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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