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Research Article

Design and Simulation of Hybrid Energy Storage System With PV, Battery and Supercapacitor using PMSM Drive for Electric Vehicle

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Abstract

This paper presents the design of a Hybrid Energy Storage System using PV, Battery, and Supercapacitor. The proposed system uses PV as the primary source of energy while Battery and Supercapacitor are the secondary sources of energy, they would supply the power to load when the PV Power is less to fulfill the demand of the load. In this paper, the supercapacitor supplies the high-frequency current reference along with the battery error current which is given as the reference for the SC Energy Storage System whereas the Battery provides the low-frequency component resulting in an improved voltage profile as compared to that of the conventional methods. The proposed system provides better performance and higher efficiency.

Keywords: *Hybrid Energy Storage System(HESS), Photo Voltaic(PV), Supercapacitor(Ultracapacitor), Battery, Bidirectional DC-DC converter, Permanent magnet synchronous motor (PMSM), Electric Vehicle*

Introduction

Increasing pollution leads to the development of automobiles using renewable energy sources. Air pollution has dangerous consequences of conventional automobiles that use fossil fuels such as petrol and Diesel. Hence, automobiles are switching to the development of Electric Vehicles with pollution free emission and reduced consumption of fossil fuels in turn preserving the environment. In the last few years, there has been considerable development in Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) [7]. As the price of petrol and diesel keeps on increasing day by day the interest of people is also switching towards EVs and HEVs. Renewable energy sources such as wind and solar are the most available resources but due to the intermittency of the power available from these sources, Hybrid Energy Storage System is used [5]. Battery has high energy density and low power density that means low charge/discharge cycles while Supercapacitor has high power density means high charge/discharge cycles so with the combination of battery and supercapacitor a HESS is developed which yields an increase life span of the battery as the charge/discharge cycles are taken care of by the supercapacitor [3].

PV has intermittency of power and hence it cannot be used for uninterruptable power supply. Battery is highly reliable and can fulfill all desirable characteristics like low power density alone. But that will increase the battery pack size which will cause an increase in weight and cost. Thus, to prevent this Hybrid Energy Storage System (Hybridization) is done with supercapacitor as it has high power density and can easily charge and discharge when there is demand for peak power that is during acceleration and regenerative braking [2], [9]. When PV power alone is not capable of supplying the load then the Battery and supercapacitor will supply the remaining power that is not supplied by PV.

An ideal ESS in a standalone PV system should have both high energy and high power capacities to handle situations such as solar irradiation changes and load step changes. Thus, the target is to harness the benefits of both the storage systems to design a hybrid energy storage system with high power and energy density. By utilizing a battery-Supercapacitor HESS the following merits can be achieved: i) longevity of battery life ii) reduction in battery size and hence the cost iii) reduction in battery stress and iv) improvement in the balance between generation and load demand [8].A supercapacitor is 100 times more powerful than the traditional capacitor.The presented method is based on decoupling of low and high frequency current components [4]. It utilizes the error current of battery additionally to the high frequency current reference to control the SC while the remaining amount of the current is used as a reference to control the battery ESS [4].

Block Dıagram

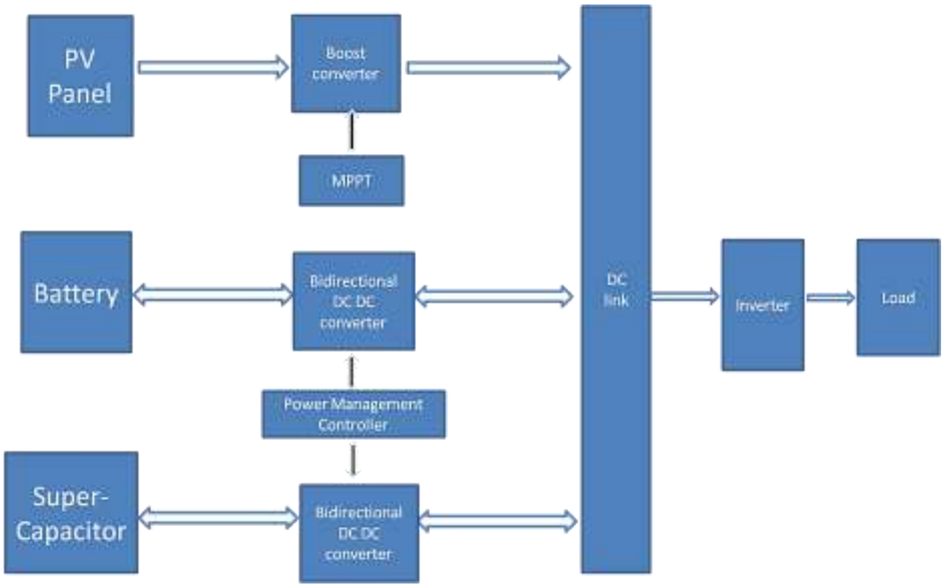

FIG.1. BLOCK DIAGRAM FOR THE PV, BATTERY, AND SUPERCAPACITOR BASED HYBRID ENERGY STORAGE SYSTEM

A standalone PV system along with the combination of battery and SC arrangement is shown in Fig. 1. The PV panel is connected to the load using a DC-DC boost converter. A Boost converter is used with PV to extract the maximum power from the PV panel. Here Perturb and Observe method (P&O) is used for MPPT. HESS gets connected to the load using bi-directional DC/DC converters. HESS is used to maintain the output DC link Voltage constant (V_{DC}) even if there is a mismatch between generation and demand. When the demand is more than generation, V_{DC} drops from its reference value, hence HESS will discharge to provide the surplus demand. Similarly, when the demand is less than the generation, V_{DC} increases from its reference value, hence HESS will be charged to absorb the surplus power. Buck-boost converter is used as a bi-directional converter to facilitate the bi-directional power flow between the load and HESS. This paper presents the load as PMSM Motor.

A. PV PANEL

A Photovoltaic (PV) array that consists of a number of modules is taken into account as the fundamental power conversion unit of a PV generator system [1]. The photovoltaic (PV) cell is nothing but a p-n junction fabricated in a thin wafer of semiconductor. Solar power is directly converted to electricity through the photovoltaic effect. Here Waree Energies WU-120 is used for MATLAB/SIMULINK purposes.

Table 1 summarizes characteristics of WU-120 module by Waree Energies. The specifications are given below

TABLE.1. SPECIFICATIONS OF WU-120 MODULE

Characteristics	Specifications
Typical extreme power(Pmpp)	120.7W
Voltage at extreme power (Vmp)	17V
Current at extreme power (Imp)	7.1A
Short-circuit current(Isc)	8A
Open-circuit voltage (Voc)	21V
Temperature coefficient of open-circuit Voltage(Kv)	-0.358 (%/deg.C)
Temperature coefficient of short-circuit current(Ki)	0.052(%/deg.C)
Approximate effect of temperature on power	-(0.5±0.015) (%/deg.C)

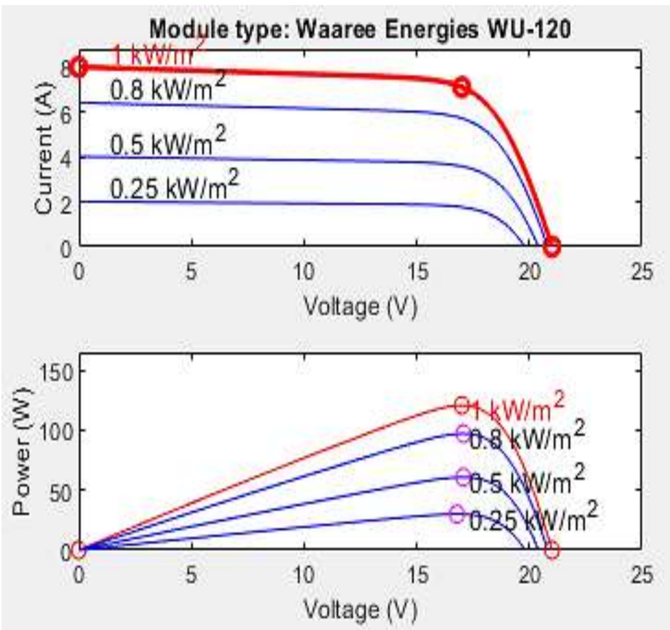

FIG.2. (a) I-V AND (b) P-V FAMILY CURVES FOR DIFFERENT IRRADIATIONS

B. MPPT CONTROLLER

The Maximum power point tracking control algorithm is generally used to extract the maximum capability of PV modules power with the respective solar irradiance and temperature at a particular instant of time by MPPT controller [1]. For efficient tracking, several algorithms are developed to track maximum power point. In this paper, the Perturb & Observe method is used for MPPT. In this, the incremental change in the value of power P is measured. If the measured P value is positive, the operating voltage is increased to get MPP, if the measured value of P is negative, then the direction of voltage adjustment is reversed and the operating point is tried to make closer to the MPP value. The flow chart algorithm is shown in Fig. 3

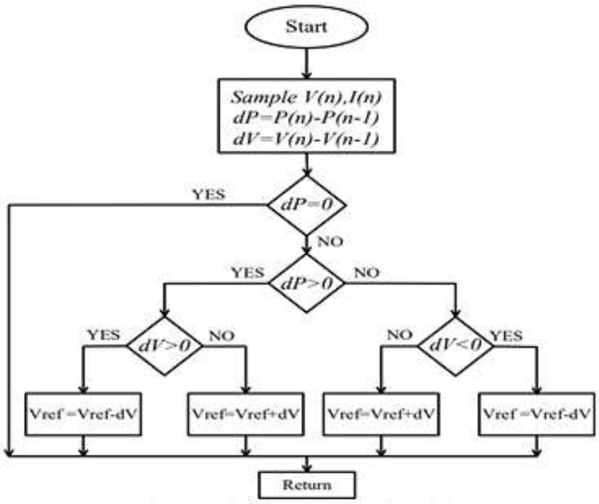

FIG.3. FLOWCHART OF PERTURB AND OBSERVE METHOD

Without MPPT PV power is always less than the maximum PV power for particular irradiation.

C. BATTERY

Lithium Ion batteries are used in EVs as they have high energy density as compared to lead acid batteries and are more efficient. Here 24V lithium ion battery is taken for simulation purposes. The discharge curve of the battery used is shown in Fig 4.

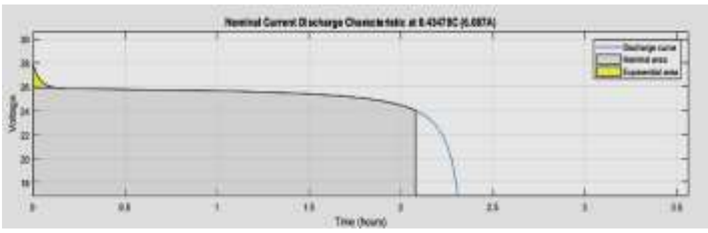

FIG. 4. NOMINAL CURRENT DISCHARGE CHARACTERISTICS

D. SUPERCAPACITOR

A supercapacitor (SC) is a type of high-capacity capacitor with a capacitance value much greater than other traditional capacitors, but with lower voltage limits. It generally stores around 10 to 100 times more energy per unit volume or mass than the traditional electrolytic capacitors, can accept and deliver charge much faster than batteries and is able to tolerate many more charge and discharge cycles than rechargeable batteries. It has high power density and can be recharged instantly. Supercapacitor doesn’t use the traditional solid dielectric material instead they use the electrostatic double layer capacitance or electrochemical Pseudo capacitance [6]. As the area for the charge accumulation increase the Supercapacitors are used for storing high power than normal capacitor. Here Electrostatic Double layered Capacitor is used.

The calculation of the value of capacitance can be done by the following equation:

$$Q=CV \qquad (1)$$

$$C=\frac{Q}{V} \qquad (2)$$

$$C=\frac{\int idt}{V} \qquad (3)$$

The specific capacitance values can be calculated through the CD (Charge Discharge) and CV (Cyclic Voltammetry) curves.

E. BOOST CONVERTER

The Boost converter is used to boost the output voltage of PV array to the required load voltage. Fig.5 shows the basic boost converter circuit.

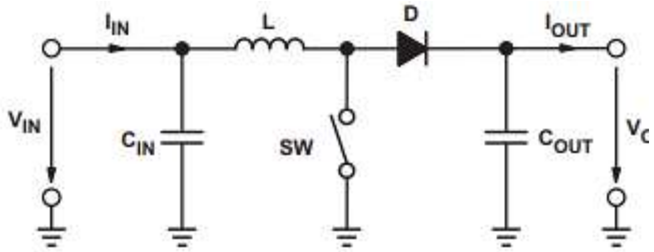

FIG.5. BASIC CIRCUIT OF BOOST CONVERTER

The first step to calculate the switch current is to find out the duty cycle, D, for the minimum input voltage. The minimum input voltage is checked as it yields the maximum switch current.

$$D = 1 - \frac{V_{in\_min} * \eta}{V_{OUT}} \qquad (4)$$

V_{in_min}-Minimum Input voltage

V_{OUT}-desired output voltage

η= efficiency of the converter, e.g. estimated 80%

The efficiency is added to the duty cycle calculation, as the converter has got to deliver also the energy dissipated. This calculation gives more practical way to measure the duty cycle than just the equation without using the efficiency factor.

The next step to calculate the maximum switch current is to calculate the inductor ripple current.

$$\Delta I_L = \frac{V_{in\_min} * D}{f_s * L} \qquad (5)$$

f_s= minimum switching frequency of the converter

L = selected inductor value

$$I_{OUT\_Max} = (I_{L\_min} - \frac{\Delta I_L}{2}) * (1-D) \qquad (6)$$

I_{L_min}= minimum value of the current limit of integrated switch (as per the data sheet)

ΔI_L=inductor ripple current

$$I_{SW\_Max} = \frac{\Delta I_L}{2} + \frac{I_{OUT\_Max}}{1-D} \qquad (7)$$

The above equations give the values of the different parameters of the boost converter.

The Control Structure

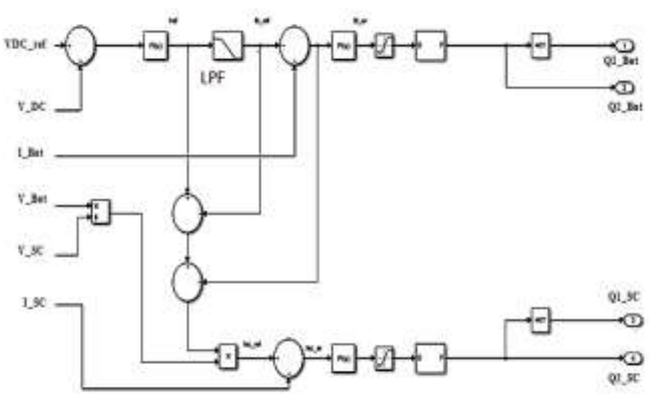

FIG.6. CONTROL SCHEME FOR BATTERY AND SUPERCAPACITOR

Fig.6 shows the block diagram of the control strategy used for simulation purpose. This algorithm reduces the stress on battery and hence increase the lifetime of battery [4]. In the given algorithm, the DC output voltage (V_{OUT}) is compared with a reference voltage (V_{Ref}), and the error is fed to the proportional-integral (PI) controller. The PI controller generates the total current required (I_{Ref}) from HESS. I_{Ref} is separated into low frequency component and high frequency component as

$$I_{B\_Ref} = \text{lowpassfilter}\ (I_{Ref}) \qquad (8)$$

$$I_{Hfc\_Ref} = I_{Ref} - I_{B\_Ref} \qquad (9)$$

The low frequency component of current is fed as the reference current to battery. I_{B_Ref} is then compared with the actual battery current (I_B), and the error(I_{B_err}) is given to the PI controller. The PI controller generates the duty ratios. These duty ratios are fed to the PWM generator to generate switching pulses corresponding to battery switches of bidirectional converter (Q1_Bat, Q2_Bat). Due to the slow dynamics of the battery, I_B may not be able to track the I_{B_Ref} instantly. Therefore, the uncompensated battery power is given as

$$P_{B\_Uncomp} = (\ I_{Hfc\_Ref} + \ I_{B\_err}\ ) * V_B \qquad (10)$$

This uncompensated battery power is then to be compensated by the SC. Therefore, the reference current of SC is taken as shown in below equation

$$I_{SC\_Ref} = \frac{P_{B\_Uncomp}}{V_{SC}} \qquad (11)$$

I_{SC_Ref} is compared with the actual SC current (I_{SC}) and the error is fed to the PI controller. The PI controller generates the required duty ratios. These duty ratios are given to the PWM generator to generate switching pulses corresponding to SC switches (Q1_SC, Q2_SC).

Control Of Permanent Magnet Synchronous Motor (Pmsm) Drıve

In this paper, for regulating the speed of PMSM the control strategy used is dq control method in which parameters are controlled and transformed using Clark’s and Park’s transformation. Step input torque and three phase output voltage of Inverters are given as input to PMSM. The output of PMSM includes stator line currents (I_a, I_b, I_c), rotor speed (ω_e), electromagnetic torque (T_e) and rotor angle (Θ). The actual rotor speed is compared with reference speed and the error is fed to a PI controller which generates I_{Q_Ref} current. By applying inverse Park’s transformation I_{abc_Ref} is generated. I_{abc_Ref} and I_{abc} (feedback taken from PMSM stator output terminals) are compared in PWM Inverter and

PWM inverter generates three phase voltages V_a, V_b, V_c and this three phase voltages are given to PMSM input terminals from which the rotor speed is regulated.

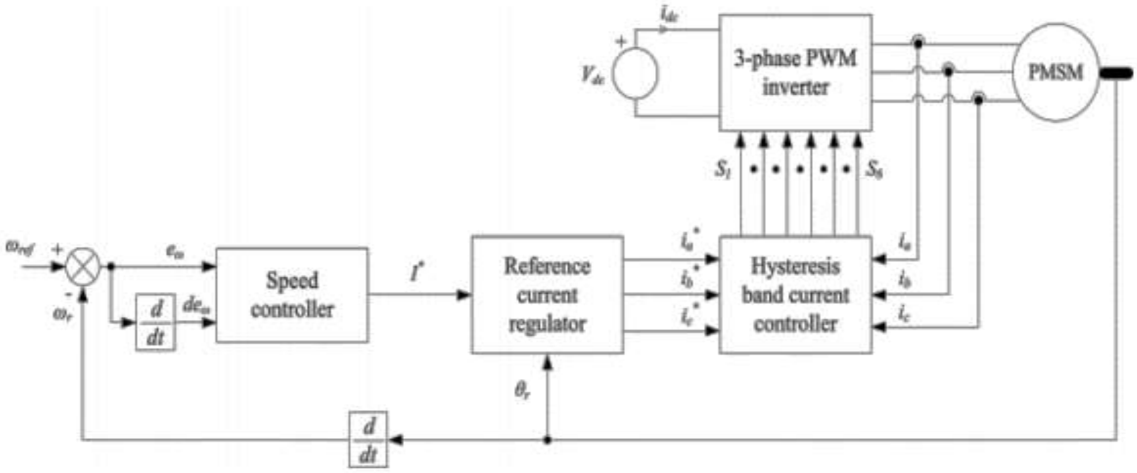

FIG.7. BLOCK DIAGRAM OF PMSM DRIVE

Sımulatıon Results

The presented control strategy is validated using Matlab/Simulink for variation in solar irradiation and constant temperature as shown below:

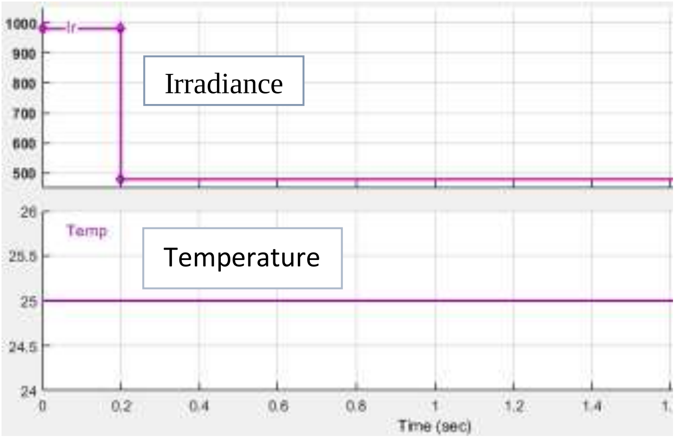

FIG.8. IRRADIANCE AND TEMPERATURE INPUT TO PV ARRAY

The objective is to maintain the output voltage at V_{Ref} = 50 V even if the irradiance is reduced. The initial State of Charge (SOC) of the battery is set at 50%. Fig. 9 shows the PV output results.

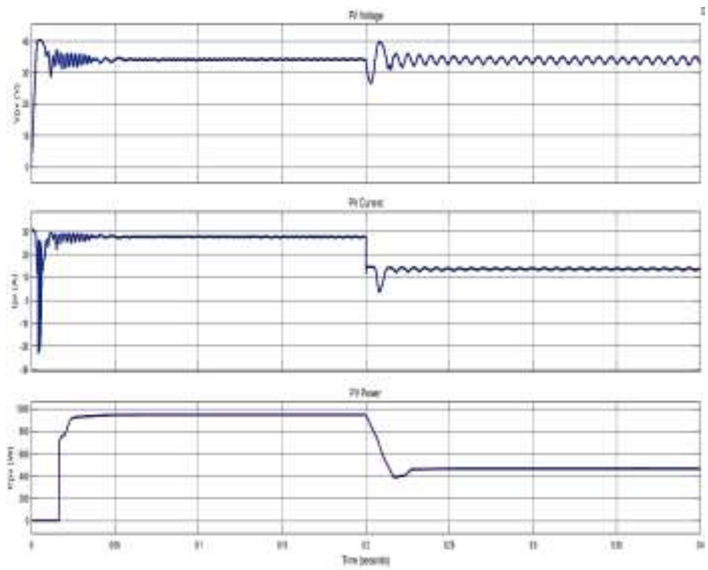

FIG.9. PV VOLTAGE, PV CURRENT AND PV POWER

As shown in the above figure the changes in the irradiance reduces the output current of the PV array and hence the PV power also reduces but the load voltage should not change as the battery and supercapacitor provides the remaining power.

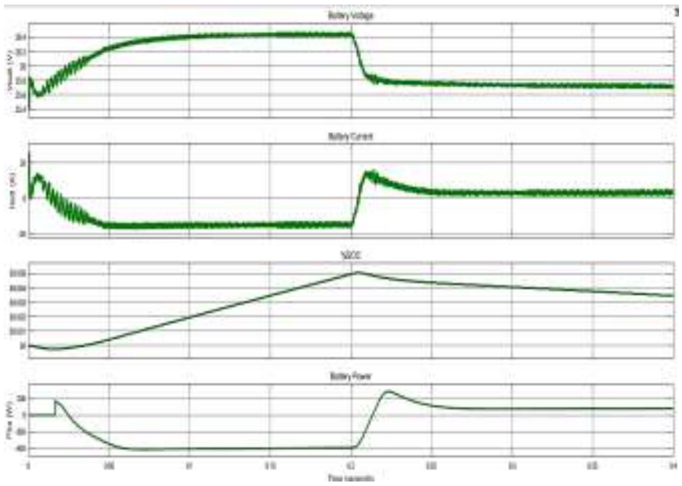

FIG. 10 VOLTAGE, CURRENT, %SOC AND POWER OF BATTERY

As shown in the figure the battery gets charged when the demand of the load is less than the generated power by PV hence the battery gets charged and when the irradiance reduces the PV power is less and thus the battery gets discharged and supplies the load along with the supercapacitor as shown in Fig 11.

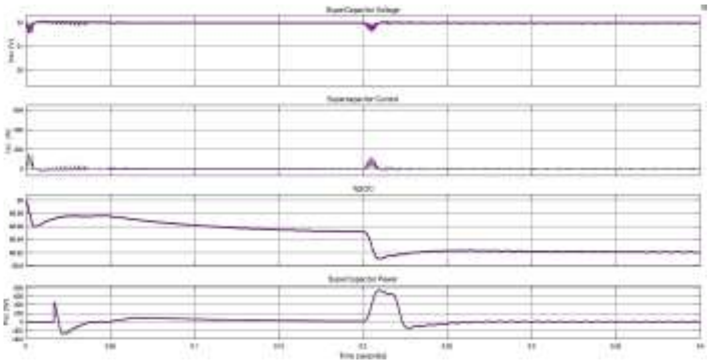

FIG.11 VOLTAGE, CURRENT, %SOC AND POWER OF SUPERCAPACITOR

The output power of the combined Hybrid Energy storage system with DC load is as shown below in Fig 12.

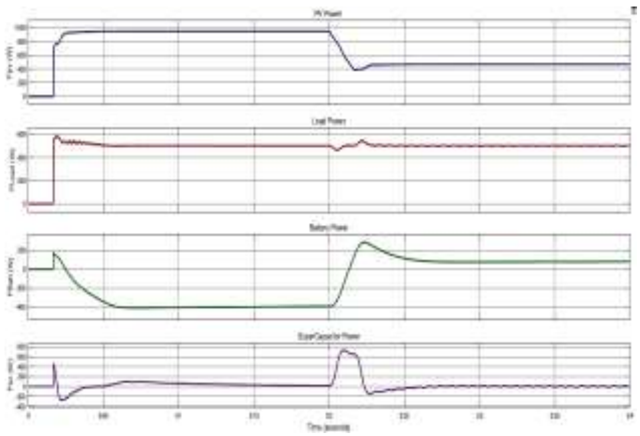

FIG. 12 WAVEFORMS OF PV POWER, DC LOAD POWER, BATTERY POWER AND SUPERCAPACITOR POWER

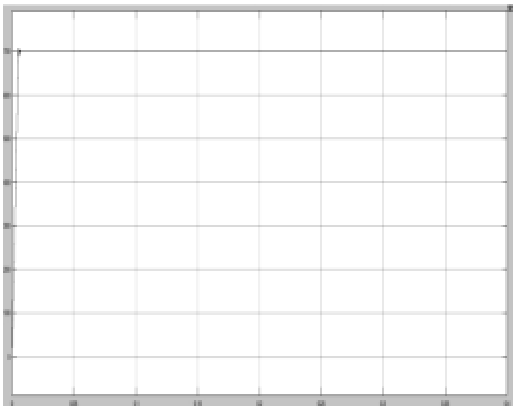

FIG.13. REFERENCE ROTOR SPEED SET CONSTANT AT 700 RPM

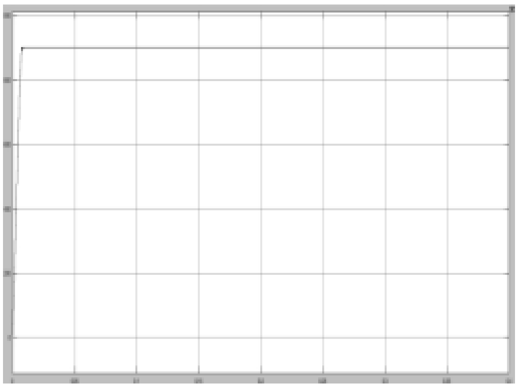

FIG.14. ROTOR OUTPUT SPEED REMAINS CONSTANT AT 900 RPM

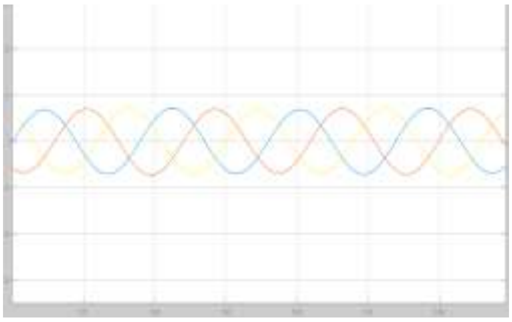

FIG.15. THREE PHASE INVERTER OUTPUT LINE CURRENTS WAVEFORM

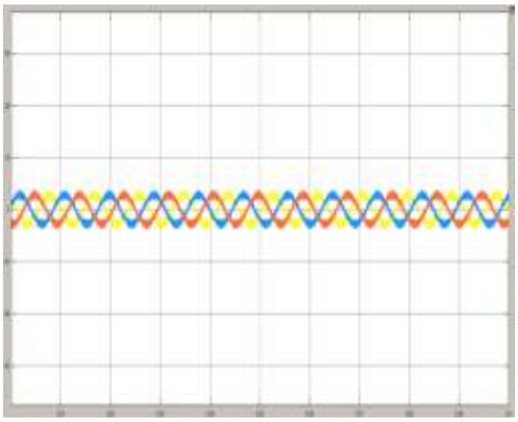

FIG.16. THREE PHASE OUTPUT LINE CURRENTS WAVEFORM OF PMSM MOTOR

Conclusıon

The proposed hybrid energy storage system is designed to ensure the continuity of power supply to PMSM motor. In this energy storage system when the demand is less than the PV generated power then the auxiliary sources that is the Battery and Supercapacitor gets charged and the output dc voltage remains constant at 50 volts till 0.2 sec, while when the demand is higher than the PV generated power then the auxiliary sources provide the remaining power to the load and keeps Load Power constant and also dc link voltage constant at 50 volts even after 0.2 sec. In this paper by using proper LCL filtering technique the three phase output line currents from the inverter (which is sinusoidal with low total harmonic distortion compared to unfiltered normal hybrid energy storage system) is given to the PMSM motor which results in better running performance of motor and hence better performance of the overall proposed hybrid energy storage system as compared to normal hybrid energy storage system is achieved.

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