Decentralized dynamic power control in an islanded DC microgrid with hybrid energy storage system

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ABSTRACT

The integration of renewable energy resources to utility grid calls for selection of suitable storage system to store generated energy with reliable supply of demand and selection of efficient control system for smooth control of the grid. Battery is the most common energy storage system. Combining a supercapacitor to it makes the system performance better during transients. This paper proposes a hybrid energy storage system with a battery and a supercapacitor to reduce transient power fluctuations and improve the life span of the battery by reducing the charging/discharging cycles with the incorporation of supercapacitor. The battery compensates constant power fluctuations whereas the supercapacitor compensates the transient power fluctuations. This system design offers improved performance, with better regulation of dc link voltage, frequency regulation compared to microgrid with single energy storage. The dynamic performance of the system under varying load conditions has been improved. The work proposes the power management algorithm, which helps in efficient monitoring and smooth control of the entire system. Integration of supercapacitor to the storage system enhances the performance of the microgrid, increases life span of battery and reduces the stress on battery. The DC link bus voltage is efficiently regulated and the demand is supplied reliably.

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1. INTRODUCTION

The increasing demand for electricity calls for research on different energy sources to generate electricity, storage systems to integrate into microgrids to store energy generated from renewable sources, control techniques to have effective control and co-ordination of the grid components. A well-designed grid including renewable energy sources like solar photovoltaic PV, windmills, hydro, bioenergy and suitable energy storage system can deliver reliable and uninterruptable power to demand like hospital, school, community or can work in grid connected mode to improve system's reliability. Effective control circuit is the crucial part for the system's satisfactory behavior. In the recent times, DC microgrid is gaining popularity and being implemented in residential and industrial sector [1]–[3].

Harnessing solar energy is gaining popularity due to the latest conversion technologies and advancement in solar panel design and fabrication process. However, integration of a suitable storage system to the microgrid becomes essential as the solar energy is intermittent and dilute in nature. Battery is a significant and popular energy storage device, finding application due to its high energy storage. Several research works have been carried out to improve battery performance. Lead acid, nickel cadmium, lithium polymer, nickel-metal-hydride, lithium ion and sodium-sulphur are few types of popular batteries in use. However, making the storage system hybrid improves the life cycle of the battery, reduces rating of the battery to be selected, and improves overall reliability and performance of the grid. A supercapacitor becomes a suitable choice to make storage system hybrid since the battery is a high energy density component, and the supercapacitor is a high-power density component which can take care of transients occurring on the system and reduce the stress on battery [4], [5].

A microgrid with solar PV, hybrid storage system consisting of battery and supercapacitor supplying the loads has been simulated. The incremental conductance maximum power point tracking MPPT algorithm extracts maximum power from the solar energy. The implementation of proportional integral PI and Hysteresis Controller for the control application enhances the switching operation, reliability of performance. The designed system is simulated in Simulink and the output waveforms are analyzed. The system proves to improve regulation of DC link voltage, reliable supply to the loads and will be an attractive alternative of power in future for small community, school, hospital, and other sectors [6], [7]. The proposed model of the microgrid consists of solar PV, hybrid energy storage system (consisting of battery and supercapacitor), constant and dynamic loads, as shown in Figure 1. MATLAB/Simulink is used to simulate the system [8], [9].

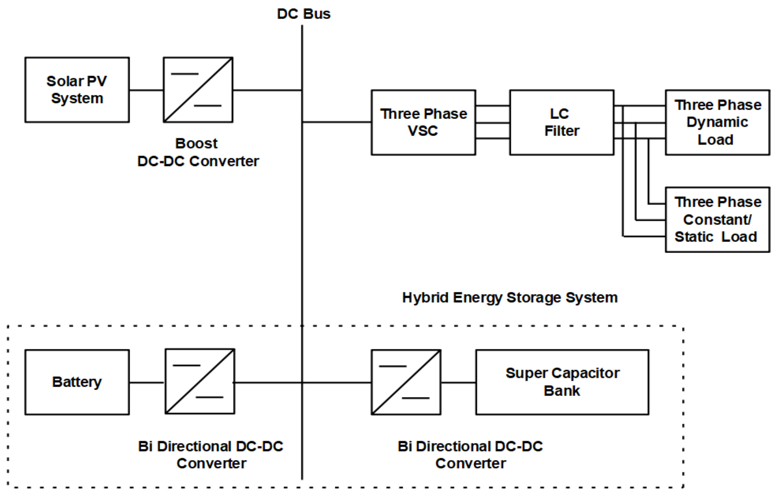

Figure 1. Microgrid system architecture

2. PROPOSED SYSTEM MODEL

2.1. Modeling of renewable energy system

The proposed system has solar PV, since it is found to be an attractive alternative for green power generation. A 10kW rating solar PV module has been used in the grid [10]–[12]. The solar PV system has incremental conductance (IC) MPPT algorithm incorporated to extract maximum power. The equivalent circuit of a solar PV is shown in Figure 2.

The equations used to model the solar PV panel are as (1).

$$I_L = N_p\, I_{PV} - N_p\, I_{rev}\,[\exp(\frac{qV_{PV}}{kTAN_s}) - 1] \quad (1)$$

Where I_{PV} is the photo current of in ampere, V is the PV array output voltage in volts, N_p is the number of parallel connections of solar PV modules, N_s is the number of series connections of solar PV modules, A is the p-n junction ideality factor, T is the cell temperature in Kelvin, I_{rev} is the cell reverse saturation current in ampere. The solar PV current (I_{PV})in ampere at temperature T is given by (2):

$$I_{PV} = I'_{SC} + k_i(\, T - T_r^{'})\,(\frac{S}{100}) \quad (2)$$

Where I'_{SC} is the short circuit current of the solar cell at reference temperature $T_r^{'}$ and radiation; k_i is the short circuit current co-efficient; S is the solar radiation expressed in mW/cm^2. The power from the PV array can be calculated using in (3) and (4).

$$P=VI \tag{3}$$

$$P = N_p I_{PV} V - \text{Np Irev} [\exp(\frac{qV_{PV}}{kTAN_s}) - 1] \tag{4}$$

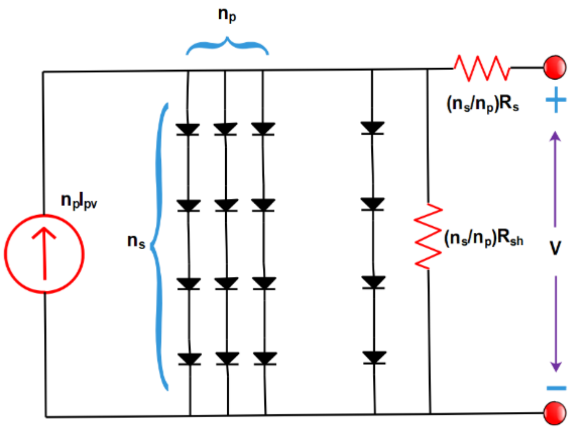

Figure 2. Solar PV equivalent circuit

2.2. Modeling of DC-DC boost converter for solar PV system

A DC-DC boost converter is used to connect the solar PV system to the DC bus. The maximum power point tracking (MPPT) algorithm provides gating signals to the converter switches and helps in operating the solar PV system at maximum power point [13]–[15]. The inductor (L) and capacitor (C) values required for the boost converter circuit are determined using in (5) and (6).

$$L = \frac{V_i \times V_d}{V_o \times f_s \times \Delta I} \tag{5}$$

$$C = \frac{I_o \times V_d}{V_o \times f_s \times \Delta V} \tag{6}$$

Where V_i is the input voltage in volts, V_o is the output voltage in volts, V_d is the difference between input and output voltages in volts, ΔV is the voltage ripple, ΔI is the current ripple, f_s is the switching frequency (Hz).

2.3. Modeling of energy storage system

Energy storage is crucial since the loads are dynamic in nature. Batteries are the first choice for energy choice because they possess high energy density. However, their power density is low. The low power density of the batteries limits the charge/discharge cycles of the battery and reduce its life span [16], [17]. An energy system can achieve improved performance by incorporating two or more types of energy storage devices. However, the cost, size and implementation issues limit the number of storage devices connected to the grid. One of the favorable devices connected along with battery to make the system hybrid is supercapacitor. Supercapacitor is a high-power density and low energy density device. The charge/discharge rate of the supercapacitor is high and has around 500000 cycles of lifespan. So, if the energy storage system is made hybrid, the supercapacitor can mitigate transient power fluctuations, the battery can have improved performance [18]–[20].

2.4. Modeling of battery energy storage

Lead acid batteries are commonly used devices in energy storage system. The battery circuit is shown in Figure 3. If V_{oc} represents open circuit voltage (V), V'_{oc} represents full charge open circuit voltage (V), T represents temperature of electrolyte in °C, S represents the state of charge of battery and K is a constant in volts/°C, then V_{oc} is given by (7):

$$V_{oc} = V'_{oc} - [1 - S] \times K \times [273 + T] \tag{7}$$

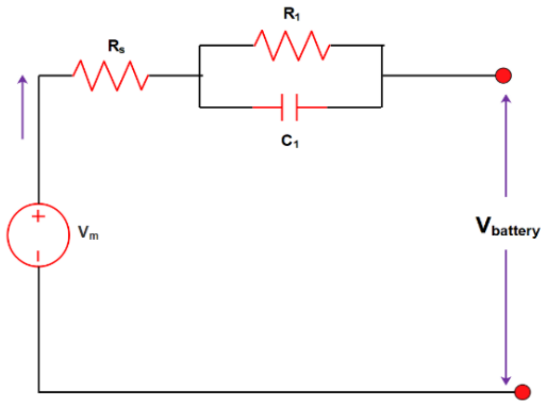

Figure 3. Battery equivalent circuit

2.5. Modeling of supercapacitor energy storage

Supercapacitors are of different types: electric double layer capacitors, hybrid and pseudo capacitors depending on storage mechanism and or cell configuration. The supercapacitors possess conventional energy storage in electrostatic charges and also consists of an electrolyte to store electrostatic charge in the form of ions. There is no electrochemical reaction inside a supercapacitor [21], [22]. A higher charge density is possible in a supercapacitor due to the presence of porous carbon electrodes having high internal surface area. The movement of ions is much slower than electrons, which enables longer time constant for charging and discharging processes in comparison to electrolytic capacitors. Let us consider a supercapacitor with the following system variables:

– Maximum voltage = VCAPMAX
– Working/nominal voltage = VCAPNOM
– Minimum allowable voltage = VCAPMIN
– Discharge time = discharge
– Power requirement = PC
– Current requirement = IC
– Capacitance of each cell = Ccell
– Cell voltage = Vcell

A simplified model of a supercapacitor consists of 3 ideal circuit elements – a capacitor with cell capacitance of C_{cell}, series resistor R_{series} and a parallel resistor $R_{parallel}$. Let n_s be the total number of capacitors in series connection. The total maximum voltage for this connection is equal to (ns × V_{CAPMAX}). The total equivalent resistance, R_{eq} = n_s × R_S. The total capacitance of the capacitor bank is given by $C_{bank} = \frac{C_{cell}}{n_s}$. The minimum capacitance C_{MIN} required can be obtained by neglecting R_{eq} under constant discharge power:

$$\text{PC} = \frac{1}{2} C_{MIN} \left(V_{CAPNOM}^2 - v(t)_{bank}^2\right) = \text{PC t} \quad (8)$$

Where $v_{bank} = terminal\ voltage\ of\ SC$

$$C_{MIN} = \frac{2\, P_C\, t_{discharge}}{V_{CAPNOM}^2 - V_{CAPMIN}^2} \quad (9)$$

Since constant power is delivered, determination of minimum voltage, V_{CAPMIN}, and maximum current I_{Cmax} can be done based on current conducting capabilities of super-capacitor [23]–[25].

$$V_{CAPMIN} = \sqrt{V_{CAPNOM}^2 - \frac{2P_C t_{discharge}}{C_{min}}} \quad (10)$$

$$I_{CMAX} = \frac{P_C}{\sqrt{V_{CAPNOM}^2 - \frac{2P_C t_{discharge}}{C_{min}}}} \quad (11)$$

2.6. Control algorithm for bidirectional DC-DC converter

The bidirectional converter employs hysteresis control, as shown in Figure 4. The control scheme has two loops, an external droop control loop and an inner voltage control loop. A first order low pass filter is used to attenuate high frequency noises. A hysteresis regulator is employed which consists of a hysteretic differentiator and a PI controller. The hysteric differentiator takes instant action and PI controller gives zero steady state error. Figure 5 shows the hysteresis droop controller architecture incorporated for the converter control.

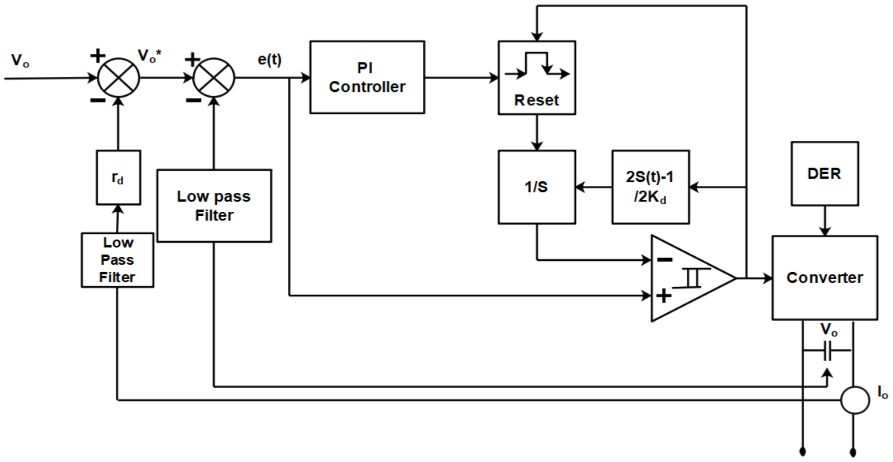

Figure 4. Hysteresis droop controller architecture

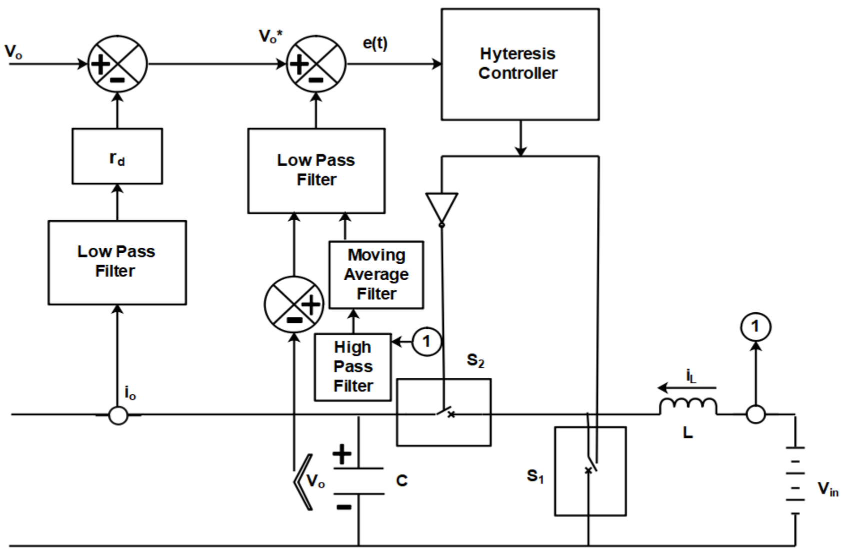

Figure 5. Hysteresis droop controller architecture

3. RESULTS AND DISCUSSION

The proposed microgrid has been implemented with a solar PV, lead acid battery, supercapacitor and loads connected to the DC bus. The DC bus voltage is maintained at 800 V. Hysteresis current controlled algorithm is incorporated for the control of bidirectional DC-DC converter. The system is simulated with 10kW PV array, 445 V and 22.47 A at maximum power, battery rated capacity of 200 Ah and 80% State of Charge, and a 3F supercapacitor. The Simulink model is shown in Figure 6. The system is simulated in MATLAB/Simulink and performance is observed and behavior of grid operation is analyzed in waveforms from Figure 7 to Figure 12. The load occurring on the grid is varied at three intervals during the simulation. The grid operates reliably by regulating the DC bus voltage constant.

From the waveforms, it is evident that the transient power is supplied by the supercapacitor and the steady state power is supplied by the battery. The battery's performance and life cycle are improved by the introduction of the supercapacitor to the grid. It is observed that the stress on battery is reduced during transient state due to supercapacitor action. The variation in SoC of battery has also been effectively reduced.

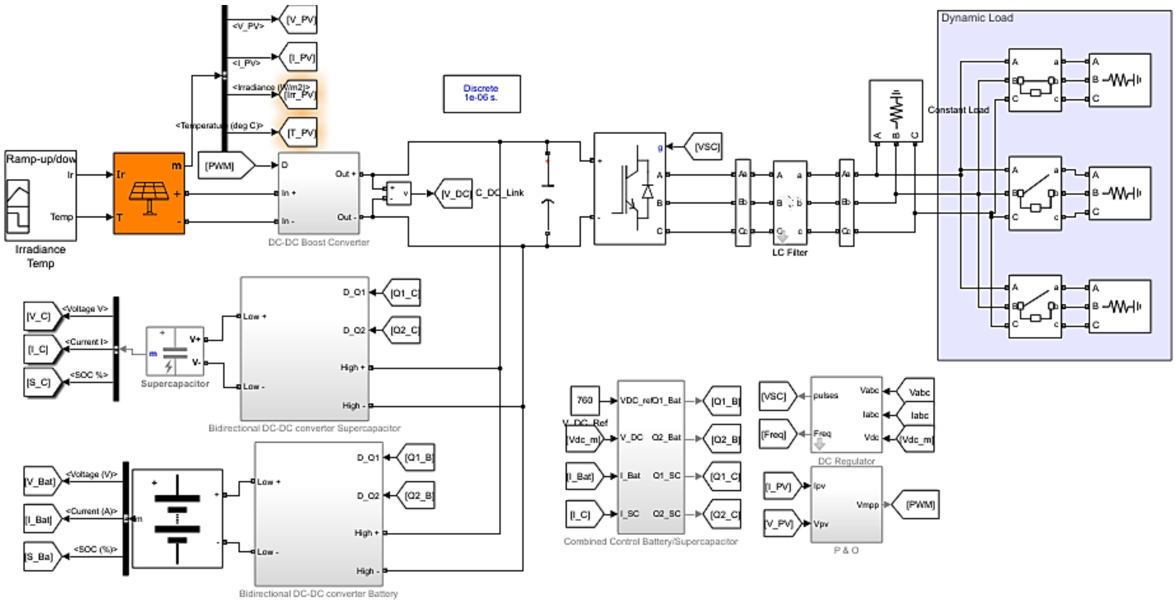

Figure 6. Simulink model for the proposed microgrid

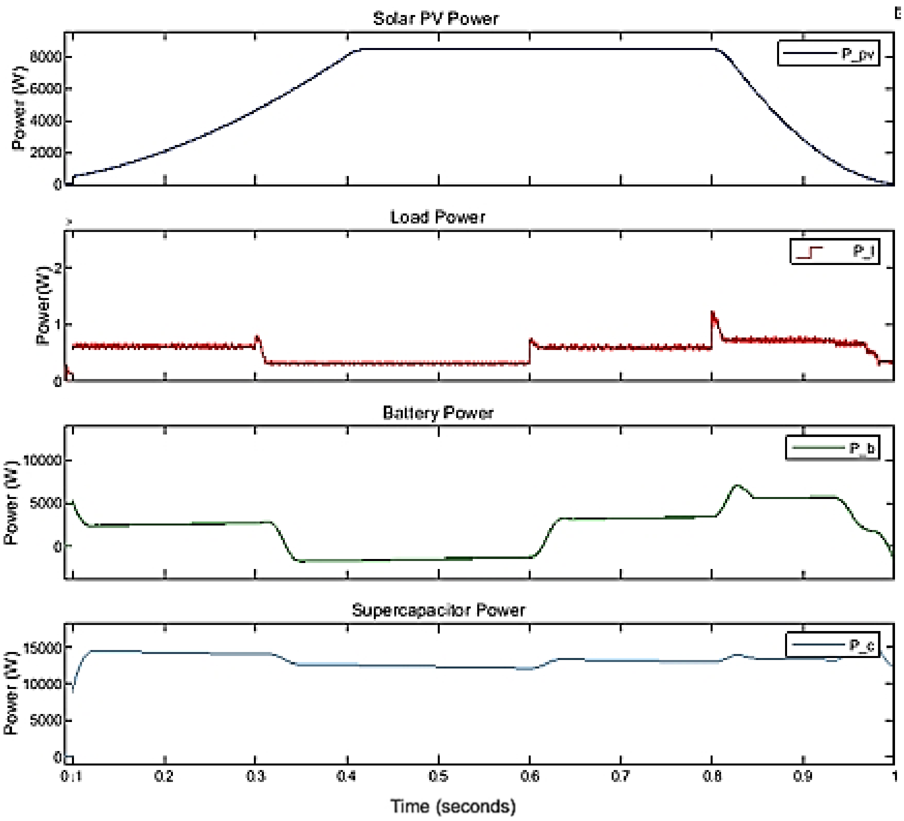

Figure 7. Power waveforms

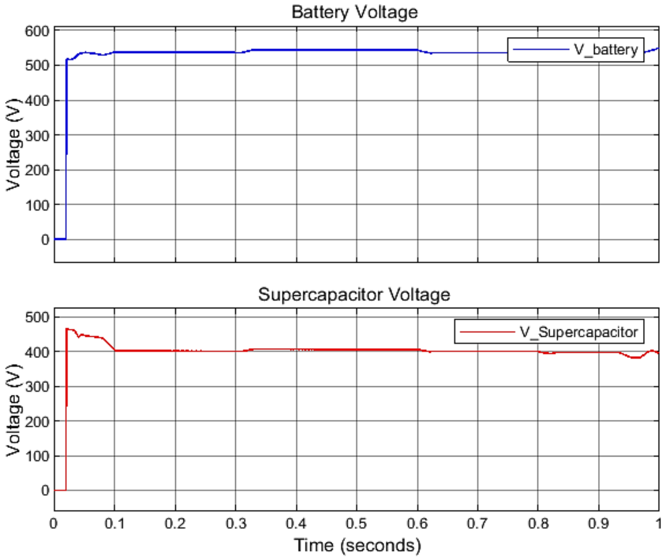

Figure 8. Battery and supercapacitor voltage

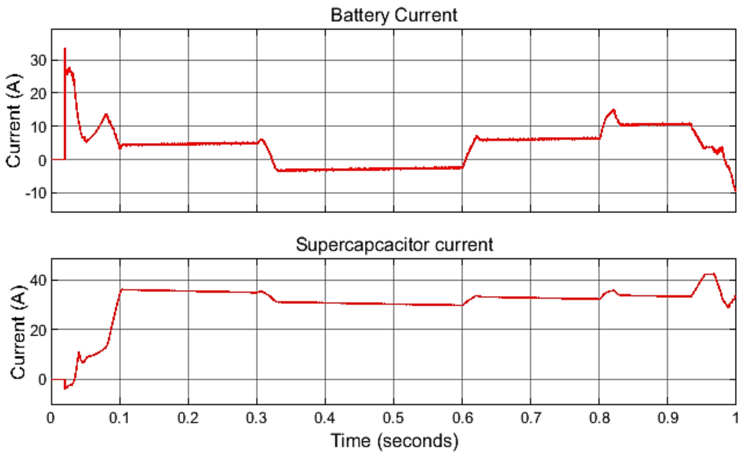

Figure 9. Battery and supercapacitor current

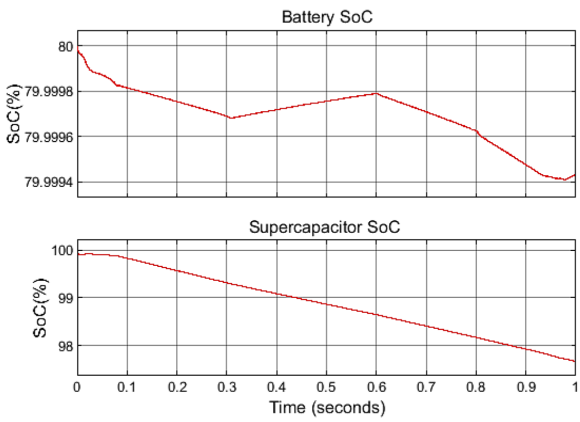

Figure 10. Battery and supercapacitor SoC

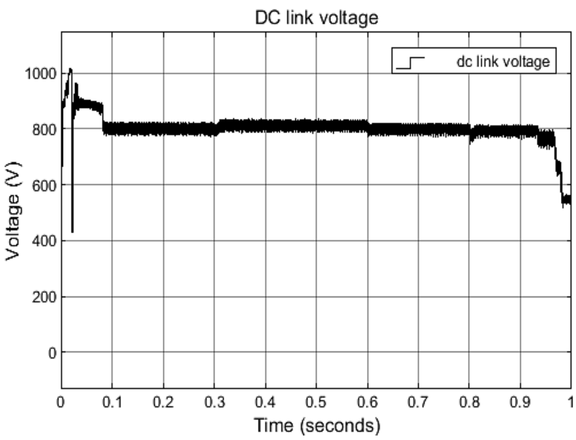

Figure 11. DC link voltage

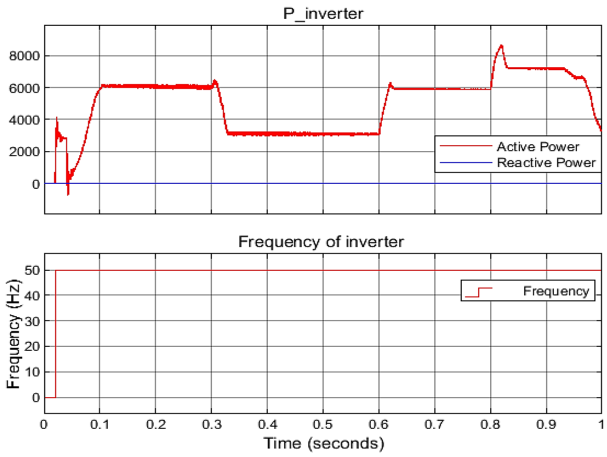

Figure 12. Waveforms of inverter output power and frequency

4. CONCLUSION

It is observed that introducing the supercapacitor improves the behavior and life cycle of the battery. The DC link voltage regulation has been improved. The hysteresis controller and PI controller along with moving average filter in the converter control scheme has proved to enhance the overall switching action. Decoupled control strategy in synchronous reference d-q frame has been adopted for voltage and frequency variation control. The total harmonic distortion of the inverter output is found to be 4% which is within acceptable limits and low in comparison to battery system alone. The system reliability can be further improved by integrating multiple energy resources.

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