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POWER CONTROL AND OPTIMIZATION IN DC MICROGRIDS: A HARMONIOUS AND EFFECTIVE APPROACH

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ABSTRACT

An energy storage system, loads, and renewable energy sources all work together through power management in a DC microgrid, which is a small-scale power system. Over the past ten years, there has been a notable increase in both academic and industrial research on DC microgrids. When it comes to integration of renewable energy sources, control simplicity, efficiency, and dependability, DC microgrids outperform AC microgrids. Power generated from renewable sources is subject to variation, which can potentially result in undesirable variations. In the case of solar power generation, load demand variations lead to system instability and battery stress. High system variations have a negative effect on the DC microgrid's dependability and battery life. Using a hybrid energy storage system (HESS) at a DC microgrid that consists of batteries and a supercapacitor (SC) can help with this issue. In order to minimize battery loss and meet the generation demand mismatch, a new coordinated power control improves the power-sharing between batteries and SC. In this study, a standalone DC microgrid with a battery and supercapacitor is proposed as a means of optimizing capacity and minimizing loss. The MATLAB simulations show how these techniques greatly improve system performance overall and extend battery life.

Keywords: DC Microgrid, Renewable sources, Hybrid energy storage system (HESS), Supercapacitor, Optimization.

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1. INTRODUCTION

The high-level integration of RESs raises several technical issues, such as low fault ride-through capability, high fault current, low system inertia, and generation reserve. The International Renewable Energy Agency (IREA) predicts that 66% of energy demand will be met by RESs [1]. MG concept was reintroduced in 2002 by R.H. Lasseter as a future low voltage distribution system to integrate distribution generation, MGs can work in grid-connected or Islanded operation mode. They are an effective, reliable, and environmentally friendly solution to integrate distributed generation into the main grid[2]. Instead of increasing conversion efficiency, designers have removed the conversion processes and utilized a direct current (DC) distribution because of the increasing DC loads in a technologically advanced society[3].Although renewable energy sources provide a clean energy alternative, they cannot be dispatched and are intermittent. These features of RES have led to problems in the microgrids concerning electricity quality, voltage control, and stability. DC microgrids are vastly found in two different categories of operating conditionswhichareisolated/islandedmodeandutility-connectedmode[4]. According to the power properties, microgrids can be divided into AC and DC microgrids. AC microgrids have been comprehensively researched because of their similarities to the traditional AC power system. Nowadays, the advantages shown within DC microgrids arouse the increasing interest of scholars around the world. Compared to AC microgrids, DC microgrids require less conversion stages and transmit more DC power through a given cable. Moreover, DC systems are inherently efficient without any skin effect and can decrease line losses[5]. For instance; energy sources those have DC output like PV systems and batteries can be directly connected to DC microgrids without using complex power electronics inverters. Similarly, most energy storage units can be connected to the DC microgrids through DC-DC converters[6]. The high-frequency power variations generally require ESS elements with high power density with fast response time, while low-frequency or long-term power variations prefer high energy density and low-cost ESS elements, a single type of energy storage element in standalone MG applications limits the potential of storage systems[7]. Among all HESS combiners battery-SC HESS has been the popular combination in HESS research because of their wide availability, relatively low cost compared to other ESS elements, similarity in working principle, and most important. The intermittent nature of solar electricity, however, seriously impairs the reliability of such DC systems[8]. A power management system that efficiently controls the energy generated by solar PV, batteries, and supercapacitors can be used to address this issue[9]. The control strategy of HESS has often been studied and practiced in the literature. The output coefficient of the SC is determined by sampling the charge and discharge state of the battery[10]When the output power of renewable energy is large as variation in load demand, the supercapacitor can effectively suppress the short time high-frequency power fluctuation, and the battery can suppress the long-time low-frequency power fluctuation. When the power output of renewable energy is stable and enough, the energy storage system is in a charge state and can fully absorb renewable energy. When renewable energy cannot meet the demand for microgrids, the energy storage system can also supply power to all or important loads independently. Many researchers have been working on the power management and voltage control of the HMG during the past decades [11]. This research aims to clearly understand transient and dynamic operation responses of hybrid battery-SC-based HESS configurations in the DC microgrid[12].

The efficient power management control for microgrids with energy storage should increase the reliability and resiliency of the microgrid based on the distributed energy resources[13].Several researchers have used the PSO algorithm in DC microgrid management of generation or demand side[14]. So far, all these works deal either with only power resource management (production side) or consumption shifting and scheduling. The parameter of the algorithm is optimized particle swarm optimization (PSO) to alleviate the peak demand and short charge and discharge period of the battery [15][16]. Many researchers work with the optimal result by particle swarm optimization (PSO) considering the cost[17], Efficiency[18], and reliability[18][19].

The rest of this paper is structured as follows: The configuration of the DC microgrids is described in Section II. A detailed mathematical model is presented in Section III. Simulation results are presented in Section IV to control and optimize the performance of the proposed method. The conclusions are drawn in Section V.

2. SYSTEM CONFIGURATION AND MODELING OF DC MICROGRID

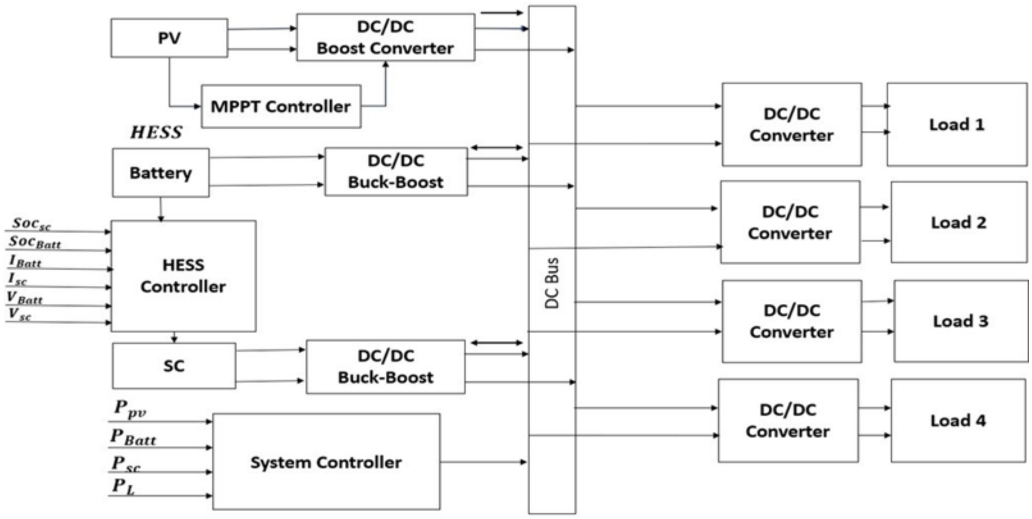


Figure 1. Model of the DC Microgrid

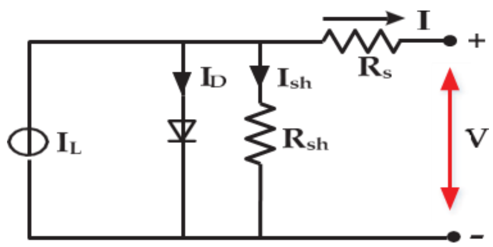
ADC microgrid comprising of PV panel, loads, and HESS is considered as shown in Figure 1.To tackle the variability associated with solar power generation, the hybrid energy storage system (HESS) components boast significant specific power density and energy density. Photovoltaic (PV) panels connect to the DC bus through boost converters, while bidirectional DC/DC converters (BDDC) link supercapacitor and battery modules to the system. The function of the power management is to regulate the DC bus voltage during power source, load variations and reference current generation for battery, supercapacitor and PV converter control. The power management algorithm is configured with battery SOC level e.g. 20% ≤ SOCbat ≤ 80%, respectively, and supercapacitor level e.g. 60% ≤ SOCsc ≤ 90%, respectively. The power management algorithm is designed with the following objectives:

- To maintain the power balance during demand-generation disparity.
- To retain the battery and supercapacitor SOC throughout the limits and remove the current oscillation of the hybrid energy storage system at the edge of SOC.

Table 1. Component rating of the DC microgrid

Parameters	Specifications
PVarray	V_{oc} = 21V,I_{sc} = 8,V_m = 17V,I_m = 7.1A
Battery(LeadAcid)	24 V, 30 Ah
Supercapacitor	29 F, 32 V
DC-DCconverter	L_{pv} = 10 mh,L_{bat}= 2 mh , L_{sc}= 1.5 mH , C = 440 µF , R = 32 Ω

2.1 Mathematical model of solar cell



F
igure 2. Ideal electrical circuit of solar cell

The voltage-current characteristic equation of a solar cell [20]Module photo-current:

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times \frac{I_r}{1000} \qquad (1)$$

Where, I_{ph}: photo-current (A); I_{sc}: short circuit current (A); K_i: short-circuit current of the cell at 25 °C and 1000 W/m^2; T: operating temperature (K); I_r: solar irradiation (W/m^2).
Module reverse saturation current I_{rs}:

$$I_{rs} = I_{sc}/[exp(qV_{OC}/N_s k_n T) - 1] \qquad (2)$$

where, q: electron charge, = 1.6 × 10^{-19}C; V_{OC}: open circuit voltage (V); N_s: number of cells connected in series; n: the ideality factor of the diode; k: Boltzmann's constant, = 1.3805 × 10^{-23} J/K.
The module saturation current I_0 varies with the cell temperature which is given by

$$I_0 = I_r \left[\frac{T}{T_r}\right]^3 exp\left[\frac{q \times E_{g0}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \qquad (3)$$

Where, T_r: nominal temperature = 298.15 K; E_{g0}: band gap energy of the semiconductor, = 1.1 eV;
The current output of the PV module

$$I_0 = N_p \times I_{ph} - N_p \times I_0 \times \left[exp\left(\frac{\frac{V}{N_s} + I \times \frac{R_s}{N_p}}{n \times V_t}\right) - 1\right] - I_{sh} \qquad (4)$$

$$V_t = \frac{k \times T}{q} \qquad (5)$$

$$I_{sh} = \frac{V \times \frac{N_p}{N_s} + I \times R_s}{R_{sh}} \qquad (6)$$

Where, N_p: number of PV modules connected in parallel; R_s: series resistance (Ω); R_{sh}: shunt resistance (Ω); V_t: diode thermal voltage (V).

The output power of a single cell is as:

$$P_{cell} = V_{cell} \, . I_{cell} \qquad (7)$$

The photovoltaic measure of performance is defined as the ratio of electrical energy produced during a solar incident (GT is solar radiation) and the efficiency of a single cell can be expressed in equation 8.

$$\eta = \frac{P_{cell}}{A_{cell} \, . G_T} \qquad (8)$$

2.2 Maximum power point tracking (MPPT)

MPPT is one of the essential components in the DC microgrid and also in a hybrid system based on renewable energy resources[21].There are many widely fundamental types used to provide high performance tracking the maximum power, which is called incremental conductance (INC) MPPT[22].

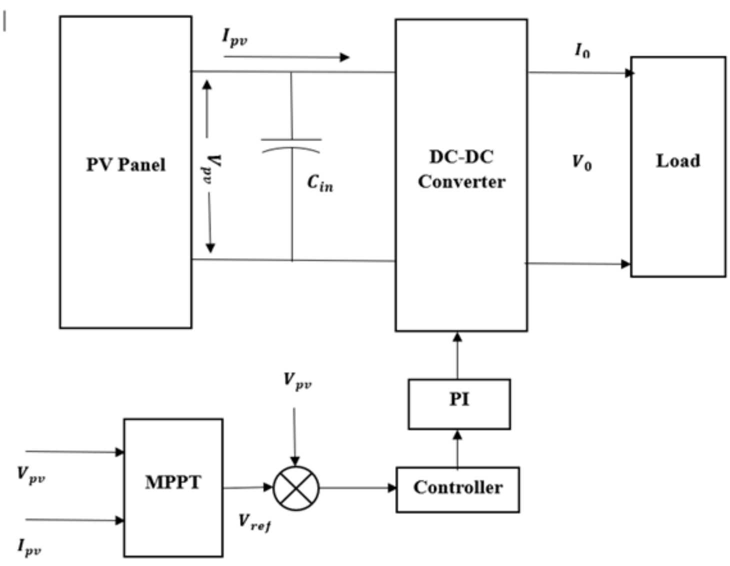


Figure 3. Standalone system with MPPT

The above figure exposes the PV Panel block diagram with MPPT depending on the control mechanism. The mathematical of these cases can be expressed as:

$$\frac{dP}{dV} = \begin{cases} > 0 & V < V_{mpp} \\ = 0 & V = V_{mpp} \\ < 0 & V > V_{mpp} \end{cases}$$

2.3. Mathematical modeling of battery

Battery with such a simple controlled voltage source with constant durability is constructed in series as shown inthe figure.The battery life decreases significantly for rapid charging and discharging characteristics. It is therefore preferable that the battery must be charged and discharged safely and within SoC limits, which is considered 20% ≤ SOCbat ≤ 80% to maintain better battery life.

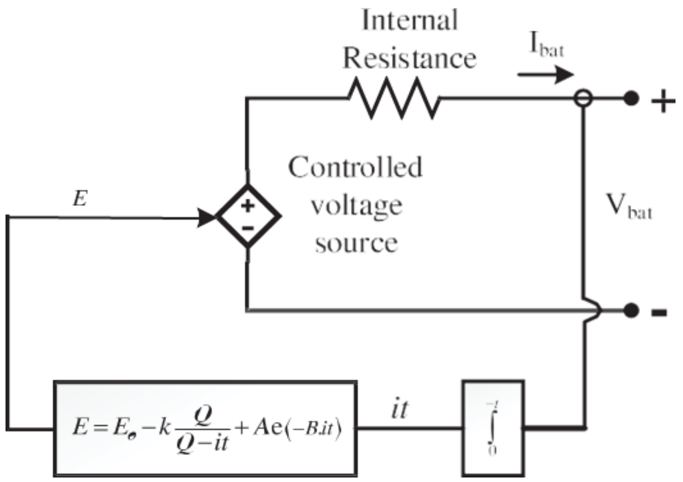


Figure 4. Equivalent circuit of battery model

$$V = E_0 - K\left(\frac{Q}{Q-\int idt}\right) + A \cdot e^{(-B\cdot\int idt)} + R_0 i \qquad (9)$$

The SOC is defined by the ratio of the amount of energy available in the storage device at the time instant to its rated energy capacity[23].

$$\% \text{ SOC} = (1-\frac{1}{Q}\int idt) * 100 \qquad (10)$$

Where E0 represents the open circuit voltage of a battery at full capacity (V);K is the polarization resistance coefficient (Ω); Q is the battery capacity (Ah); i is the battery current (A);R_0 is the internal resistance (Ω); it = ∫ idt is the removed charge (Ah);A and B are empirical constants (V), (1/Ah).

2.4. Mathematical modeling of supercapacitor

The application of the SC would cause problems with power quality and thermal stability when dealing with loads that fluctuate and require more immediate power[24]. Including SC helps to enhance and alleviate most of these challenges. This method establishes shifting loads by using controlled switches to link several power loads in parallel. The ordinary capacitor and the BESS are connected via the supercapacitor (SC).The SC is connected in parallel to increase the potential energy storage[25].

$$\eta_{eff} = e^{-\frac{2R_{ESR}C_{TOTAL}}{t_{dch}}} \quad (11)$$

Where;η_{eff}: energy efficiency; R_{ESR}: total equivalent series resistance; C_{TOTAL}: total capacitance; t_{dch}: discharging time.

$$V_c(t) = V_o e^{-\frac{t}{R_T C_{total}}} \quad (12)$$

$$v(t) = v_C(t) + v_{R_{ESR}}(t) \quad (13)$$

Where;$V_c(t)$: voltage of the supercapacitor; V_o: voltage at initial condition; t: time.
so that, voltage V(t)

$$V(t) = V_o \left(1 + \frac{R_{ESR}}{R_T}\right) e^{-\frac{t}{R_T C_{total}}} \quad (14)$$

Voltage discharge ratio

$$d = \frac{v(t)}{V_o} = \left(1 + \frac{R_{ESR}}{R_T}\right) e^{-\frac{t}{R_T C_{total}}} \quad (15)$$

3. COORDINATED POWER CONTROL STRATEGY AND OPTIMIZATION MODEL

In the proposed control strategy, to fulfill load demand during low irradiances as well as during transients[26], a DC microgrid consisting of standalone PV is proposed that incorporates HESS. In such a HESS system, the battery fulfills the supply of continuous energy while the SC supplies instant power to the load in confirmation of their energy density/power density relations[27]. The control parameters are used in the analysis as shown in Table.2

Table 2. Control parameters used in the analysis

Parameters	Specifications
Vdcref	48V
SOCbat,min	20%
SOCbat,max	90%
SOCsc,min	20%
SOCsc,max	100%
Kp,vandKi,v	0.36,1000
Kp,batandKi,Bat	5,100

Kp,scandKi,SC	0.34,2100
SwitchingFrequency	25kHz

3.1 Particle Swarm Optimization

PSO is a type of global random search algorithm based on swarm intelligence. Itwas introduced by Dr. Eberhart and Dr. Kennedy in 1995[28]. It is inspired by the social behavior of bird flocking and fish schooling. Particles are randomly initialized and their position and velocity are updated with each iteration. The steps of the PSO algorithm are as follows:

- Step 1: Initialization of parameters such as swarm size, number of iterations, acceleration coefficients, inertia weight, limit of search space, and velocity. The position of the particles is randomly initialized within the bounds of the search space.
- Step 2: The value of the objective function is found at a particular time.
- Step 3: The values of the particle's best position (Pbest) and global best position (Gbest) are obtained.
- Step 4: The velocities and positions of the particles are updated as per the following relations (29):

$$v_i^d(t+1) = wv_i^d(t) + c_1R_1(t)\left(pbest^d(t) - p_i^d(t)\right) + c_2R_2(t)\left(gbest^d(t) - p_i^d(t)\right) \quad (16)$$

$$p_i^d(t+1) = p_i^d(t) + v_i^d(t+1) \quad (17)$$

where w is the inertia factor (adjusting the global optimization ability and local optimization performance) and c1 and c2 are acceleration constants, where the former is the individual learning factor of each particle and the latter is the social learning factor of each particle. These are usually set as c1 = c2 ∈ [0, 4].

- Step 5: When the objective function is minimized and the maximum number of iterations has been reached the algorithm is stopped.
- Step 6: The optimal values of the parameters are obtained.

The algorithm is used for optimization, and the mathematical model of the objective function is described as

$$\min y = f(x)$$

$$= f\,(Ppv+Pbat+Psc-Pload) \quad (18)$$

The energy consumption per unit mileage is set as the evaluation standard for the algorithm. It is shown as

$$f(x) = \text{fitness} = \frac{energy}{distance}$$

$$= \text{fitness} = \frac{Bat.+SC}{distance} \qquad (19)$$

The energy consumption of the HESS needs to consider the consumption of various components including the battery power, supercapacitor power, DC/DC converter loss, and PV power. A flowchart of the PSO is shown in Figure 5[30].

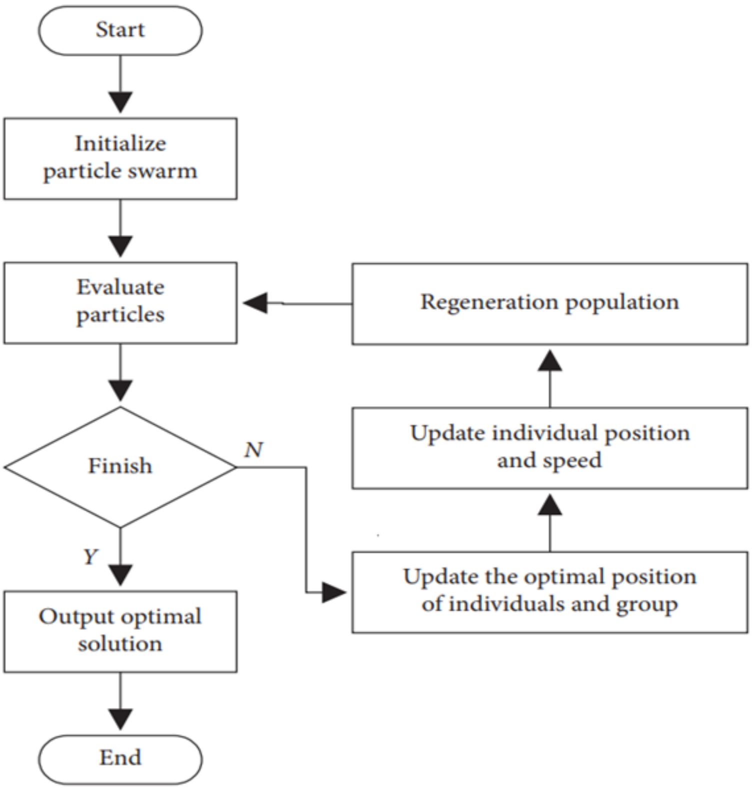


Figure 5. Flowchart of PSO.

4. RESULTS AND DISCUSSION

Photovoltaic generation is commonly deployed in remote rural sites that are not available on the utility grid.However,the intermittent nature of solar irradiance and the relatively large fluctuation in load may lead to system instability. Therefore,a battery is normally included in the system. This proposed system demonstrates the effectiveness of HESS in reducing the stress on the battery.

The simulated power generation and load profile are shown in figure 6.To demonstrate the effectiveness of HESS in mitigating battery stress, a battery-only is also simulated for comparison purposes. The simulation results showing the power exchange in the battery for charging and discharging are illustrated in figure 7.

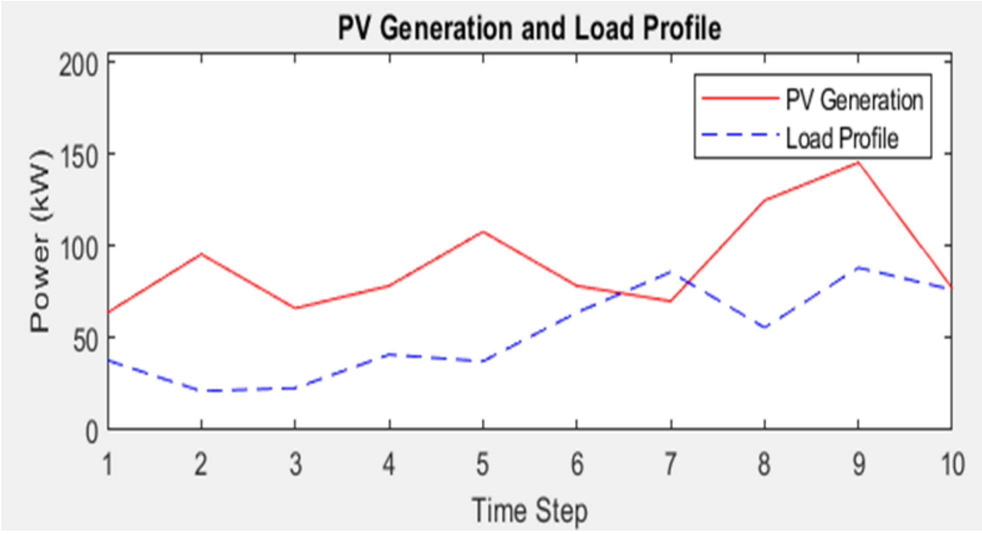


Figure 6. Power generation and load profile

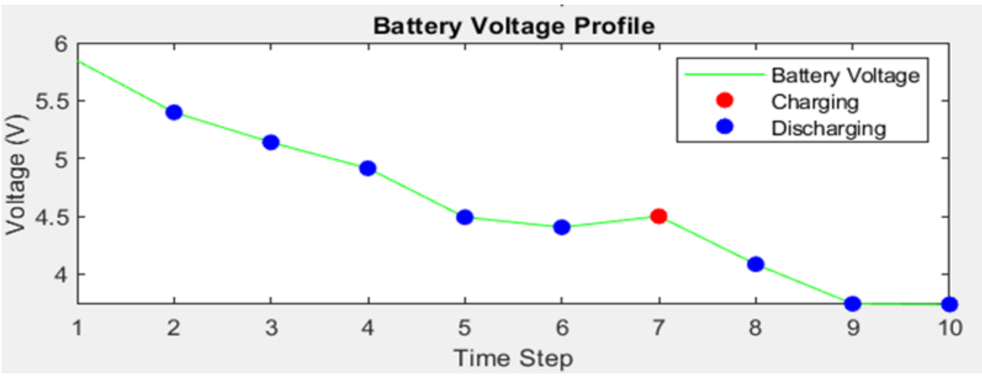


Figure 7. Battery voltage and battery charging, discharging

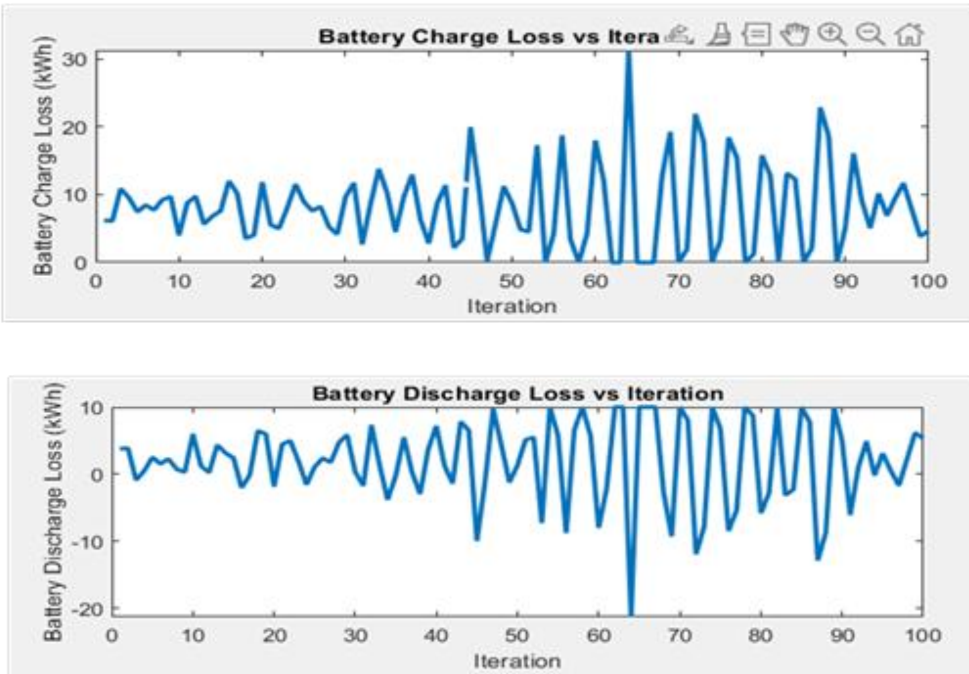


Figure 8. Battery charging and discharging loss

When load demand is larger than the power of generation in this situation the power can be managed according to the load requirement fulfilled through the battery. It is continued till the SOC of the battery falls below 30% due to continuous discharge as shown in Figure 8. PSO optimizes the charging and discharging power of the battery as shown in figure 9.

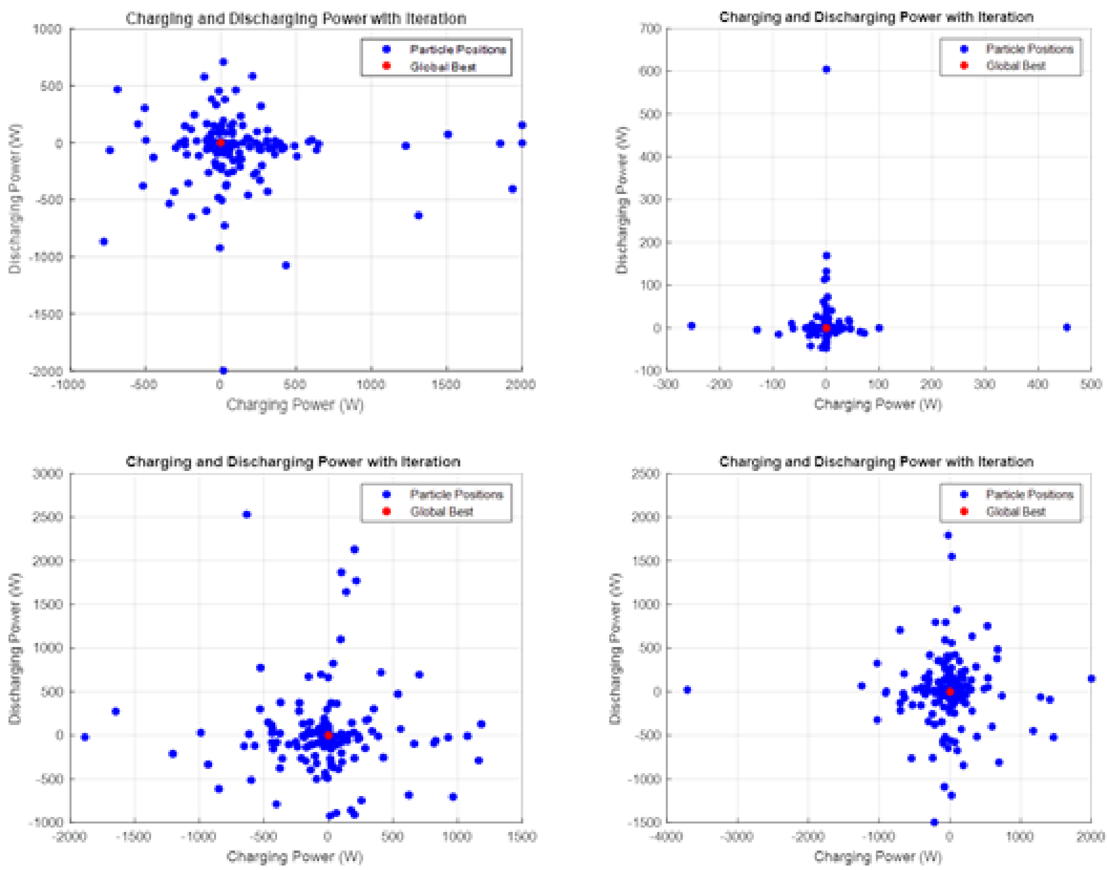


Figure 9. PSO Battery charging and discharging power

5. CONCLUSION

A novel coordinated power control strategy is an approach to enhance the overall performance and battery service life by handling generation-demand power variation in a standalone DC microgrid. The large variance in generation and load power demand is compensated by using a hybrid energy storage system (HESS) that consists of batteries and a supercapacitor. The optimization problem was developed to solve using a framework in which the particle swarm optimization algorithm, was effectively verified by comparing results with those obtained from other recently developed algorithms. The impact of variation on output results is analyzed. In contrast, renewable sources and load demand significantly affect the battery lifespan since efficiency plays a direct role in it. The simulation results showed that the battery life increased when the sudden variation in the system and it is compensated for by the supercapacitor, therefore improving the performance of the system and reducing charge and discharge loss. Additionally optimizing the size and capacity of the battery system can help to improve its response time and minimize the effect of voltage fluctuations on the reference current.

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