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Modelling and control of grid connected microgrid with hybrid energy storage system

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ABSTRACT

This paper presents a photovoltaic (PV) microgrid with battery and super capacitor hybrid energy storage systems. The proposed microgrid system is designed for both grid connected and standalone mode with coordinated control-based energy management system, which controls DC link voltage, voltage and frequency balance at point of common coupling. DC link voltage control is implemented using dual loop PI controller-based voltage controller and inverter control is based on D-Q reference frame technique. The microgrid system is demonstrated in MATLAB/Simulink. The presentation of the planned energy supervision system is analyzed for varying generation and load condition. In the proposed microgrid the battery energy storage system is utilized to provide long term energy during average power requirement and supercapacitor energy storage system is utilized to provide short term power requirements during sudden load variation, generation variation and during transition of modes. Designed energy management system performs effectively in grid connected mode, standalone mode with smooth transition between the modes. And it maintains dc bus voltage of the microgrid constant irrespective of load and generation variations and also during mode changing conditions.

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1. INTRODUCTION

The increasing power demand and pollution produced by the conservative energy sources arises the need for clean energy generation from renewable energy sources [1], [2]. Due to the vast reduction in the photovoltaic (PV) panel price and installation price along with the improved techniques to boost the PV system efficiency. PV based power generation is booming [3]. Intermittent and uncontrollable nature of the PV system along with the need for continuous supply to critical loads poses a requirement for energy storage devices [4], [5]. Energy storage devices are commonly used to reduce power fluctuation, to provide peak power shifting, and to supply power during emergency conditions. Depending on the characteristics of the energy storing devices, these devices are classified into high power and energy density devices. Heigh power density devices can provide high power for short periods of time, whereas high-energy density devices can provide energy for long periods of time. Some of the power electronics loads requires high power during the starting only for short duration of time [6]. Designing the battery for such a high current rating will increase the cost of the system, and this type of energy requirement creates stress on the battery during the charging process as well as during discharging cycles. The battery responds slowly to these fast-changing loads causes stability issues in the microgrid system. Due to these issues, hybrid energy storage system is implemented to decrease the stress posed on battery and also to improve its life span [7]. In order to overcome difficulties of renewable energy sources microgrid is introduced. Microgrid helps in the smooth penetration of intermittent renewable energy sources to the main grid [8]. Operating the microgrid in both grid connected and standalone mode helps in achieving economic benefits by selling the electrical energy to utility grid during peak hours and by buying deficit electrical power during the base load period. Renewable energy sources (RES) improve the reliability of the DC microgrid, still efficiency may not be significant till proper energy management control methods are applied to share the energy between RES, energy storage devices and loads [9]. Gui *et al.* [10] and Pannala *et al.* [11] presented diverse power handling methods based on dc link voltage regulation for RES combined DC microgrid.

Un necessary switching of power sources in Microgrid is overcome by regulating the several generating power bases and loads concurrently, and supercapacitor is also combined to improve battery life and to offer smooth mode transition. However, the control strategy proposed for energy management on the battery, due to SOC restrictions, the battery is not being used to its maximum potential and the diesel generator is being run consistently at its best efficiency to meet the proposed system's energy requirements. It does contribute to the carbon emission [12]–[15]. In literature battery and super capacitor-based system are reported validates the utilization super capacitor improves the battery life and better handling of transient power requirements [16]–[19].

From the present literature energy management schemes are either rule based or optimization-based energy management system [20]. Rule based Energy management scheme such as fuzzy logic and threshold method is reported in the literature [21], [22]. In the case of fuzzy based system rules are fixed by experience and expertise, however achieving global optimization is difficult in fuzzy based energy management systems. In threshold-based energy management schemes threshold is applied on state of charge of the device that stores energy to sustain the optimum operation of the grid. However, this method requires complex mathematical formulation. Ali *et al.* [23] in case of optimization-based energy management schemes such as model predictive control, neural network, dynamic programming was reported in the literature. In case of model predictive and dynamic programming-based energy management schemes it involves heavy mathematical formulation and calculation burden. Hence, a coordinated control-based energy management system is used in this work for a microgrid with a hybrid energy storage scheme. Proposed system is designed to handle efficiently under different operating modes and to provide smooth transition between the modes, attain power factor of the system unity and quick dc bus voltage stabilization in both the modes, along with fulfilling the transient power requirements due to sudden generation and load changes.

2. MICROGRID STRUCTURE

The planned DC microgrid scheme consists of PV system with battery and supercapacitor energy storage. The PV system is coupled to DC bus through boost converter and it is controlled by incremental conductance maximum power point tracking (MPPT) algorithm. Battery and supercapacitor are connected parallel to dc link via DC-DC bidirectional converter. The DC bus is coupled to the utility over single-phase voltage source inverter as shown in Figure 1. Two controllers were designed to control energy storage devices and voltage source inverter. Controls for the Inverter is designed such that it can act in either grid connected mode or in standalone mode. Likewise, DC-DC bidirectional controller control is designed to control the bidirectional control switching depending on the power requirement of load and generated power levels.

A perfect PV array consisting of 8 module strings is applied for the planned microgrid system. The model, 1Soltech 1STH-250 W is applied. Specifications of the model presented is given in the Table 1. Incremental conductance (IC) MPPT is algorithm [24], [25] is used maximize the output of the PV array system. The Algorithm is depicted in Figure 2, In this algorithm voltage and current is sensed and compared with the previous values. The IC algorithm is constructed based on the power curve slope of the PV array. The slope of MPP is 0 at MPP. so that P = VI and P/V = 0. Taking in to account that $\Delta I/\Delta V = -I/V$ if $P = MPP$ and $\Delta I/> -I/V\ if\ P < MPP$ and $\Delta I/\Delta V < -I/V$ if $P > MPP$. The instantaneous conductance can be compared with the rate of change of current with respect to voltage i.e with $\Delta I/\Delta V$.The reference is increased or decreased until $\Delta I/\Delta V = -I/V$ is reached. The operation of the PV array is maintained once the maximum power is attained.

Lithium-ion battery and supercapacitor combination is used as hybrid power reserve. The main objective of the proposed energy storage scheme is to utilize high energy density of battery for average power requirement and to use super capacitor which is high in power density for transient/sudden power requirements due to sudden load or generation changes. Both the models implemented for this planned system is available in MATLAB/Simulink library. The specifications of the battery and super capacitor is given in the Table 1.

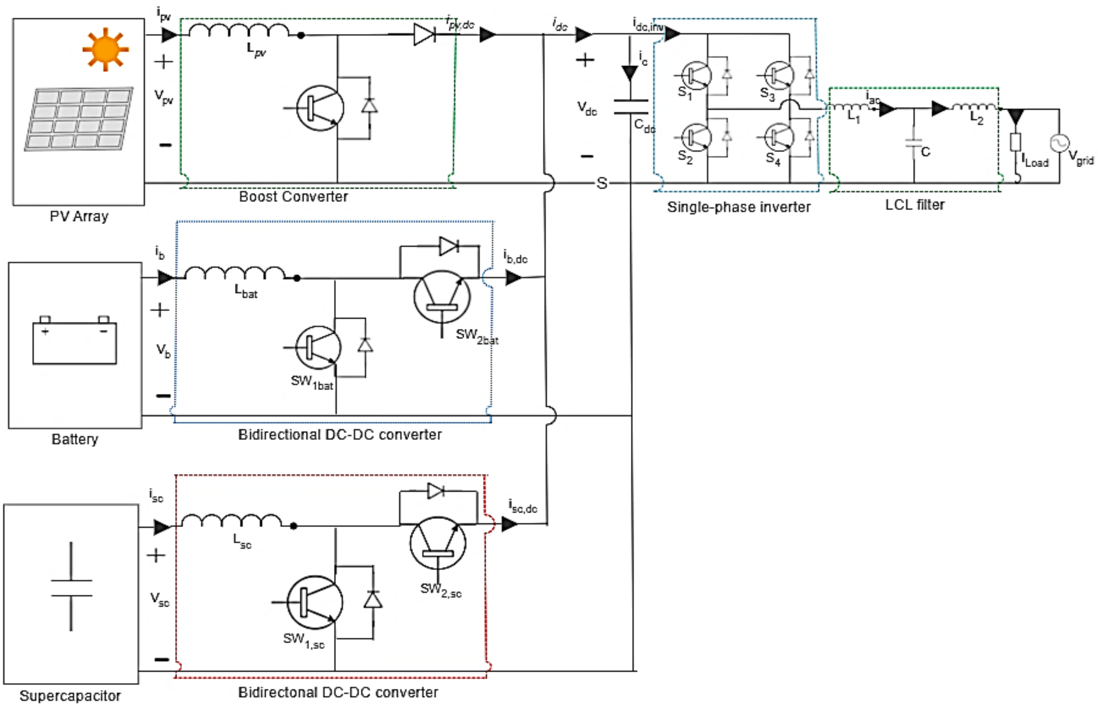

Figure 1. Microgrid with hybrid energy storage system

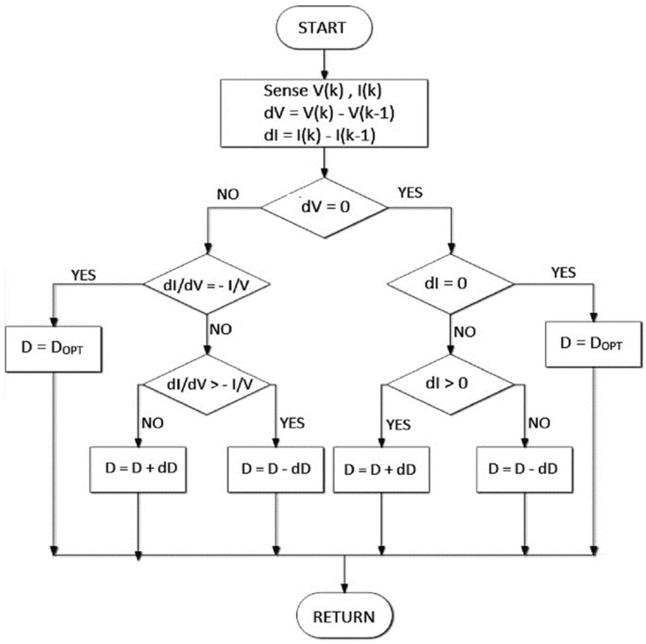

Figure 2. Incremental and conductance MPPT algorithm [24]

Table 1. Microgrid system parameters

Components	Parameters	Value	Components	Parameters	Value
PV module	Maximum power	250 Wp	DC link	Voltage	400 V
Battery	Capacity	20 Ah	DC load	Resistance	320 Ω
	Nominal voltage	12 V	AC load	Power	1000 W
		16 V	Utility (1 -phase)	Voltage and frequency	230 V(RMS) and 50 HZ
Ultracapacitor	Rated voltage		Controllers	Battery	K_p= 0.2 K_i=0.05
	Capacitance	58 F		Ultracapacitor	KP =0.2 Ki=0.05
		170 A		Outer voltage loop	Kp= 0.01 Ki=0.1
	Maximum current				

3. ENERGY MANAGEMENT

The proposed energy management control strategy consists of three controllers. One is DC link voltage controller, MPPT controller for PV boost converter, Inverter controller. MPPT controller is explained in previous section. The operation of DC link voltage controller and inverter controller is explained below.

3.1. DC link voltage controller

A standard dual cascaded PI Controller based current control method is utilized for maintaining the DC link voltage constant. The presented control strategy consists of voltage regulating loop, battery current regulating loop, super capacitor current regulating loop. Structure used is as shown in Figure 3. The outer loop is a voltage regulating loop which produces current reference to the inner regulating loop. This reference current value can be positive or negative depending on the load requirement and generation availability. This reference current is divided into two components using filter controller as low frequency(average) load current requirement and high frequency(transient) load current requirement. Average load current component is compared with the available battery current and difference is given to PI controller for generation of switching pulses for DC-DC bidirectional converter of the battery. In order to compensate the slow response of the battery some portion of battery error current is added to transient current component and is considered a supercapacitor reference current. And this reference current is compared with the actual supercapacitor current and error signal is given to the PI controller to generate switching pulses for bi-directional converter connected to supercapacitor. Depending on the duty cycle provided by the control approach the battery and supercapacitor will be discharging/charging.

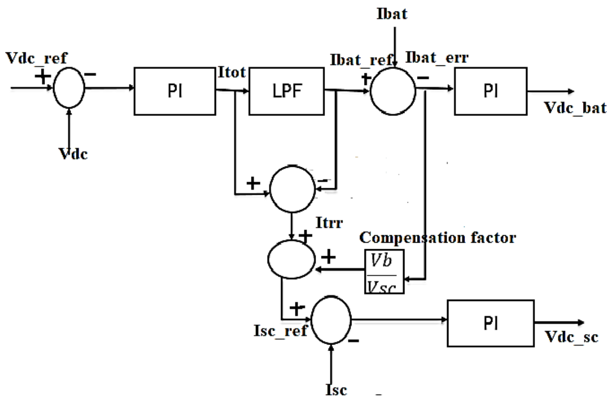

Figure 3. Battery and super capacitor controller

3.2. Inverter control strategy

This paper presents a dual loop energy management control scheme of a single-phase voltage source inverter for utility (grid) connected photovoltaic system with battery and supercapacitor energy storage. It consists of current control loop and voltage control loop. The proposed method is based decoupling of active power current and reactive power current components to feed the active power to the grid using vector control. The goal of this research is to control the bi directional power flow at grid, improve efficiency of transferring power of PV to grid, reduce the harmonic distortion by proper designing of LCL filter. The proposed LCL filter is designed such way that the total harmonic distortion is kept within 5%. The simulation results of the proposed system will be shown in next chapters.

The energy management system proposed is based on the power available from PV generation and DC load is considered as critical load and Ac load is considered as non-critical load. The 800 W margin is fixed for PV to maintain the charging levels of battery. The energy management system is designed in such way that, in grid connected mode, if PV power is less than 800 W, grid will supply the AC load. And if the PV is more than 800 W, it will contribute to AC load. Based on this reference current for inverter control is generated in grid connected mode. In case of stand-alone mode, if PV power is less than 800 W, it will supply half of the AC load, if more than 800 W it will supply full AC load. Based on this reference current for inverter control is generated in stand-alone mode. Phase angle required for Park transformation and inverse park transformation is generated using PLL.

The proposed inverter control strategy is shown in Figure 4, and is applied in dq reference frame. Using Park transformation, the inverter current is converted/transformed to dq reference frame. The converted current components are synchronized with grid voltage phase angle using PLL. The converted current components Id and Iq are reference currents corresponding to active and reactive power necessities compared with actual currents and error signal is given to the two proportional–integral (PI) controllers to generate voltage signals which are then inverse park transformed and provided to pulse with modulation generator to produce switching pulses for inverter. Reference current for d-axis, i.e Id_{ref} is designed in order to control DC link voltage. Reactive current component Iq_{ref} is maintained zero to feed only active power and achieve unity power factor.

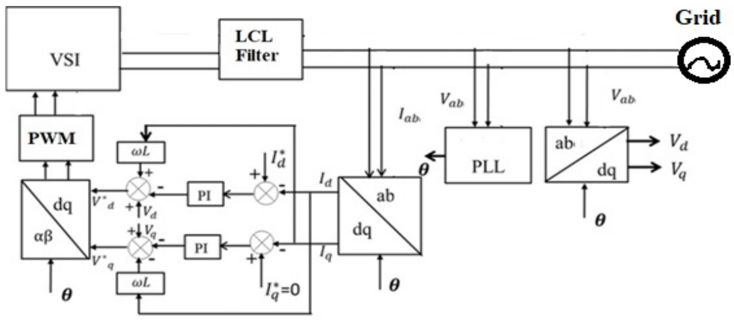

Figure 4. Inverter control strategy

3.3. LCL filter design

Designing a LCL filter plays a vital role in grid connected system. Compared to filters like L and LC, LCL filter efficiently reduces the inverter current harmonics [26]. In this proposed paper LCL filter is designed such that THD is maintained within 5%. To design LCL filter, ripple current is considered as 10%. and L1, L2, C, and frequency required are calculated as follows [27] and filter parameters are given in the Table 2.

$$\Delta_{Lvar} = 10\%\ I_{max} \tag{1}$$

$$L_1 = \frac{Vdc}{4*fsw*\Delta Lvar} \tag{2}$$

$$L_2 = \frac{0.1*Vac^2}{S*2\pi f} \tag{3}$$

$$\Delta L = \frac{0.2*S}{Vac} \tag{4}$$

$$C = \frac{0.05*S}{Vac^2*2\pi f} \tag{5}$$

$$f_{res} = \frac{1}{2\pi} * \frac{L1+L2}{\sqrt{L1L2C}} \tag{6}$$

$$f_g = 10 * f \tag{7}$$

$$f_{ss} = 0.5 * f_{sw} \tag{8}$$

Table 2. LCL filter parameters

LCL filter Parameters	Values
Inductor L1	7.7 mH
Inductor L2	0.7518 mH
Active power (S)	2000 W
Capacitor	6.02 µF
Dc Link voltage (Vdc)	400 V
Grid Voltage (Vac)	230 V(rms)
Grid frequency(f)	50 HZ
Switching frequency	7500 HZ

4. RESULT AND DISCUSSION

The simulation of the planned system is given in the Figure 5. The PV array of capacity 2 KW is utilized along with supercapacitor and battery hybrid energy storage scheme. A controlled voltage source is utilized for simulation of utility grid. Battery and supercapacitor are combined to DC bus via bi-directional DC-DC converter and PV system via Boost converter. DC bus is coupled to utility grid via two-way DC-AC converter. In each mode the PV power generation is varied along with DC load. The performance analysis based on maintaining persistent Dc link voltage and power factor at unity in grid connected mode, and harmonic distortions within the limits. Analysis is carried out for three cases namely: i) standalone mode, ii) grid connected mode, and iii) transition mode.

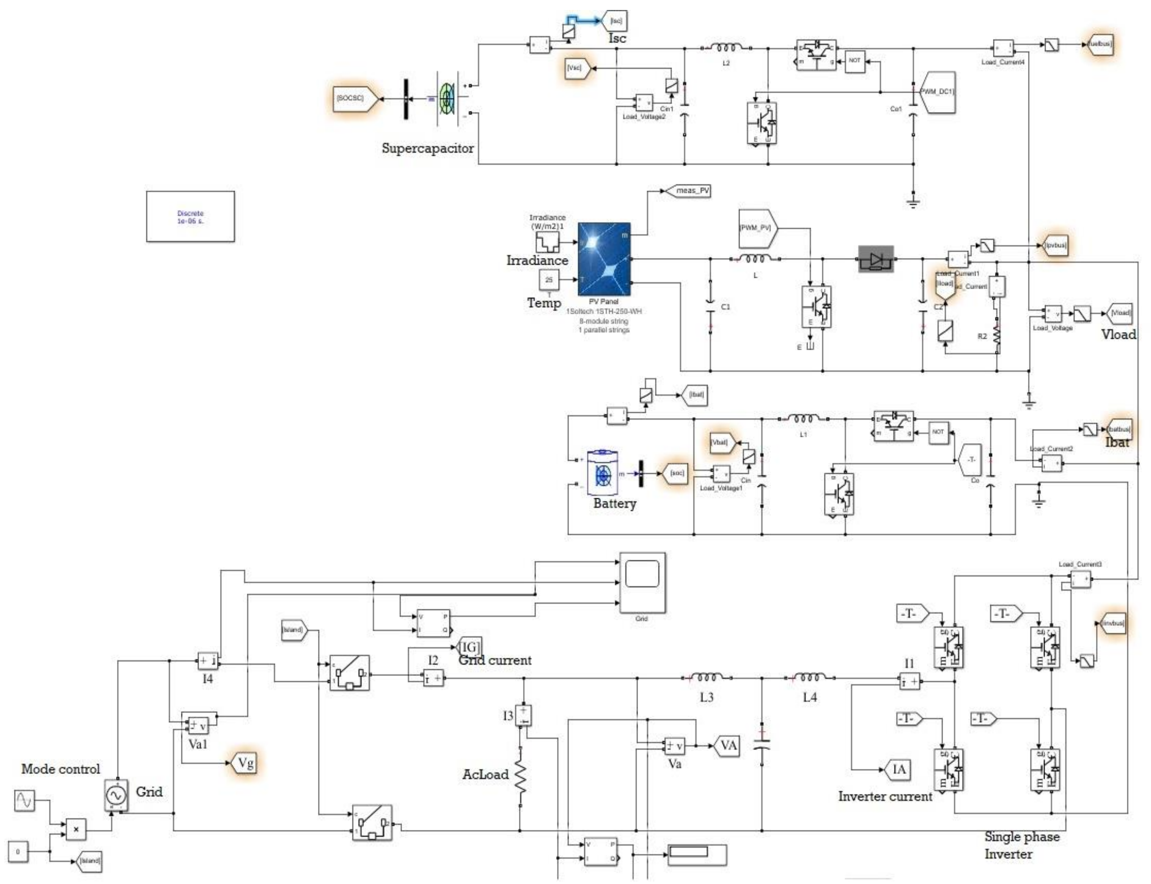

Figure 5. Microgrid simulation

4.1. Standalone mode

Standalone operation of the microgrid is analyzed by varying PV generation along with ac and dc load. From Figure 6, it is observed that PV power generation varies from 2000 W to 1500 W from 1 to 2 sec and 1500 W to 1000 W from 2 to 3 sec, from 1000 W to 300 W 3 to 4 sec, and ac load is 1000 W and DC load is 450 W. From 0 to 1 sec PV generation is 2000 W which more than the AC and DC load requirements, and extra energy is employed to feed the battery as shown in Figure 6. Again from 1 to 2 sec PV power (1500 W) more than generation, and PV supply power to both the loads. From 2 to 3 sec PV power is 1000 W which less than the load requirement and it is provided by battery system and PV again from 3 to 4 sec PV power is 300 W which is less than the load demand and is supplied by battery and super capacitor. From Figure 6 grid current drawn is zero as microgrid is operating in standalone mode and from Figure 7, it is observed that irrespective of these variations in generation DC link voltage is maintained constant.

4.2. Grid connected mode

As the system is designed such that whenever generation from PV system is less than the 800 W, load requirement will be fulfilled by the utility grid and for PV generation above 800 w it will contribute to grid. From

Figure 8, it is observed that from 0 to 1 sec PV power generation is more than that of 2000 W and it is also more than the AC load requirement 0f 1000 W and DC load requirement of 450 W. PV system supplies both the loads and the extra power is used for charging the battery and supercapacitor. Similarly, from 1 to 3 sec as PV power is more than the 800 W. PV and battery contributes to the both loads from 2 to 3sec as from Figure 8. It is also observed that from 0 to 3 sec the Grid current is zero and the load power is supplied from the PV from 1 to 2 sec, and from 2 to 3 sec PV and battery together supplied. But from 3 to 4 sec PV power generation is reduced to 300 W from 1000 w, which less than 800 W, hence now microgrid supplied from utility grid as observed from the increase in grid current and power as described in Figure 8. In the Figure 9, It is also observed that regardless of variations in generation and load requirements, DC bus voltage is maintained at 400 V.

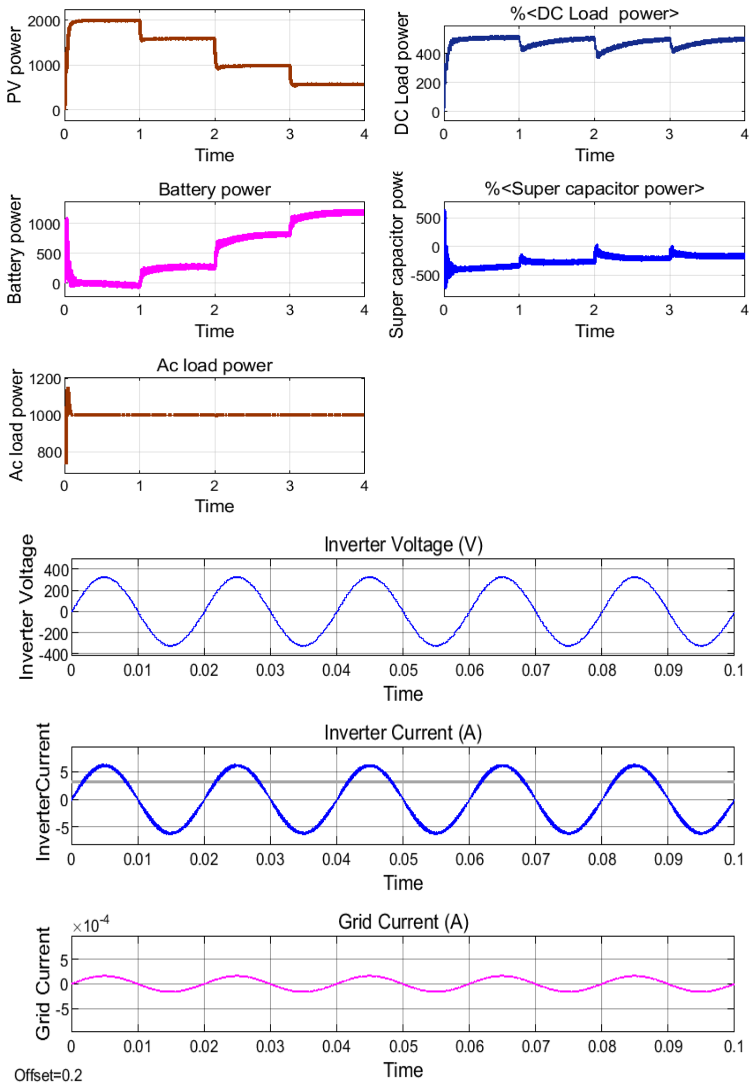

Figure 6. Simulation results for standalone mode

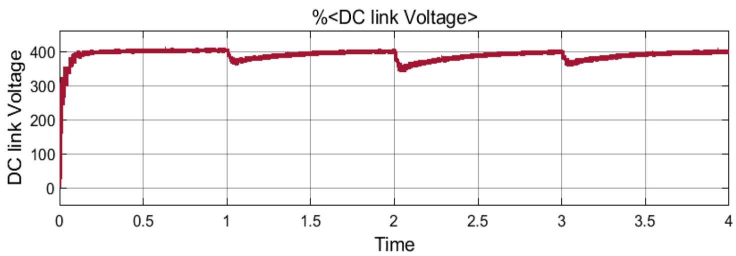

Figure 7. DC link voltage

4.3. Transition from utility connected mode to standalone mode

To analyze the sudden transition in modes of operation during emergency conditions, the microgrid is suddenly changed into standalone mode at 1.1 sec from utility connected mode as shown in Figure 10. It is observed that grid current and voltage is zero after 1.1 sec due to this change in the mode. And, from grid power (Figure 10) it is been observed that at 1.1 sec sudden increase in power due to this sudden change. And this transient power requirement is fulfilled by super capacitor followed by battery as shown in Figure 11 and from Figure 10, it is noticed that DC bus voltage is maintained at 400 V regardless of this sudden change in operating mode of the grid It is also noticed that DC load and AC load is supplied continuously irrespective of this mode change as depicted in Figure 11 by battery supper capacitor power. Inverter voltage, current and grid current for this transition mode is depicted in Figure 11. Inverter current total harmonic distortion is sustained at 2.26% as shown in Figure 12 and it is within 5% as mentioned in the IEEE standard 519-2014.

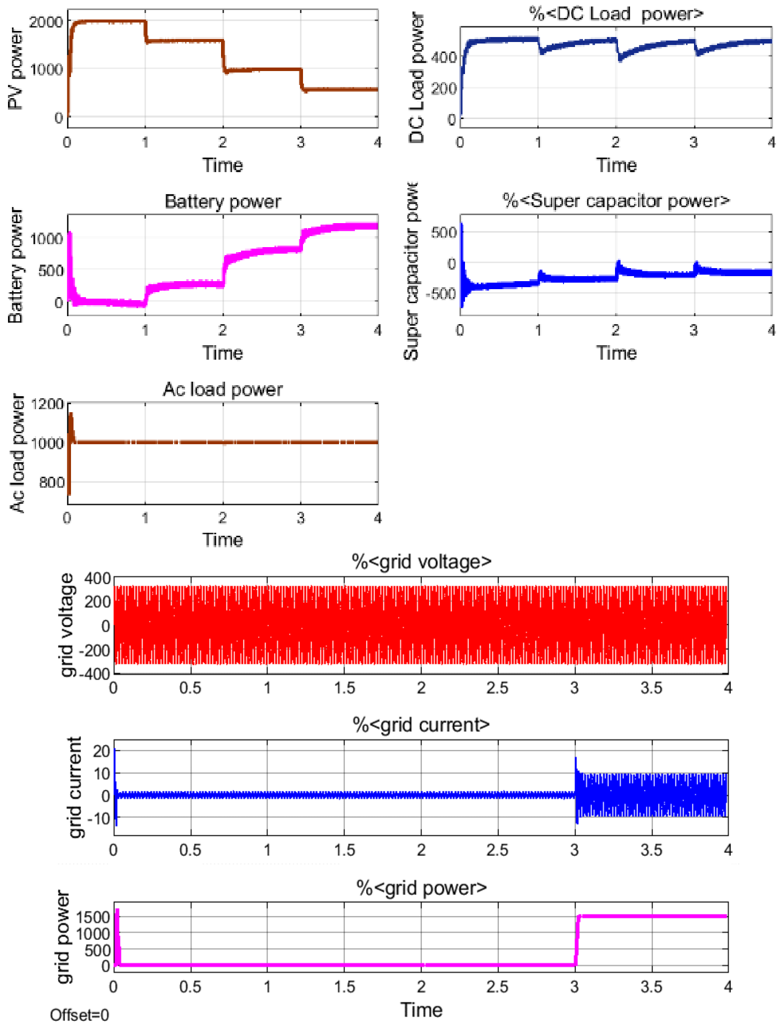

Figure 8. Simulation results for grid connected mode

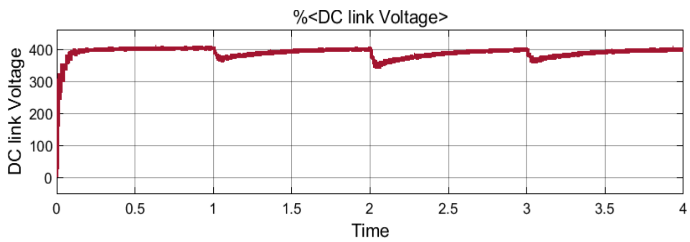

Figure 9. DC link voltage

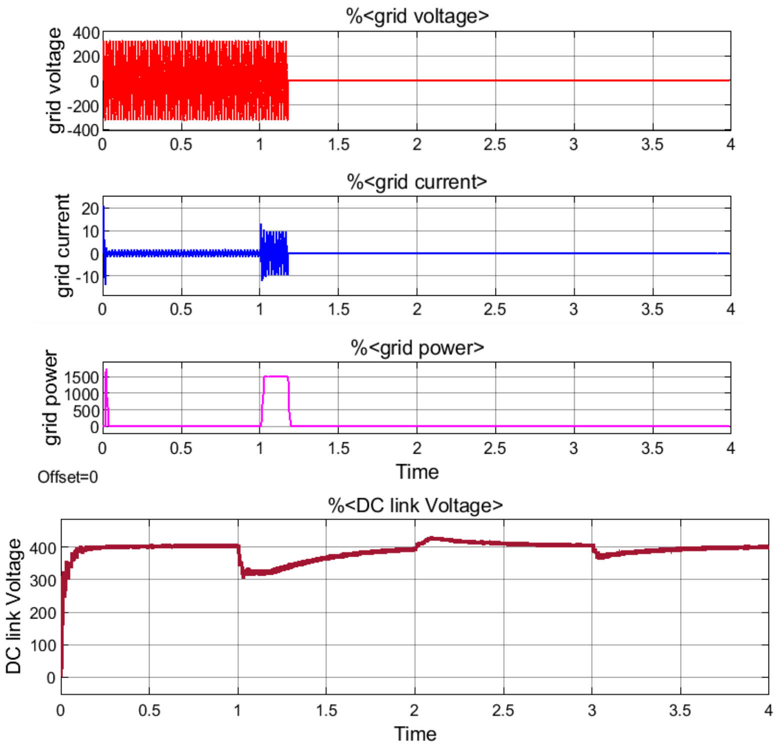

Figure 10. Grid voltage, grid current, grid power and DC link voltage during transition

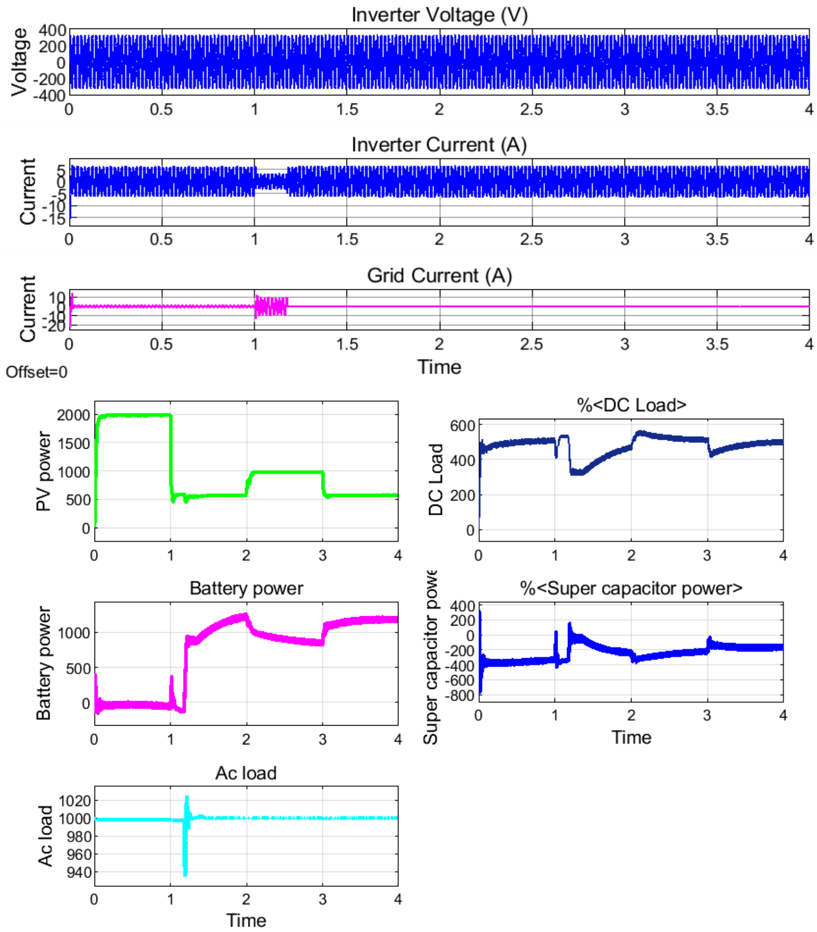

Figure 11. Simulation results for transition mode operation

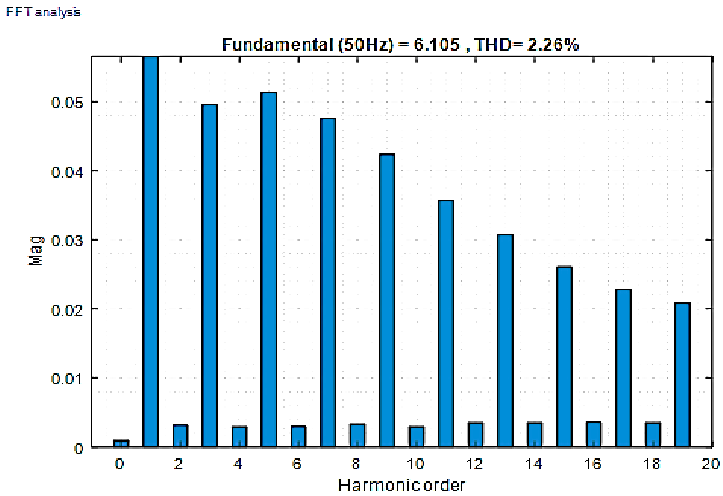

Figure 12. Total harmonic distortion of the proposed system

5. CONCLUSION

An energy management system is designed for the microgrid with PV as main energy source along with battery and super capacitor hybrid energy storage systems. PI Controller based coordinated control-based energy management system is modelled for both grids connected as well as standalone mode. DC side of the grid is controlled by dual loop controller which controls battery and supercapacitor bi-directional converters. Inverter control for utility connected mode and islanded mode is designed using dq reference frame technique. Based on the mode of operation switching pulses were generated for inverter and DC-DC converters. Operation of the proposed system is verified at grid connected mode, standalone mode, and changeover of mode from utility connected mode to standalone. From the results obtained the proposed energy management system efficiently sustains the DC link voltage constant, and it maintains unity power factor in ac side of the grid. And, it is observed that grid stability is maintained in all the operating modes of the microgrid by fulfilling AC and DC load requirements and the LCL filter designed such that harmonics in the inverter current is limited to 2.26% which plays important role in grid.

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