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Dipak Kumar Dash (✉ dipak.nitrkl@gmail.com)

IIT(ISM) Dhanbad

Pradip Kumar Sadhu

IIT (ISM): Indian Institute of Technology

Alok Kumar Shrivastav

Techno International Batanagar

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A Sliding Mode Controller for Boost Inverter Based Power Management System Using Battery and Photovoltaic System

Dipak Kumar Dash⁺, Pradip Kumar Sadhu^{*}, Alok Kumar Shrivastav^{**}

^{+,*}*Department of Electrical Engineering, Indian Institute of Technology (Indian School of Mines) Dhanbad*

^{**}*Department of Electrical Engineering, Techno International Batanagar*

{Corresponding author's email: ⁺ dipak.nitrkl@gmail.com}

Abstract- A design tool with appropriate characteristics must be available to support the power management process. A major role of the battery is the Charge State (SOC) or simply the power of the battery measured using the original voltage value. A photovoltaic panel with a 12V DC voltage of 650W is used in this process. The approach is simulation/modeling which aims to improve battery charging process and controlling the power flow using sliding mode controller to enhance the performance. The goal is to research the energy and power loss of a smart battery-buffered load controller (BBSL) when used for the primary frequency controls on demand (PFC). Firstly, the depletion of battery energy arising from the PFC charging and discharge methods is evaluated. This research analyses the influence of PFC droop properties and dead-bands on the energy loss in a Lithium ion battery, by simulation measurements using a single stage BBSL. The model represents a nonlinear current-dependent resistance to the total voltage decrease of the battery. The energy loss simulated as the energy lost in this resistance is thus measured. HPSO-algorithm used in this analysis is one of the photovoltaic models used in photovoltaic systems, with maximum power, and with optimal conditions. The results showed that the battery charging simulation

increased by 0.05% every 30 minutes. Furthermore, the simulation validation using Matlab/Simulink is carried out with data in accordance with the prototype design, at an efficiency of 88.4%.

Keywords- Battery, charging current, HPSO algorithm, SOC, Battery energy storage systems.

1. Introduction

Photovoltaic technology is designed to capture solar energy, the most significant energy source on the earth. However, the largest percentage of the installed photovoltaics is still used as a backup energy source and a smaller percentage as a main source of energy in rural areas. Almost every household that uses a photovoltaic system needs a backup battery. The produced electricity cannot always be used immediately. Therefore the battery will store the energy, and it can be used at night, or when demanded [1]. BESS system is one of the main contributors to empowering this transition and the achievement of demand-side control. Battery energy storage systems (BESS) are suitable not only for grid-scale systems but also for load-side applications under the framework of dynamic demand control (DDC) and demand response control (DRC). Situated at the load side, load-scale BESS can be utilized for a wide range of functions. Primary frequency control (PFC) is one of the services that can be implemented through DDC strategies using load-scale BESS [2-3]. Research related to solar irradiance in tropical climate conditions has been investigated [4]. Sometimes the output voltage of the photovoltaic system is higher than the voltage of the battery. Therefore, it is needed to regulate before starting to charge the battery. Hence, Solar Charge Controller (SCC) can be used to regulate the voltage charging the battery [5]. Application of photovoltaic power sources for interconnection systems for Microgrid systems on the island [6]. Battery capacity is an important characteristic that shows the

capability of the battery to store electrical energy. The unit of measure is Amperes-hours (Ah). Each cell has a voltage of 6V, and each of them is capable of providing power until the voltage level drops to 3.15V. Furthermore, if the voltage of each cell is 3.15V, it will continue to decrease, and its effective capacity will be used [5].

In order to design the photovoltaic system, first, the information about how much power is one area/household needs is required. An excellent way to identify the demanded power is with a simulation on Matlab/Simulink. In this research, a 500W photovoltaic system is being examined in the simulation program. There are few inputs that affect the final production of power, among others: solar irradiance, temperature, panel voltage, panel current, and battery charging process [6]. The MPPT method is a strategy for optimizing the generated power and finding the maximal power point in which the photovoltaic needs to work using the SEPIC converter to increase and decrease the voltage. Moreover, it applies the HPSO, which is based on an observation of a P-V curve and the distinction of power with respect to the voltage. It is shown that the performance of the converter is greatly influenced by the duty cycle. With the MPPT method, the power transferred to the load is maximized. In this example, the highest efficiency is achieved when the load is 52 Ohms or when it is equal to 47.5% [7].

It is important to comprehend the connection between the variation of the photovoltaic module slope angle and the generation of electrical energy. The purpose of this observation is to find the optimal position of the photovoltaic system to increase the absorption of solar energy when connected to a battery charging system. This prototype will work when the battery voltage levels are in the minimum or maximum state. When the battery voltage is in the minimum state, the charging process will automatically start, and when it has reached the maximum state, the charging process will stop [8]. It

is crucial to inspect the voltage during the process of charging in order to keep the battery safe for further uses and to preserve its life. Solar Charge Controller (SCC) is adequate for DC voltage and can stabilize the voltage from the photovoltaic that is charging the battery.

A similar study to help maximize the photovoltaic efficiency is using a Dye-Sensitized Solar Cell (DSSC) device. Additionally, the model parameter was calibrated to prognosticate the maximal efficiency from a DSSC with unknown inductor values. The I-V curve helps to install the photovoltaic system successfully using Trusted Capability Maturity Model (TCMM) with combining resistors in series, with an efficiency of 5.46% and a tolerance of $<0.1\%$ [10].

To keep the battery performance in good shape, it is necessary to prevent overcharging. To detect the situation, it is required to have information about the battery capacity. Therefore, battery is equipped with a sensor that functions to check whether the battery is working optimally and to provide information about value of the SOC. The entire control system in battery charging is based on the SOC. In this study, an automatic battery charging device with solar power is analysed. It can charge several batteries based on their voltage level. First, it charges the battery with the lowest voltage level, and it estimates its SOC, then it automatically starts to charge the one with a higher voltage level. The SOC shows the capacity of the battery in percentage, and it is an important parameter for the battery management system. However, SOC cannot be measured directly [11].

The study's purpose is to design an automatic battery charger that uses solar power and to model a photovoltaic system using the HPSO algorithm with a buck-boost converter. The presence of the MPPT in the photovoltaic system is a significant feature that helps to improve the efficiency of the entire power plant. The charging process will

start when it detects the lowest SOC level. The charging current starts to flow if the SOC of the battery is below than 30%, and it stops when the SOC level is 100%. According to the initial setup of the battery charging system, the sensor will read the lowest SOC value in this case, which is based on the measurements of voltage and current from each battery. It is important to mention again that this battery charging system is modelled using Matlab/Simulink software with MPPT controller and HPSO algorithm. The HPSO algorithm is practically a buck-boost converter circuit whose purpose to optimize battery charging and improving the efficiency of the battery.

2. Literature Review

Photovoltaic (PV) devices generate electricity directly from sunlight via an electronic process that occurs naturally in certain types of material, called semiconductors. As long as the semiconductive material is exposed to solar radiation, PV will produce electrical energy. The I-V characteristic of photovoltaic is a typical I-V curve. In order to capture an I-V curve, it is needed to perform the Standard Test Condition (STC) - 1000 Watt per square meter (this number refers to the amount of light energy falling on a given area at a given time) and the temperature of the solar cell needs to be 25°C. There are three most important points on the I-V curve - Maximum Power Point (MPP), Open Circuit Voltage (Voc), Short Circuit Current (Isc) [10][12][13][14]. Alternative energy technologies produce clean energy to meet the world's needs in terms of transportation. Efficiency, storage, and utilization of energy systems play an important role in energy consumption. The level of efficiency for renewable alternative energy technologies provides technical capabilities for experimental and model implementation [7]. The proposed approach to the efficiency of renewable energy sources is calculated computationally [15]. The electric potential of solar photovoltaic and biomass has been implemented in Bangladesh. The efficiency of

the feasibility of this hybrid energy system to provide sustainable electricity [16]. Application of grid energy storage technology to maximize the absorption of renewable energy. Different optimal strategies for Battery Energy Storage Systems (BESS) coordinate with wind-based generators. Charging and using BESS for network operational constraints are node voltage limits, feeder current limits, and node power balance, etc [18].

2.1. Maximum Power Point Tracker (MPPT)

The output values of the photovoltaic systems are nonlinear. The P-V and I-V curves have a peak point that changes along with temperature and irradiance. To achieve high efficiency in the production of electrical energy, the photovoltaics should have a stable output at its maximum point. Photovoltaics do not work automatically at their maximum power, the PV system needs to have MPPT in order to find the point easily and maintain their presence [19]. The quality of the performance of the PV system directly depends on the quality of the MPPT system. If the quality of the performance of the system is needed, the quality of the MPPT system needs to be measured. Therefore the MPPT is an electronic system and it can produce maximum power compared to the mechanical tracking system that changes the position of the module towards the solar position [10][20]. The MPPT technique is based on an iterative method that is on time and complex for comparative techniques. The most commonly used approach is the P&O algorithm. This algorithm is utilized to improve time performance and computational complexity. This technique is flexible for digital signal processing [21]. The maximum power tracking, perturb and observe (PO) algorithm is the simplest algorithm. This research uses a maximum power tracking algorithm with a modification of the P&O algorithms. This condition was tested in steady and dynamic conditions using MATLAB/Simulink. The simulation results

obtained are compared with P&O algorithms to produce efficiency for maximum power tracking in a fast time [22][23].

HPSO algorithm is one of the Maximum Power Point (MPP) tracking techniques based on incremental measurements of the conductance changes. By comparing the incremental measurements, it can be noticed that the variations in power, voltage, and current are caused by the changes in the temperature and solar irradiance. Figure 1 shows the working concept of the algorithm for finding MPP values in every circumstance. When the value of the conductance is zero then it will maintain at the MPP point. When the value is more than zero, the algorithm will detect the value towards the left, when the value is less than zero, it will detect the value towards the right. Therefore, the system can control the reference voltage in order to maintain power at its maximum point by adjusting the magnitude of the PWM [20][24].

Figure 1. HPSO curve

BBSL AND LOSSES EVALUATION

The main purpose of the BBSL controller is to control the power consumption of conventional loads according to the operating status of both the grid and the battery. The battery energy storage system will enable the BBSL to autonomously achieve

different DDC and DRC functions while meeting the load power demands. The contribution of the BBSL to DDC and DRC will depend on the power capability and energy capacity of its associated battery. Here, we focus on the PFC function which is discussed in the following section. Fig.1 shows a diagram of the BBSL. Since the BBSL controller and the battery will result in additional power and energy losses, it will affect the efficiency of the load. For this reason, we investigate the power and energy losses of a BBSL.

Fig.1. A diagram of the BBSL.

As shown in Fig.1, the grid power flow to the load is given as,

$$P_G = P_L + P_{BBSL} \quad (1)$$

where P_G is the grid power delivered to both the BBSL, P_{BBSL} , and the load, P_L . P_{BBSL} covers the battery power P_B , and power consumed by the BBSL controller P_C .

Therefore, the grid power can be written as,

$$P_G = P_L + P_B + P_C \quad (2)$$

Including control and detecting electronic unit, the inverter and DC/DC converter, the BBSL controller implements the power conversion and control. The total power loss P_C

of the BBSL controller can be divided into an almost-constant part consumed by the control and detecting electronic unit and a part consumed by power electronic circuits. The latter part changes with the power flow processed by the converters. We may assume it proportional to the power flow. Battery storage will result in power and energy losses during charging, discharging and energy storage. The total loss is dependent on the battery type and the way to use the battery. In the following sections, we will mainly discuss the battery energy losses of a BBSL controller working in primary frequency control.

A. Battery Power Control and PFC Function

In this work, battery power control is designed mainly for the implementation of load-side PFC. At the same time; we also wish to keep the battery SOC around a certain value, for instance, 80%. For this reason, the battery power P_B is controlled in two components, line frequency dependent component $P_{Bf}(\Delta f)$ and offset component $P_{Bs}(SOC)$ for battery SOC compensation as,

$$P_B = P_{Bf}(\Delta f) + P_{Bs}(SOC) \quad (3)$$

The grid power in (2) becomes,

$$P_G = P_L + [P_{Bf}(\Delta f) + P_{Bs}(SOC)] + P_C \quad (4)$$

It is worth mentioning here that the battery is restricted to discharge its energy only to the associated load and not to feed energy back to the grid. In other words, the BBSL control will meet the condition $P_G \geq 0$.

Demand-side PFC is the droop control strategy at load-side. The conventional droop control strategy applied to governors in synchronous generator systems is used to control the BBSL. According to the North American Electric Reliability Corporation (NERC) standards, there are two droop control strategies namely the

linear response droop and step response droop [25]. The regulation of the battery power is given as follows:

$$P_{Bf}(\Delta f) = \begin{cases} G_b \cdot \Delta f ; & |\Delta f| > \Delta f_{th} \\ 0 & ; |\Delta f| \leq \Delta f_{th} \end{cases} \quad (5)$$

where G_b is the battery power gain in (W/Hz) calculated as follows

$$G_b = \frac{1}{R} \left(\frac{p.u.W}{p.u.Hz} \right) \times \frac{P_{B,ref}}{60 (Hz)} = \frac{1}{R} \times \frac{R_{B,ref}}{60} \text{ (W/Hz)} \quad (6)$$

where R is the droop setting in (p.u. Hz/ p.u. W) and $P_{B,ref}$ is the reference power of the battery PFC operation. Δf_{th} is the frequency deviation threshold according to the dead-band. $\Delta f = (f - f_o)$ is the frequency deviation and f_o is the frequency scheduled value. The offset power $P_{Bs}(SOC)$ compensates the battery energy used in the over-frequency and under-frequency regulation and thus preserve the SOC. It is defined based on the SOC deviation as follows:

$$P_{Bs} = (SOC_{set} - SOC) \times B \times P_b \quad (7)$$

where SOC_{set} is the set value of SOC. The SOC in this equation is in per unit instead of percent. P_b is the battery rated power and B is a gain used to adjust the speed of the offset power compensation to keep the SOC around its set value.

Therefore, the battery power equation can be written as,

$$P_B(\Delta f, SOC) = [P_{Bf}(\Delta f) + P_{Bs}(SOC)] \quad (8)$$

$$P_B(\Delta f, SOC) = G_b \cdot \Delta f |_{|\Delta f| > \Delta f_{th}} + [(SOC_{set} - SOC) \times B \times P_b] \quad (9)$$

According to the standards of generation units, the capacity headroom for PFC is 10 % of the rated capacity of the generation unit participating in PFC while the remaining capacity can be managed to meet a targeted demand. The reference capacity for the BBSL system can be ten times the rated power of the battery with the same droop values, R used in generators, to use the entire capacity of the battery

for PFC participation and thus have an effect similar to PFC generation. Therefore, the used Lithium ion battery pack that has an appraisal power of 21.6 W may supply pfc at the power reference $P(B, \text{ref}) = 10 \text{ to } 21.6 \text{ W} = 216 \text{ W}$. However, the expected power rating of a BBSL should extend from the laptop to a house power supply, i.e. from 100 to 20 kVA.

3. Method

Optimal determination of the location of Solar Photovoltaics (SPV) and Battery Energy Storage Systems (BESS) in the battery cycle charging system. Optimal management of charging and using the BESS cycle by absorbing SPV as a source of electricity. Significant increase in load deviation index, increase in node voltage profile, reduction in feeder power loss without reverse power flow [3]. Energy management strategy to oversee the flow of power in stand-alone dc microgrid. This power plant consists of photovoltaic and battery storage systems, combined with supercapacitors. Microgrid is modeled using the Matlab/Simulink/SimPowSys environment [8][18][25]. Configuration and control strategies for a Modular Multilevel Converter (MMC) based on Photovoltaic Battery Energy Storage (PV-BES) systems. The BES system for converters is connected to dc from the BES sub-module using several isolated converters. The effectiveness of power leveling techniques using the PV-BES system uses a time-domain simulation in a MATLAB software environment [24].

3.1. Maximum Power Point Tracker (MPPT)

In this paper, an automatic battery charger is designed using solar power and a PID is used as a controller. The controller is connected with a 60Ah battery and a 500W PV that has a function to supply the controller if the battery starts to run out.

insensitivity to parameter variants, and non-linearities. SMC switches device dynamics with an intermediate control input, which allows the system to slip over a selected surface with desired characteristics including stabilization and performance resistance. The state model associated to the dc link of bus and the infinite grid shows the subsequent relations [5]:

$$\dot{X} = h(x) + z(x) \cdot u \quad (10)$$

Where, $X = (x_1, x_2, x_3)^T = (i_d, i_q, v_{dc})^T$ is the state vector, $u = (u_1, u_2)^T = (v_d, v_q)^T$ is the input vector and the state model of the system can be expressed as:

$$h(x) = \begin{pmatrix} h_1(x) \\ h_2(x) \\ h_3(x) \end{pmatrix} = \begin{pmatrix} -\frac{R}{L} \cdot h_1 + \omega \cdot h_2 - \frac{e_d}{L} \\ -\frac{R}{L} \cdot h_2 + \omega \cdot h_1 - \frac{e_q}{L} \\ \frac{i_{pv}}{C} - \frac{e_d \cdot x_1 + e_q \cdot x_2}{C \cdot x_3} \end{pmatrix}, z(x) = \begin{pmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \end{pmatrix} \quad (11)$$

The state model of a nonlinear (11) is given for the grid-connected PV inverter, the SMC is ideal for this system. The goal is to control the voltage of the output terminal x_3 (i.e. v_{dc}) at the full output of the PV array source by means of the built controller. The power factor of a required value can also be achieved by intervention on the status x_2 (i_q part of current flowing via grid) (to regulate the reactive power delivered to the grid). Therefore, the model outputs of such two conditions expressed as: $y = (y_1, y_2)^T = (x_1, x_3)^T = (i_d, v_{dc})^T$. The similar orders of y_1 and y_2 are $d_1 = 1$ and $d_2 = 2$ approximately. Therefore, the state model specified by equation (11) can be expressed as:

$$\begin{pmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{pmatrix} = M(x) + N(x) \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \quad (12)$$

Where;

$$M(x) = \begin{pmatrix} f_1 \\ \frac{i_{pv}}{C} - \frac{1}{C \cdot x_3} (e_d \cdot f_1 + e_q \cdot f_2) + \frac{(e_d \cdot x_1 + e_q \cdot x_2) \cdot f_3}{C \cdot x_3^2} \end{pmatrix}$$

$$N(x) = \begin{pmatrix} 0 & \frac{1}{L} \\ -\frac{e_d}{LCx_3} & \frac{e_q}{LCx_3} \end{pmatrix} \text{ is a non-singular decoupling matrix.}$$

The control scheme can be expressed as:

$$\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = M^i(x) \cdot \left[\begin{pmatrix} i_{qref} \\ \cdot \\ V_{dcref} + \lambda e_2 \end{pmatrix} - N(x) + K_0 \cdot S_l + K \cdot S_{gn}(S_l) \right]$$

$$\text{Where: } S_l = \begin{pmatrix} S_{l1} \\ S_{l2} \end{pmatrix} = \begin{pmatrix} e_1 \\ \cdot \\ e_2 + \lambda e_2 \end{pmatrix}$$

4. Results and Discussion

The automatic battery charger in its design has several logic components such as PIDs, PWM generator, First order filter etc. This controller logic is used as a battery charging controller and it will be connected to the PV system. The test duration was 2 minutes with an average weather temperature of 30°C, and an average solar panel temperature of 38°C. The test was done with voltage values of the batteries - battery 1 of 11.59 V with a SOC value of 41.86% and battery 2 of 11.95 V with a SOC value of 98.91%. Figure 4 (a) shows the battery voltage deviation during the charging process.

(a)

(b)

Fig.4. Practical frequency deviation and simulated SOC for one-day PFC simulation.

To study the effect of the droop settings and dead-bands on energy loss, different experimental tests were conducted with the 21.6W Lithium ion battery. Figure 5 shows the flow of the current through the battery while the process of charging is active. The charging current in the battery has a maximum value of 4.99 A.

(a) frequency deviation

Fig.5. Simulation results of frequency deviation, SOC, battery current and battery power.

Figure 6 shows the increasing of the SOC value of batteries. The SOC value of battery 1 increases from 41.86% to 50.6%.

(a) Frequency Deviation

(b) % of SOC

(c) Battery Current

Fig. 6 Experimental results of frequency deviation, SOC, battery current, and battery power

Figure 6 (a) shows a simulation that recorded an increase in the battery SOC value of 0.05% (from 50.01% to 50.06%) for a simulation test time of 2 seconds, and spent 30 minutes. Figure 6 (b) shows the charging current that flows through the battery during the charging process. The charging current increases to a value close to 45A, it starts to decrease, and it approaches the value of 40A. The variation is different from the charging voltage shown in Figure 6 (c). Figure 6 (d) shows the variation in battery power. As for the increasing in SOC, it can't be seen significantly because of the length of the Simulink battery charging simulation process. Based on the design, test, and simulation, the final efficiency is 82.37% calculated with solar irradiation of 1000W/m² and temperature of the solar cells of 25°C in the MATLAB/Simulink environment.

Figure 7 is the irradiation condition of solar cells with different efficiency values. The change in output power is low, the solar irradiation gets smaller. Therefore, the efficiency value is calculated while simultaneously comparing the maximum power and ideal solar cell power during the simulation.

Figure 7. The efficiency and maximum power

Conclusion

A battery-buffered smart load is used for primary frequency control of the load side to check energy loss of Lithium ion batteries. The loss in battery energy therefore depends heavily on the time of death and drop. Also, simulation results showed that lowering the droop constant increases energy loss as the regulation charge-discharge current is increased. The results can provide valuable insights into the design of load-side PFC to compromise the benefits of the battery to the frequency control and the energy lost in the battery in the PFC load-discharge energy exchange, on the one hand, and the power lost by the converters. If the charging process is done with implementing the standard test conditions, the increase of the SOC value in each iteration is greater compared to the value obtained in Matlab/Simulink simulation. Based on the results of the simulation made in Matlab/Simulink concerning the prototype design and using the MPPT HPSO algorithm, the calculated final efficiency is 88.4%.

Compliance with Ethical Standards

1. **Disclosure of potential conflicts of interest:** The authors declare that they have no conflict of interest.
2. **Research involving human participants and/or animals:** This paper does not contain any studies with human participants or animals performed by any of the authors.
3. **Informed consent:** Informed consent was obtained from all individual participants included in the study
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Authorship contributions

1. All authors made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; or the creation of new software used in the work;
2. All authors drafted the work or revised it critically for important intellectual content;
3. All authors approved the version to be published; and
4. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Figures

Figure 1

HPSO curve

Figure 2

A diagram of the BBSL.

Figure 3

Power Management Using SMC controller

(a)

(b)

Figure 4

Practical frequency deviation and simulated SOC for one-day PFC simulation.

(a) frequency deviation

(b) % of SOC

(c) Battery Current

(d) Battery Power

Figure 5

Simulation results of frequency deviation, SOC, battery current and battery power.

(a) Frequency Deviation

(b) % of SOC

(c) Battery Current

(d) Battery Power

Figure 6

Experimental results of frequency deviation, SOC, battery current, and battery power

Figure 7

The efficiency and maximum power