Control and energy management of grid-connected pv system with battery-supercapacitor hybrid energy storage

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Abstract. An optimized energy management technique to reduce the cost and increase the effectiveness of a photovoltaic (PV) system is proposed in this paper. It is based on the optimum sizing of the energy storage system, to meet the needs of the system in normal conditions, while in the critical cases, the AC residential load will be supplied by the grid itself. In addition, the surplus of the PV power will be injected to the grid. However, to extend the battery life and reduce its size, a supercapacitor has been combined with the batteries, to quickly respond to the short-time peak current demand, while the battery will deliver a smooth current. Furthermore, the proposed algorithm will supervise the battery state of charge (SOC) and satisfy the highest priority load demand under different situation. A simulation work is carried out to evaluate the control of the whole PV system and determine the performance of proposed algorithm. Finally, the obtained results show the effectiveness of the proposed management algorithm, including the control techniques of different components of the whole system.

1. Introduction
The climate change, the fossil fuel exhaustion and the shifting to the low-carbon economy are the driving forces behind the accelerating deployment and the development of renewable energy[1]. In the recent years, photovoltaics (PV) have impressively invade the international energy markets at exponential growth rates [2], it has been shifted from being simple power source for those who do not have grid access to an alternative of conventional energy sources. However, the impressive expansion of the photovoltaic systems has requested an enhancement of the power quality to meet different loads requirements, such as voltage stability, supplying continuous and instantaneous power, fast transient response. Lowest cost way that permits the PV system to supply various loads and meet their needs, is to combine batteries and supercapacitor to create hybrid storage system.

By utilizing the battery-supercapacitor hybrid storage system, the PV system can effectively gain beneficial properties of both components, which leads to reducing the size of the battery banks and increase the battery lifetime. The battery banks are able to store high energy density and release it over a long time; on the contrary, the supercapacitor has high power density, it is capable to charge very fast and release large quantity of power in short period of time[3],[4].
In this work, the aforementioned hybrid storage system is integrated in a PV-grid connected system in order to be controlled and tested under different cases, which is shown in Figure 1. Connecting this system to the grid has two main benefits; injecting the surplus energy to the grid and using the grid as a backup system to supply the load in the critical cases, this will help to avoid the batteries oversized. Then, to manage and to optimize the photovoltaic power under different scenarios, a newly algorithm has been proposed, it takes into account, the PV extracted power, the battery state of charge (SOC), the quick response of the supercapacitor, the load needs, and the grid-injected power as shown in Figure 1.

![Figure 1. Block diagram of the proposed PV system](image)

The simulation of the hole system is carried out in MATLAB Simpowersystems, the control of the different converter will be discussed in the next section.

2. PV array modeling

In this work, a commonly one diode, five parameters solar cell model has been used [5], which is shown in Figure 2. The output current is the difference between the photocurrent $I_{ph}$ and the diode current $I_D$ with the shunt resistance current $I_{sh}$ as presented in equation (1).

$$I_{pv} = I_{ph} - I_0 \left[ \exp \left( \frac{V_{pv}+R_s J}{V_{therm} m} \right) - 1 \right] - \frac{V_{pv}+R_s J}{R_{sh}}$$ (1)

Where $I_0$ is the diode dark saturation current, $V_{therm} = K T/q$ is the thermal voltage of the cell, $K$ is Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K), $T$ (Kelvin) is the temperature of the p-n junction of the diode, $q$ is the electron charge; $R_s$ and $R_{sh}$ are the series and shunt resistance of the cell, respectively; and $m$ is the ideality factor of the diode.

![Figure 2. One diode photovoltaic cell model](image)

3. PV system description

Figure 1 depicts the configuration of the hole system, the PV generator is connected to DC-DC boost converter, which is used to extract the PV array’s maximum power, the battery and the supercapacitor are combined to create a hybrid storage buck-up system, the remaining energy is stored and recovered from the storage system through bidirectional buck-boost converter, it operates in buck mode when the battery starts saving power, while the boost mode is used for injecting power to the AC load or to the grid. Besides the DC-DC converters, the DC bus linked the PV to the AC load through a three phase
inverter and to the grid using the same inverter connected a inductor filter $L_f$, this later is used to filter out the ripples in the injected current.

4. Hybrid storage system configuration
The optimal active hybrid system topology was chosen to connect the battery and supercapacitor in one combination. It has the advantage of combining their advantages and solving the disadvantages of supercapacitor voltage variation and matching by placing DC-DC converter between the supercapacitor and the DC bus [6]. The power requested $P_{str \_ref}$ by the supervisory is met by supply base power from the battery $P_{bat}$ and the transient power from the supercapacitor $P_{sc}$, as shown in Figure 3.a, the references of the both powers are obtained from low pass filter as shown in Figure 3.b. while Figure 3.c depicts the output powers of the battery and the supercapacitor according to the given reference.

![Figure 3. Topology and control of Storage system (a) parallel topology (b) power control (c)delivered power](image)

5. Control techniques
To maintain the system in the maximum power point (MPP), Perturbation and Observation (P&O) algorithm has been used [7], in addition, for keeping the DC bus voltage at a constant value and reaching a unity power factor, the voltage oriented control (VOC) technique has been applied to the three phase inverter[8], while the phase locked loop (PLL) technique was used to synchronize the inverter with the grid, finally, the battery and supercapacitor control diagram is shown in Figure 4.

![Figure 4. Supercapacitor control diagram](image)

6. Results and discussion
In order to validate the performance of the proposed system, to check the behavior of all components that are working together, and to verify the management algorithm under all the possible cases, a typical day has been simulated, by adopting 1 hour to 1 second and simulating the system for 24 seconds. In addition, the battery capacity (Ah) was divided by 3600 Ah, so that it will be possible to simulate one cycle. Comparing Figure 5 of the solar irradiation and Figure 7 of the PV output power, it can be clearly seen that maximum power has been extracted over the day. For the other results and figures, it is useful to analyze them according to load variation and to the battery SOC.
From 1s to 5s: In this period, it is assumed to be night time, both loads were supplied by the storage system. However, for protecting the battery against deep discharging, the load of lowest priority had switched off at $t=2.8s$, when the SOC reach 30%.
From 5s to 15s: The PV started generating power but the storage system is still needed to supply the highest priority load, at $t=6s$, the delivered power reached the needs of the load and the supervisory switched back on the second load. It is clear from Figure 11 that the battery started charging also; meanwhile, at $t=14s$, when the SOC reached 90%, the supervisory stopped the battery charging to be protected against the overcharging and the surplus energy delivered to the grid.

From 16s to 24s: It can be clearly seen from the three Figures 9, 11 and 13 that during this interval, the battery reached again 90% after contributing with the PV to deliver a huge amount of energy to the loads, where a small power was injected to the grid, after that, the battery came back to support the PV. Furthermore, Figure 15 shows how the used regulator kept the DC bus voltage constant despite the huge power demand for short time period. Meanwhile, Figure 12 and 14 evidently demonstrate the high complementarity between the battery and the supercapacitor. The current injected to the grid is shown in Figure 6 with its zoom in Figure 8, while the grid voltage is given in Figure 10.

7. Conclusion
The simulation results confirm the high efficiency of the proposed management algorithm, as well as the benefits of using hybrid energy storage system. The PV system has been simulated in the worst cases, where the load requested a peak current, even though, the hybrid storage system responded to this demand without destabilizing the system performance.

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