG control structures, the considered converter control loop adds intentional inertia to the frequency characteristic and consequently the converters show the inertial behavior. The proposed control strategy is demonstrated in Fig.2. The power controller block will calculate the instantaneous powers and deliver them to the low-pass filters subsequently. The following formulas describe this unit.

$$p(t) = 1.5(v_{od}.i_{od} + v_{oq}.i_{oq}) \tag{1}$$

$$q(t) = 1.5(v_{od}.i_{oq} - v_o q.i_{od}) \tag{2}$$

The VSG block will assign the magnitude of the voltage and the frequency of any DG considering the mode of operation (island or grid-connected). Once the MG is going to be grid-connected, the pre-synchronization mechanism should be done in advance. This process will generate two different values for the converter controller which are ω_{synch} and E_{synch},

TABLE I
FULL CONVERTER SPECIFICATIONS.

Parameter	Value	Parameter	Value
V_{DC}	800 V	$P_{Nominal}$	10 kW
L_f	7 mH	$f_{Nominal}$	50 Hz
R_{Lf}	0.1	$V_{Nominal}$	220 V (RMS)
C_f	$50\mu F$	$Q_{Nominal}$	0
ω_c	31.41	$f_{Switching}$	8 kHz
K_p	0.05	J	0.44
K_q	4×10^{-3}	D	50
K_{p-vc}	1	K_{i-vc}	500
K_{p-cc}	100	K_{i-cc}	6×10^4
ω_n	$2\times\pi\times 50$	F	1
$K_{p-synch}$	50	$K_{i-synch}$	1

respectively. The other blocks named as voltage & current controller implement the well-known voltage and current control algorithms introduced in [1] and they aren't described here because of page limit. But all the coefficients are available in Table I.

B. Synchronization with the main grid

The grid-synchronization is the process of decreasing the difference in the magnitudes and the phases (frequencies) of the MG voltage and the grid at the common coupling point (PCC) to a negligible value. The pre-synchronization process in [11] is implemented on all MG's DGs. The virtual flux observation method tends to define a vector perpendicular to the grid voltage, which will be with lower harmonics. Then, the pre-synchronization process will align the voltages towards the q direction in the new d-q frame (perpendicular to grid voltage). This control strategy is implemented on all MG DGs to have the smoothest connection to the grid. The PCC will be connected to bus 1 while connecting to the main grid. The synchronization controller coefficients are available in Table I as $K_{p-synch}$ and $K_{i-synch}$.

III. SIMULATIONS & RESULTS

Aiming to examine the capability of the suggested MG frequency & voltage control strategy in both island and grid-tied modes of operation, two separate scenarios are defined in a 3-node MG [17]. The MG is depicted in Fig.4. Three identical full-bridge inverters are designed and implemented in Matlab/ Simulink. Full specifications of the inverters are listed in Table I.

A. Scenario 1: load change

The island MG as in Fig.4 starts its operation from time= 0 sec, then the resistive-inductive load of 16.8 kw + 12 kVAr is switched in at bus 1 at time= 1 sec. Examining different characteristics of the MG following this event is critical. The DGs should control the voltage and frequency within permitted intervals.

1) Frequency of the MG: According to [18] there is no specific standard for the maximum permitted rate of change of frequency (ROCOF) in an island MG. But about the minimum point of frequency (Nadir), an operating frequency of 50±1.5 Hz is accepted from generator's point of view. The frequency of island 3-bus MG is demonstrated in Fig.5. starting from t= 0 sec, the frequency was 50.1 Hz as the DGs are working under nominal active power values. At t=1 sec following a load change, the frequencies in all DGs decrease according to their inertial response. As Fig.5 shows, the ROCOF in DG1 is the maximum among three DGs, as it is the nearest DG to the load change point. The frequency Nadir is around 0.05 Hz, which is within standard limit.

2) Voltage of the MG: The DGs in the island 3-bus MG should keep the voltage levels within the standard limits. As according to Fig.6, starting from t=0 sec, the phase voltages in all three buses are on nominal value (220 V). As the load change happens, the voltage levels decrease proportional to the distance from the load-change location, but the maximum voltage loss is nearly 5 V, which is permitted. One another important parameter is to provide an output voltage containing low percentage of harmonics (namely low THD). According to Fig.7, the output voltage has a 0.55% THD which is lower than 3%, which is an standard limit considering the voltage level of 380V [19].

3) Active and reactive powers of DGs: Any of three DGs has a nominal 10 kW active power. Starting from t=0 sec, the island MG is in no-load condition and the active powers are zero in Fig.8. Then at t=1 sec, following the load change, all three DGs react to the event. The DG 1 is the nearest to the load change, so it has the biggest over-shoot in its active power response. Then, they all finally reach an identical active power at 5.6 kW, which is one third of the real power of the load. As all three units are adjusted by similar inertia (J) and damping coefficient (D), they share the active power equally. In case of reactive powers, the more a generating unit is near to the load change point(namely, the interfacing impedance is smaller), the more it participates in reactive power serving to the load. The DG1 has generated 6 kVAr, DG2 has generated 4 kVAr and the DG3 has generated 2 kVAr.

B. Scenario 2: pre-synchronization and connection to the grid

The islanded MG should be capable to have a smooth transition to the grid-tied mode. As the main focus of this research have been on island operation of the MG, the pre-synchronization method introduced in [11]is used to do the pre-synchronization process and then the connection to the grid is done. The pre-synchronization controller's coefficients are assigned in Table I. This method tends to remove the angle differences between the voltages at grid and the PCC via aligning the q-axis elements of PCC and grid voltage. The MG has two local loads of 5.8 kW and 7.3 kW in buses 1 and 3, respectively.

1) Frequency of MG: The pre-synchronization unit is supposed to change the frequency so as to reach the rated

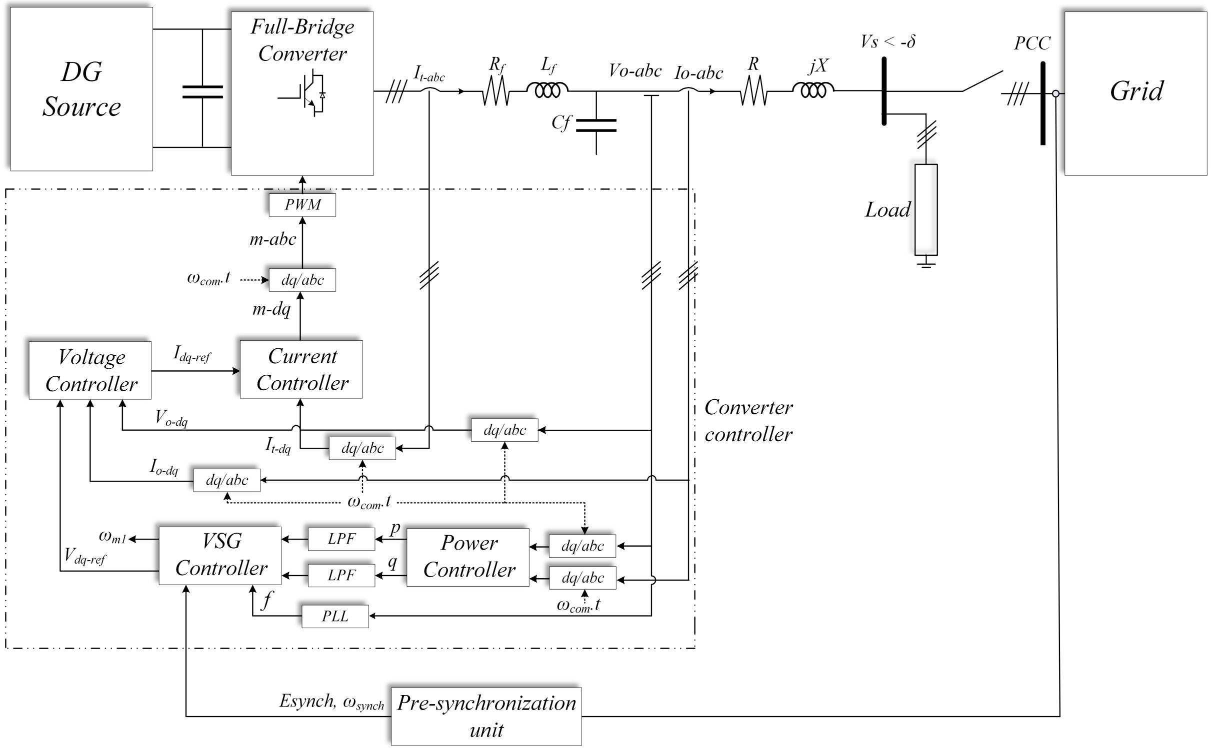

Fig. 2. The general block diagram for the proposed control technique.

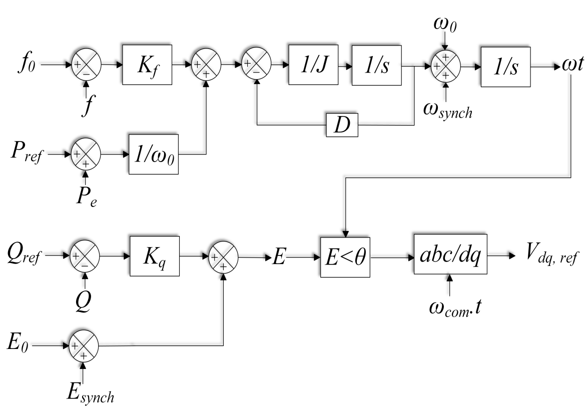

Fig. 3. VSG structure [11].

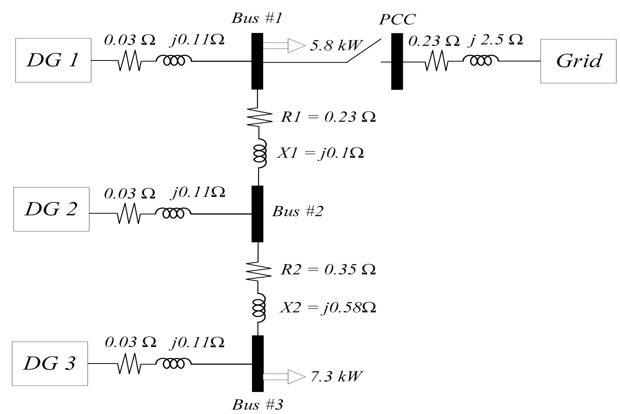

Fig. 4. Simulated three-bus test MG.

frequency of the grid (namely 50 Hz). Fig.10 demonstrates the MG frequency in this scenario. Starting from time= 0 sec, the frequency is 50.05 Hz as all three DGs are generating lower than their nominal active power (all three active powers in Fig.13 are lower than 10 kW). At time=1 sec the pre-synchronization unit starts its operation and the frequency drops to 49.68 Hz and then it reaches its nominal value in half second. Afterwards, at time=2 seconds the MG is connected to the network at PCC. since the frequencies and the magnitudes of the voltages are the some, there has been a soft transition.

2) Voltage of MG buses: Another important parameter are the voltages of MG's buses which should be controlled either

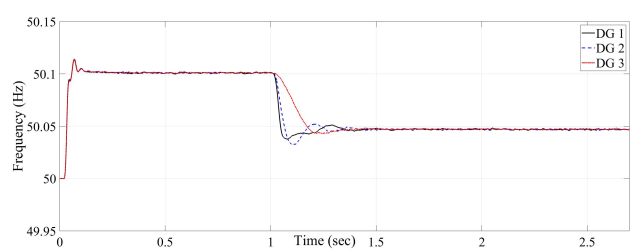

Fig. 5. Frequency of MG in scenario 1.

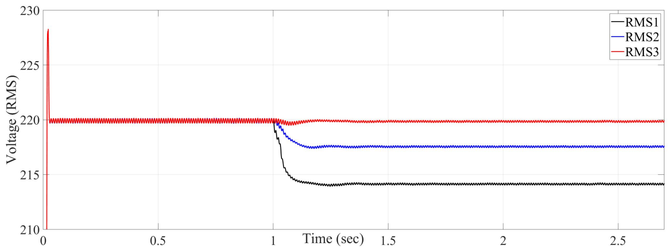

Fig. 6. Voltages of buses in scenario 1.

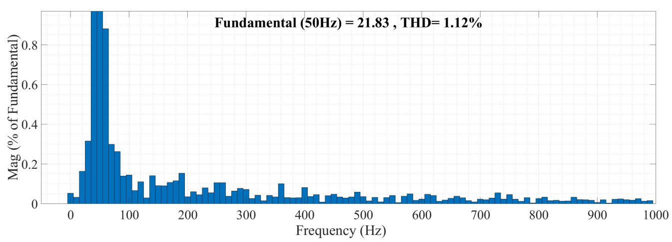

Fig. 7. THD of output voltage in scenario 1.

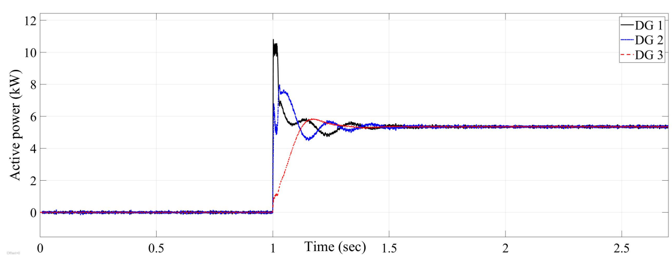

Fig. 8. Active Powers of DGs in scenario 1.

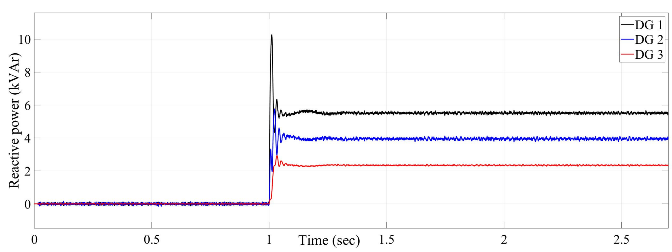

Fig. 9. Reactive Powers of DGs in scenario 1.

in island or connected to the grid. reviewing the Fig.11, the voltages have been nearly 220 V before time=1 sec. Then at time=1 sec the pre-synchronization unit starts its operation and an instant over-voltages are seen in all three buses. As the voltage magnitudes reaches 215 V which is a permitted value, the pre-synchronization unit has a good performance. Afterwards, the connection to the grid is done at time= 2 sec which has been without any voltage oscillation. The pre-synchronization mechanism lowers the phase differences

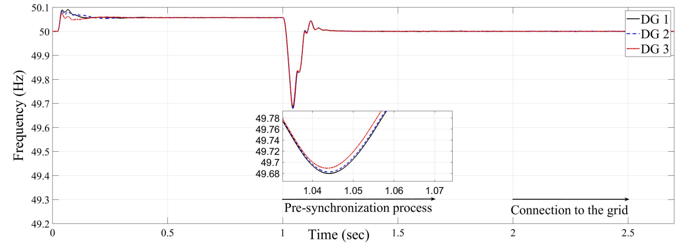

Fig. 10. Frequency of MG in scenario 2.

between the grid voltage and the voltage of PCC and other buses as it can be seen in Fig.15.

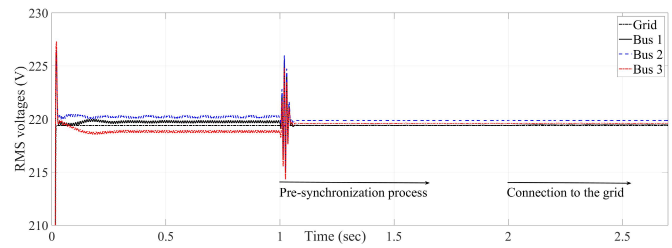

Fig. 11. RMS Voltages of MG's buses in scenario 2.

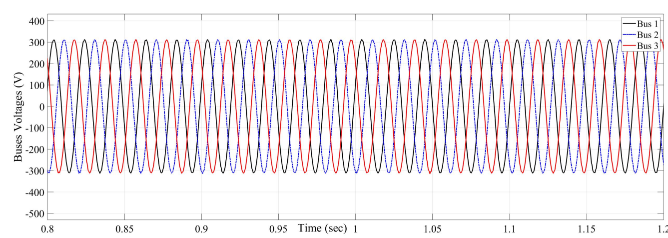

Fig. 12. Voltages of MG's buses in scenario 2.

3) Real & reactive powers of DGs: The active powers generated by DGs are demonstrated in Fig.13. Starting from time=0 sec, the DGs generate identical values of active powers because of similar inertia and damping coefficients. This value is one-third of the total active power of the MG which is 4.36 kW. At time= 1sec, the pre-synchronization is initiated. The active power of DG1 is nearly constant. In case of DG 2, the active power lowers to nearly 2.5 kW and the output of DG3 reaches 6.3 kW. Analyzing this numbers reveals that following the pre-synchronization process, even though the frequencies in all buses are identical, DGs which have local loads on their buses participate more than the DGs which doesn't have local loads on their buses, the active power generated by DG3 is nearly 3.2 kW and its local load is 7.3 kW which is the highest participation, on the other hand, the local load at bus 2 is zero and DG2 is injecting 1.2 kW which is the lowest participation. Afterwards, at time= 2 sec transition to grid-connected is done and apparently a small active power oscillation is seen which is damped after half of a second. However, the reactive power injected by DGs are shown in Fig.14. Apparently, the reactive powers are nearly 0.2 kVAr which is a negligible value. As the nominal value of reactive power for all DGs is 0 kVAr, these output values are according to the expectation.

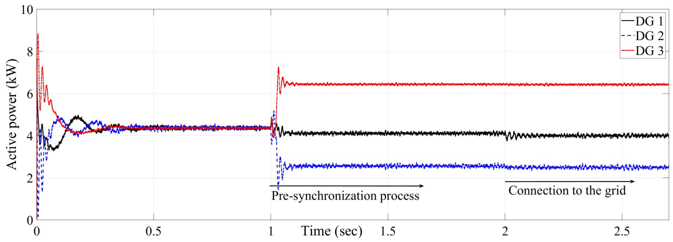

Fig. 13. Active powers of DGs in scenario 2.

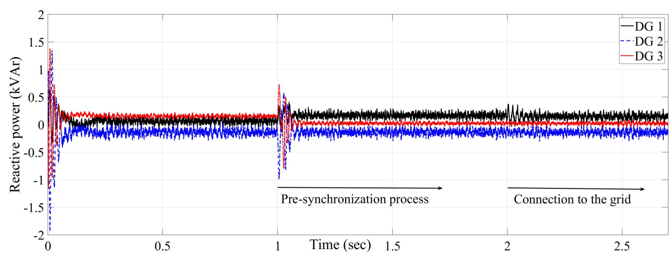

Fig. 14. Reactive powers of DGs in scenario 2.

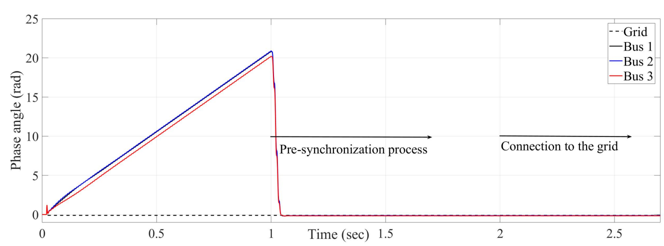

Fig. 15. Phase angles of voltages in scenario 2.

IV. Conclusion

A novel control framework for adjusting the frequency & voltage of island MG based on the VSG idea and controlling all the DGs in common reference frame is proposed and examined through two scenarios to consider both island and connected to the grid situations. In island operating mode, the frequency is controlled within permitted values and its rate of change is adjusted using inertia and damping coefficients (J and D). The MG's voltage also is controlled within permitted levels in severe load change scenario. The active power sharing is adjusted by the values of inertia and damping coefficients, considering identical values for all three DGs, they have shared the active power equally and generated similar values of active powers. On the other hand, the pre-synchronization process tends to change the frequencies of all DGs so as to reach the grid frequency. Following the pre-synchronization process, the active power of any DG will become nearly equal to its local load. The smooth connection to the grid is done afterwards.

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