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Assessment of Performance of Integrated Solar PV System with Hybrid Energy Storage System

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Abstract— It has now been a well-known fact, as a result of extensive research, that energy obtained through solar radiation is intermittent in nature with nearly unpredicted fluctuations in output power. By the virtue of such irregularities, the stability and power quality of Photo Voltaic based power system operation are affected. The present work is aimed to achieve the PV system stability by using battery and ultra-capacitors to support a stand-alone PV power system. Certain loads like induction motor or DC motor draws large current at the time of starting resulting in deep-discharging of the battery as a consequence of which the battery undergoes accelerated aging. Using ultra-capacitors in conjunction with the battery takes care of the sudden initial power demand of the dynamic systems. In the present work a practical approach has been presented to derive the benefit of using ultra-capacitor in conjunction with battery to store energy obtained by solar PV system. Furthermore, the performance of the ultra-capacitor and battery hybrid energy storage scheme is tested and verified by applying different loads on the system. The experimental setup consisted of a 24V, 6.5Ah, lead acid battery bank unit; 3.33F, 24.3V, ultra-capacitor bank unit; a 70W, 32V, PV Panel; dc-dc converter unit; inverter unit, controller unit and load. A comparison has been done between input and output voltages and current waveforms of the inverter with and without ultra-capacitor bank.

Keywords – Solar Photo Voltaic (SPV), Battery Energy Storage (BES), Ultra-Capacitor (UC), Hybrid Energy System

I. INTRODUCTION

The persistent rise in energy consumption, the accelerating price, the effect of inducing contamination in the environment due to the usage of fossil fuels and the global warming concern motivated the researchers towards making renewable energy sources more efficient. The technologies working in the field of renewable energy have attained increased reliability level, and proved to be competitive as compared to conventional power generating systems [1-6]. The renewable energy sources, as a stand-alone unit, have potential to provide sustainable electricity to the remote regions where conventional power grid fails to serve. The increasing demand for renewable energy has resulted in the development of proper energy storage system with appropriate energy dispensing mechanism [7-12]. The interest in utilizing Solar PV technology is also spreading very fast. With the further advancement in the PV technology the leveled cost of energy by solar power systems is now comparable with the conventional energy sources [13][15]. PV systems can be used as a stand-alone system or it can be part of a hybrid system. The question of availability of solar energy systems has not been addressed satisfactorily by available technological schemes. Therefore, battery integrated solar systems have higher reliability as compared to battery-less solar systems. Still the currently available battery integration systems with solar is unable to cope up with the power requirements of dynamic loads. In order to overcome this shortcoming, researches have been conducted in the concept field of developing efficient energy storage devices [16-19]. The storage devices are capable to alleviate the fluctuations in generated power by the PV systems and hence inject smooth power to the utility grid. A single storage device is unable to effectively reduce the fluctuations in power, because of frequent high charging and discharging power flow from the storage devices. PV system integrated with energy storage devices such as battery and ultra-capacitors is capable to handle the power fluctuations in an effective manner. Battery and ultra-capacitors respond faster to an instantaneous increase or decrease in power output. These energy storage devices improve quality of power produced by the PV system by smoothing the power [20-26]. To escalate the lifetime of battery, an ultra-capacitor bank is used along with battery to take care of the battery stresses caused due to transient responses. The ultra-capacitor storage systems have practically very large cycling capability but it suffers from lower energy density as compared to a battery. The high power density feature of ultra-capacitors helps batteries during peak load demand. The operating temperature of ultra-capacitor is large with a longer effective life [27-31]. In present work a practical experimental setup is used to analyze the performance of Solar PV system along with hybrid energy storage system. Using the energy storage device improves the performance by absorbing faster load variations so that the power supplied to load is smooth. A DC-DC bidirectional converter, acting as charge controller, is used for the charging and discharging of the ultra-capacitor and battery. The developed system provides superior reliability and eff ectiveness. The main contributions of this work are: (1) Design and development of a stand- alone PV power system with Hybrid energy storage system; (2) devising a control algorithm for controlling charging and discharging of battery and ultra-capacitors through dc-dc converter to support the PV output power; (3) Selection of appropriate number of series and parallel operated ultra-capacitors for proper power sharing. Consequently, in this work the improvement in availability of a hybrid solar system with battery and UC is analyzed.

The remaining sections of the paper are organized as follows: In section II, the system configuration for the experiment is presented, in section III the components of the energy storage system have been described, the results and discussion are presented in section IV and finally in section V conclusion is drawn regarding experimental results obtained.

II. PROPOSED WORK

The energy storage system setup, as shown in figure 1, consists of a Photo Voltaic module, a DC to DC converter, Battery Bank, Ultra capacitor bank, uncontrolled rectifier, inverter, filter, controller, static transfer switches (relays), AC load and DC load. The actual setup is shown in figure 2. The functioning of the setup is that the solar PV module takes energy from the sun light (photons) and converts it to electric power. The output of the PV is DC and is fed to the DC bus bar through the DC to DC converter. Battery bank and UC bank are also connected to the DC bus bar through bi-directional DC to DC converters. The DC bus bar maintains the 24V DC power and the DC loads are directly connected to this bus bar. The AC load requires the inversion and stepping up of the DC bus bar voltage which is achieved in the inverter section. The main AC line is fed to uncontrolled rectifier which is used to cater the DC loads in the event of unavailability of PV, battery and UC. The rectifier output is also used to charge the battery and UC when the PV is not available. AC loads are fed directly through the main line when the PV system is down.

III. SYSTEM COMPONENTS

(i) Photo Voltaic System:

The reported solar energy constant or solar power density is 1.373kW/m^2 in the outer atmosphere. Earth's atmosphere is responsible for absorbing and scattering a portion of this energy and the energy that is finally received on the surface of the earth is about 1kW/m^2. Solar PV cells convert the solar energy into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunications, and television can be run from photovoltaic electricity [2, 4]. A PV cell is similar to a p-n junction diode and it works on the basis of photo voltaic effect. A PV cell creates free charge carriers when light is incident on it. Figure 3 represents equivalent circuit of a PV cell which consists of a current source in parallel with a diode and a resistance that represents the path for leakage current during saturation.

The total output current of the cell can be obtained by the following expression:

$$I_{out} = I_{pv} - I_D$$

where,

$$I_D = -I_0 \times S; \quad S = (e^M - l);\ M = QV/KT$$

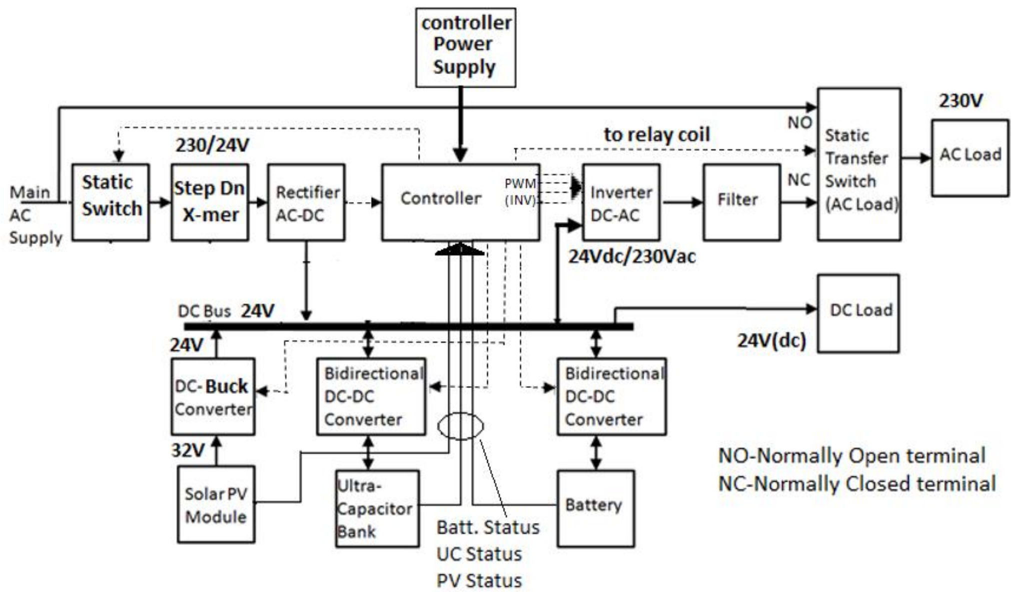

Figure: 1 Block presentation of System setup.

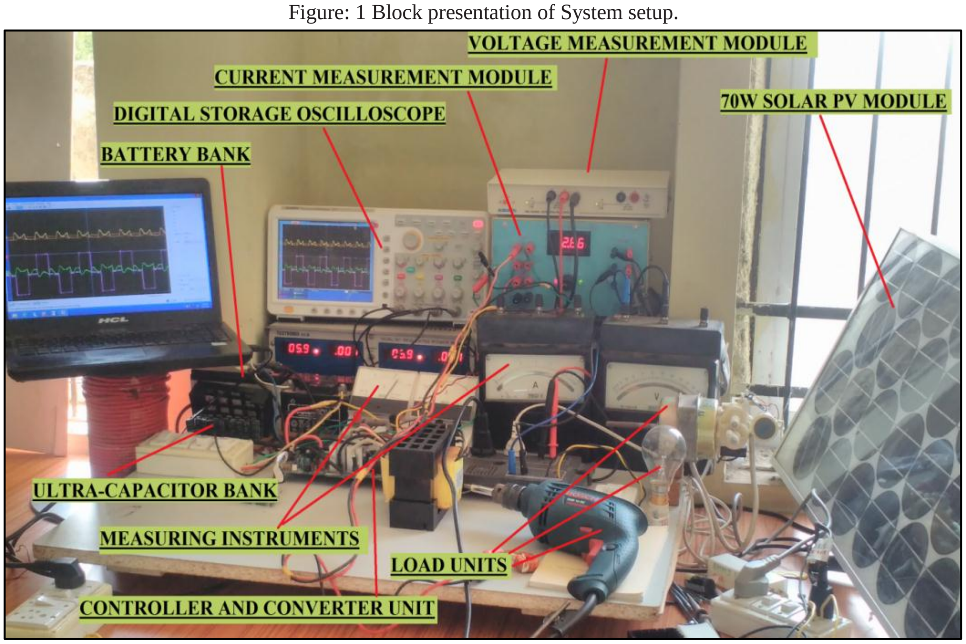

Figure: 2 Experimental System setup.

where,

I_{out} = output current to the converter

I_{pv} = current from pv cell

Q = electronic charge

V = terminal voltage

I_0 = the reverse current due to saturation

I_D = current through the diode

T = operating temperature of pv cell

K = the Boltzmann constant

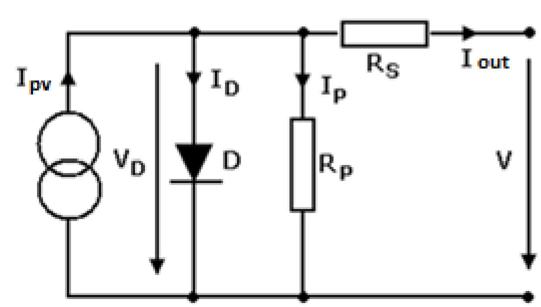

Figure: 3 PV Electrical equivalent circuit [4].

A 70W, 32V, PV panel is utilized in the setup to supply the DC bus. The dc bus voltage is maintained at 24V dc so a dc-buck converter is used to step down 32V PV output to 24V at DC bus.

(ii) PV Charge Controllers

PV cells are required to be protected against any reverse current flowing through it on account of batteries being discharged under the event of absence of sun light. For fulfilling the purpose mentioned above, charge controllers are used. As discussed above, a PV cell resembles a p-n junction diode. Therefore, in the absence of sunlight the PV acts as a short circuit to the battery and causes it to discharge with enormous current and heat generation due to its high internal resistance. So, a charge controller also protects the battery from getting short-circuited through the PV system [5, 10]. In order to protect the PV module and the battery, a step-down DC-DC converter is employed in this circuit to act as a charge controller. Figure 4 presents the circuit configuration of the charge controller employed with the PV module.

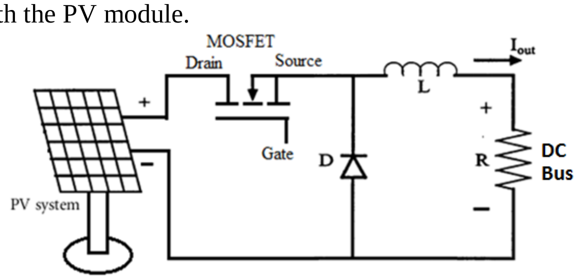

Figure: 4 Step down DC to DC converter

The step-down chopper configuration helps in maintaining the two voltage levels: 32V at the output of the PV module and 24 V at the DC bus bar. The operation of the buck converter can be divided into following two modes:

Mode 1: In this mode, the MOSFET switch is turned on and the PV output is connected to the DC bus through the high current inductive choke coil. The inductor stores the energy during this period.

Mode 2: In this mode, the MOSFET switch is turned off and the charged inductor pushes the current through the dc bus and the free-wheeling power diode. The value of inductor for the circuit is so chosen so as to maintain the continuity of current through the output.

The converter is made to operate in these two modes as long as the PV output is available with 32V at the terminals. But as the PV voltage goes down below 28V (due to the absence of solar radiation or other reasons) the converter is shut down through the controller by stopping the PWM pulses.

The switching of the MOSFET is done by utilizing pulse width modulation (PWM) technique. The PWM is generated in the microcontroller unit and the output is amplified and isolated before applying it to the gate terminal of MOSFET. The voltage appearing at the output of the converter is the function of duty cycle. The expression for the average voltage appearing at the output of converter, V_o can be expressed as:

$$V_o = \frac{T_{on}}{T_{on} + T_{off}} V_s = \frac{T_{on}}{T} V_s = \delta V_s \quad (1)$$

where, T_{on} = on duration; T_{off} = off period;

$$T = T_{on} + T_{off} \quad (2)$$

$$\text{Duty Cycle } (\delta) = \frac{T_{on}}{T_{on} + T_{off}} \quad (3)$$

the frequency of interruption is calculated by

$$f = \frac{1}{T} \quad (4)$$

The MOSFET employed in the circuit is P55NF06. Microcontroller ATMEGA 328 is employed to generate PWM for the converter. The switching frequency of the device is maintained at 1.2kHz. For isolation purpose, opto-coupler EL3021 is used. The 250µH inductor is used in the circuit with the output capacitor of 560µF, 50V (not shown in the figure). LEM LV 25-P hall effect voltage sensor is used to monitor the PV voltage and the signal is sent to the microcontroller to control the duty cycle.

(iii) DC-DC converter Unit

The proposed hybrid energy storage system consists of a battery bank and an ultra-capacitor bank. These are connected to the DC bus through Bidirectional DC-DC converter. The function of this bidirectional dc-dc converter is twofold. Firstly, in boost mode the converter connects the charged battery and/or Ultra-capacitor to the DC bus. In this mode, the energy stored in the battery or UC is supplied to the DC bus. Secondly, in buck operation mode the DC bus supplies the discharged battery and UC through the converter [9, 11]. The Bidirectional DC-DC converters are PWM controlled which are generated in the controller section. The controller continuously monitors the charge (voltage) status of the battery and the UC. As the voltage decreases to 18V the voltage transducer sends the status to the controller and the controller individually changes the mode of operation of the two converters by changing the PWM inputs to the switches. The circuit diagram of the converter is presented in figure 5. The operation of the converter can be divided into following four modes:

Mode 1: In this mode, the converter is made to operate in buck mode where DC Bus supplies power to the battery/capacitor. The buck mode can be further into two stages: in first stage the SW1 is turned on while keeping SW2 off. The current takes the path from DC bus terminal A; through SW_1; through inductor, L and Capacitor C_{out} to UC Bank (or Battery). C_{out} is chosen large enough so as to maintain the voltage constant across the load. In second stage of buck mode SW1 is switched off and the charged inductor pushes the current through the output capacitor, C_{out}; through diode, D_2 and back to inductor, L. the value of the inductor choke is selected such that to maintain the current continuous throughout the cycle.

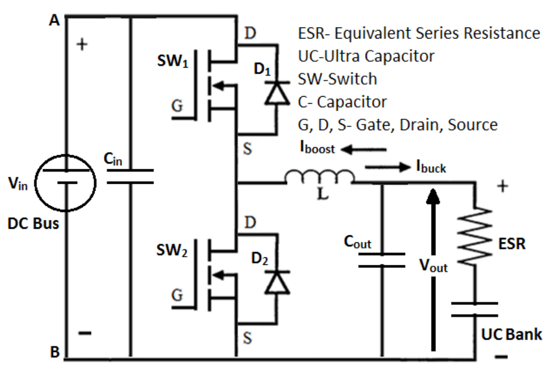

Figure: 5 Bidirectional DC-DC Converter

Mode 2: In this mode, the converter is made to operate in boost mode where the charged UC bank or the battery bank supplies the power back to the DC bus. This mode can also be divided into two stages: in first stage the switch SW2 is turned on while SW1 is kept off. In this stage the UC /Battery bank charges the inductor through switch SW2. In second stage SW2 is turned off and the load voltage in addition with the inductor voltage, forward biases the diode D1 and hence supplies the power back to the DC bus. The switching pulses provided to the two switches are complementary in nature and is controlled by the controller. The switching frequency utilized for this converter is 1.2kHz. The input and output voltages follow the following relation while operating in steady state:

$$V_{out} = \delta V_{in} \text{ (in buck mode)}$$

$$V_{out} = \frac{V_{in}}{1-\delta} \text{(in boost mode)}$$

The MOSFET IRF540N with V_{DS}=100V and I_D=33A is used for switches SW1 and SW2. This MOSFET has built-in diode connected between drain and source. Value of C_{in} and C_{out} is 2200uF/50V and inductor L is 100mH. LEM LV 25-P hall effect voltage sensor is used to monitor the UC/Battery bank voltage and the signal is sent to the microcontroller to control the duty cycle of the converter.

(iv) Inverter System

The inverter is required to convert power from DC to AC so as to cater the power requirements of AC loads. In the proposed system, the inverter is constructed using four power MOSFETs which form a bridge circuit. MOSFETs have the advantage of low switching losses. The output of the MOSFET bridge circuit is a square wave output which has a very high percentage of total harmonic distortion (%THD), to bring the THD to a permissible level an L-C filter circuit is introduced in between inverter and converter transformer [11, 16]. The converter transformer is a step-up transformer to meet the required 230V AC at the load end. PWM signals are used for gating the MOSFETs, which are generated in the control unit using microcontroller.

The general layout of a single-phase full bridge inverter system is presented in figure6.The capacitor C_{in} is connected across the DC source to maintain the voltage constant. IRF2805 (with V_{DS}=55V and I_D=75A), are used as switches which has inbuilt diode in anti-parallel. The gate signals provided to the switches are in pair (S1-S4 and S3-S2). S1 and S4 are gated for first half of the period and S3 and S2 for another half of period. The pulses generated are complementary in nature. Microcontroller ATMEGA 328 is employed to generate PWM signals for the devices. The switching frequency is maintained at 10kHz with a dead time of 5µs.

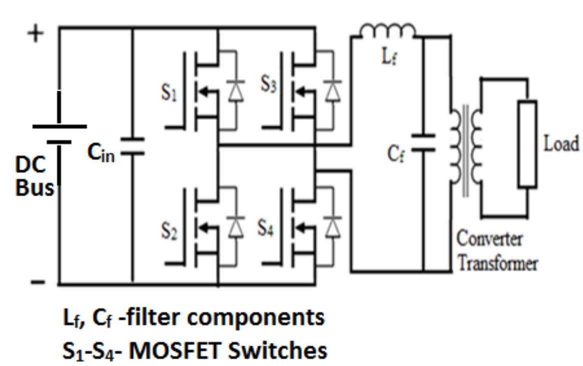

Figure: 6 Inverter system

(v) Battery Unit

A stand-alone photo-voltaic system requires energy storage in order to make the system self-sufficient and reliable to supply the load during off-solar periods and at the night time. Owing to the better energy storage Lead Acid batteries have been used in this work. Cost-effectiveness and power reliability of a PV power system rely on the provision made for storage of electrical energy. Lead-acid batteries are preferred as it gives the long-lasting performance of storing energy [28-30].

Two 12V, 6.5Ah, Lead acid batteries are connected in series and used for maintaining 24V at DC bus. Every battery is specified with the nominal number of complete charge and discharge cycles which are used to estimate the life of batteries for particular application. Two factors that are identified responsible for limiting cycle life of batteries used with PV systems are incomplete charging and prolonged operation at a low state-of-charge (SOC) [28-32]. An active solution for the required storage capacity and the maximum depth-of-discharge of the battery is achieved by employing UC. UC plays a vital role in achieving this by preventing the battery to attain maximum depth of discharge under the event of frequent starting of the dynamic electro-mechanical loads.

(vi) Controller Unit

The control unit sets the platform to have interaction between various components of the energy storage system. In order to execute the control process, the control unit takes the input in analog and digital form from different voltage and current sensors, charge status detector. The controller recognizes the inputs, compares with the set values, processes it if required, and issues the signal to output switches (relays, MOSFET's, etc.) to perform necessary operation. The controller used for this work is 8-bit microcontroller: ATmega328.The controller senses the availability of the utility, the PV array output power, the power required by the load and state of charge of the battery and UC and compares them to each other or to a reference value as per the designed control algorithm instruction and then send a control signal to the system output switches. Table 1 summarizes the modes of operation of the proposed system. S_{Load}, S_{PV}, $S_{Utility}$, $S_{Battery}$, and S_{UC} are the load power, PV array output power, utility power, battery power and UC power respectively. The complete sequencing is presented in figure7.

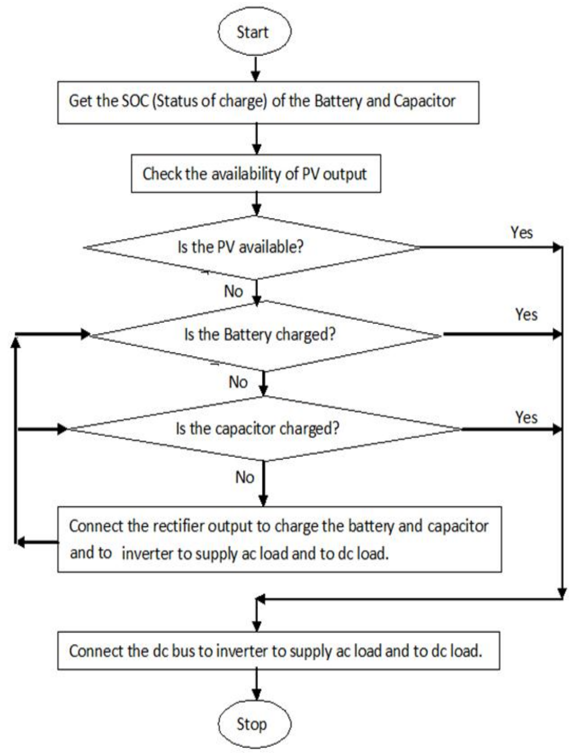

Figure. 7. Controller switching sequence algorithm

(vii) Ultra-capacitor unit

UCs are large capacitance electrochemical type double layer capacitors. The capacity of an UC depends on the manner in which its electrodes are designed. For a well-designed electrode, the order of capacitance available is in the range of thousands of farads [31, 32].

Table:1 System mode of operation

Modes	Status of Source	HES system controller priority
Mode:1	$S_{PV} = 0$	$S_{Load} = S_{UC} + S_{Battery}$
Mode:2	$S_{UC} + S_{battery}=0$	$S_{Load} = S_{Utility}$
Mode:3	S_{PV}, S_{Load}	$S_{Load} = S_{UC} + S_{Battery} + S_{PV}$
Mode:4	S_{PV}, S_{Load}	$S_{Load} = S_{PV}$

- In mode 2 when PV is not available then Battery and UC are both charged through utility.
- In mode 4 the excess PV is used to charge Battery and UC.

UCs are designed to operate at a low voltage of about 2.3-2.7V. In order to meet the high voltage demands, the ultra-capacitors are connected in series. In order to maintain the capacity of the UC, the series strings must be connected in parallel as shown in figure 8. As compared to an electrolytic capacitor, the energy density of an UC is 100 times larger but as compared to the lead acid battery it is much smaller. However, the power density of UC is 10 times larger than that of a lead-acid battery. UC has a fast charge-discharge capability owing to its very low internal resistance, it has a longer life cycle, it requires minimal or almost no-maintenance and it is free from emitting any matter that may prove to be harmful to the environment. The energy storage system presented uses 9 capacitors of 2.7V rating in series to attain required 24V and three such combinations are connected in parallel to get adequate Ah capacity. The UC units are thus arranged to build a UC bank which is capable to meet the demand of short-term peak load. The energy supplied by UC bank can be expressed as:

$$S_{UC} = \frac{1}{2} C(V_i^2 - V_f^2) \quad (5)$$

where,

S_{UC} = Energy supplied by UC

V_i = voltage measured initially.

V_f = voltage appearing after final discharge.

C = Capacity of UC bank.

Evaluation of UC bank Capacity.

$$C = N_{||} \times \frac{C_{1\_unit}}{N_{series}} \quad (6)$$

C = UC bank Capacity

Where,

$N_{||}$ = no. of parallel unit

C_{1_unit} = Capacity of one UC

N_{series} = no. of UC in series

$$C = 3 \times \frac{10F}{9} = 3.33F$$

$$V_{UC\_Bank} = N_{series} \times V_{1\_UC} \quad (7)$$

Voltage of the UC bank = $9 \times 2.7V \cong 24V$

Figure.8. Ultra Capacitor Bank

IV. Results and Discussions

The hybrid energy system performance is evaluated using three different loads which include a single- phase capacitor start and run type induction motor with 230V, 55W capacity, 60W incandescent lamp acting as a resistive load and AC series motor. The experimental setup shown in figure 2 has been used to obtain input and output waveforms of voltages and currents with all these loads. The waveforms are presented in figures 10 and 11. The description of signals acquired in the digital storage oscilloscope (DSO) is outlined in the table 2.

Table 2: Signals acquired from DSO

Channel	Quantity
Ch1	Inverter Input Voltage
Ch2	Inverter Input Current
Ch3	Inverter Output Voltage
Ch4	Inverter Output Current

Figure 9 shows the variation in all the quantities when a single-phase induction motor with a resistive lamp load is operated from the inverter output without UC bank. It is apparent from the waveform of current that the motor draws a high current initially and then achieves a normal state; at the same time the voltage experiences a dip. In figure 10, the same set of load condition is prevailing but this time a charged UC bank is connected with the battery bank.

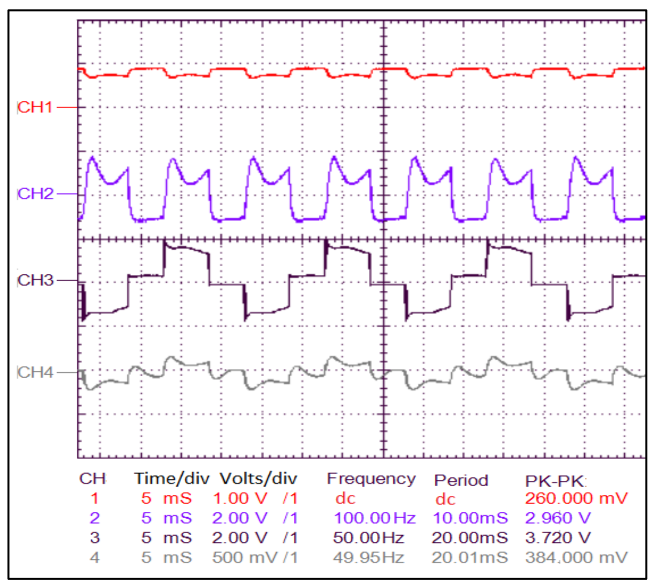

Figure. 9. Waveforms without UC bank.

From the waveform of figure 10 it can easily be observed that the initial rise in the current waveform in the previous case is curtailed by the capacitor bank power and the dip in the voltage waveform is also improved.

Figure 11-14 shows the comparison of the waveforms on an individual basis. MATLAB/SIMULINK software is utilized to clearly observe the difference.

The inverter input voltages are plotted in figure 11. The MATLAB environment has been used to compare the two situations where system is supplying load without UC and then with UC. The sudden dip in the initial part of the voltage waveform in each cycle is curtailed by the UC power. This prevents the system to undergo large voltage variation and minimizes the filter requirement in the input side of the inverter.

In figure 14, the current drawn by the motor takes a peak value which toils the battery and hence the battery has to suffer deep discharge cycles.

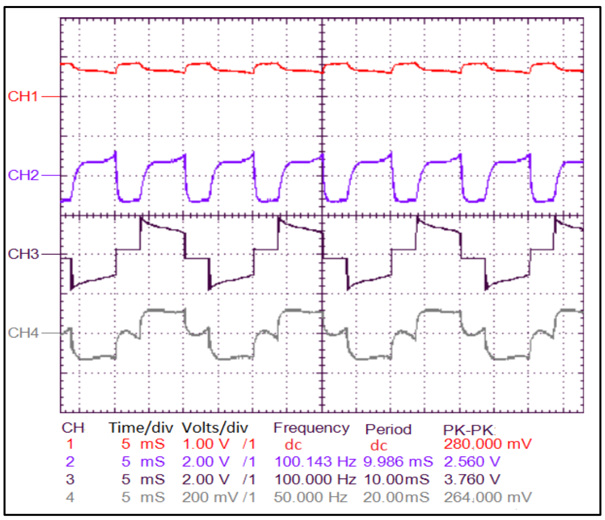

Figure. 10. Waveforms with UC bank.

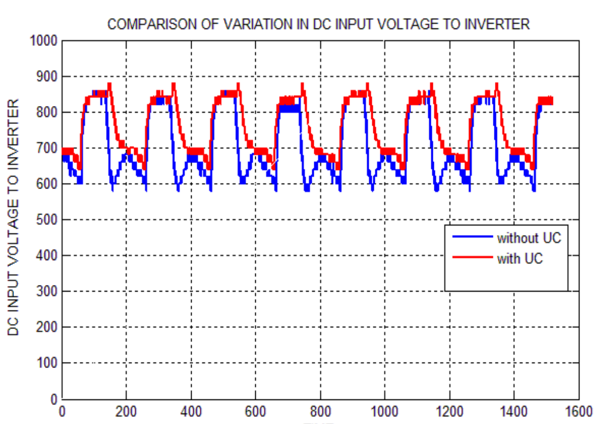

Figure. 11. Inverter input voltage waveform comparison with and without UC bank (Voltage scaled 25X; Time in ms).

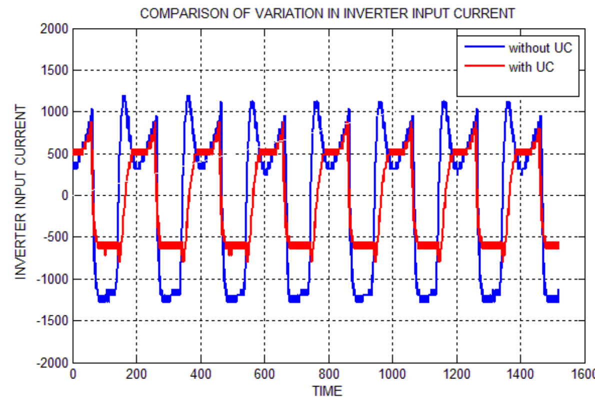

Figure.12. Inverter input current waveform comparison with and without UC bank (Current in mA; Time in ms).

With Ultra capacitor, the waveform shows considerable improvement in leveling up the extremes. In figures 13 and 14 the similar phenomena can be observed with the inverter output voltage and current waveforms. The output of the inverter takes a quasi-square wave shape which changes with variation in the load parameters.

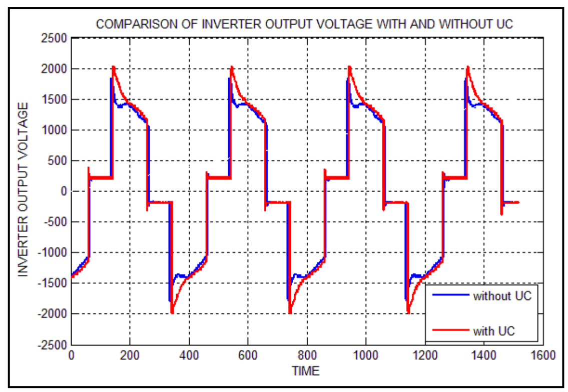

Figure. 13. Inverter output voltage waveform comparisons with and without UC bank (Voltage scaled 10X; Time in ms).

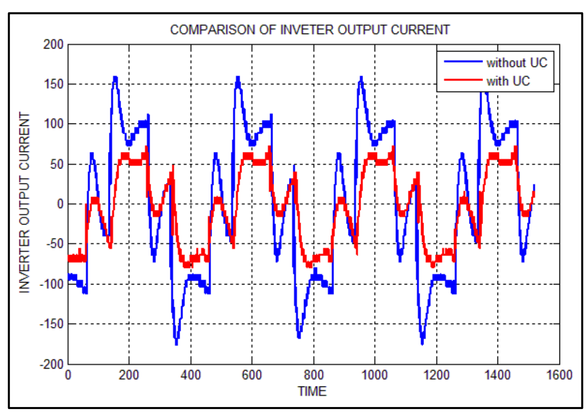

Figure. 14. Inverter output current waveform comparisons with and without UC bank (Current in mA; Time in ms)..

V. CONCLUSION

The work presented in the paper is aimed towards proving the potential of ultra- capacitors to cater sudden power demand placed by inductive loads particularly at the time of starting. The specialty of UC lies in the fact that is capable of charging and discharging at very high rate. Therefore, UC is employed for a number of high power applications. Owing to its high charge and discharge rate UCs can be employed to the places where high chunk of power is required at frequent intervals. The potency of UC is realized in this work by connecting it with the battery to a PV based power supply system. A 60W, 230V single phase induction motor is employed as the load and the performance is analyzed both with battery storage alone and battery with UC. The result obtained indicates that with the current UC capacity of 3.3Farad at 24V, the percentage reduction in the exhaustion of battery is nearly 20-25% and as the capacity of the UC is increased the significant reduction in battery power exhaustion can be achieved. From the above it can be concluded that the higher capacity of UC will help the battery to operate in the stable region of operation. Solar PV system along with the UC and battery combined storage can provide reliable long lasting power to all such loads which undergo dynamic cycles.

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