DC Microgrid Energy Management System Containing Photovoltaic Sources Considering Supercapacitor and Battery Storages

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***Abstract*—The tendency to use renewable energies in DC microgrids (MGs) has been increased in the past decades. Due to the unpredictable behavior of renewable resources, it is vital to utilize energy storage resources in the MG structure. The generation sources and storages in DC MGs should be chosen in order to meet the maximum demand in both grid-connected and islanded mode. Also, penetration of power electronic based devices is essential to connect these resources to the network. The control of these devices are another challenge in this regard. So, a proper configuration along with an efficient control approach is needed for development of DC MGs. In this paper, a new structure for DC MG is presented which includes solar photovoltaic (PV) as generation sources and supercapacitor and battery as storages. Furthermore, an innovative control method based on voltage variations is introduced for the proposed structure. It is shown that simultaneous usage of battery and supercapacitor improves the performance of the MG in handling the abrupt load changes in the both grid-connected and islanded mode operations. To evaluate the performance of the proposed structure and control algorithm, different conditions are simulated in MATLAB/Simulink software and the results are presented. The results confirm a high degree of performance for proposed structure and control method.**

***Index Terms*—DC Microgrid, Energy Management, Distributed Control Method, Battery Storage, Supercapacitor**

NOMENCLATURE

Abbreviations

PV	Photovoltaic
MG	Microgrid
DG	Distributed Generation
DBS	Distributed Bus Signal
MPP	Maximum Power Point
$PandO$	Perturb and Observe
CC	Constant Current
SOC	State of Charge

Parameters and Variables

A	Ampere
V	Volt
W	Watt
F	Farad
H	Henry
$G(s)$	Function
s	Input of function
C_f	Capacitance of low pass filter
L_f	Inductance of low pass filter
f_s	Switching frequency
C_{grid}	Capacitance in bidirectional converter output
P_{out}	Maximum load power
V_{grid}	DC link voltage
V_{ripple}	Maximum acceptable DC link voltage
L_{batt}	Inductance in input of battery
C_{batt}	Capacitance in input of battery
D	Incremental converter switching cycle
r_{ESR}	Internal battery resistance
$\Delta i_{\text{battery}}$	Maximum acceptable charge/discharge current
L_{pv}	Inductance in input of PV
Δi_{pv}	PV current variation
L_{SC}	Inductance in input of supercapacitor

I. INTRODUCTION

A. Motivation and Background

Nowadays, use of renewable energies as a suitable choice for clean energy is expanding. Recent advances in increasing the efficiency and reliability in MGs have made renewable energies good choices for decentralizing electric power generation. Since most renewable sources, such as PV systems, fuel cells and variable speed wind power plants produce DC voltages with variable voltage and frequencies, use of power electronic converters is necessary to connect these resources to the network [1]. In addition, new loads such as electric vehicles, as well as common loads require DC power. So, the wide applications of DC networks over the AC ones are reasonable. DC MGs have advantages in terms of cost and efficiency; in addition, they can convert DC to AC or AC to DC power in AC MGs to aggregate the mentioned loads and renewable energy sources [2]–[5]. Power systems in commercial centers containing sensitive loads [6], industrial [7] and aerospace industries [8] are examples of typical DC MG applications.

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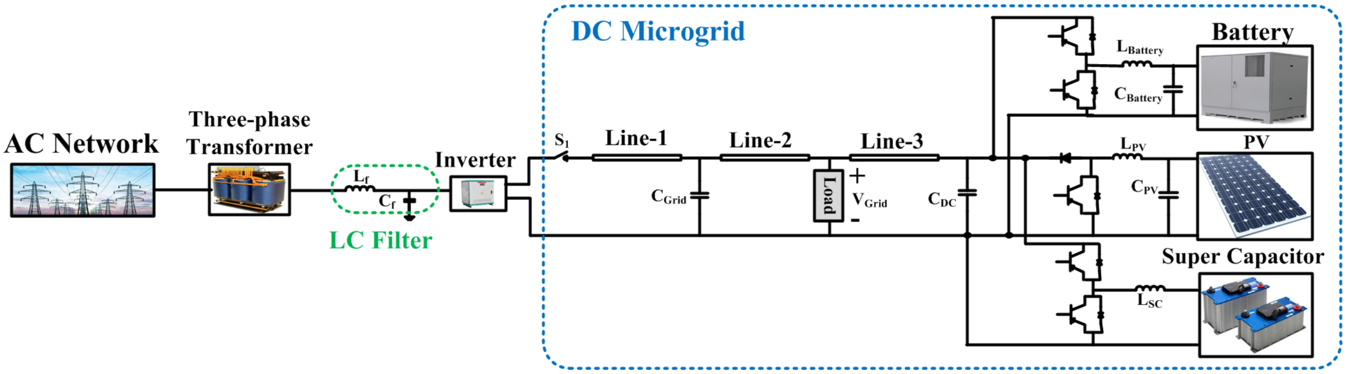

Fig. 1. Proposed system structure

Due to the unpredictable behavior of renewable energy sources, the use of energy storage resources for continuous islanded operation is required. In systems consisting of a storage and renewable energy, the storage provides the power difference between the source and the load in unpredictable conditions. Indeed in such conditions, a supervisory control strategy for energy management is needed.

Similar to AC MGs, a power management system is required for guaranteeing the reliable operation of renewable energy sources and storages in DC MGs [3]. In the grid-connected mode, the renewable source is in the maximum power state and provides its generated power to the network [5]. The network also has the task of balancing power and adjusting DC voltage. In the case that the MG operates in islanded mode, the renewable energy production capacity should be able to meet all demand for the load. If the renewable source power cannot meet the load demand, the storage provides the difference between demand and production. Also, in the case of higher output power than the load demand, additional power is stored in the storage source to keep the balance in the network [8]. So in this paper, the focus is on proposing a proper DC MG configuration along with an efficient control and energy management approach.

B. Relevant Literature

In recent years, different researchers proposed various structures, control methods and energy management approaches for DC MGs. In what follows, a widespread literature survey is presented which is tried to consider all of the important and recent reports in this regard. Based on the presented literature survey, one can find out that there is a gap in this important research field.

- *Proposed configurations*

Different structures with various elements have been suggested for DC MGs in order to meet their vital requirements. In ref. [9], a novel DC MG structure is provided to feed a residential complex. The supercapacitor has also been added to the system as the main storage source for feeding sensitive loads during disturbances. Ref. [10] discusses the application of fuel cells along with PV, electric vehicles and battery storage. In this configuration, only the islanded mode of operation has been studied. Utilization of various interfaces for PVs and battery storage has been considered in [11]. In this research, the applicability of PVs with distributed and centralized battery storage system with a separate battery storage for each load is studied. This configuration is not cost-efficient and implementable in real-world applications. Another structure based on battery storage and PV has been presented in [12]. The primary and secondary battery storage is utilized to cover the power of loads in different time periods. This structure is not also suitable considering the fast dynamic behavior of DC loads and complex communication.

- *Proposed control and management systems*

The source of power and storage supplies in DC MGs should be considered as being capable of meeting the maximum demand in islanded mode. However, achieving this goal is not possible in DC renewable energies due to lack of definitive production and the need for accurate control of resources during different disturbances is crucial [13]–[15]. In [16], operation of a DC MG with several different sources has been presented, but the control system has not been addressed. However, ref. [17] provides a control method for DC MGs with the presence of different storage resources which are paralleled to the source of power generation. In ref. [18], an islanded DC network with PV, fuel cells, a battery management system and a DC distributed bus control system is presented in various operating modes. However, the grid-connected mode and fluctuations of islanding are not discussed in details. In [19], PV voltage control is introduced with DC/DC converters in DC distributed isolation systems. In this system, PV voltage changes have been considered in the design of the DC bus control system. However, the transient state, grid connectivity and energy storages have not been thoroughly investigated. In [20], a distributed control method known as the DC Bus Signal (DBS) is developed and implemented for an Nano-grid based on renewable energy sources. In this method, voltage level variation of the DC bus is used as a communication link between supply resources and storages. However, the relationship with the AC network and the constraints which exist in the MG are not considered.

C. Contributions and Organization

In this paper, a new method is proposed for the operation and control of a DC MG, including PV, supercapacitor, and battery. The energy density of supercapacitors is several times higher than the dielectric capacitors. The high power density allows the supercapacitor to withstand a large charge and discharge current over a short period of time, but the low energy density of these capacitors makes it impossible to feed energy over a long time interval continuously. The usage of both battery and supercapacitor boosts system productivity. Moreover, using the proposed structure, load can be fed within a long period of time. Also an improved power control strategy is presented based on DC link voltage changes to manage battery power, PV and supercapacitor in the network.

Considering the presented literature review, the main contribution of the paper can be summarized as follows:

- Simultaneous application of suprcapacitor and battery storage in configuration of DC MG
- A new distributed-based, low computational burden and cost-efficient structure for the control system
- A simple and high-performance energy management methodology for DC MG
- Considering different challenging conditions in the evaluation of the method.

The present paper is arranged as follows. Section II identifies the structure of suggested DC MG. In this section, an overview on the general information of the MG is presented. In section III, the control system is well-explained using the information of control method for the PV, battery and supercapacitor. The design consideration is presented in section IV. The simulation studies and results are brought in section V and finally, conclusions are given in section VI.

II. Structure of Proposed DC MG

The proposed DC MG structure is shown in Fig. 1. This structure consists of a PV with a DC/DC converter, a battery system with an incremental-decreasing bidirectional DC/DC converter and a supercapacitor with a bidirectional DC/DC incremental-decreasing converter. In the proposed structure, the battery system and supercapacitor are used to balance power in situations where there is a shortage or overcapacity. Also, an AC/DC converter is utilized for bidirectional power supply (from AC network to MG and from MG to AC network). Different conditions may indicate that supercapacitors, batteries and PVs are in different situations. For this reason, it is necessary to use a control method to coordinate their performance in different operating conditions. In the proposed structure, PV, as the main source of DC power supply, is controlled in a way that it can generate its MPP. However, in some cases, it may be necessary to change the function of PV which will be discussed in the control system. Supercapacitors and batteries also have a duty to provide continuous power supplies with their discharge.

III. Proposed Control System

A. PV controller

Based on the conditions under which the MG operates, PV must be able to operate in MPP mode or in the voltage control mode. A simple solution to this goal is to use two separate control circuits, which the system switches to, according to the conditions which it is in. This method causes fluctuations when switching from one to the other. Meanwhile, a detector is required to check the correct mode of operation of PV and command the control system. In this section, a new control method is proposed for the correct functioning of PV in different situations. The block diagram of the control system is shown in Fig. 2. In this control system, the basis of decision-making for the status of the PV is the voltage of DC bus. If the voltage is greater than the specified value ($1/1$ times of the unit value), PV will operate in MPP mode. In this case, the voltage setting is based on the battery, supercapacitor and the network. In this case, depending on the microgrid conditions, the battery and the supercapacitor may be charged or discharged. But if the DC bus voltage is pulled out of this range, PV goes to the voltage control mode to maintain the bus voltage and fine-tune the proper operation of the MG. The control system works using the following procedure: the average value of $Vgrid$ is subtracted by the permitted value, which is here 1.1 times of the reference voltage. The obtained value passes from the function $G(s)$. According to [21], the function $G(s)$ defined as:

$$G(s) = 50\left(\frac{1 + s/5884}{1 + s/60318}\right)^2 \quad (1)$$

Then the output signal is saturated between zero and negative values. So, if the output signal has a positive value, the saturation block will force this value to be zero and the system will work using the voltage output from the PandO block. With this condition, the PV system is in MPP mode. But if the output of the $G(s)$ block is negative, this value is multiplied by the negative sign of the summation block and summed up with the PandO output, and the new voltage is the reference for control, therefore PV goes to the voltage control state.

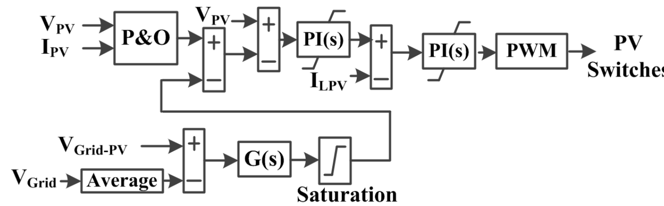

Fig. 2. Block diagram of the PV control system

B. Battery controller

In different conditions that occur for a MG, battery can be charged, discharged or operate off-circuit. Battery performance is controlled by the DC bus voltage level. Figure 3 shows the block diagram of the control structure of the battery. If the DC bus voltage is in the predetermined range (here, 0.95 to 1.1 times of the reference value for the DC bus), the battery retains its previous mode. This is done with the dead zone block. If the DC bus voltage is lower than the bottom limit (0.95 times of the reference value), the battery controller only commands the lower switch in the bidirectional converter structure and, using the high-power switching diode, increases its voltage to reach the desired level. In this mode the battery is discharged

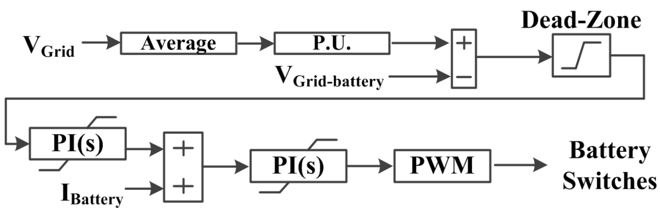

Fig. 3. Battery control diagram block

by constant current (CC) to maintain the DC bus voltage in the allowed range. Now, as the DC bus voltage passes from the higher limit (1.1 times of the reference value), the battery controller only commands the upper switch in the bidirectional converter structure and reduces the voltage by using the low-switch diodes until the battery charges with CC circuit method and return the DC bus voltage to the specified range. It should be noted that battery charging/discharging by the CC method can increase battery life, but the amount of current that the charging/discharging happens into, will vary depending on the voltage variation of the DC bus. The initial value of the proportional-integral controller changes each time when the battery state changes.

C. Supercapacitor controller

Supercapacitor performance is controlled by the DC bus voltage level. Block diagram of supercapacitor control structure is very similar to the battery control system. The difference in operation between the two systems is in the predetermined range (here it is 0.99 to 1.11 times of the reference value for the DC bus). In addition, the coefficients of the proportional-integral controller in the structure of the supercapacitor controller are different with the battery controller coefficients in order to achieve a faster response.

IV. Design Consideration

In the design procedure of the MG elements, factors such as cost, size and efficiency are considered. In the structure shown in Fig. 1, a PV model with 1soltech 1sth-215-p, the lead-acid battery and a three-phase transformer with a star-triangle configuration and ratio $173V/20kV$ are used. Table 1 shows the general characteristics of the DC MG. The inductance and low pass filter capacitor at the input of the DC MG are calculated according to equation (2) [22]:

$$C_f L_f = \frac{1}{8\pi^2 f_s^2} \tag{2}$$

Considering fs is $20kHz$, which is the switching frequency of almost all converters [23], and the value of $100mH$ for the inductor, the capacitance value will be equal to $16.3nF$. Also, the amount of capacitance installed in the output of a bidirectional converter is calculated for DC voltage stabilization according to equation (3):

$$C_{\text{grid}} = \frac{P_{\text{out}}}{6 \times V_{\text{grid}} \times V_{\text{ripple}} \times f_s} \tag{3}$$

In this equation, the maximum load power in this structure is considered to be $5kW$, the DC link voltage is equal to $400V$, and also V_{ripple} is the maximum acceptable DC link voltage, which in design been considered as the 2% of the Vgrid. Therefore, C_{grid} is calculated as $13\mu F$.

Table 1. General Specifications of DC Grid

Parameter	Value	Unit
Dc link voltage	400	V
Number of PV series Panel	2	-
Number of PV parallel panel	10	-
Each panel's rated power	21	W
PV open circuit voltage (Voc)	35	V
PV short circuit current (Isc)	7.8	A
Supercapacitor capacity	12	F
Supercapacitor inner resistance	8.9	mΩ
Supercapacitor rated voltage	100	V
Battery rated voltage	300	V
Maximum charging / discharging current	13	A
Battery capacity	10	Ah
Effective network line voltage	20	kV
Network frequency	50	Hz
X / R network ratio	7	-
Network short circuit power	10	MVA
Transformer short circuit power	5	kVA

In the design of the bidirectional DC-DC converter output filter, which connects the battery to the grid, providing a low ripple charge/discharge current, plays an essential role. Thus, considering 2% ripple of charge/discharge current, the amount of LC elements is calculated according to (4):

$$L_{\text{batt}} C_{\text{batt}} = \frac{(1-D)DV_{\text{grid}}}{8 f_s^2 r_{ESR} \Delta i_{\text{battery}}} \tag{4}$$

In this equation, D is the incremental switching cycle of the bidirectional converter, r_{ESR} indicating an internal battery resistance of 0.05Ω and $\Delta i_{\text{battery}}$ is the maximum acceptable change of charge/discharge current which is $0.26A$. To get the maximum value for C_{batt}, D is equal to 0.5. So assuming L_{batt} is equaled to $2.5mH$, the value of C_{batt} is equal to $1mF$. The value of the inductor in the output of the incremental DC-DC converter, which connects the PV to the grid, is taken from equation (5). In this equation, Δi_{pv} is PV current variation with the assumption of 2% ripple. In terms of MPP, based on the specified PV, the current is equal to $15A$, so the amount of acceptable variation of current is equal to $0.3A$.

$$L_{pv} = \frac{V_{grid}}{4 \Delta i_{pv} f_s} \tag{5}$$

By inserting the values in equation (5), the value of L_{PV} is calculated as 16. Equation 5 can also be used to calculate the value of L_{SC}. Assuming that the maximum output power of the supercapacitor is $4kW$ and the minimum supercapacitor voltage in the full discharge condition is considered $30V$, the maximum charge/discharge current of the supercapacitor is $133A$. Therefore, the acceptable change in the supercapacitor current is $6.6A$. By setting the determined values, the value of L_{SC} is equal to $2mH$.

V. Simulation and Results

To evaluate the performance of the proposed structure and the control system, MATLAB/Simulink software has been utilized. Table 2 shows the characteristics of the simulated

Table 2. General characteristics of the simulated system

Parameter	value	Unit
Diode Direct Voltage Drop	0.4	V
Diode conduction resistor	0.01	Ω
IGBT conduction resistor	0.02	Ω
Inductance of the input LC filter	100	μH
Inductance Impedance of filter	0.1	Ω
Input LC filter capacitor	3.16	nF
C_{grid} capcitor	13	μF
L_{batt} inductance	2.5	mH
Inductance Impedance of L_{batt}	0.2	Ω
C_{batt} capacitor	1	mF
L_{pv} inductance	16	mH
Inductance Impedance of L_{batt}	0.1	Ω
L_{sc} inductance	2	mH
Inductance Impedance of L_{pv}	0.1	Ω

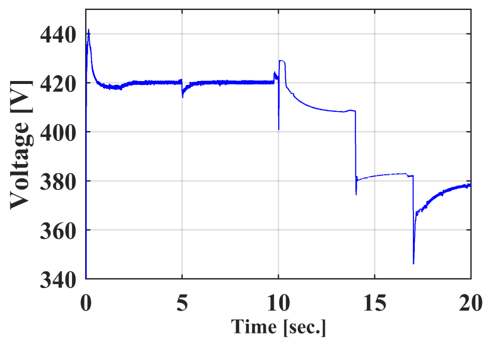

Fig. 4. Voltage of grid variations

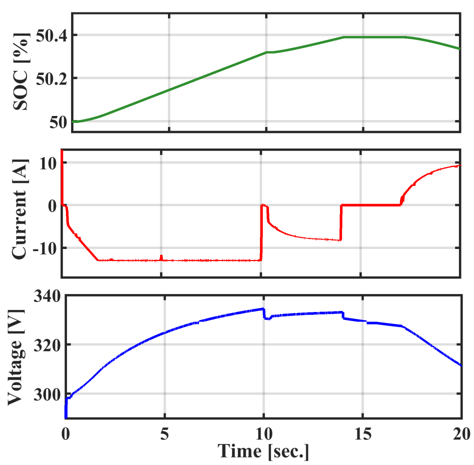

Fig. 5. Voltage, current, and SOC changes of battery

system. In the simulation, the DC MG is connected to the AC network for 10 seconds and then it will be disconnected. Different system modes are simulated for 20 seconds. During these 20 seconds, the amount of sunlight is also assumed to be variable. In the range of 0 to 5 seconds, the radiation level is $1000W/m^2$, in the range of 5 to 9.8 seconds, $700W/m^2$, and from 9.8 seconds later radiation is $905W/m^2$. Also, load varies over time. The load is constant from zero up to 14 seconds and it is equal to 500Ω. At the moment of 14 seconds, a 30Ω load will switch and be parallel to the previous load. At the moment of 17 seconds, a 40Ω resistance will be series

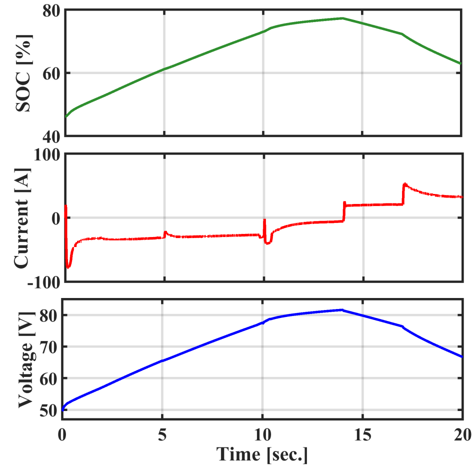

Fig. 6. Voltage, current and SOC changes of supercapacitor

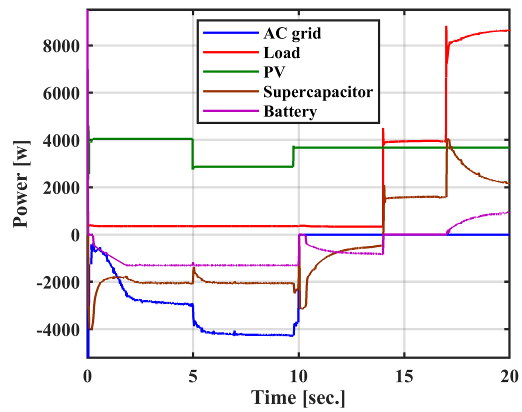

Fig. 7. Variability of various MG elements

with two previous loads and the load will increase. The initial charge rate of the battery and supercapacitor in the simulation is 50%. The control system of the bidirectional converter which is installed on the AC network side, will work in a way so that the DC link voltage remains at a voltage of $1.05pu$.

Figure 4 shows the voltage variation of the grid during the simulation interval. For the times of load variations and radiation changes, the DC link voltage changes, but it returns to its acceptance value using the control system. So, it is revealed that the proposed control system operates correctly.

Figure 5 shows the voltage, current and state of charge (SOC) in the battery. In this figure, negative current indicates charging and positive current means discharging of the battery. Regarding Fig. 5, the battery charges up to 14 seconds due to being higher than the voltage of the DC link. Also, the SOC is increased in this time interval. However, the value of charging current is proportional to the voltage difference with the set value for the upper limit. As a result of supercapacitor fast operation, the battery is not active during intervals of 14 to 17 seconds. Depending on the value of the DC link voltage shown in Fig. 4, after 17 seconds, the voltage level lowers the bottom limit of the battery controller, and the battery starts to discharge.

Figure 6 shows the voltage, current, and SOC variations of supercapacitor. As it can be seen, supercapacitor has been shown to be faster than the battery in relation to the DC voltage outflow from the permitted range. Supercapacitor performance at different time intervals is justified based on the DC link voltage and control logic.

Figure 7 shows the power changes of the various grid elements. Injection power of the AC network is zero after 10 seconds, and changes in load power at the switching moments are quite clear. Also, the power of PV has changed by varying the intensity of the radiation.

VI. Conclusion

In this paper, first the necessity of using DC grids is discussed and then a novel DC MG structure presented. The proposed structure consists of PV as a renewable energy source and battery and a supercapacitor as storage resources. The resources were chosen in a way to allow MG to meet load demands in both grid-connected and islanded modes. Also, an improved power control method is suggested based on DC voltage bus changes to manage battery power, PV and supercapacitor. The control method triggered the supercapacitor to show faster response time than the battery in regard with load fast variations, and the battery provides long-term power. Using the proposed structure and control system, the DC link voltage remains within the permitted range. To assess the proposed methodology, different challenging conditions such as load fluctuations, upstream network disconnection and solar radiance variations have been simulated. The results confirm that the method has the high ability to preserve its high performance in such situations.

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