Transition Control and Operation of Hybrid Energy System

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2024 IEEE International Conference on Smart Power Control and Renewable Energy (ICSPCRE) | 979-8-3503-7700-2/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICSPCRE62303.2024.10675007

***Abstract*—Microgrids are a modern class of power systems, consisting of loads and distributed generation resources within a defined electrical boundary. Distributed generation consists of renewable interfaced to the AC grid via inverters (Inverter-Based Resources or IBR) or units such as Diesel Genset (DG), which can be directly connected to AC bus. Microgrids are designed to be operational in both grid-connected and grid-forming modes. During the grid-forming (or isolated) mode, either the IBR or the DG operates as the voltage-frequency regulating unit, with the other operating in active and reactive power-controlled mode. For grid connection, a synchronization process is required, in order to prevent large power flow in either direction. A smooth transition is required from islanded mode to grid-following mode to avoid damage to loads. A transition control is also required, in case of planned or unplanned islanding of the system from the grid. In this paper, control for synchronization of microgrid to the grid is presented. The operation of a Hybrid energy system for grid-connected and island mode is described. DG control in grid-following mode or active power control is shown and a control is proposed for smooth transition from island to grid-connected mode and grid-connected to island mode. The system is simulated and validated in MATLAB/Simulink.**

***Index Terms*—Grid-connected Mode, grid-forming, Inverter Based Resources, Grid Synchronization, Diesel Genset, Transition control**

I. Introduction

Microgrid (MG) is a modern power system that designed to operate grid-connected and island mode. The control in both modes is different. There are different control of converters for Distributed energy sources (DERs) as grid-forming, grid-following (grid-feeding), and grid-supporting mode. Grid-forming control maintains the voltage and frequency of microgrid and it operates in island mode, grid-following control operates with the grid's voltage and frequency by supplying active and reactive power to the grid and it operates in only grid-connected mode. Grid-supporting converters can operate in both the grid-connected and island mode. The grid-supporting converter also participates in the regulation of grid voltage and frequency by delivering proper value active and reactive power [1]. In recent years the attraction towards grid-forming converters is more. In case of grid unavailability DG is used as a backup or it can also operate in grid-connected mode. In normal operations of MG in grid-connected mode, voltage source converters (VSC) or inverters delivers maximum available power to the grid also it can support reactive power as ancillary services [2].

With increasing blackout numbers in distribution systems due to manmade and natural disasters, the frequent isolation and reconnection of loads without a power deviation have grown to be a problem. An overview of a control scheme for seamless transition is described as well as the challenges during transition and existing techniques for transition. MG is a promising solution for resilient and efficient operation. So facilitating the smooth transition with utility is the key feature for today's MG control which needs to be. It ensures the uninterrupted supply to the critical load [3].

The voltage difference of $\pm 10\%$, frequency difference range of 0.3 Hz, and phase difference of 20^o are included in the IEEE standard 1547.2003 for synchronization criteria [4].. The grid synchronization process for both DG and VSC is done by detecting the magnitude of voltage, phase angle, and frequency at PCC and checking if it lies in the desired range then the grid closing switch is closed [5]. DG is generally used either as standby or prime. In islanding mode, DG simultaneously supplies load as well as charges the battery. [6]. Grid synchronization with the generator is discussed in [7] with a feed-forward compensation method for fast synchronization. Modeling and operation of DG with inverter-based resources in the following mode is described [8].

Islanding is a sate when a part of an electric power system is isolated from main electric power system but solely continues to supply load. This may happen due to faults occurring on the grid side or fluctuation in grid voltage and frequency so intentionally we disconnect the microgrid from the main grid, this is called intentional islanding. There are hazards and risks of islanding like threats to crewmen or personal safety, deterioration of equipment life, and degradation in power quality as it is possible that the load and power imbalance may occur. A maximum delay of 2sec for detection of unintentional islanding. The time for fault detection of inverters corresponding to abnormal grid situations has shown in the IEEE 1547 and IEC 61727 standards. The transition of grid-connected to island mode for the unintentional islanding condition with the droop mechanism is described [9]. The decoupled synchronous control of grid-forming and following mode is described in [10] and used in this paper.

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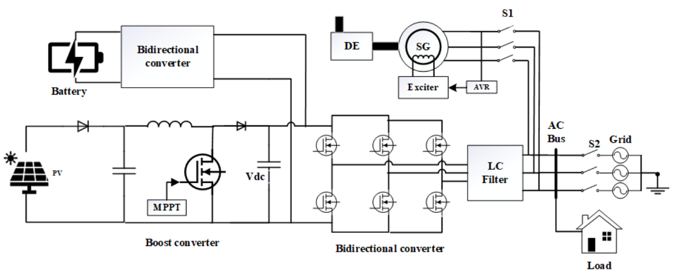

Fig. 1. Hybrid energy system configuration

II. System Configuration, Control Strategy and Operating Mode of System

In this hybrid energy system, sources are considered as PV, BESS, DG, and Utility Grid. In Figure 1. the block diagram of the hybrid energy system is shown. When switch S2 is closed and S1 is open then the PV and BESS are connected with the grid in PQ mode. When S1 is closed and S2 is open then DG will provide the grid-forming mode and PV and BESS will be in grid-following mode. When both switches S1 and S2 are closed then PV, BESS, and DG will be in the grid-following mode with the grid as grid-forming.

A. PV, BESS and DG Control

For extraction of maximum power from PV, the Perturb and Observe algorithm is used. Boost converter control is used for power extraction. Only PV can not operate in grid-forming mode. For the grid-forming mode, one Distributed Energy Resources (DER) with Voltage and frequency (v-f) control converter must be present. So BESS with a bidirectional converter to charge and discharge and also to maintain the DC link voltage is used. The DC-link capacitor is used to maintain the DC-link voltage constant. BESS can used for grid-forming assets. For emergency power, DG is used as a backup. DG is used in PQ control mode when it is connected to the grid. DG can used in grid-forming mode and others as BESS, PV is in PQ mode. DG is modeled as an automatic voltage regulator (AVR), Diesel Engine (DE), and Exciter as shown in Figure 1.

B. Operating Mode of System

Among hybrid energy systems, different operation mode is considered as shown in Table I. Five modes are considered. When the grid is available then it is the primary source and other sources will follow the grid. In mode I PV and Battery combined IBRs or VSC operate in grid-following mode, Similarly with DG as grid-forming VSC works in the grid-following mode. In mode III BESS is used as a grid-forming asset. In mode IV all the sources are combined in which the grid is the main source and DG and VSC operate in the grid-following mode.

Mode	Energy Sources	Grid-Forming Source
Mode I	PV, BESS,Grid	Grid
Mode II	PV, BESS, DG	DG
Mode III	PV, BESS	BESS
Mode IV	PV, BESS, DG, Grid	Grid
Mode V	Grid, DG	Grid

TABLE I
OPERATING MODE OF SYSTEM

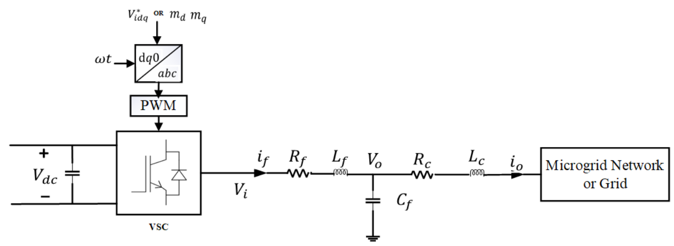

Fig. 2. Basic circuit diagram of VSC control with grid or microgrid network

III. Microgrid Operation and Transition Control

A. Island Mode

This control mode is also known as v-f control or Grid-forming Control. In this mode PV and BESS are combined to a common DC-link voltage and with the VSC it is inverted to AC. For this control, reference voltage and frequency are provided to control the VSC in v-f mode. Figure 2. shows the VSC control circuit diagram and Figure 3. shows the island mode control block diagram. In this case, the DC-link voltage is maintained at 800 volts to get the output voltage of 277.14 volt rms or 480-volt line-to-line voltage. Because we know that, $V_{id} = m\frac{V_{dc}}{2}$, where m - modulation index, $\omega_o = 2\pi * 50$ - reference frequency, $V^*_{odq} = 277.14 * \sqrt{2}$ is reference voltage given in grid-forming mode.In this L_f and C_f is the LC filter used for harmonic mitigation. VSC will provide constant output voltage V_o.

Note - Star (*) is representing reference value, suffix 'g' representing grid.

Now, using KVL equation at VSC output terminal, using abc to dq0 transformation, we have, in eq. 1 and 2

$$L_f \frac{di_{fd}}{dt} + R_f i_{fd} = \omega_o L_f i_{fq} + V_{id} - V_{od} \quad (1)$$

$$L_f \frac{di_{fq}}{dt} + R_f i_{fq} = \omega_o L_f i_{fd} + V_{iq} - V_{oq} \quad (2)$$

Similarly by using KCL at Vo, converting to abc to dq0 transformation, we have eq. 3 and 4

$$C_f \frac{dV_{od}}{dt} = \omega_o C_f V_{oq} + i^*_{fd} - i_{od} \quad (3)$$

$$C_f \frac{dV_{oq}}{dt} = -\omega_o C_f V_{od} + i^*_{fq} - i_{oq} \quad (4)$$

Converting into Laplace domain, we get

$$I_{fd}(s)(sL_f + R_f) = \omega_o L_f I_{fq}(s) + V_{id}(s) - V_{od}(s)$$

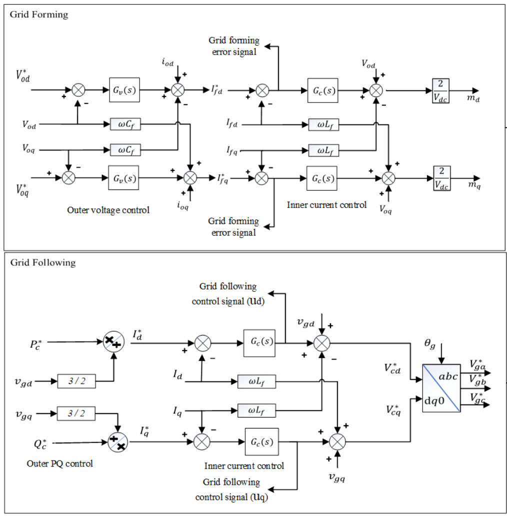

Fig. 3. Grid-forming and Grid-following control block diagram

Put, $u_d = \omega_o L_f I_{fq}(s) + V_{id}(s) - V_{od}(s)$ and, $u_q = \omega_o L_f I_{fd}(s) + V_{iq}(s) - V_{oq}(s)$ so,

$$m = \frac{2}{V_{dc}} * [u_d - \omega_o L_f I_q(s) + V_{od}(s)]$$

where f_{sw}=switching frequency

Voltage and frequency reference is provided to the outer voltage controller. And abc to dq0 transformation used for control of the system. Outer voltage control will provide a current reference for inner current control and it will provide PWM signal to VSC. In island mode, DG is also used as grid-forming source and DG alone can supply load and charge the battery.

B. Grid-Connected Mode

This control mode is also known as PQ control mode or Grid- following control In Figure 3. a diagram of PQ control is shown. Power reference is provided to the outer controller and it generates current reference for the inner controller. And the generated PWM signal is provided to VSC. Reference power is given to control as per power requirement microgrid. We have, power in the dq0 domain is-

$$s = \frac{3}{2}(V_{gd} + jV_{gq})(i_{fd} + ji_{fq})^* \tag{5}$$

And $P_c = \frac{3}{2}(V_{gd}i_d + V_{gq}i_q)$ and $Q_c = \frac{3}{2}(V_{gq}i_d - V_{gd}i_q)$ are active and reactive power.

For synchronization of VSC with grid q-component of V_{gq} is made zero. So we get reference current is $i^*_{fd} = \frac{2}{3}\frac{P^*_c}{V_{gd}}$ and $i^*_{fq} = -\frac{2}{3}\frac{Q^*_c}{V_{gq}}$. This grid-following control is used with grid and also same control used with DG as grid-forming and VSC in grid-following mode.

When the DG is synchronized with the grid then we can provide reference power to DG as shown in Figure 4. Reference power minus measure power is given to the PI controller and it is added to the reference frequency and given

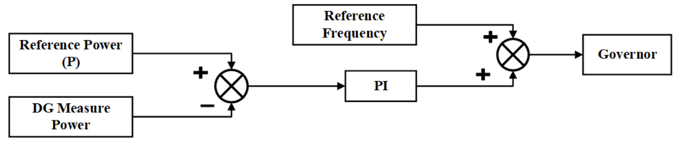

Fig. 4. DG control in Active Power (P) control mode

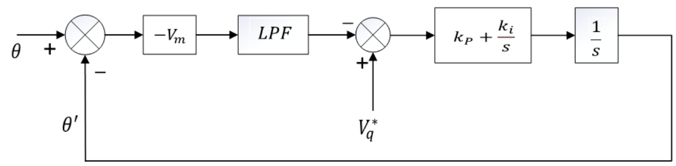

Fig. 5. Phase locked loop for VSC synchronization with grid

to the governor. So governor will make changes and provide the required power from DG.

C. Synchronization of VSC and DG with Grid

Phase Locked Loop (PLL) is used for synchronization of VSC with the grid. PLL detects the frequency and phase and the block diagram of PLL is shown in Figure 5. We know that, $V_a = V_m sin(\omega t)$, $V_b = V_m sin(\omega t - 120)$, $V_c = V_m sin(\omega t + 120)$

From abc to dq0 transformation we get, $V_d = V_m cos(\theta^{'} - \theta)$ and $V_q = V_m sin(\theta^{'} - \theta)$ Where, $\theta^{'}$ is VSC and θ is grid phase angle, If $(\theta^{'} - \theta)$ is very small, then we have $V_d = V_m$, $V_q = V_m(\theta^{'} - \theta)$. In this made q component (V_q) is zero to synchronize VSC with grid and also to send power to grid at unity power factor.

Also for DG synchronization with the grid is done with PLL by checking voltage magnitude, phase angle, and frequency. Figure 6. shows the condition of synchronization if the voltage phase and frequency lie in the operating range or match then switch GCB (grid connect circuit breaker or switch S2) is closed. Once DG is synchronized then the control is given to DG to work in PQ control mode. The above PLL can used to detect phase and frequency.

D. Transition Between Island to Grid-Connected Mode and Grid-connected to island mode with Proposed Control

For the smooth transition between island to grid-connected mode and vice versa, A method for a mechanism of smooth transition is proposed in which PI controller of inner current control is modified as shown in Figure 7. The difference

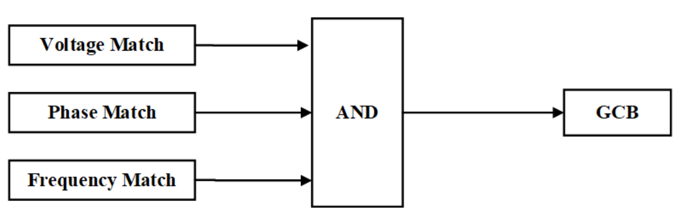

Fig. 6. Synchronization process of DG with Grid

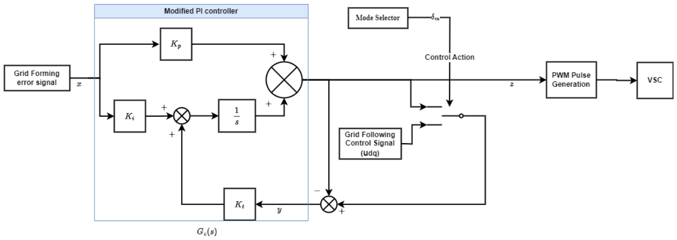

Fig. 7. Control for a smooth transition with modified PI controller

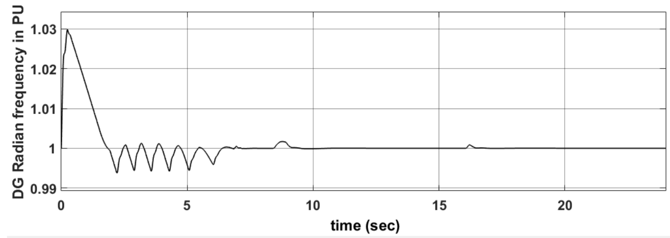

Fig. 8. Reference frequency of DG in PU

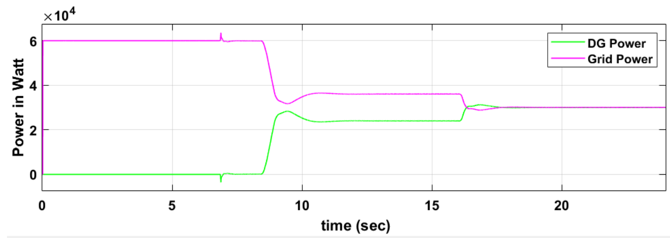

Fig. 9. DG and Grid Power

between the reference inner current control signal of the grid-following and the reference inner current control for grid-forming is fed to the PI controller and it will make error zero to smooth the transition between island to grid-connected mode. When transitioning from islanding to grid-connected mode then first synchronizing is done then the control of the VSC signal is changed from v-f to PQ mode. When all sources are operating and the grid is out then the system goes into island mode with DG as grid-forming control and VSC as following control.

When the grid is suddenly out then the grid-forming control signal is given to VSC, when the grid comes the grid-following control signal is given to VSC as shown in Figure 3. When DG, VSC and Grid are working together and then if grid is sudden goes out then the DG is used as a grid forming asset and VSC is in grid-following mode with DG. The mode selector is taken as-

$\delta_m = 0 : Grid - Connected\ Mode$

$\delta_m = 1 : Island\ Mode$

The grid-forming error signal shown in Figure 7. is taken from Figure 3. which is used here. Also, the grid-following the control signal is taken as shown in Figure 3. The modified proposed PI controller for $G_c(s)$ is described below.

When the grid is available and synchronization criteria are met then the mode selector signal is given for the grid-following control. Mode Selector (δ_m)= 1, which means VSC is in island mode, When the grid comes then made δ_m= 0, then VSC is in grid-connected mode.

In Figure 7, where K_p and K_i are the proportional and integral coefficient of inner current control of grid-forming control. The duty cycle (z) from the inner control given to VSC is given as

$$z = K_p\delta_m x + \int (K_i\delta_m x + K_t(1-\delta_m)y)dt \tag{6}$$

Where (y) is error between z and grid-forming control signal (u_{dq}), which is both the d and q component control signal. K_t is tracking coefficient.

Suppose Initially system is working in grid-forming mode So, δ_m= 1 then the duty cycle (z) given to VSC is

$$z = K_p\delta_m x + \int (K_i\delta_m x)dt \tag{7}$$

when grid-connected then δ_m= 0 then duty cycle is

$$z = \int K_t * ydt \tag{8}$$

So when mode selector δ_m changes then with tracking coefficient it will smoothly track the changes that occur and provides a smooth transition.

IV. Results and Discussion

Different operating modes and transition result is shown. The different cases of load are considered and the assumption taken as the operating voltage of both grid and microgrid is equal. The system specification considered as PV is 40kW, BESS is considered as 52kWh and DG is 80kVA to supply peak load of 70kW.

A. Grid and DG Synchronization and DG control in PQ mode

DG is synchronized with the grid and once synchronized it is controlled in PQ mode. Figure 8. shows the reference radian frequency per unit (PU). In the synchronizing process, we can see that initially frequency fluctuates, and around 6.85 sec the criteria for synchronization are matched then it is connected to the grid. In Figure 9. Intially DG is supplying zero power and we can see some fluctuation in the power of DG at 6.85 sec, to supply total load of 60kW, initially all the load is supplied by the grid. At 8.45 sec power reference for DG is set as 24kW, So 36kW is supplied by the grid and at 16 sec power reference of DG is changed to 30kW so grid is also supplying 30kW.

B. Operation of DG, VSC and Grid

As discussed in mode IV all four sources are combined in this case, the grid as the main source(grid-forming) and VSC and DG are in the following mode. Figure 10. shows the power of DG, VSC, and Grid. Here the peak load is 70kW. DG power is controlled to supply 24kW and VSC is 28kW. We can see the control of DG power and VSC is working. Figure 11. shows the load voltage in rms and it is maintained by the grid.

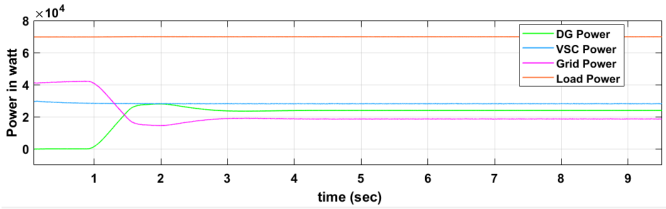

Fig. 10. DG,VSC and Grid Power

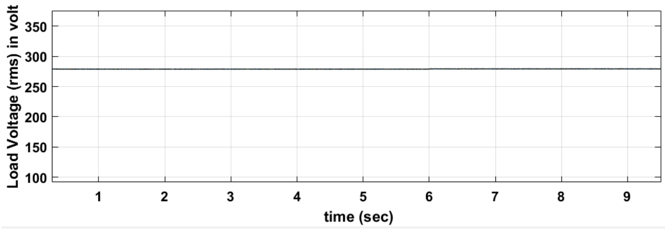

Fig. 11. Load rms voltage

C. Operation of DG and VSC

In this DG will be in grid-forming mode and VSC in grid-following. To supply a total load of 60kW power, the VSC reference is given as 25kW and it changed to 35kW at 7 sec. In Figure 12. from 0 to 7 sec VSC is supplying 25kW and the rest of the load is maintained by DG. And power reference of VSC is changed at 7 sec so DG power was reduced. Figure 13. shows the PU frequency of DG, at 7 sec, rise in DG frequency when power supplied by DG is decreased.

D. Transition from Island to Grid-Connected Mode

As discussed in Table I. Initially the system is operating in mode III then it is synchronized with the grid and transitions to mode I Figure 14. shows the power of PV, BESS, and Grid. From 0 to 6 seconds, the microgrid operates in island mode with BESS as grid-forming. At 2, 4 sec solar irradiance changes. The total load is 60 kW, since PV's available power is 15 kW so BESS is supplying 45 kW. When irradiance is changed at 2 sec then BESS power decreases to 42kW and PV power increases to 18kW. At 6 sec when the grid comes and the criteria for synchronization are met then the grid-following control signal is given to VSC and the reference power set to VSC is 35 kW. So after 6 sec grid starts supplying power of 25kW and combined PV and BESS power supplying 35kW. To charge the battery reference power of VSC made negative.

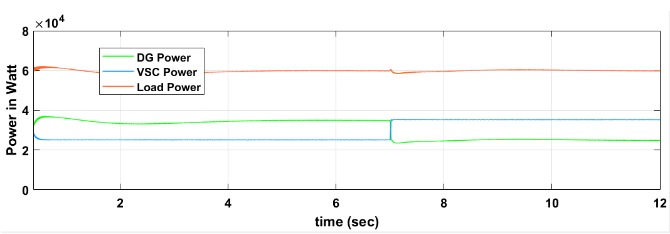

Fig. 12. DG, VSC and Load Power

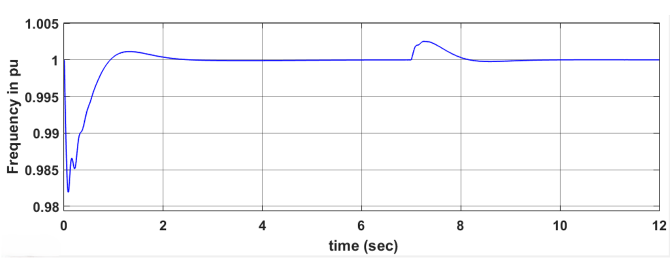

Fig. 13. PU frequency of DG

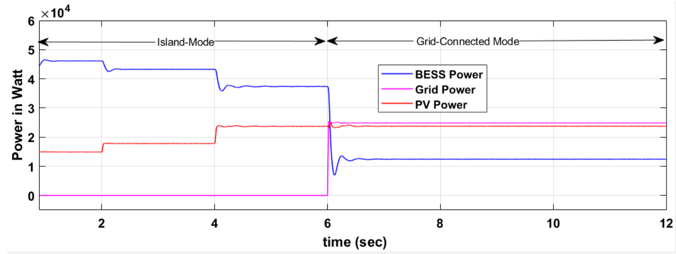

Fig. 14. PV, BESS and Grid Power

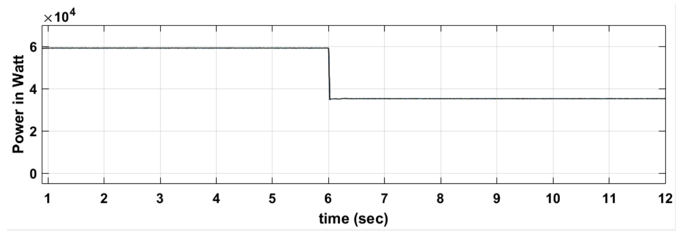

Fig. 15. VSC power

Figure 15. shows the power of VSC (combined BESS and PV), initially in island mode it supplies 60kW then at 6 sec transitions to 35kW. In this, we can see the smooth transition. Figure 16. shows the load rms voltage, initially in grid-forming control rms voltage is different and after the transition to grid-connected mode it changed to grid rms voltage.

E. Transition from Grid-Connected Mode to Island Mode

In Figure 17. initially from 0 to 4 sec system is working in grid-connected mode, to supply peak load of 70kW, VSC is supplying 28kW and DG start supplying power of 24 kW (PQ control of DG signal given after 1 sec) and grid is supplying 18kW power. At 4 sec grid is disconnected, so the DG is now working as a grid-forming asset. So from figure we can

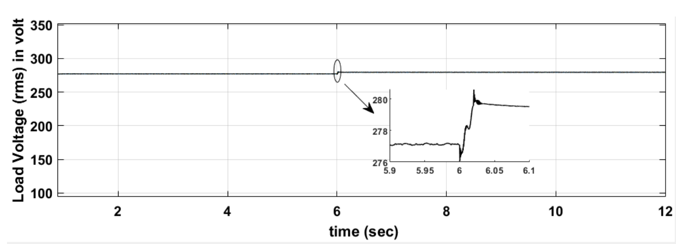

Fig. 16. Load Voltage in rms

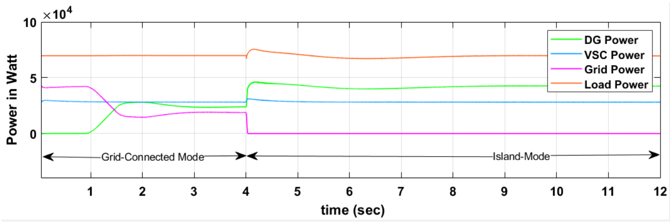

Fig. 17. Power of DG, VSC and Grid in case of transition from grid-connected to island mode

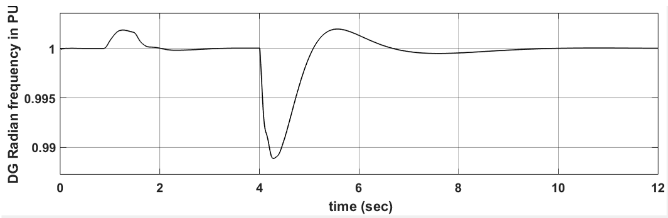

Fig. 18. Radian frequency of DG in PU

see grid power is zero and VSC is supplying 25kW and DG is now supplying 45kW. There is a transition at 4 sec from grid-connected to island mode with DG as grid-forming asset. We can see the load balance is maintained and the control of transition occurring smoothly.

Figure 18. shows the PU radian frequency of DG, we can see when grid is disconnected then at 4 sec there is dip in frequency of DG and then it compensate it. Figure 19. shows the rms load voltage, at time of transition, voltage is dip and then the AVR of DG compensated the voltage. And in Figure 20. shows the terminal voltage of DG in PU as discussed at time of transition voltage is dip then it compensate by DG's AVR.

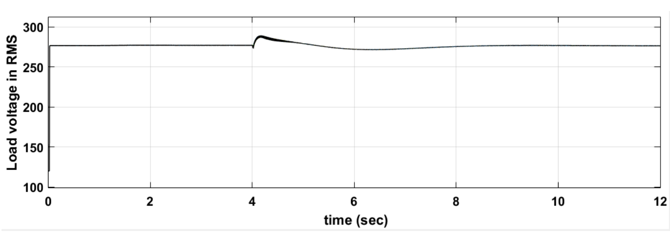

Fig. 19. RMS load voltage

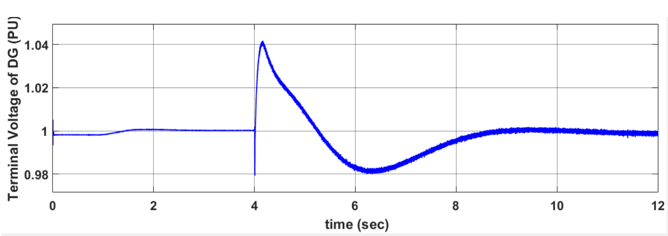

Fig. 20. terminal voltage of DG in PU

Conclusion

In this paper, a control strategy is outlined and tested to synchronize the assets of the microgrid to the grid. From the results, we can observe that the islanded to grid-connected mode and grid-connected to island mode transition is accomplished smoothly. The control of DG in the grid-following mode is also shown. A case of operation of each asset as grid- forming source is shown. The DG will be in grid-forming mode when sudden islanding occurs. In the case of the operation of all sources together the control of the grid-following mode of DG and VSC is working smoothly.

Acknowledgment

I would like to express my gratitude to Caterpillar Inc. for facilitating this opportunity. I would also like to thank my guide Dr Bhookya Nagu for his guidance throughout this project and Krishna Gudur for his invaluable insights.

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