Modelling and simulation of microgrid power system including a hybrid energy storage system

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Abstract. " Microgrid technology is evolving rapidly with increased use Renewable energy (RE) in electricity sector. In this paper, an isolated DC microgrid is simulated with solar photovoltaic (PV) as the RE source to supply power to resistive DC charges along with a hybrid energy storage system (HESS) for battery and supercapacitor. Various cases of load and solar insolation variability are simulated to validate the proposed power management strategy for controlling the DC bus voltage. The output waveforms are compared with and without HESS, and beneficial reduction in transient voltage is observed when using the HESS. A case using IEEE 9bus is also simulated to evaluate device output with a constant demand for load. It is found that in all cases HESS helps to minimize transients of the DC bus voltage effectively. The HESS also compensates for very large transients resulting in sudden changes in the output of PV or load demand.

Keywords: DC microgrid, HESS, renewable energy, IEEE 9bus, Battery

1. Introduction

May be microgrid described as "an integrated, widely distributed energy distribution network characterized by a two-way electricity and information flow, capable of monitoring and reacting to changes in everything from power plants to consumer preferences to individual appliances."[1] Most of the electronic charges connected to the current power grid are DC charges. AC-DC power conditioning units are needed to link them to the AC grid which creates additional system losses. The losses are easily minimized by using a DC microgrid. Owing to isolation from fault, islanded DC microgrids also provide power to critical loads when input from the main grid is inaccessible. Different researchers focused on the DC microgrids [2-6].

Solar and Wind energy are among the most frequently harvested sources of Renewable Energy (RE) available [7]. However, storage devices are needed in microgrids because of the intermittent power available from these sources. Such devices include banks of batteries, supercapacitors (SC), flywheels and other heat storage technologies. Batteries are high in energy density and can provide long-term power. SCs have a high-power density and provide a faster charge and discharge rate. Such RE sources are either unidirectional or bidirectional power conditioning systems attached to the DC bus. Several microgrids with combinations of different generations and energy, including PV, Fuel Cell and SC [8]. PV, wind and fuel cell [9]. PV and battery [10]. It was researched for power grid applications as well as applications for electric vehicles. Has investigated a wide range of intelligent control strategies for managing hybrid energy devices [11-14]. The idea of hybrid storage was extensively studied, but the control of bus voltage during storage charging and discharging modes was not considered a constraint. In [8], [15] hybrid energy storage systems (HESS) are used, but the SC bank is used in combination with the battery bank to provide power for both transient and base load. The benefit of using hybrid energy storage in a DC microgrid had been illustrated in this paper. The battery banks provide the backup power for the base charge while the SC banks only provide the transient power backup during abrupt changes in the use of load power or PV. This saves SC
use by discharging it during transitional time only. Using hybrid energy storage allows the DC bus voltage to be controlled more rapidly and the transient voltage peak compared to a single storage unit (battery).

2. Modelling microgrid and configuration

Figure 1 displays the schematics of the microgrid architecture simulated in this article.

![DC Microgrid Schematic](image1)

**Figure 1.** Schematic of DC Microgrid [16]

It consists of PV arrays as the renewable electricity source, Battery and SC banks as a hybrid power storage device, DC-DC power converters as air conditioning units and resistive DC charges. All the devices are wired to a DC bus A-380V [16].

2.1 Modelling of PV cell

The photovoltaic of this type is basically described by a circuit with a DC current source, a diode and a resistance as shown in Figure 2. The current intensity of the source depends on solar radiation and the voltage and current characteristics of the diode, which in turn are dependent on temperature [17].

![Ideal Circuit of Solar Cell](image2)

**Figure 2.** Ideal circuit of solar cell

The operation of the system is described by Kirchhoff’s law, as the balance between the $I_L$ module generation current and the current on the $I_D$ diode [17].

$$I = I_L - I_D$$  \hspace{1cm} (1)

The characteristic equation of current with respect to voltage, is described as.

$$I = I_L - I_0 \left( \exp \left( \frac{V + IR_s}{V_T} \right) \right)$$  \hspace{1cm} (2)

the values of the generated current $I_L$, the inverse saturation reference current of the diode $I_0$, ref, the empirical parameter of adjustment of the photovoltaic curve $\gamma$ and the series resistance of the module are calculated. $R_s$, according to the parameters described below. Being $V_T$ the thermal voltage, which depends on the absolute temperature (300 K)

$$V_T = \frac{kT}{q}$$  \hspace{1cm} (3)

Where the constant of the electric charge on the electron with a standard uncertainty 4 and the Boltzmann constant 3, according to the National Institute of Standards and Technology [17], are respectively. $q =
1.602176 \times 10^{-19} \text{ C} \& K = 1.38065 \times 10^{-23} \text{ J/K}. \quad \text{Therefore, the value of the thermal voltage } V_T \text{ is } V_T = 25 \text{ mV}. \quad \text{To determine the generated current } I_L, \text{ the linearly dependent relationship of the incident radiation must be taken into account}

\[ I_L = I_{\text{ref}} \frac{G_T}{G_{\text{ref}}} \]  

(4)

Where the photocurrent of the module under reference conditions \( I_{\text{ref}} \) is equivalent to the short-circuit current under reference conditions \( I_{\text{sc, ref}} \)

\[ I_{\text{L, ref}} = I_{\text{sc, ref}} \]  

(5)

The empirical parameter for adjusting the photovoltaic curve is given by

\[ \gamma = \frac{q(V_{\text{mp, ref}} - V_{\text{oc, ref}} + I_{\text{mp, ref}} R_s)}{k T_{\text{ref}} \ln \left( 1 - \frac{G_T}{G_{\text{ref}}} \right)} \]  

(6)

the rated voltage reference \( V_{\text{mp, ref}} \), open circuit voltage reference \( V_{\text{oc, ref}} \), rated current reference \( I_{\text{mp, ref}} \). The reverse saturation current of diode \( I_0 \) depends on the temperature of the \( T_C \) module and its reference parameters.

\[ I_{0, \text{ ref}} = \left( \frac{T_C}{T_{\text{ref}}} \right)^3 \]  

(7)

Wherein the inverse saturation reference current of diode \( I_{0, \text{ ref}} \), short circuit current \( I_{\text{sc, ref}} \) is defined from:

\[ I_{\text{0, ref}} = \frac{I_{\text{sc, ref}}}{\exp \left( \frac{q V_{\text{oc, ref}}}{k T_{\text{ref}}} \right)} \]  

(8)

The analytical derivative of voltage with respect to temperature under open-circuit reference conditions is given by:

\[ \frac{\partial V_{\text{oc}}}{\partial T_C} = \mu V_{\text{oc}} = \frac{e}{q} \ln \left( \frac{I_{\text{sc, ref}}}{I_{0, \text{ ref}}} \right) + \frac{T_C^2 I_{\text{sc, ref}}}{I_{\text{sc, ref}}} \left( 3 + \frac{q e R_s}{k T_{\text{ref}}} \right) \]  

(9)

In order to get a good approximation of the crystalline modules, the values of the generated current \( I_L \), the inverse saturation reference current of the diode \( I_{0, \text{ ref}} \), the empirical parameter of adjustment of the photovoltaic curve \( \gamma \) and the series resistance of the module are calculated. \( R_s \), according to the parameters described below. Additionally, to determine the value of \( R_s \), it is assumed that the slope of the Current-Voltage curve is zero in the short-circuit condition [17].

\[ \left( \frac{dv}{dv} \right)_{v=0} = 0 \]  

(10)

Based on the technical conditions of the manufacturer of the chosen monocrystalline photovoltaic panel, the short-circuit current of the module is established under reference conditions \( I_{\text{sc, ref}} \). Due to the solar array is widely used in application of electrical circuit, so add the shunt resistance to the ideal circuit in Figure 2 to become more efficient and more protect. The new circuit is called electrical model of solar cell is shown in Figure 3.

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**Figure 3.** simple ideal electrical circuit of solar cell

The analysis of the above circuit according to method analysis of basic circuit in Figure 3, \( I_D \) is the current in the diode, \( I_L \) is the saturation current, \( q \) the electron charge, \( T \) is the absolute temperature of the diode
junction, \( k \) is the Boltzmann constant, \( n \) is the ideality factor of the junction of a diode PN and \( U_{\text{cell}} \) is the voltage of the photovoltaic module, \( I_{\text{cell}} \) is the current of the photovoltaic module. \( R_s \) and \( R_{sh} \) model is the losses in the module, and \( I_{sh} \) is the current flowing through the resistance \( R_{sh} \), the output power of each cell in the PV module, the total output power of module and electrical efficiency of the PV module, the final expression for electrical equations can be written as below.

\[
I = I_L - I_D - I_{sh} \tag{11}
\]

\[
I_L = \frac{G_{\text{ref}}}{G_{\text{ref}}} \cdot \left( I_{\text{ref}} + \mu I_{\text{cell}} \cdot (T_{\text{cell}} - T_{\text{cell, ref}}) \right) \tag{12}
\]

\[
I_{sh} = \frac{R_{sh}}{R_c + I_{\text{cell}} R_s} \tag{13}
\]

\[
I = I_0 \left( \frac{\exp \left( \frac{U_{\text{cell}}}{a} \right)}{\exp \left( \frac{U_{\text{cell}}}{a} \right)} - 1 \right) \tag{14}
\]

\[
V_{oc} = a \ln \left( \frac{I_L}{I_{sh}} \right) \tag{15}
\]

\[
P_{\text{cell}} = U_{\text{cell}} \cdot I_{\text{cell}} \tag{16}
\]

\[
P_{\text{tot}} = N_s \cdot U_{\text{cell}} \cdot I_{\text{cell}} \tag{17}
\]

\[
\eta = \frac{P_{\text{cell}}}{A_{\text{cell}} G_T} \tag{18}
\]

2.2 Battery bank: Batteries are a very important element in a photovoltaic solar system that operates in island mode. Its main function is to store the energy that is not consumed by the loads, to later be used when the generation of the panel is less than the load. In addition to this, it allows stabilizing voltage levels in the event of a transient occurrence in the system [18]. In the following paragraph, the specifications of the bidirectional converter built for charge and discharge control will be addressed. The battery's state of charge (percent SOC) is calculated using the current integration method as shown in equation (2) where \( Q(t_0) \) is the battery's initial charge at time \( t_0 \), where \( \alpha \) is the charge / discharge efficiency and \( i \) is the battery's current [16]

\[
SOC(t) = \frac{Q(t_0) + \int_{t_0}^{t} \alpha I dt}{\text{Rated capacity}} \times 100 \tag{19}
\]

2.3 Supercapacitor Bank

The first supercapacitor, created by General Electronics in 1957. This supercapacitor was based on a system with a double layer in the clear using a porous carbon electrode [19]. Compared to batteries, these devices can charge and discharge extremely fast, while providing a much higher load capacity compared to traditional capacitors. Supercapacitors can be recharged 100,000 times compared to only a few thousand recharge cycles for traditional batteries [20]. Compared to batteries, the rate of self-discharge is higher but the power provided by a supercapacitor is only for a short time. Once supercapacitors are charged there are no chemical reactions, while the batteries undergo an internal chemical reaction when being charged. During discharge this chemical reaction will be reversed to provide the absorbed energy [21]. The SC bank's percentage of SOC is defined as the ratio of total energy (Qc) to rated energy (Q0) , and is calculated by equation (3).

\[
SOC = \frac{Q_c}{Q_0} = \frac{C_{\text{RC}} I_{\text{max}}^2}{2} \tag{20}
\]

Where C is the SC bank's relative capacitance, Vc is its voltage, and Vmax is the absolute complete charge value of SC bank voltage [16].

2.4 dc-dc convertor

Unidirectional Boost Converter for PV: At any given insolation Maximum power output is given by the PV plate. This is ensured by the MPPT controller which provides the gate pulses with a unidirectional boost converter [22] using the Incremental Conductance Algorithm (INC) [23]. The converter increases output voltage of 275V PV to bus voltage of 380V. The corresponding curves I-V and P-V for the MPPT process are shown in Figure 4.
2.5 Bidirectional DC-DC Converter for HESS:
A bidirectional DC to DC converter allows transfer of power in both directions between two DC sources. For example, the use in applications like battery charging circuit and uninterruptable power supplies for these converters is the result of the reverse direction of power flow, and also maintained the voltage polarity [24]. For power conversion applications a bidirectional DC to DC converter is used. In this converter power which is best suited for electrical applications, two full bridge converters (inverter and rectifier) are used [25]. The reference current signal (Iref) for the converter ‘s internal current control loop is the output of the voltage control loop. Since the battery bank is only supplying the low frequency power, a low pass filter is used to isolate the low frequency portion (ILFref) from Iref. That is given as a reference to the battery converter's current control loop. The reference current high frequency component (IHFref) (Iref) is easily obtained with equation.

$$\text{IHFref} = \text{Iref} - \text{ILFref}$$  \hspace{1cm} (21)

This IHFref is supplied as the reference signal for SC bank's current control loop. Figure 5 shows the implementation of this algorithm by MATLAB which makes the current SC reference zero during a steady state.

![MATLAB model for current reference generation of Battery and SC](image)

3. Simulation Results of PV system with HESS
This section studies the stability analysis for the case of IEEE 9 bus system. The proposed scheme is implemented by MATLAB software environment. The main purpose of proposed large-scale PV system (LSSPV) is to confirm that the proposed approach gives excellent results for cases of variable solar radiation as well as load changes. It is expected to regulate the DC bus voltage with battery and super-capacitor units
in such a way that the super-capacitor provides the fast-changing components of the required DC bus voltage compensating current while the battery unit provides the slow varying components. The all simulation results are implemented under two disturbances: fault occurs at 0.49 and remove at 0.51 as well as the load is changing at bus 6 from 60 MVAR to 80 MVAR.

In order to make the simulation is more realistic, the input irradiance to PV is changed under three steps during 1.4 sec starting from 1000 W/m², 500 W/m², and ending at 300 W/m² respectively as shown in Figure 6. It can be seen that the output mean power of each PV is very tracking to the change of irradiance and also in the meanwhile, the temperature changes for each PV when compared without HESS as shown in Figure 7a and 7b. The INC maximum power tracking confirms that it is beneficial with large scale PV penetration. While Figure 8a and 8b shows the total output AC power of large-scale PV system that penetrated at bus 4. It can be seen that the value of total AC power is equal to 470 KW and this value is equal to the sum of each power of PV in Figure 7 which implies the system is very stable and does not affect by a fault that occurs. Figure 9a and 9b shows how the DC bus voltage changes shortly following the transients, quickly recovering and stabilizing at the rated (500V). It noted that, the DC bus voltage of PV system with HESS has lower oscillation during the period of fault.

To confirm the proposed scheme is beneficial for improving transient response of voltage profile, the proposed system is comparing with and without large scale PV system and HESS as shown in Figure 10a, 10b and 10c. It can be seen that the buses voltage has lower overshoot at the period of the fault and rapid recovery and stabilizing within acceptable limit when penetrating the LSSPV at bus 4 as shown in Figure 10b, but when compared the response of IEEE 9 bus without LSSPV, we observed that the buses voltage has high overshoot at fault period and does not return to steady-state at the short time as well as the values of voltage exceed the acceptable limited between 0.9 and 1.05 PU as shown in Figure 10a.

In order to proof the robustness of proposed PV system, the power of buses, rotor speed, load angles and relative angles of machines are obtained during and after the occurrence of fault, to analyze the stability as shown in Figures 11 – 14. From these figures, it is noticed that the oscillation during the fault is less and also it is damping out after removing the fault.

In order to accurately compare PV system and PV system with HESS, the simulated test results of magnitude voltage are tabulated in Table 1.

![Step Change of Irradiance](image)

**Figure 6.** Reference step change of irradiance
Figure 7. Tracking output power of each PV (a) without HESS, (b) with HESS

Figure 8. AC output power of large-scale PV system (a) without HESS, (b) with HESS.

Figure 9. DC link Output voltage (a) without HESS, (b) with HESS
Figure 10. Bus voltages (a) without large scale PV penetration and BESS (b) with large scale PV penetration and without HESS, and (c) with large scale PV penetration and HESS.

Figure 11. Rotor speed of machines with PV system and (a) without HESS, (b) with HESS.
Figure 12. Rotor speed of machines with PV system and (a) without HESS, (b) with HESS.

Figure 13. Load angle of machines with PV system and (a) without HESS, (b) with HESS.

Figure 14: Relative angle of machines with PV system and (a) without HESS, (b) with HESS.
| Bus No. | V(pu) std. | V(pu) without PV | V(pu) with PV | V(pu) with PV & HESS |
|--------|------------|------------------|---------------|---------------------|
| 1      | 1.04       | 1.041            | 1.042         | 1.04                |
| 2      | 1.025      | 1.029            | 1.029         | 1.026               |
| 3      | 1.025      | 1.027            | 1.023         | 1.026               |
| 4      | 1.026      | 1.028            | 1.021         | 1.024               |
| 5      | 0.996      | 0.9988           | 0.9913        | 0.9988              |
| 6      | 1.013      | 1.015            | 1.009         | 1.012               |
| 7      | 1.026      | 1.029            | 1.023         | 1.023               |
| 8      | 1.016      | 1.019            | 1.012         | 1.014               |
| 9      | 1.032      | 1.035            | 1.019         | 1.021               |
| average| 1.022±0.0125| 1.0246±0.0123    | 1.0188±0.014  | 1.02±0.011          |

4. CONCLUSION
In this paper, a power management strategy for DC microgrid with renewable solar energy source and hybrid storage devices is proposed and tested with various simulation case studies to maintain regulated bus voltage. The economical use of SC power to combat transient power fluctuations is studied and bus voltage fluctuations are effectively managed with HESS due to sudden power changes. Real data on solar insolation is used for validating the proposed strategy under these variations. Following the above work, the integration of the DC microgrid with the main AC grid may be investigated in order to improve its power management strategy.

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