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# Experimental investigation of a new smart energy management algorithm for a hybrid energy storage system in smart grid applications

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ABSTRACT

Renewable energy sources (RES) are becoming an important part of energy continuity for today's electrical power grid, since RES are intermittent and unstable. Energy storage technologies are the only solution for this energy sustainability problem. In this study, a new Smart Energy Management Algorithm (SEMA) is proposed for Hybrid Energy Storage System (HESS) supplied from 3-phase 4-wire grid connected photovoltaic (PV) power system. HESS consisting of battery and ultra-capacitor energy storage units is used for energy sustainability from solar PV power generation system. Several different operation cases in HESS have been analyzed and experimentally tested by using the proposed SEMA. In experimental tests, load status of one sunny day and PV power profile have been created and tested dynamically by using SEMA and some of the test results in eight different operation modes are given in this paper. The battery group is charged with 1320 W power by the system and remaining energy is transferred to the grid with 5% current harmonic via the inverter in one of the operation modes. The HESS is the most effective energy storage system due to its high power density, fast response, and high efficiency. The proposed system has been verified simulations results and experimental tests.



## 1. Introduction

Grid-connected solar photovoltaic (PV) power generation systems are the most widely used type of solar energy applications nowadays. Currently, the large scale grid-connected PV power generation systems are considered to be one of the main ways to decrease costs, reduce energy consumption and develop the reliability and flexibility of power systems all around the world. A developing trend for PV generation is connection of a large power grid and participates in power flow dispatching [1–5]. PV systems associated with energy storage systems are widely used as energy supplies in remote areas or emerging micro grids. Energy storage devices offer energy buffer for intermittent PV generation to confirm a reliable and sustainable energy supply [6–9].

There are many research papers employing different energy storage technologies for dealing with the challenge of RES. Simulation and experimental results of applying a novel algorithm for the charging and discharging of a battery energy storage system at the grid level are presented in Refs. [10–12]. Hybrid energy storage technologies are preferred instead of sole storage unit in the second generation of storage technologies. There are various studies about optimum usage of hybrid energy resources and hybrid energy system management [1,13–15]. In addition, sizing of storage technologies used in hybrid system, power and energy capacity calculations are another important subjects [6]. Energy storage technologies also have important role to prevent factors affecting power quality.

Integration of 3-phase 4-wire inverter structure to smart grid and management of micro grid arrangement are the innovative approaches of this study. Usage of a Support Vector Machine load predictive energy management system to control the energy flow between a solar energy source, relations between load variations and HESS including ultra-capacitor and battery units has been investigated in Refs. [16–19] to improve the reliability of delivered power. In Refs. [20–25], a new control algorithm for a hybrid energy system with a renewable energy source, a polymer electrolyte membrane fuel cell (PEMFC), ultra-capacitor and a PV array is proposed to improve power quality and efficiency. A scheme consisting of wind and photovoltaic generation subsystems, a flywheel storage system is proposed in Refs. [26–30] for a micro-grid power

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**Nomenclature**

*Acronyms*

| | |
|---|---|
| HESS | Hybrid energy storage system |
| MPP | Maximum power point |
| MPPT | Maximum power point tracking |
| PEMFC | Polymer electrolyte membrane fuel cell |
| PV | Photovoltaic |
| P&O | Perturb and observe |
| RES | Renewable energy sources |
| SEMA | Smart energy management algorithm |
| SOC | State of charge |

*Variables*

| | |
|---|---|
| f | Grid frequency (Hz) |
| $I_{MPP}$ | Current at MPP (A) |
| $I_{BAT\_REF}$ | Battery reference current (A) |
| $I_{PH}$ | Short circuit current (A) |
| $L_g$ | Grid impedance (mH) |
| $P_{BAT}$ | Battery power (W) |
| $P_{BAT\_C}$ | Battery charge power (W) |
| $P_{BAT\_D}$ | Battery discharge power (W) |
| $P_{BST}$ | Boost converter power (W) |
| $P_{LOAD}$ | Load power (W) |
| $P_{max}$ | Photovoltaic maximum power (W) |
| $R_g$ | Grid resistance (mΩ) |
| $V_{OC}$ | Open circuit voltage (V) |
| $V_{BAT}$ | Battery voltage (V) |
| $V_{gabc}$ | Grid voltage (V) |
| $V_{MPP}$ | Voltage at MPP (V) |

generation system. In Refs. [31–35], an energy management system for stand-alone hybrid systems composed by PV panels, a wind turbine and two energy storage systems, which are a hydrogen system and a battery, is examined. Adaptive load shedding scheme for frequency stability enhancement in microgrids, non-cooperative game theory based energy management systems, distributed smart decision-making for a multi-microgrid system and real time experimental implementation of optimum energy management system in standalone microgrid by using multi-layer ant colony optimization are investigated by Marzband et al. [36–39].

The biggest challenge with incorporating renewable energy into the current electrical power system is the fact that the energy produced by renewable energy sources is inconsistent and variable with meteorological conditions. A sunny day without any cloud, the more electric power can be produced with solar energy, but the amount of the produced electrical power is fluctuating continuously by depending on the climatic condition and solar irradiation of the day. Usage of energy storage technology has become an essential solution for providing more power quality to the loads by using smart micro grid structure. Solution of this problem given above is the main aim of this study. The proposed system has a new HESS to the solar power generation system with the proposed SEMA. The proposed SEMA offers control of the load management and shifting between utility source, HESS and photovoltaic power system.

Smart grid technology is only available solution to integrate energy storage systems to the solar power system which is the most promising type of RES. In this study, design, analysis and development of a HESS consisting of a battery and ultra-capacitor unit supplied from solar power system for 3-phase 4-wire smart grid structure and controlling of dynamic response of the system in different operation cases have been provided by using the proposed SEMA. Hence, the combination of HESS with photovoltaic power source and developed SEMA are main contributions of this study. Furthermore, smart energy management of these units has been handled in terms of energy sustainability and power quality should be provided in smart gird structure.

In this paper, eight different operation cases in the proposed system have been analyzed and experimentally verified and tested by using SEMA. In the experimental tests, one sunny day load and solar PV power profile were created and tested dynamically by using SEMA. The HESS together with SEMA is the most effective energy storage device due to its high power density, fast response, and high efficiency. The major contribution of this study contains design; development and detailed analysis of the proposed SEMA for HESS based smart grid applications. The block diagram of the proposed system is given in Fig. 1.

Renewable sources as PV's have intermittent characteristics. Therefore, they should be used with an energy storage system [40]. Usage of only battery energy storage system alone, causes DC bus voltage fluctuations during instant load changes. Usage of the battery unit with ultra-capacitor group increases stability of the system. Also, SEMA perceives the dynamic changes and ensures that the system is operated at steady state cases [41–44].

## 2. Hybrid energy storage system

In this section, grid-connected PV system supported by HESS composed of battery and ultra-capacitor unit in 3-phase 4-wire 4-leg inverter structure is experimentally investigated in a smart micro grid structure. The block diagrams of the HESS and SEMA is shown in Fig. 2. Experimental studies are performed with a HESS supplied from PV power under different operation cases.

PV modules having 5 kW power are used as a renewable energy source in the experimental laboratory setup. The HESS is used as energy storage to overcome the fluctuating of PV power generation and to meet the energy demand in weak solar power condition.

The SEMA is proposed and developed between the battery, ultra-capacitor and PV power to achieve the following goals:

1. Keeping the power equilibrium of all the system,
2. Control of the produced PV power based on the maximum power point tracking (MPPT) algorithm,
3. Increase the performance of the battery by preventing its action with high frequency ripple currents and high rate of depth of discharge to increase the battery lifetime.

Battery and ultra-capacitor units are used together in the proposed HESS. Ultra-capacitors have higher power density but lower energy density. In contrast, the batteries have higher energy density. Therefore, battery and ultra-capacitor energy storage units are used together to get higher power and energy density [45–51]. PV panels work as a current source to deliver appropriate energy to the grid. When the micro grid is connected to the main grid, PV panels provide power under MPPT mode as a current source. A DC/DC bidirectional converter provides energy for the DC bus and the energy storage system from the grid. The battery bank is controlled to discharge properly, until they are totally discharged. By utilizing battery and ultra-capacitor together in a hybrid energy storage system as shown in Fig. 2, the battery size can be reduced and a higher state of charge (SOC) can be maintained.

## 3. Control structures of boost and bi-directional converter

There are eight different operation cases based on energy flow in the proposed power system. These cases are transferring power from PV to the load and energy storage system, transferring power from grid to energy storage system and load, the last one is the

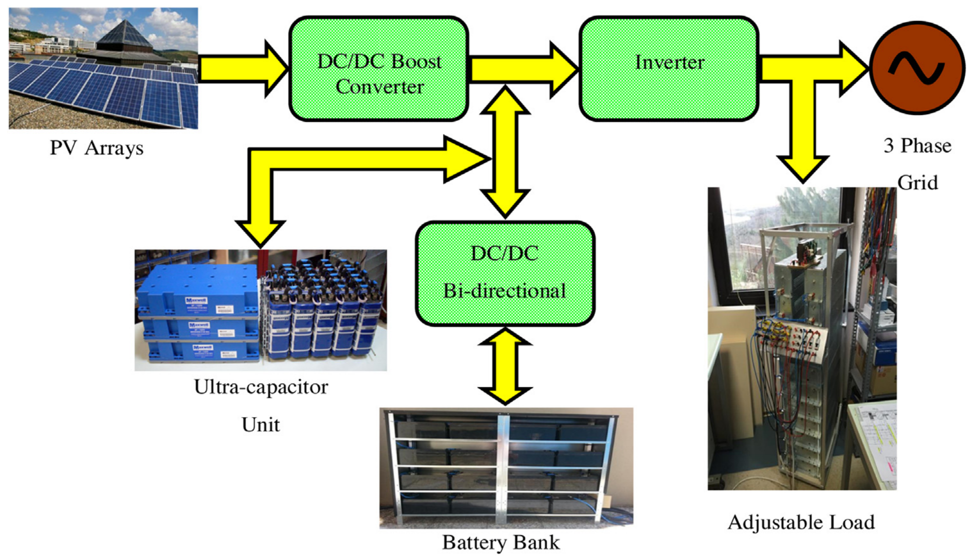


**Fig. 1.** The proposed HESS block diagram.

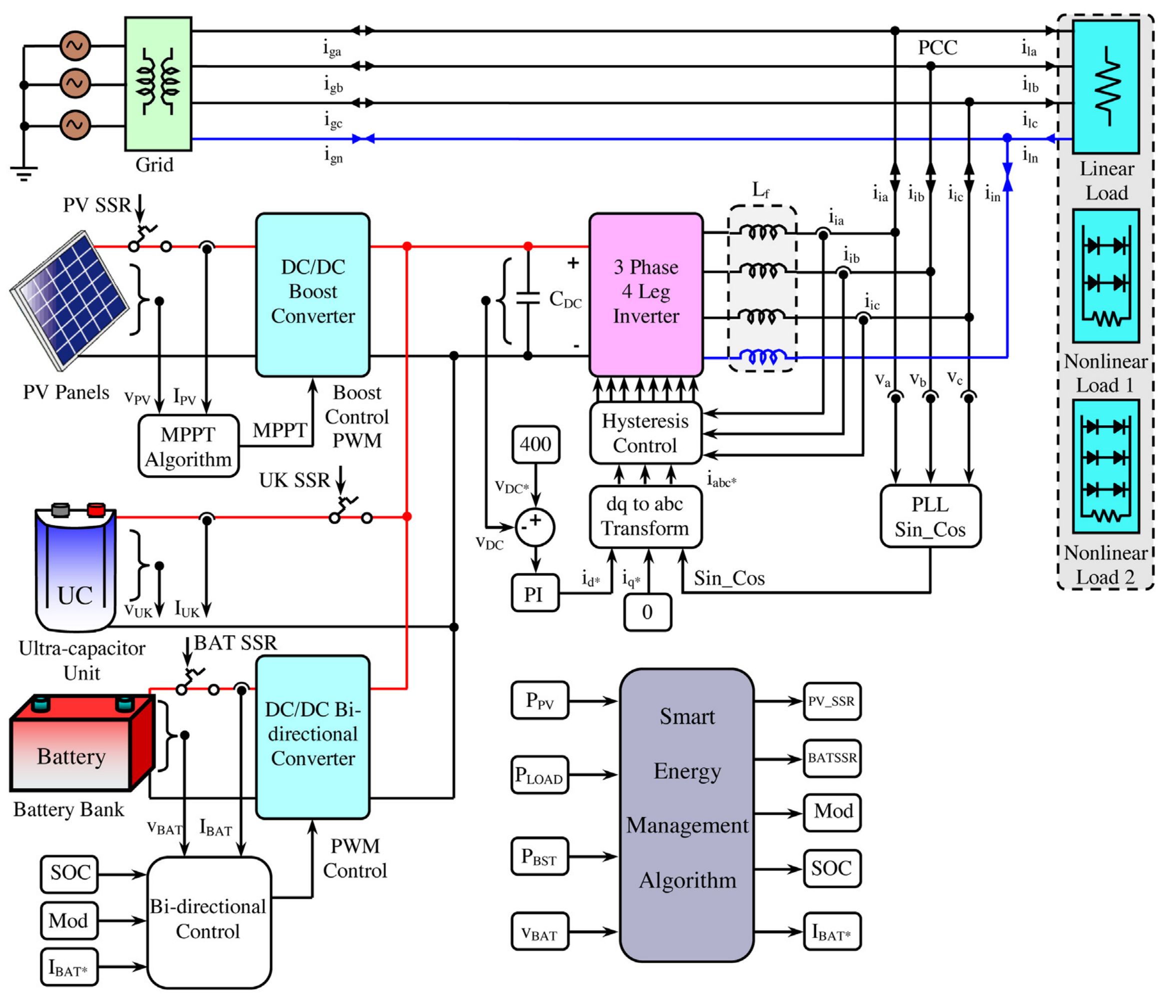


**Fig. 2.** Block diagram of HESS and SEMA.

lack of photovoltaic power. In the experimental test system, photovoltaic modules, inverter output, load, grid and battery power are measured. In addition, the study includes state changes between these eight different cases.

The performance of the battery bank is enhanced with the help of the proposed SEMA as ultra-capacitor unit captures the ripple while sharing the steady state power component with the battery. Moreover, the ultra-capacitor helps the battery operation by avoid-

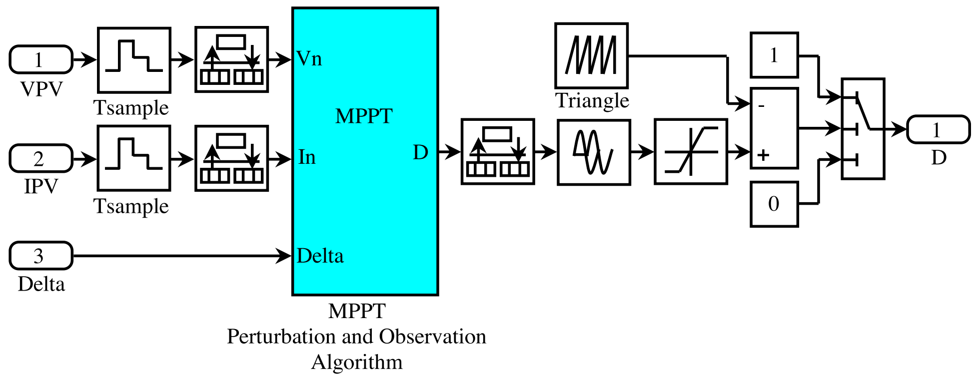


**Fig. 3.** MPPT control algorithm.

ing in high rate of depth of discharge area. The proposed SEMA is able to achieve power balance in the HESS while providing the maximum power from the PV panels.

A PV module's P–V (power–voltage) characteristics shows that there exists only one point ($P_{max}$) where the module delivers maximum power. MPPT is a method that enables the efficient use of PV panels. This method is a control structure that captures the maximum power point where the highest power provided by the solar panel. Maximum power point (MPP) can be determined by calculation models or search algorithms. In order to achieve this process, control mechanism evaluates variables of PV panel and changes the reference of the power converter to provide power to reach the maximum power point. In the literature, there are many methods to find MPP such as Constant voltage method, Pilot cell method, Constant current method, Perturb and observe (P&O) method, Incremental conductance method and One-cycle control method [34]. In this study, P&O algorithm is used. Fig. 3 shows perturbation-observation MPPT control algorithm block diagram used.

The proposed P&O algorithm was observed in experimental studies with over 99% of the MPPT efficiency.

Fig. 4 shows Simulink block diagram of bi-directional DC/DC converter control unit. To ensure the operation of the bi-directional converter buck mode, S2 is the PWM switch and switch S1 is always off. This control algorithm works depending on energy management algorithm. When number 3 mode incoming information namely MOD is 1, the control algorithm provides buck mode to the system. Input 5 (BAT_SSR) is battery solid state relay (SSR) information that connect DC bus to the battery via bidirectional DC–DC converter.

Fig. 5 shows the schematic diagram of the buck and boost mode control methods. In this part, current and voltage are controlled during charging and discharging of the battery bank.

Buck mode control unit is shown in Fig. 5(a). In buck mode, cascade PI controller is used. First PI controller provides to keep the

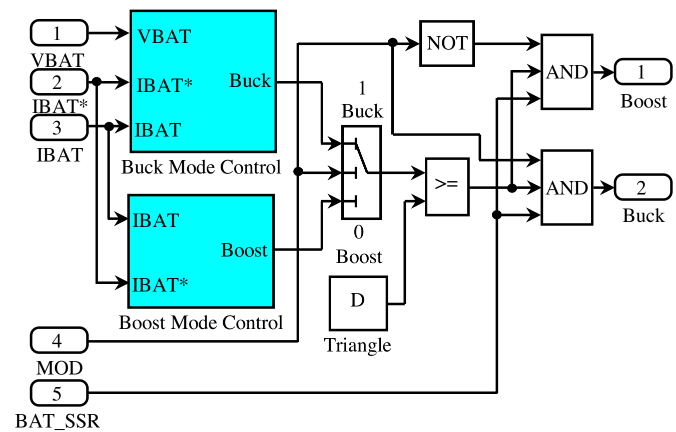


**Fig. 4.** Control structure and block diagram of the bi-directional converter control unit.

voltage of 235 V battery bank. The second PI controller controls the charging current of the battery bank. Charge current is determined by calculating the current value of energy management algorithm. Boost mode control unit is shown in Fig. 5(b). In boost mode, it is only transferred to the bus control unit based knowledge in the discharge current of the battery bank. PI controller generates an output by comparing the measured and reference current value. PI output is compared with the triangular wave at 10 kHz and switching signal is generated. Also, reference current is calculated by the SEMA in this unit.

## 4. Smart energy management algorithm (SEMA)

The energy management between the different types of energy sources and energy storage system in HESS is an interesting issue because the output power from RES is continuously fluctuating and

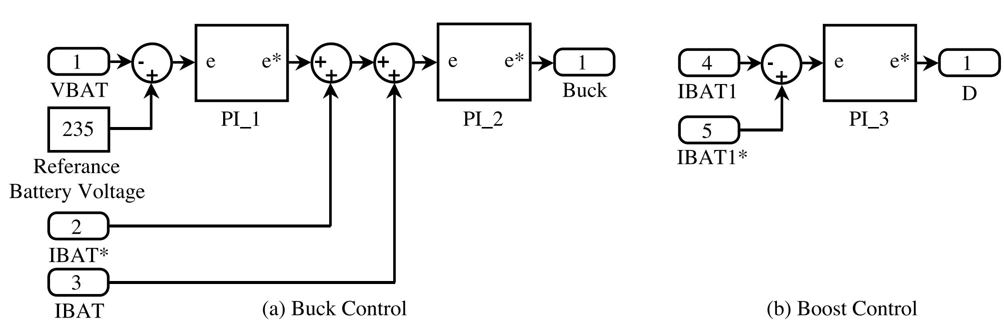


**Fig. 5.** (a) Buck (b) boost mode PI control block diagram.

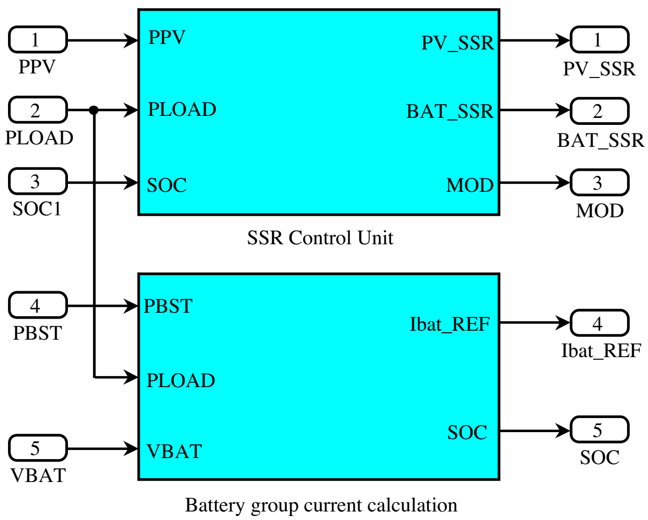


**Fig. 6.** SEMA of the HESS.

depends on meteorological conditions. Smart energy management algorithm shown in Fig. 6 is the most important control unit of the proposed HESS.

The SEMA is planned to make the power flow more effective and controls power flow in the system according to operation cases. Some limitations and bandwidths are determined in order to work properly and safely in the system. When the output power of PV is about equal to load power, within ±400 W the battery bank is deactivated. When small change occur in load power, battery bank do not provide power to the system in order to increase the battery lifetime. All battery parameters are affected by battery charging and recharging cycle. The SEMA estimates state of charge (SOC) of battery bank. The amount of current (discharge current) drawn from battery plays an important role in service life or back-up time of the battery. In case the discharge current up to the battery bank at 20% SOC withdrawn is provided. When charging battery over 95% SOC, the battery bank is protected from excessive charge current by cutting the charging current. When the output power of PV panel is lower than 50 W, PV panel is deactivated by the SEMA. When the load power is lower than 400 W, load draws energy from the grid instead of from battery bank, since reducing the switching loss and to increasing the cycle life of the battery bank.

The main important and unique technique of this study is the proposed SEMA that is different from similar algorithms including all possible working cases and dynamic response of transition between all working cases in one day. The proposed SEMA evaluates the system parameters by using pre-determined system limits including PV, battery and load power in a bandwidth, and calculates SOC and charge/discharge reference current of the battery including all possible working cases properly. The proposed SEMA aims to help to improve efficiency of the converter and inverter without engaging battery very often and allow smooth transitions between all working cases.

Battery current calculation is assessing DC/DC boost output power, the power of the battery bank, the power of the load group and battery bank voltage. According to the measured values, charging and discharging of the battery bank is determined by $I_{BAT\_REF}$. $I_{BAT\_REF}$ current is calculated by two equations while charging and discharging of the battery bank. The battery bank charging and discharging current ($I_{BAT\_REF}$) is calculated as in Eq. (4.3).

$$P_{BAT\_C} = P_{BST} - P_{LOAD} \tag{4.1}$$

While battery bank discharging power ($P_{BAT\_D}$) is calculated as in Eq. (4.2).

$$P_{BAT\_D} = P_{LOAD} - \mathbf{P}_{BST} \tag{4.2}$$

$$I_{BAT\_REF} = \frac{P_{BAT}}{V_{BAT}} \tag{4.3}$$

The SEMA calculates state of charge (SOC) of the battery as given in Eq. (4.5) by calculating the percentage in real time. The SOC counter is a typical coulomb counter. Having a current value as an input, integrating it over time and dividing per 1800 (each sample is taken every 2 s of a real time, making 1800 samples equivalent of 3600 s, which is 1 h) enables the equal to represent the number of Ampere–hours drawn from the battery bank. The next step is dividing this number by nominal capacity (Ah) of a battery bank, which – in case of the new battery – is the operator's input as a number of capacities. The output has to be subtracted from 1 and it should be multiplied by 100 to represent the state of charge. The output value of this equation is SOC value over time chart, example of which is presented in the Eq. (4.4).

$$SOC = \left(1 - \frac{\frac{1}{1800} \times \int I_{BAT}}{Ah}\right) \times 100 \tag{4.4}$$

In this section, all working cases of the proposed system are experimentally analyzed. Power flow diagrams for possible operating cases can be seen in Fig. 7. These working cases are determined by sources' and loads' current and power values.

All state variable and state transfer decisions are considered in SEMA. The SEMA decides battery bank on-off case with the "BATSSR" information. Likewise, "MOD" information provides buck or boost working case of the DC/DC converter. The DC/DC converter is used for charge or discharge of the battery bank. After determining the working case of the battery bank, charge/discharge current value is calculated by the battery bank. Calculated charge/discharge current value is sent to the bi-directional DC/DC converter control circuit. The difference of the load and PV current are calculated and inverter current is determined in battery charge/discharge current calculation block. Difference between the calculated current and PV panel current is equal to the discharge current. In battery charge status, difference between PV panel power and load power is equal to the inverter supply power. The battery charge current is determined by the difference between calculated current value and PV panel current values.

## 5. Experimental setup and results

The realization of the proposed control strategy is done by using dSPACE real-time control platform. The HESS experimental laboratory prototype used to verify the performance of the proposed SEMA is shown in Fig. 8. Data acquisition and the control system are implemented dSPACE 1103 software with digital signal processor module in the peripheral component interconnect slot of the host PC. The Semikron SKM 75GB128D is used as control switch in the converter circuits. Currents and voltages are measured by TEG and LEM transducers. In this experiment, PV panels are emulated by using Chroma Solar simulator device. DC–DC boost converter uses MPPT algorithm and provides power to the DC bus. Bi-directional DC–DC converter provides power to the battery for charging and discharging by the DC bus. Vision battery with capacity 12 V 80 Ah (32pcs), is used lead-acid battery bank and Maxwell BMOD0006 E160 with capacity of B02 6F at 160 V (3pcs), Maxwell BPAK0058 B01 with capacity of 58F at 15 V (30pcs) are used as experimental laboratory prototype. Table 1 shows the circuit parameters used in the experimental setup. The experimental system considered in this study consists of PV modules of 3 kW rated power, lead-

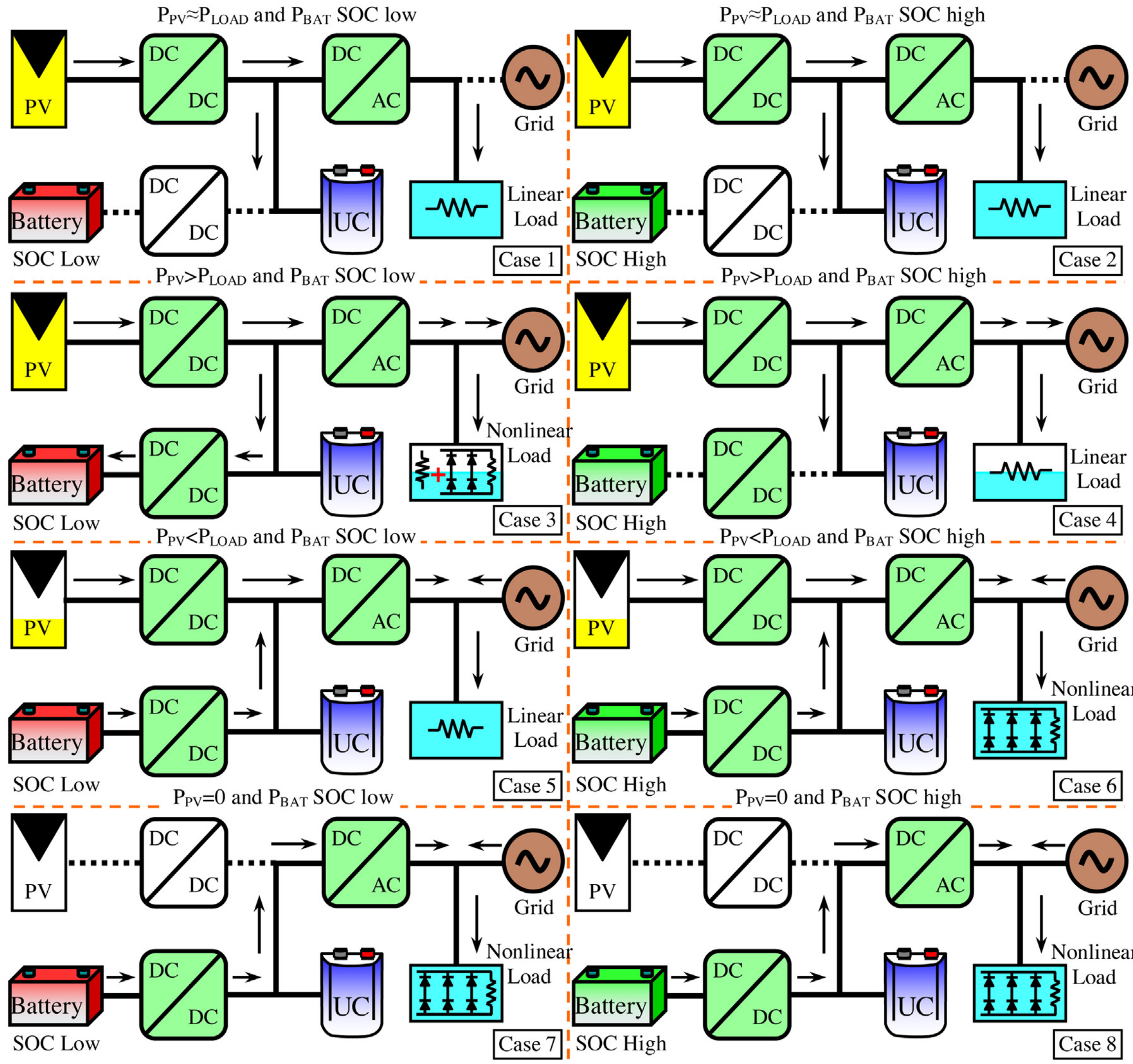


**Fig. 7.** HESS power flow diagrams.

**Table 1**
HESS experimental test parameters.

| System parameters | | Values |
|---|---|---|
| PV panels | Open circuit voltage ($V_{OC}$) | 450 V |
| | Short circuit current ($I_{PH}$) | 0–10 A |
| | Voltage at MPP ($V_{MPP}$) | 250–380 V |
| | Current at MPP ($I_{MPP}$) | 0–8,5 A |
| Grid | Voltage ($V_{gabc}$) | 110 $V_{rms}$/phase–neutral |
| | Frequency (f) | 50 Hz |
| | Impedance ($R_g$, $L_g$) | 10 mΩ, 1 mH |
| Load | Balanced resistive load | 0–3 kW |
| | Single phase full-wave diode rectifier | 0–2 kW |
| | 3 phase full-wave diode rectifier | 0–4 kW |
| Battery bank | Nominal voltage | 202 V |
| | Rated capacity | 160 Ah |
| Ultra-capacitor unit | Nominal voltage | 400 V |
| | Rated capacity | 3,93 F |

acid battery banks (160 Ah and 200 V) and ultra-capacitor units (400 V/3.93 F) to deal with load power variations as shown in Fig. 8.

In the experimental test platform shown in Fig. 8, signal-conditioning board is designed to convey the measurement results from voltage and current sensors to the dSPACE 1103 module with isolation. Three 5.2 mH inductances are connected to the inverter AC side in order to eliminate current harmonics created from switching of IGBTs.

PV modules, battery bank and ultra-capacitor unit in DC bus; grid, inverter and load in AC bus are connected with solid-state relays (SSR) in order to control (on/off) of the system components. Pre-charge resistors are used to decrease surge currents and limit to a short current in the inverter AC side. The SEMA control board is designed to control and connection of system components in the experimental test setup. In this board, control signals coming from dSPACE transmitted to the test platform in order to control all of the components rapidly and safely. In the lower side of the test setup, pre-charge resistors shown in Fig. 8 are used for preventing surge currents from PV modules, battery bank and ultra-capacitor unit. In the test setup, single-phase and three-phase full bridge rectifiers are switched separately as nonlinear loads to create unbalanced load cases and to test rapidly the transient dynamic response of the SEMA.

In order to indicate the performance of the proposed control strategy, it is compared with conventional strategy for the following cases: (1) step decrease in load demand; (2) step increase in load demand; (3) step increase in PV generation; and (4) step decrease in PV generation. Fig. 9 shows the power graphs of PV panels, load,

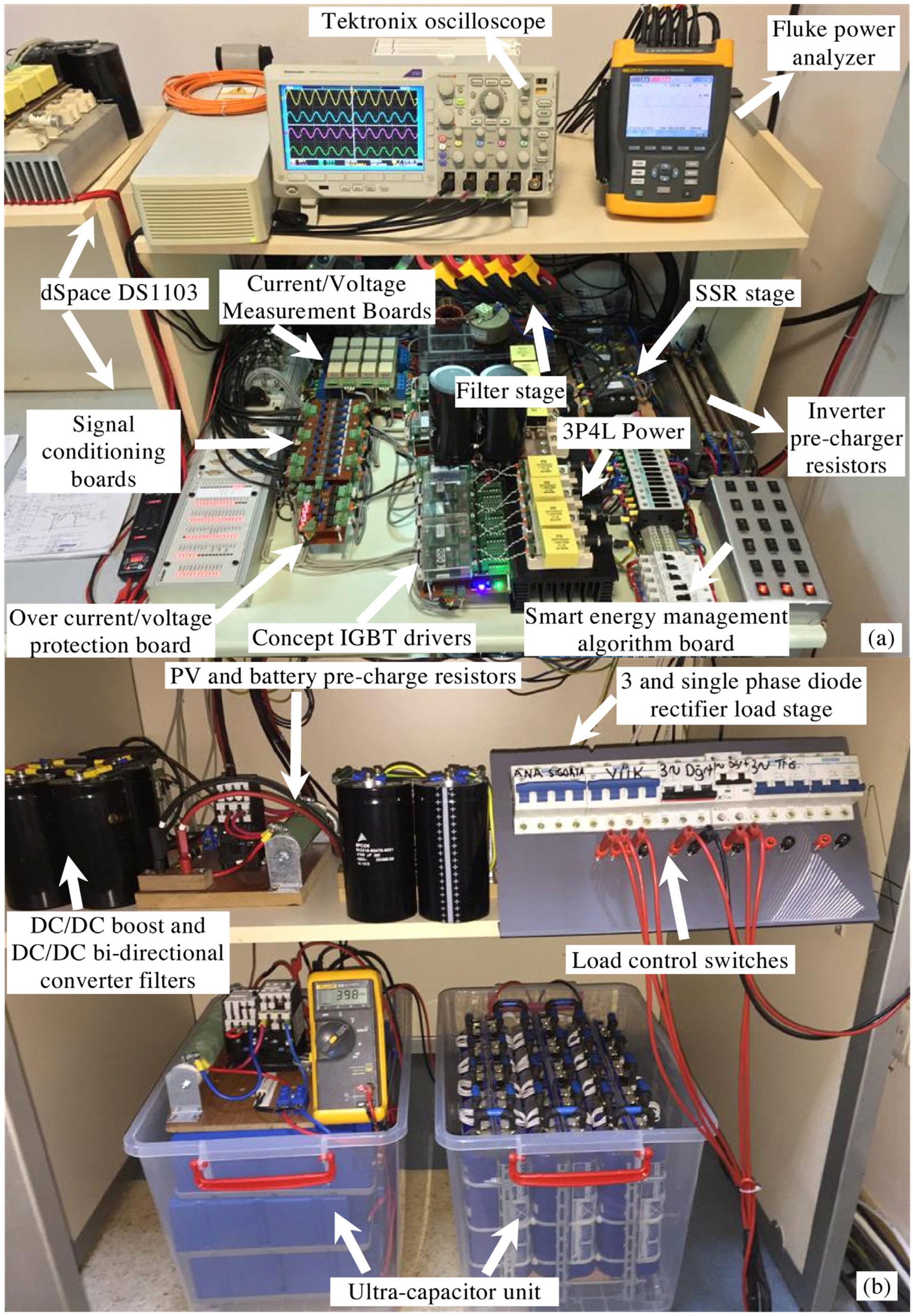


**Fig. 8.** HESS experimental setup photograph.

inverter, grid and battery bank for one day respectively. The load power values are variable because of testing eight different working cases. The time periods of the eight working cases can be seen detailed. A power-time chart is prepared for PV panels in maximum 3 kW power case.

"dSPACE DS1103" platform is used to control the 3-phase 4-wire grid connected HESS. The experimental measurements are taken and different tests are performed in the laboratory setup. Current and voltage sensors are used for measurement in real time. The experimental test results in the HESS for case 3 are analyzed in detail in this paper.

Different operating cases are presented to manage experimentally test the power flows between the various types of energy storage components, mains and load; taking into account SOC of the battery bank, the energy level of ultra-capacitor unit, the available solar power and the power demand from the grid operator. The determined experimental load demand is provided by a mixture of PV, grid and energy storage units instantaneously by using SEMA. The proposed algorithm has been tested for different load and PV profiles of irradiance and ambient temperature in the experimental test system. A typical summer day and intermittent solar radiation profile for a varying load demand has been considered in the experimental tests. The experimental test results verify the effectiveness of the proposed control structure with different battery SOC to integrate solar PV and grid as power sources and battery

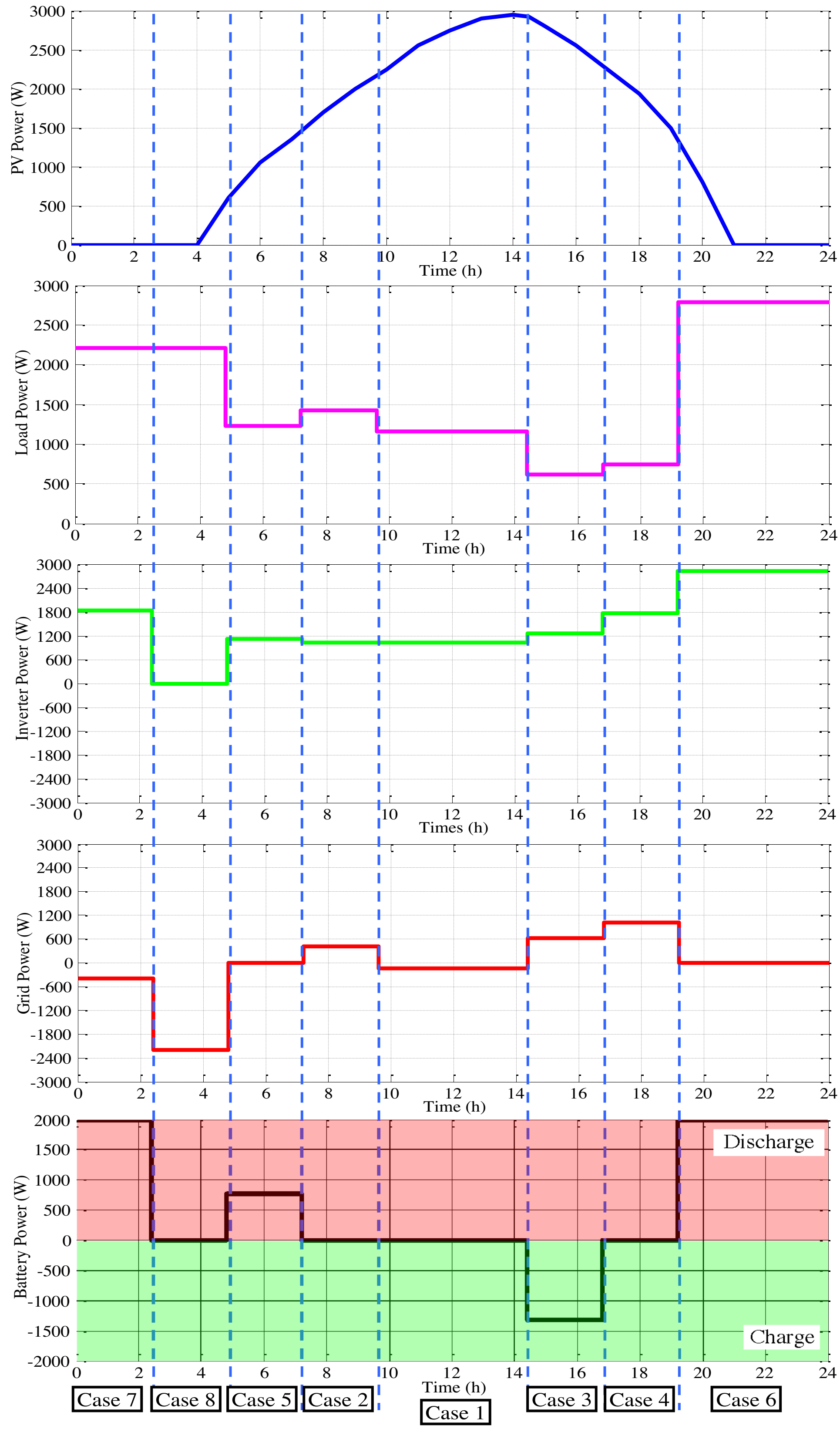


**Fig. 9.** A daily distribution of power operating cases.

and ultra-capacitor as back up energy storage to supply the load demand consistently.

The performance of the proposed experimental system is evaluated, analyzed and tested under different dynamic loading operation cases such as 620 W, 1230 W, 1420 W and 2790 W indicating the successful results of the proposed algorithm. In the experimental system, sudden variation of the load and minimal PV support case has been also tested. The sudden change in the load

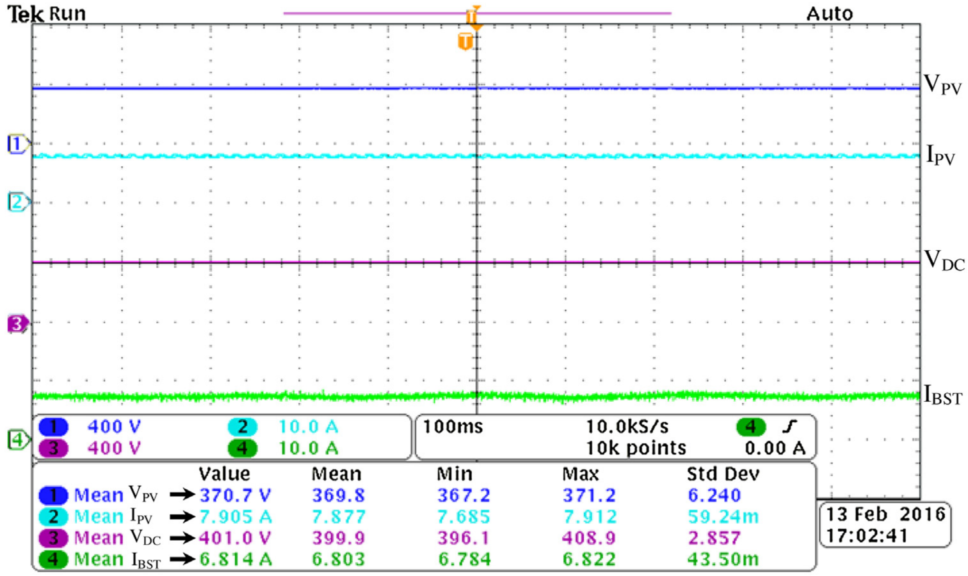


**Fig. 10.** DC/DC boost converter input/output voltage and current results for case 3.

power is effectively compensated by the support of ultra-capacitor unit.

Dynamic behavior of the HESS supplied from PV module and load profile dynamic response is shown as inverter, grid and battery bank power variation graphs in Fig. 9. In case 7, PV module power is zero; load power is 2210 W; battery bank supply the load with 2000 W by discharging via inverter. Remaining 400 W load powers is supplied from grid automatically. In case 8, PV power is set to zero and the SOC of the battery bank is very low so battery bank is deactivated. 2210 W of the full load power is supplied from mains completely.

In case 5, PV power is increased to 504 W; since the load power is 1120 W, battery bank is discharged by 765 W without any demand from the mains. In case 2, PV power is increased rapidly to 1192 W, the load power is about 1420 W; the load is supplied from both inverter and mains together. In this case 2, the battery bank is deactivated since PV able to supply the load power. Case 3 analyzed in this study very detailed, PV power is 2930 W and load power is 620 W. Since instantaneous PV power is much bigger than the load demand power, the battery bank is charged with 770 W and remaining 634 W powers are transferred to the mains. In this study, PV and load power variations are specified in certain limit in order to investigate the dynamic behavior of all possible working cases of the HESS by using the proposed SEMA. In order to investigate response and behavior of the proposed SEMA for all possible working cases, the one day load profile is chosen as given in Fig. 9.

The obtained experimental results prove that the performances of the proposed SEMA are satisfactory under both steady state and dynamic loading cases. The results of the experimental tests verify the effectiveness and feasibility of the proposed SEMA. Results obtained from the experimental setup are presented and discussed in this section. Input and output current and voltage of the DC/DC boost converter are shown in Fig. 10 for case 3. The maximum power point working voltage of PV's is 370 V and current is 7,9 A. The output voltage of the DC/DC boost converter is 400 V and current is 6,8 A.

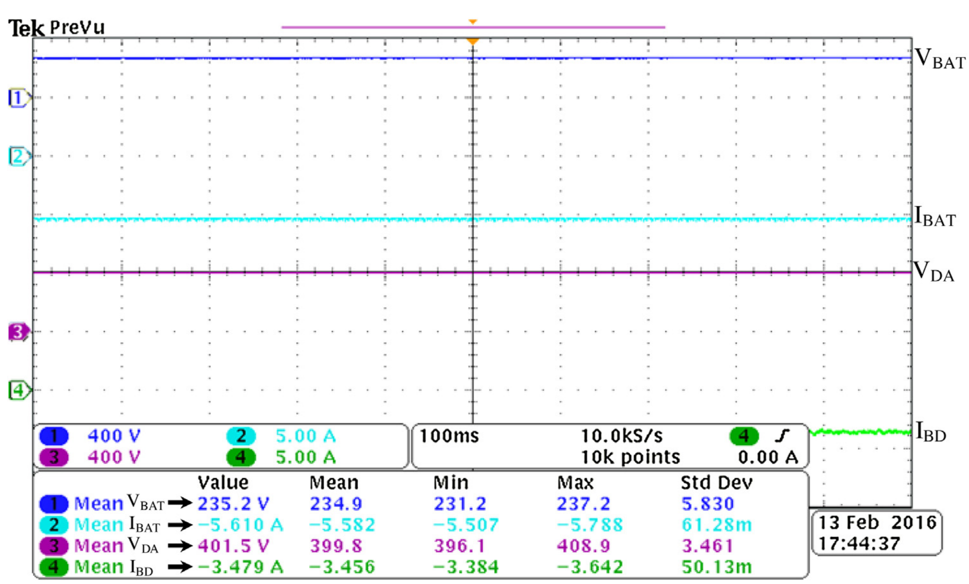


**Fig. 11.** DC/DC bi-directional converter input/output voltage and current results for case 3.

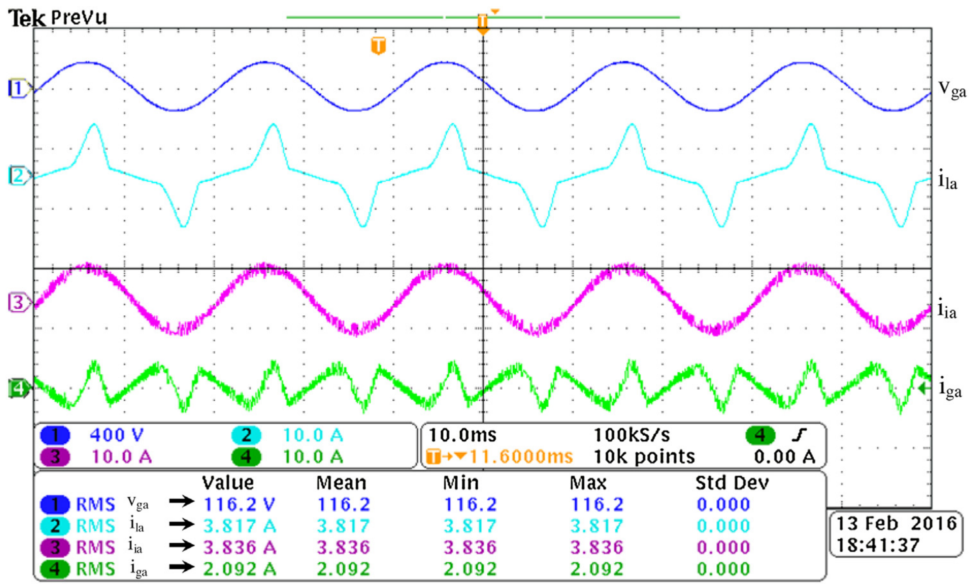


**Fig. 12.** Phase a voltage and load, inverter and grid current results for case 3.

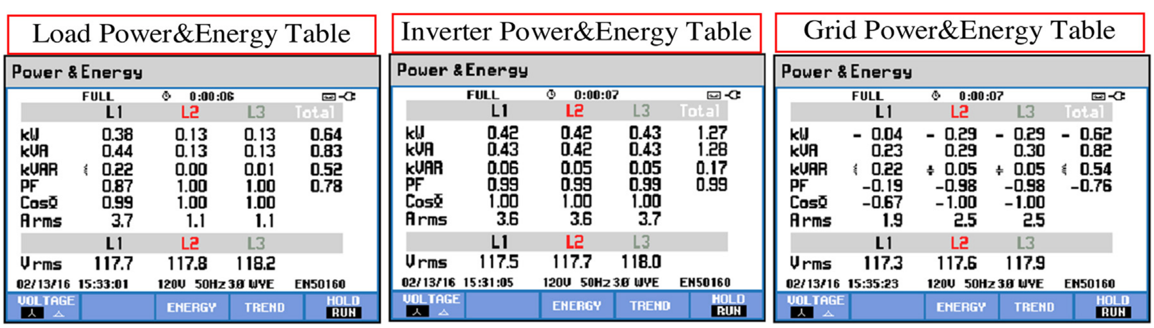


**Fig. 13.** Load, inverter and grid power and energy table for case 3.

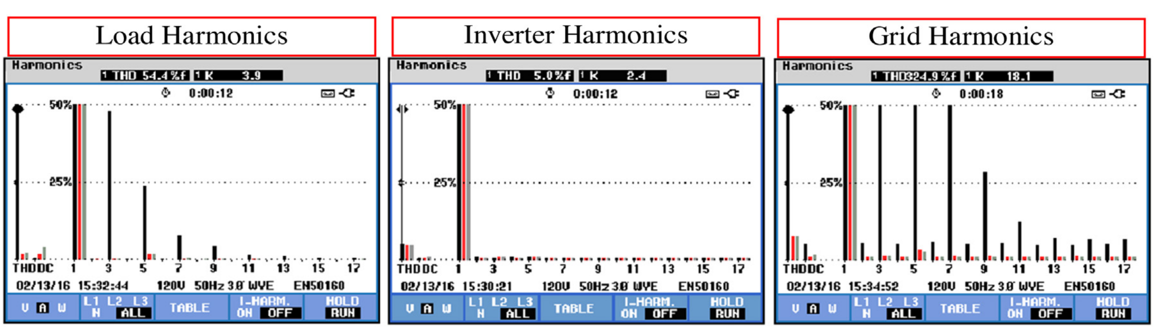


**Fig. 14.** Load, inverter and grid harmonics for case 3.

Input and output current of the bi-directional converter have been measured, and results are shown in Fig. 11. In this case, the battery bank is charged with 5.61 A. Bi-directional converter operates in buck mode in this case. Converter charges the battery bank pre-determined current value by SEMA.

PCC voltage, the load and inverter currents are given respectively for 3 phase power circuit in Fig. 12. Single-phase full-wave diode rectifier is connected to phase "a" as unbalanced load. Both unbalanced load group and neutral line current are supplied by designed HESS. Thus, single-phase loads are also supplied successfully.

Fig. 13 shows the load, inverter and grid power and energy values respectively in table for one phase. A phase of the load group is connected with single phase full-wave diode rectifier so power value is higher than the other phases. Inverter transmits power as determined by the DC current control algorithm. Also inverter only transmits active power to the system so cos $\theta$ is always 1. In case 3, the transmitted power value is negative because, power flows from the system to the grid.

Load, inverter and grid current harmonics bar graphs are given in Fig. 14. 3-phase 4-wire inverter harmonic current value is 5%, that is suitable according to IEEE 519 standard. Load harmonic value is 54.4% because of using single phase full-wave diode rectifier. This disturbing current harmonic value results from the load and this harmonics affect the grid current. All detailed numerical measurements of the experimental results are detailed in Fig. 15.

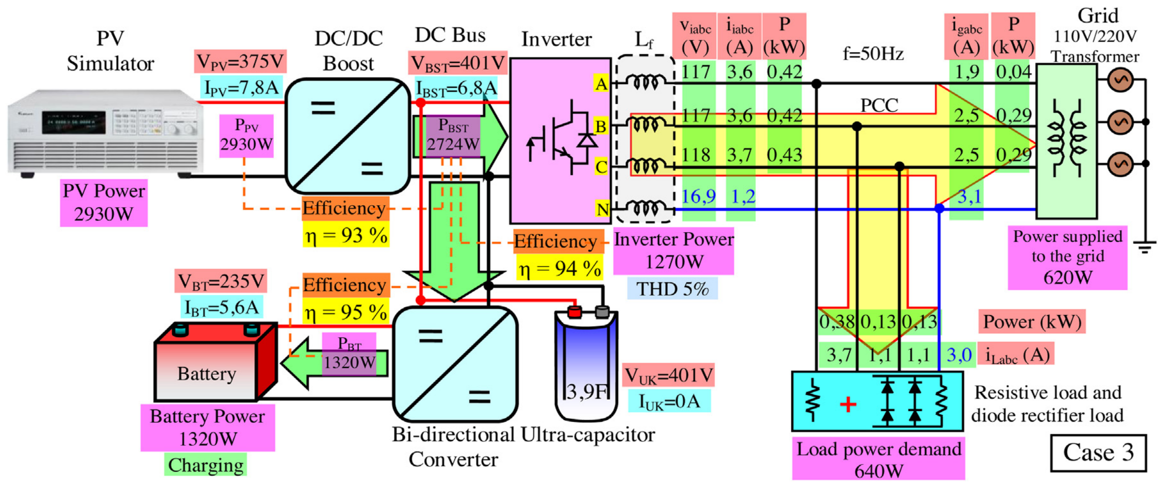


**Fig. 15.** The experimental results in the HESS for case 3.

The experimental results are explained above to confirm the proposed SEMA for power sharing among the sources (solar power and grid), energy storage and load (resistive and nonlinear load). The SEMA diverts the surplus solar power into the grid when the battery SOC extents 95% and hence protects the battery from overcharging. The SEMA control strategy also eliminates the need for a dump load by limiting the power drawn from the sources so as to match the load demand. The proposed SEMA is implemented experimentally on the HESS containing battery bank and ultra-capacitor unit. The experimental results obtained that the proposed SEMA is capable of accurately supply dynamic load requirements in different operation cases by extending of battery lifetime and optimizing of battery SOC.

## 6. Conclusions

Energy storage technology is a key element for success of smart grids, and creates new opportunities for all parties involved. Energy storage technology is an important solution in smart grid applications for efficient usage of energy source, supporting renewable energy integration to the grid and greater power production in a place that energy consumed and increasing energy access, by improving safety, reliability and flexibility of the electrical grid. Energy storage with integration of RES can smooth the intermittency of energy source, minimize reverse power flow and keeps voltage within limits, store output power and release coincidental with local load and control ramp rate of power fluctuations.

Energy storage technologies will become a complementary part of next generation RES. Today, HESS is an effective solution for improving power quality of the energy produced by RES. In this study, a new unique SEMA is proposed for HESS supplied from grid connected solar power system. Battery and ultra-capacitor energy storage units are chosen for energy sustainability from solar power generation system. Eight different operation cases of the proposed system have been experimentally tested by using the proposed SEMA. In experimental tests, one sunny day load and PV power profile have been created and tested dynamically by using SEMA and some of the test results are given in this paper. The HESS is the most effective energy storage device due to its high power density, fast response, and high efficiency application of the proposed SEMA. This paper is concluded by giving some important experimental results, recommendations and suggestions to whom, which are studying on hybrid energy storage applications including battery and ultra-capacitors in the smart grid.

In this study a new dynamic decision strategy based on SEMA for the HESS supported PV application has been proposed. The SEMA is able to define the optimal energy flows management in the composed by PV and two energy storage units which are battery and ultra-capacitor. The proposed control algorithm should be able to supply the required load power all the times, by reducing the operational costs of the energy storage system, increasing the system efficiency, and reducing energy consumption of the system. The experimental results show the validity of the proposed SEMA. The proposed method offers an option to choice the optimum control scheme, to generate cost effective hybrid systems for power supply of grid connected system.

In future work, ultra-capacitor group can be charged/discharged using a bi-directional DC/DC converter to control energy flow. But, bi-directional DC/DC converter reduces the dynamic response of the ultra-capacitor group.

The proposed SEMA can be easily debugged in processors like DSP or PIC without needed heavily computational burden in commercial applications.

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