Power management algorithm for standalone operated renewable distribution generator with hybrid energy backup in microgrid

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ABSTRACT

In a micro grid system during standalone condition the system may not be stable and might not compensate the required load. Especially for renewable source integrated micro grid system grid disconnected condition is more critical as the renewable sources are unpredictable. The renewable distribution generator needs backup module for support to the loads during standalone condition. In this paper complete distribution network with multiple renewable sources which include PV plant, wind plant and fuel cell source is modeled with power management algorithm (PMA) in only photovoltaic (PV) plant. PMA controls the hybrid backup modules supporting the PV DG. The hybrid backup modules considered for the support are battery unit and super capacitor (SC) unit. The battery and SC units charge or discharge as per the PMA controller with respect to power generated by the PV source. The charge and discharge of these units are dependent on PV power, state of charge (SOC) of battery and SOC of SC. These three sources compensate the critical load connected in the micro grid. A comparative analysis is carried out with and without backup modules and PMA during grid islanding condition on the proposed distribution network. All graphical and parametric comparisons are done using MATLAB/ Simulink software with time domain plots generated by PowerGUI tool.

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1. INTRODUCTION

In modern smart distribution networks, the power demand is increasing with a gradual increase in loads. With multiple loads connected to the distribution network it is viable to use power sources interconnected at different bus locations. These power sources can be lower-rating modules that can support a part of the load or higher ratings which can compensate for a complete local load. In conventional distribution networks these power sources can be diesel generators which generate power using fossil fuel compensating for the local loads. In modern power systems, these diesel generators are replaced with renewable sources like PV units, fuel cell modules, or wind farms [1], [2]. These sources utilize natural resources for the generation of power to the loads which can be interconnected at different locations in the distribution network. The renewable source modules have the advantage of parallel sharing of power to the load along with the main grid. The advantage of interconnecting distribution generators (DG) to the grid is either the renewable power is consumed by the local loads or is injected into the grid. The renewable DG source modules are synchronized to the grid using synchronous reference frame (SRF) control structure. The major issue with these renewable DGs is they cannot be operated in standalone conditions as the power from these modules is unpredictable. For the DG unit to operate in standalone mode during grid islanding conditions it needs a backup storage unit [3]. The backup storage unit either supports the load during power deficit conditions or stores power during excess availability. The DG module with a backup storage unit is controlled by power management algorithm (PMA) control structure with feedback [4] taken from different parameters. For the implementation of multiple DG units [5] in a distribution network including one DG unit with PMA the below bus system is considered.

As per the given distribution test network, there are 4 sub-networks with 4 feeders connected to the main grid. Bus 1 sub-network is interconnected with a PV panel and battery DG unit, the bus 2 sub-network has only one load L2, bus 3 sub-network has a wind farm DG unit and the bus 4 sub-network has a Fuel cell DG unit. All these DG units support the local loads [6] connected to the same bus. When the generated power is excess than the load demand in such case the power is injected into the main grid through the feeders. This is a very rare case that is neglected as the load demand is always higher than the DG power generation. The distribution network [7] in Figure 1 is operated in two conditions: i) grid-connected mode and ii) grid islanding mode. In grid-connected mode, the DG units are operated in synchronization with the grid with stable power generation. During grid islanding mode only the PV source is integrated with the battery and SC module supporting the local critical load L1-2. The other non-essential load L1-1 will be disconnected when the grid is unavailable by the islanding detection algorithm (IDA) [8]. The IDA takes voltage, frequency, and power feedback from the grid for the detection of grid operation. When the IDA detects any threshold value violation it disconnects the non-essential load L1-1 and makes the PV–battery–SC DG unit compensate for critical load L1-2. This DG unit in bus 1 is operated with a PMA algorithm controlling the charge and discharge of battery [9] and SC concerning PV generated power (Ppv), $SOC_{b,}$ and SOC_{sc}. This paper is included a general introduction to the proposed distribution network with considered DG units and their operating states in section 1. Section 2 is included DG unit configuration, its working principles and PMA control structure modeling with multiple parameter feedback. The results of the given system with different operating conditions and analysis are done in section 3 using MATLAB/Simulink toolbox. The final section 4 is the conclusion to the paper with finalizing results and discussion on the advantage of the PMA algorithm followed by references taken to complete the paper.

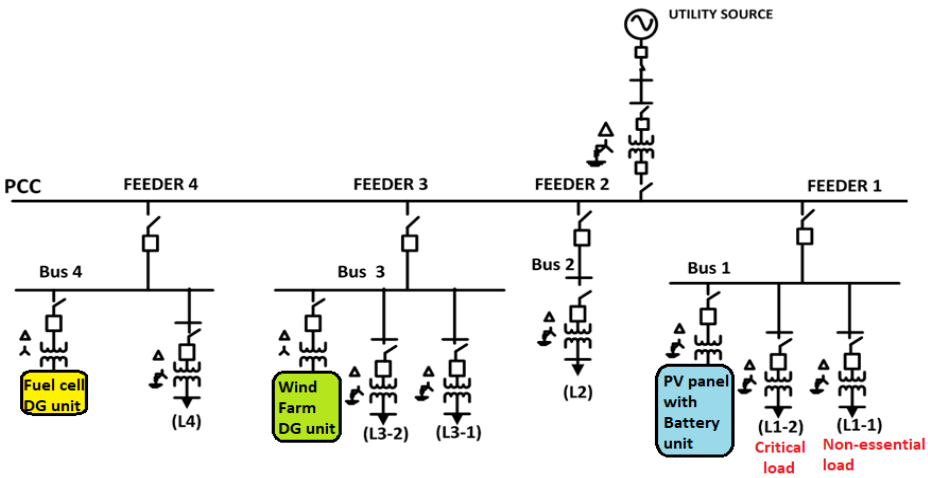

Figure 1. Distribution test network with DG unit placement

2. METHOD
2.1. DG unit's configuration

As proposed in section 1, the distribution network is introduced with three DG units at buses 1, 3, and 4 for local power sharing. Bus 1 is integrated with the PV-Battery-SC module controlled by the PMA algorithm [10]. A wind farm is integrated into bus 3 which uses permanent magnet synchronous generator (PMSG) for standalone power generation. Bus 4 is interconnected with a fuel cell module where hydrogen is the major source generation of power. All these three DG units are operated in synchronization with the grid by control [11] of the 3-ph inverter with SRF control structure [12]. The SRF control structure needs feedback on the DC link voltage at the DC side of the inverter, the 3-ph voltages of the grid, and the 3-ph injected currents of the inverter. The SRF controller is integrated withphase locked loop (PLL) which is the vital module for the synchronization of the inverters [13], [14]. The PLL [15] ensures the inverters operate at the same phase and frequency as that of the main grid. With the synchronization control, the power from these DG units is shared with the loads with parallel support of the grid. In the PMSG wind farm [16] DG unit power extraction is done by a diode bridge rectifier (DBR) connected single switch buck-boost converter. The DBR rectifies the AC voltages of the PMSG to unstable DC voltage. The DC stabilization with the required voltage magnitude is achieved by the single switch buck-boost converter controlled by maximum power point tracking (MPPT) algorithm [16]. This DG unit is a grid-dependent source that cannot be operated in standalone mode as the power generation is dependent on unpredictable wind speeds. The DG unit on bus 4 is a fuel cell module operated with a booster converter controlled by voltage feedback control for voltage stabilization. This renewable source is a restricted DG unit that can support only a part of the load and needs interconnection with the grid. The fuel cell DG unit is also a dependent source and cannot be operated in standalone mode with heavy loads connected.

For the standalone operation of the DG unit in a distribution network, the renewable source needs a backup storage device [17] that can support the load during deficit power conditions. The bus 1 DG unit which is the PV source is integrated with a battery and SC-connected two-switch bidirectional converters. The charge and discharge of the battery and SC modules are controlled by the bidirectional converters. The bidirectional converter switches are controlled by the PMA module with feedback taken from PV power, SOC_b, and SOC_{sc}. The charge and discharge state of the converter depends on the excess or deficit power availability of the PV power [18]. The complete updated internal circuit structure of the PV DG1 unit can be observed in Figure 2.

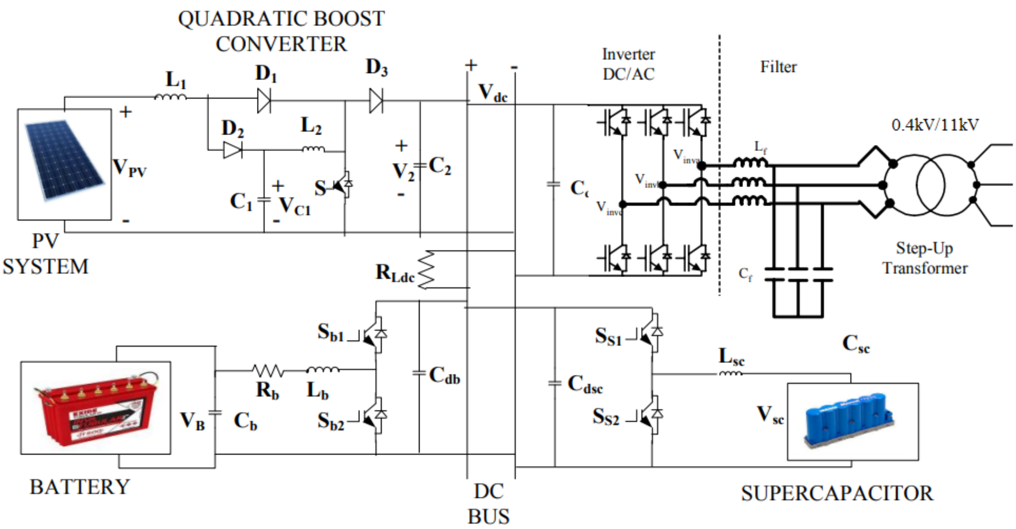

Figure 2. DG1 PV source module with battery and SC support

For maximum and efficient power extraction from the PV source, the conventional boost converter is replaced with a quadratic boost converter which is controlled by the P&O MPPT algorithm. The two switches in the bidirectional converters (S_{b1}, S_{b2} and S_{s1}, S_{s2}) duty ratios are controlled by PMA control. As per the duty ratio of the switches, the charge-discharge of the battery and SC units is decided [19]. The converter operates in buck mode during charging conditions and in boost mode during discharge conditions. All the modules are connected in parallel at the DC bus which injects the combined power into the grid by DC/AC inverter [20] through an LC filter. The inverter is operated by an SRF controller during grid-connected mode and during the standalone mode, it is controlled by a simple sinusoidal PWM technique with no feedback.

For the switching between SRF and sinusoidal PWM a grid islanding detection algorithm is incorporated into the system. The islanding detection algorithm identifies disconnection or failure of the grid and triggers the switching of the control modules. The integrated islanding detection algorithm considers the grid voltage magnitude, frequency, and power exchange [21] for the triggering of the switches. The complete structure of the islanding detection algorithm is observed in Figure 3.

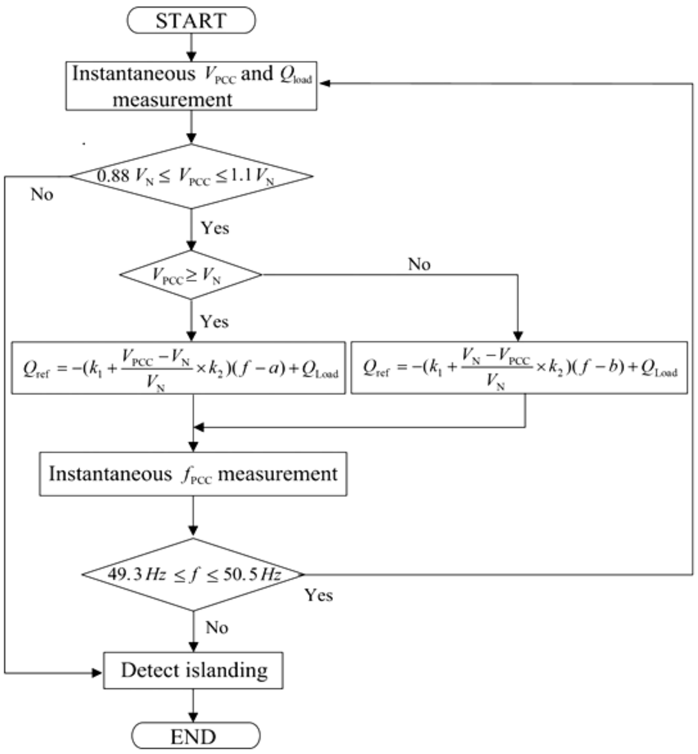

Figure 3. Islanding detection algorithm

As observed in the algorithm when the grid voltage surpasses the threshold magnitudes of 0.88-1.1puor reactive power exchange ranges or frequency limits 49.3-50.5 Hz the algorithm detects islanding of the grid [22]. The trigger signal generated by the islanding detection algorithm also triggers the breaker OFF of the non-essential load L1-1 on bus1. As the non-essential load is not critical it can be operated only during the grid-connected mode. The PV DG1 unit supports the critical load L1-2 on bus1 and the breaker of the bus1 is also turned OFF disconnecting the PV DG unit and loading L1-2 from the main grid. The PMA algorithm modeling and design for control of the battery and SC bidirectional converters are given in the next section.

2.2. PMA algorithm

The PMA algorithm is the primary control structure of DG 1 placed at bus 1 which manages the charge and discharge of the battery and SC modules. The PMA control structure generates a duty ratio for the buck and boosts switches of the bidirectional converters connected to the battery and SC. It considers the PV power generated, load demand power, battery SOC and SC SOC [23] for the control of the switches. The complete control structure of the PMA algorithm with feedback parameters can be observed in Figure 4.

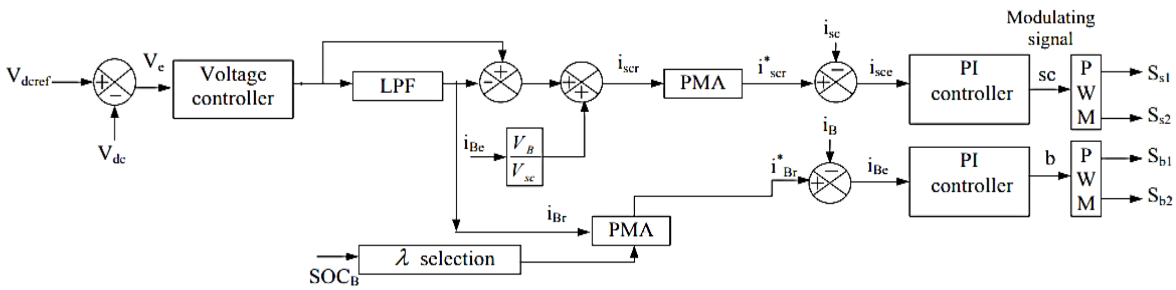

Figure 4. PMA control structure for control of battery and SC

In the given control structure, the V_{dcref} is the required reference DC voltage on the DC side of the 3-ph inverter and V_{dc} is the measured DC voltage of the same. The comparison of these voltages generates voltage error V_e fed to PI voltage controller generating i_t (required current). It is expressed as (1).

$$i_t = K_p V_e + K_i \int V_e dt \quad (1)$$

For the reduction of disturbances in the current signal, anlow pass filter (LPF) is utilized [24]. The feed-forward comparison of the LPF signal and the previous signal generates high order harmonics signal $\overline{i_{Br}}$. The higher order harmonics signal is used for the generation of SC reference current i_s given as (2).

$$i_{scr} = \overline{i_{Br}} + i_{Be}\frac{V_B}{V_{SC}} \quad (2)$$

Here, i_{Be} is the measured battery current, V_B is the battery voltage and V_{SC} is the SC voltage. Both the current reference signals i_{scr}^* and i_{Br}^* are generated by the PMA which depends on λ selection. The λ depends on the SOC of the battery which is determined by Table 1. As per the given Table 1 the value of λ varies from 0-1 concerning SOC_b. Now as per the λ value, i_{scr} and i_{Br} the reference battery and SC currents (i_{scr}^* and i_{Br}^*) are calculated as per the given Table 2.

Table 1. λ selection table

SOC_b	λ
$0.8<SOC_b<0.95$	1
$0.45<SOC_b<0.8$	0.6
$0.15<SOC_b<0.45$	0.3
<0.15	0

Table 2. PMA concerning PV power availability

	SOC range	Reference currents
Insufficient power mode	$SOC_b>L$;$SOC_{sc}>L$	$i_{Br}^* = \lambda i_t^*$; $i_{scr}^* = i_t'$
	$SOC_b<L$;$SOC_{sc}>L$	$i_{Br}^* = 0$; $i_{scr}^* = i_t'$
	$SOC_b>L$;$SOC_{sc}<L$	$i_{Br}^* = \lambda i_t^*$; $i_{scr}^* = 00$
	$SOC_b<L$;$SOC_{sc}<L$	$i_{Br}^* = 0$; $i_{scr}^* = 0$
Sufficient and floating power mode	$SOC_b<U$;$SOC_{sc}<U$	$i_{Br}^* = i_{B.ch}$; $i_{scr}^* = i_{SC.ch}$
	$SOC_b<U$;$SOC_{sc}>U$	$i_{Br}^* = i_{B.ch}$; $i_{scr}^* = i_t'$
	$SOC_b>U$;$SOC_{sc}<U$	$i_{Br}^* = 0$; $i_{scr}^* = i_{SC.ch}$
	$SOC_b>U$;$SOC_{sc}>U$	$i_{Br}^* = 0$; $i_{scr}^* = i_t'$

In the Table 2 given the 'L' and 'U' are the lower and upper limits of SOC respectively taken as 0.15 and 0.95. The considered currents are expressed as:

$$i_t^* = \frac{w_c}{s+w_c} i_t \quad (3)$$

$$i_t' = \left(1 - \frac{w_c}{s+w_c}\right) i_t \quad (4)$$

$$i_{B.ch} = \frac{-P_{Br}}{V_B} \quad (5)$$

$$i_{SC.ch} = -P_{sc}\sqrt{\frac{C_{sc}}{2E_{sc}}} \quad (6)$$

In the above given current equations 'w_c' LPF cutoff frequency (2*pi*10), P_{Br} is the power of the battery, P_{sc} is the power of SC, C_{sc} is SC capacitance and E_{sc} is the Energy stored in SC. Therefore as per the given PMA table and current expressions the reference currents i_{scr}^* and i_{Br}^* are generated as per PV power availability (sufficient, insufficient or floating) [25]. These reference currents are compared to measured SC current i_{sc} and battery current i_{Br} and the error signals are fed to current PI controllers. The individual current controllers generate a duty ratio fed to the PWM generator generating signals for bidirectional converter switches controlling the charging and discharging currents of the battery and SC. The design and modeling of the configured modules are done in the next section with results generated as per the given operating conditions.

3. RESULTS AND ANALYSIS

The distribution network with all feeder lines and buses along with before mentioned configuration of DG units as per Figure 1 is modeled in MATLAB/Simulink environment. A backup storage and support system are only provided for DG1 units for comparative analysis. The test system modules are modeled concerning the given parameters in Table 3. As per the given parameters the test system modeling can be seen in Figure 5. The test system includes a main grid source connected to the distribution network thorough a three-phase circuit breaker triggered for grid isolation creating islanding condition.

Table 3. System parameters

Name of the parameter	Value
Grid	100 MVA, 11 kV, 50 Hz
Feeder line	132 kV, pi section lines 50 kms each
Loads	L1-1 = 100 kW,10 kVAR; L1-2 = 80 kW, 10 kVAR; L2 = L3-1 = L3-2 = L4 = 100 kW, 50 kVAR;
DG1	PV module – 100 kW, Cin=100 uF, L1=L2=1 mH, C1=110 uF, Cd=12 mF. Battery module – Vb=250 V, Icap=100 Ah, Lb = 5 mH, Cb=Cdb=220 uF. SC module – Vsc=300, Csc=52 F, Lsc=5 mH, Cdsc=220 uF, Vdc ref= 500 V
DG2	Wind farm – PMSG- 50 kW, Rs=0.73051Ω, Ls=1.2 mH, Ψ = 4.696 V.s, J=8000 kg-mt2, P =15 Cin=100 uF, Lbb=1 mH, Cout=1000 uF.
DG3	Fuel cell – 35 kW, Vnom = 300 V, Inom=80 A, Vend=125, Iend=280 A. Cin=100 uF, Lb=5 mH, Cd=12 mF
Grid Islanding limits	V – 0.8 to 1.1 pu;f – 49.3 to 50.5 Hz; Q – 10 to -10 VAR

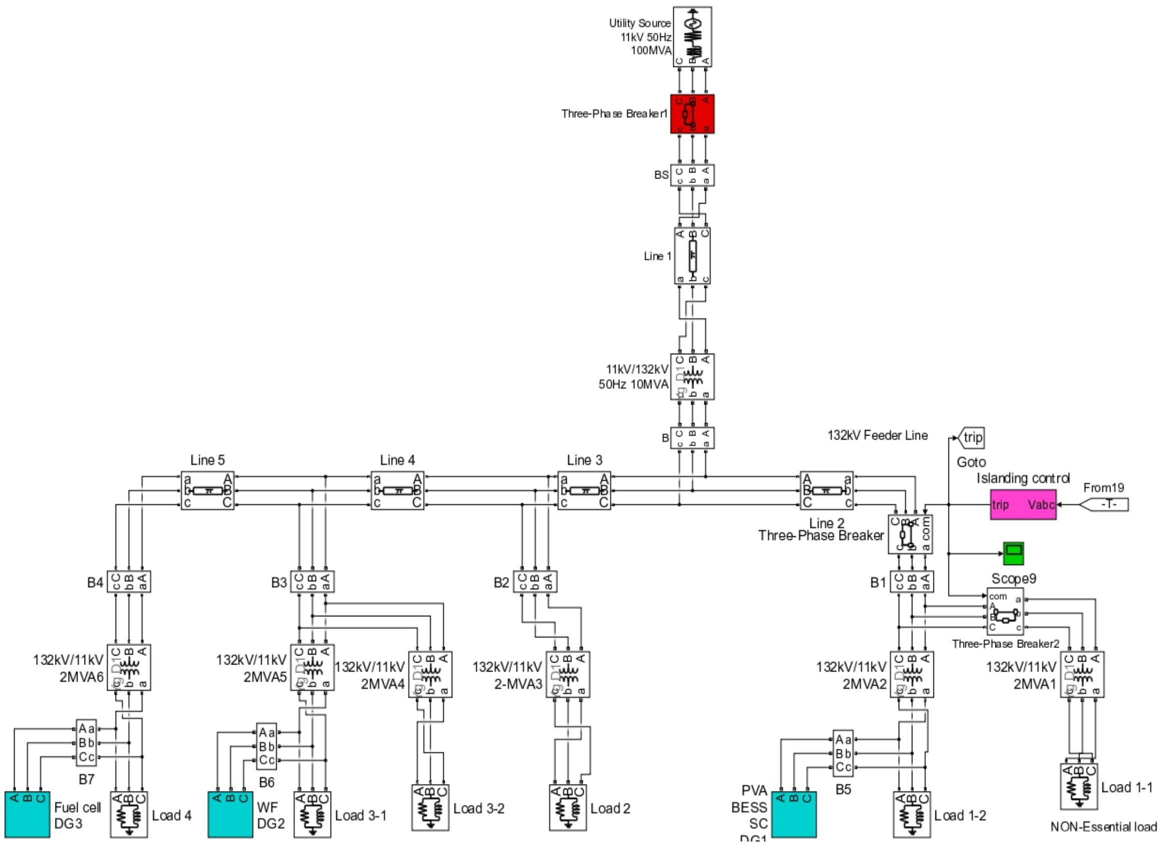

Figure 5. Simulink modeling of proposed test system

The model is run for 3sec simulation time with different operating conditions and the results are validated. Initially all the DG units are inter connected to the grid through the feeders. As 1sec the grid is disconnected and the islanding detection algorithm triggers OFF the breakers of PV module and non-essential load. However, the other two DG units are still connected to the loads. The islanding detection algorithm also switches the SRF control to independent Sin PWM inverter control. The PMA algorithm is operated from initial stage of simulation. To change from sufficient to insufficient condition in DG1 unit the solar irradiation is changed from 1000 W/mt^2 to 500 W/mt^{2}at 2 sec. With the given simulation conditions the measurements of all the parameters are taken and plotted in graphical format with respect to time. The time defined graphs validate the results and the significance of support system and PMA algorithm in the network will be done.

The Figure 6 is the 100 MVA main source P&Q injection to the distribution network compensating the loads. The source powers are the sharing powers with renewable DG units operating in parallel. As per the graph when the grid is disconnected at 1 sec, P&Q are dropped to zero completely eliminating the power injection. Even the intersection feeder bus voltage is also dropped to zero as shown in Figure 6. As per the grid disconnection the islanding detection algorithm detects the drop in voltage magnitude beyond the threshold value of 0.88 pu and triggers the breakers off at 1sec as observed in Figure 7. As per the given operating conditions of the system below are the active and reactive powers of all DG units without backup module and PMA.

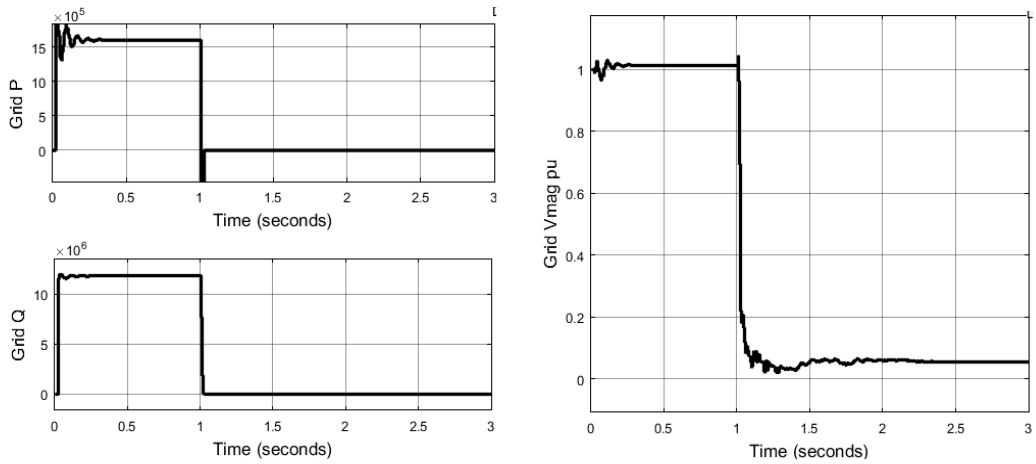

Figure 6. Grid active, reactive power and voltage magnitude

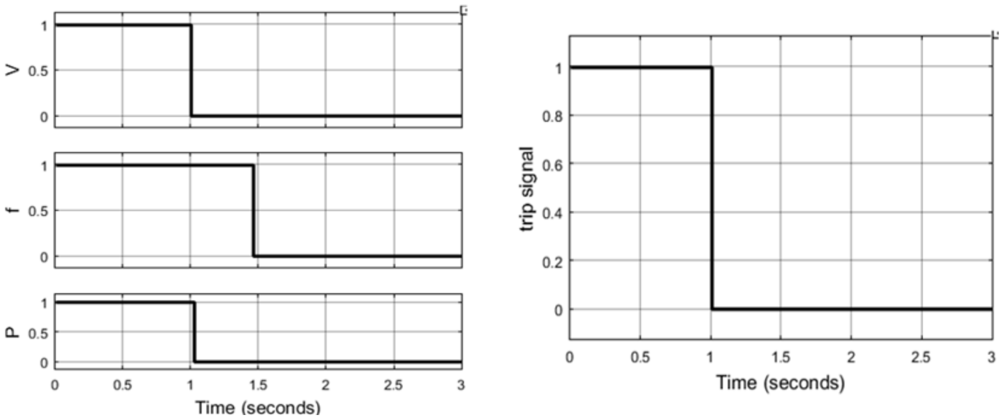

Figure 7. Islanding detection algorithm trip signals

As per Figure 8 the active powers of PV source, wind farm and fuel cell during grid connected mode are recorded at 95 kW, 45 kW and 35 kW respectively. However, the reactive power injection is maintained at zero. As soon as the grid is failed or disconnected by the isolator breaker at 1 sec, the active powers of all three DG units are dropped to zero as they cannot support the load. Therefore, this represents complete failure of the system where renewable sources are failing to compensate the local loads when the main source is disconnected from the distrubtion network. For improving the system performace to the given islanding condition, only the DG1 unit is integrated with backup and PMA modules for supporting the essential loads during grid islanding condition. The same operating modes are set and the simulation is run with DG1 unit integrated with backup and PMA modules. The active and reactive powers of the DG units recorded are shown in Figure 9.

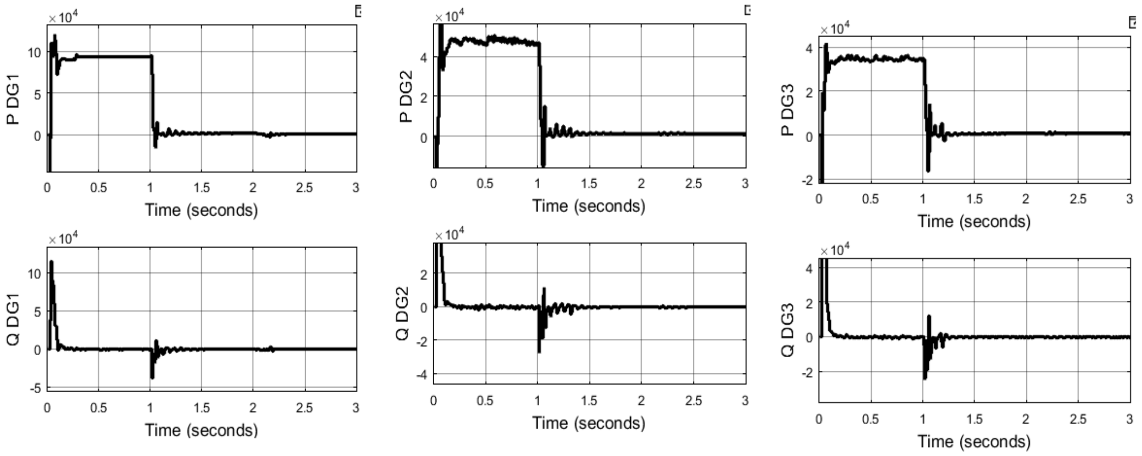

Figure 8. Active and reactive powers of all three DG units without backup module and PMA

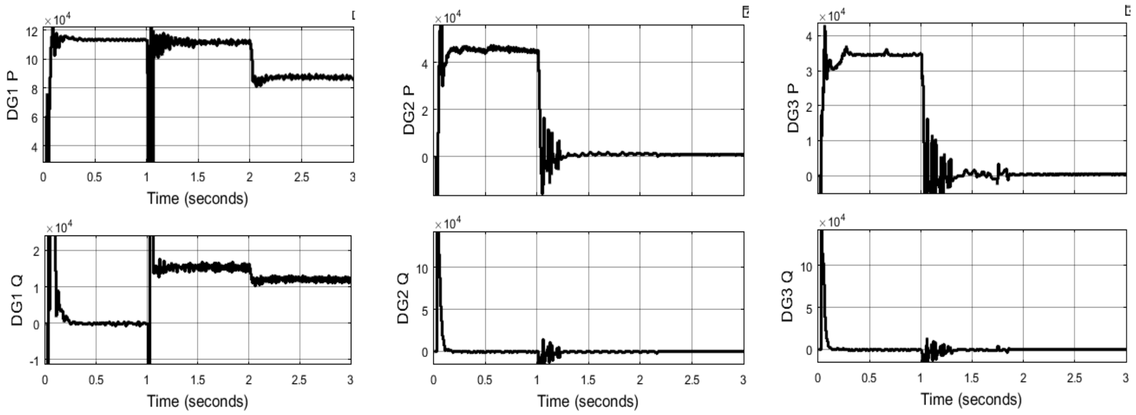

Figure 9. Active and reactive powers of all three DG units with backup module and PMA in DG1 unit

Initially the DG1 unit active power is maintained at 110 kW until 2 sec (even when the grid is disconnected at 1 sec), and when the irradiation is reduced to 500 W/mt^2 at 2 sec the DG1 power drops to 80 kW. Both the DG units 2 and 3 are failed as they are not integrated with backup and PMA modules and hence the powers of these two units are dropped to zero representing failure condition. The powers of all the modules in DG1 are recorded and are presented in Figure 10 as per the given conditions in the system.

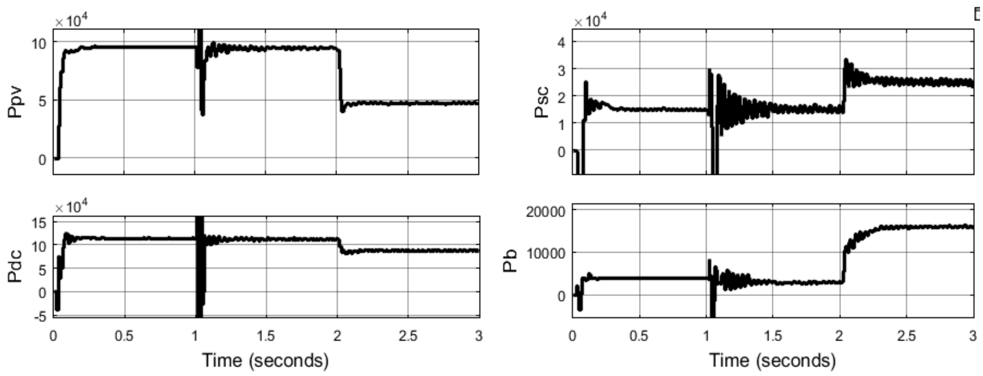

Figure 10. Power of all modules in DG1 unit

The powers of the modules in DG1 units which include PV power (Ppv), battery power (Pb), SC power Psc and total power of DG1 units (Pdc) are shown in above graph. During initial state the power form the battery and SC are 4 kW and 15 kW. The discharge power of battery and SC are increased when the grid is disconnected from the distribution network compensating essential load (Load 1-2). The islanding detection algorithm disconnects the non-essential load (Load 1-1) from the network and only the essential load on bus1 will be compensated by DG1 unit. The essential and non-essential load active reactive powers are shown in Figure 11.

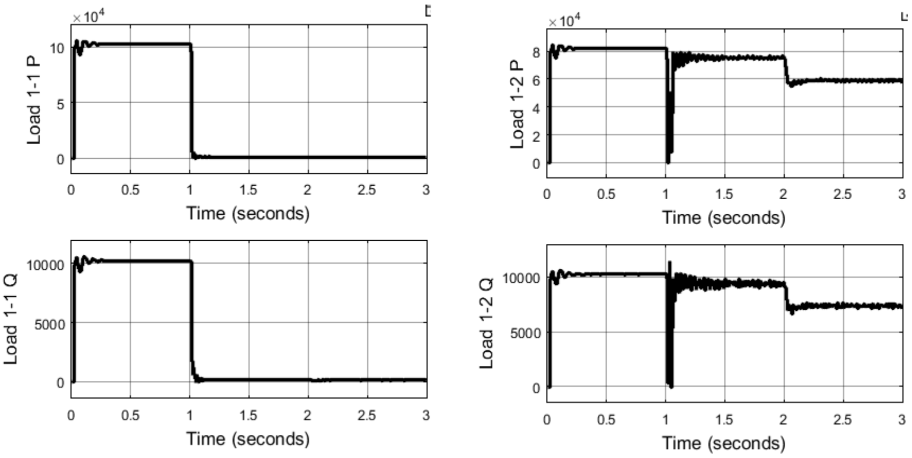

Figure 11. Bus1 loads (1-1) (1-2) active and reactive powers

For the given conditions in the network the PV, battery and SC characteristics are changed as per the availability of grid and load demand. The charge and discharge characteristics are controlled by PMA which makes the battery or SC operate as per the PV power availability and load demand. As observed the slop of SOC_b and SOC_{sc} are changing as per the availability of power from PV and grid. Lower the power higher the discharge of battery and SC creating higher slope in the SOC. As per the given graphs in Figure 12, it is clear that the DG1 unit is supporting the critical load L1-2 disconnecting non-essential load L1-1. The L1-2 load demand 80 kW is compensated by PV power of 50 kW, 20 kW battery power and 10 kW SC power.

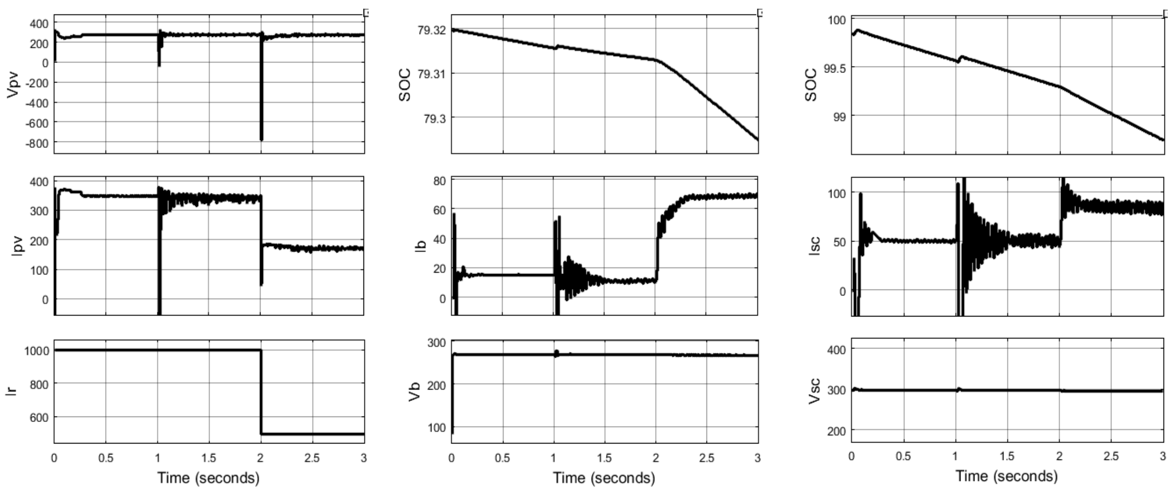

Figure 12. PV battery and SC characteristics

The other two DG2 and DG3 units are failed to compensate the local loads as they have no back up support with PMA control during grid islanding condition. An active power comparative graph with and without PMA for DG1 unit can be observed in Figure 13. As per the given graphs in Figure 13 the active power injection is maintained even after the grid is disconnected by the isolator switch when the DG1 unit is integrated with backup and PMA modules. However, when the grid is connected, reactive power injection is zero and during islanding mode the reactive power of essential load is compensated by the DG1 unit.

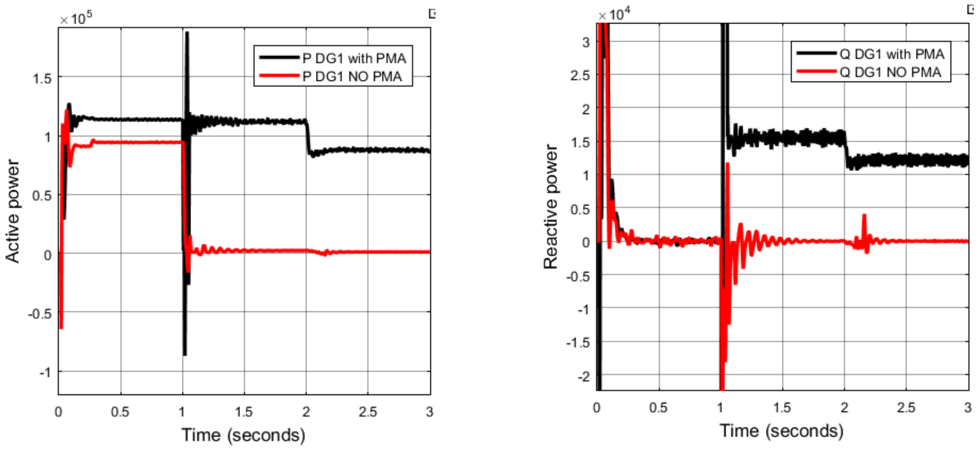

Figure 13. Active and reactive powers comparison of DG1 unit with and without PMA

4. CONCLUSION

The distribution network is implemented with renewable energy DG units at multiple locations as per the given test system. The drawbacks of the islanding mode operating condition are eliminated at the Bus1 location by providing backup storage sources battery and SC modules in the DG1 unit. The PV source is supported by battery and SC modules for compensating the critical load controlled by the PMA controller concerning PV power and load demand. The islanding detection algorithm identifies the grid disconnection and removes the non-essential load from Bus1. The power compensation of the critical load on Bus1 is done by the PV source, battery, and SC modules as per the irradiation changes. The PMA control optimally calculates the required power from the battery and SC modules as the PV power availability and load demand. As per the analysis DG2 and DG3 units are more susceptible to grid islanding conditions as compared to backup power PMA-integrated DG1 units.

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