Optimization of DC Microgrid for Renewable Energy Integration

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Abstract: ***This paper analyses the possibility to develop in optimizing the utilization of renewable energy sources within microgrids. The renewable wind and solar power generation forecast are aggregated, and it is proposed to support the quantification of the operational reserve and maintain the equilibrium of the microgrid's real-time supply and demand. One potential solution is a microgrid that can be vertically integrated with high-rise buildings which are frequently encountered in urban areas.***

Keywords: Distributed energy resources, Droop control, State Of Charge (SOC), Microgrid, Multilevel energy storage, Power electronic conversion, Solar power, Wind power.

1. Introduction

Renewable energy plays an important rule within the society; it is not only increasingly making us more energy dependent, but also creating greater environmental awareness. Once renewable energy technologies have been developed, energy can be produced anywhere. The rooftop generation of renewable energy harvested from wind and solar can be connected to the ground level via a microgrid where the Electric vehicle (EV) charging stations could be supplied. A battery is crucial in this case, to support and maintain the balance of supply and demand. The primary requirement for a DC microgrid operation is to maintain the common DC bus voltage within an acceptable range [2]. According to its optimization, it is proposed to set a droop as a function of the battery's expected State Of Charge (SOC). The optimization program helps to determine a solution that minimizes the operation cost of the DC microgrid.

When wind and solar energy are combined, it leads to reduced local energy storage management [3]. The combination of battery energy storage system and supercapacitor technologies can form a multilevel energy storage. In this, the battery energy storage system is responsible for balancing the supply and demand, whereas supercapacitor employs cache control to compensate for fast power fluctuations and smoothen the transients encountered by a battery with higher energy capacity. Micrograds or hybrid energy systems have been demonstrated to be an effective structure for local interconnection of distributed renewable generation, loads and storage. Most current microgrid implementations combine loads with sources, try to use the available waste heat [4].

The battery and the supercapacitor have a better transient response; however, their loss of energy density does not provide enough autonomy to the system. The proposed hybrid energy storage system, having an advanced control system, taking advantage of each storage system and avoiding the cause of degradation and limitation of them, can emerge as the technological solution for the problem commented. The distributed renewable of generation, loads and storage to be an effective structure for local interconnection have been shown in a Microgrid or hybrid energy systems [5-10].

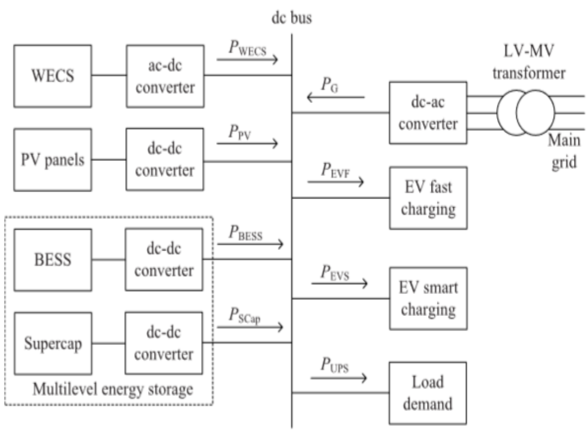

Fig. 1: Layout of a DC microgrid [1]

2. Outline of DC Microgrid

A schematic of a DC microgrid is given in Fig. 1, along with the conventions employed for power. The DC bus connects wind energy convention system (WECS), PV panels, multilevel energy storage comprising of the Battery Energy Storage System (BESS) and the supercapacitor. EV smart charging points, grid interface and EV fast charging station are also connected to the DC bus. The WECS is integrated into the DC bus via AC-DC converter. PV panels are connected to a DC bus through a DC-DC converter.

The BESS can be implemented through flow battery technology connected to the DC bus via a DC-DC converter. The technology that can provide fast and frequent access to stored energy is the supercapacitor [11,12]. The supercapacitor has considerably less energy capacity than the BESS. However, it is used for compensating for fast fluctuations of power and hence it provides cache control as detailed in the research done by K. Strunz and H. Louie [11].

It is connected close to the LV-MV transformer to minimize losses and voltage drop. An LV DC microgrid is well suited for naturally demarcated power systems [13]. For positive values of P_G, the microgrid takes power from the main grid. For negative values of P_G, the microgrid supplies power to the main grid. There is a variation in the voltage supply, grid frequency, harmonics, as well as other power quality due to the imbalance of active and reactive power that are introduced in a grid by renewable energies.

H. Kakigano, Y. Miura and T. Ise [12] proposed a low-voltage bipolar-type DC microgrid, which can supply high-quality power. In their work, a system of a residential complex has been represented as the instance of the DC microgrid. In this system, each house has a Co-Generation System (CGS), such as a gas engine or fuel cell.

When the system connects to the utility grid, the deficient power is compensated from the utility grid, but when the system disconnects from the utility grid, the surplus or deficient power is compensated by the energy storages such as a battery and a supercapacitor (Electric Double-Layer Capacitor: EDLC). The main objectives of this paper are to develop new system operation and control methods for the proposed DC microgrid to provide secure and reliable supply to the connected loads.

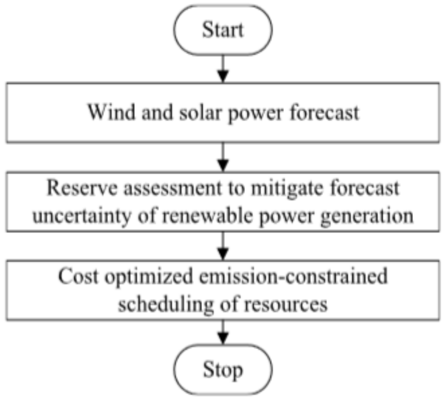

Fig. 2: Overview of Optimized scheduling approach [1]

3. Proposed System

The algorithm for optimized scheduling of the microgrid is given in Fig. 2. In the first stage, wind and solar power generations are forecasted. Then, wind and solar power forecast are aggregated to produce the total renewable power forecast model. The aggregated power generation data are utilized to assign hourly positive and negative energy reserves to the BESS for the microgrid operation. The positive energy reserve of the BESS provides the energy stored, which can be readily supplied to the DC bus on demand. The negative energy reserve provides the part of the BESS to remain uncharged to capture access power on demand.

The BESS can only be charged and discharged in the operation area in the normal operation mode, which is scheduled by optimization. The objective of the optimization is to minimize the operating cost of the microgrid in interconnected mode and provide uninterrupted power supply (UPS) service in the autonomous mode. In the interconnected operating mode, an adaptive droop control is devised for the BESS, which is selected based on the deviation between optimize and real-time SOC of the battery.

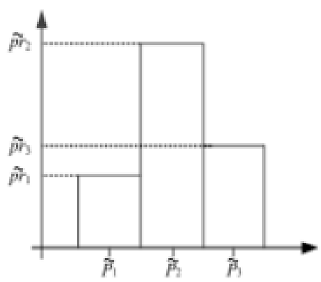

Fig. 3: Wind or solar forecast uncertainty for 1h [1]

4. Aggregated Model

The uncertainty of wind and solar power can be presented by a three-state model. The forecast uncertainty data of the wind and solar power generations are made available for the urban microgrid.

In Fig. 3, the output power state and the probability assigned to that state are available. State 1 represents a power forecast lower than the average power forecast $\tilde{P}_1$ with the forecast probability of $\tilde{P}r_1$ assigned to it. The average power forecast and the probability of forecast assigned to it give state 2. State 3 represents a power forecast higher than the average power forecast. Then wind and solar forecasts are aggregated to produce the total renewable power forecast model.

In the three state model k = 3 which is the number of individual states. Table 1 shows that the forecast data of wind and solar generation provided for 1h. For example, at the probability of 50% the wind power will be 50kW.

Table 1: Example of Wind and Solar Power Forecast Data

Individual state	State 1	State 2	State 3
Wind forecast	0.25	0.50	0.25
Wind power(kW)	40	50	60
Solar forecast	0.25	0.50	0.25
Solar power(kW)	15	20	25

As the microgrid has two generation resources with three individual states, i.e. k = 3, then the combined state is N = K^2, which is equal to 9 in this case. Figure 4, shows the combined states in the forecast uncertainty model of wind and solar power.

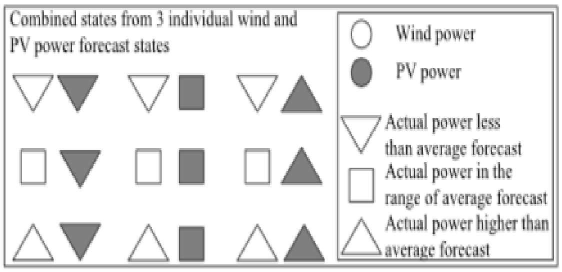

Fig. 4: Aggregation of wind and solar power forecast in microgrid [1]

For the wind and solar power forecast shown in Table 1, nine combined states are defined as shown in Table 2. In each of these combined states, the powers of all those individual states are summed up, and the probability of a combined state is equal to the product of the probabilities in individual state, considering the individual states are not correlated.

If an aggregated state *m* covers a number of combined states *L*, then the probability of having one of those aggregated states is the sum of the probabilities of those combined states.

$$\widetilde{pr}_{A,m} = \sum_{l=1}^{L} \widetilde{pr}_{l,m} \quad \text{.........................} (1)$$

where, $\widetilde{pr}_{A,m}$ is the forecast probability of renewable power at the aggregated state *m*, and $\widetilde{pr}_{l,m}$ is the forecast probability of renewable power at the combines state l within the aggregated state *m*.

$$\tilde{p}_{A,m} = \frac{\sum_{l=1}^{L} \widetilde{pr}_{l,m} \times \widetilde{pr}_{l,m}}{\widetilde{pr}_{l,m}} \quad \text{......................} (2)$$

Table 2: Example of Combined States of Wind and Solar Power Forecast

Combined states n	Counter L	Aggregated state m	Power output $\tilde{P}_{l,m}$ (kW)	Probability $\tilde{p}r_{l,m}$
1	1	1	40+15 = 55	0.25×0.25 = 0.0625
2	2	1	40+20 = 60	0.25×0.50 = 0.1250
3	1	2	40+25 = 65	0.25×0.25 = 0.0625
4	2	2	50+15 = 65	0.50×0.25 = 0.1250
5	3	2	50+20 = 70	0.50×0.50 = 0.2500
6	4	2	50+25 = 75	0.50×0.25 = 0.1250
7	5	2	60+15 = 75	0.25×0.25 = 0.6250
8	1	3	60+20 = 80	0.25×0.50 = 0.1250
9	2	3	60+25 = 85	0.25×0.25 = 0.0625

In the example shown in Table 2, employing equations (1) and (2) we get as follows:

$$\tilde{p}r_{A,1} = 0.0625 + 0.1250 = 0.1875$$

$$\tilde{p}_{A,1} = \frac{55 \times 0.0625 + 60 \times 0.1250}{0.1875} \, kW$$

$$= 58.33 \, kW$$

A summary of the aggregated three-state model for renewable power generation is provided in Table 3.

Table 3: Aggregated Three State Power Forecast Model for 1h

Aggregated state *M*	1	2	3
Probability $\widetilde{pr}_{A,m}$	0.1875	0.6250	0.1875
Power output $\tilde{P}_{A,m}$ **(kW)**	58.33	70	81.67

5. Existing System

The researchers L. Roggia *et al.* [15], proposed a novel integrated converter topology for interfacing between the energy storage system and the DC bus for a residential microgrid application. The proposed DC-DC converter is the integration of the full-bridge and a forward converter. Full-bridge converter is in the authority of the energy storage system discharging stage, whereas the forward converter is liable for the energy storage system charging stage.

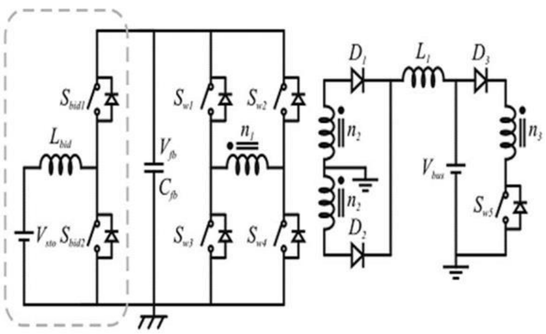

Fig. 3: Proposed integrated full-bridge-forward DC-DC converter including bidirectional converter [15]

During discharging stage of the energy storage system, the bidirectional converter boosts the voltage from the energy storage system to an intermediate level, whereas during the energy storage system's charging stage, it performs voltage post regulation or remains with S_{bid1} ON and S_{bid2} OFF acting as a low-pass filter, thus it eliminates the switching losses. A three-winding transformer is required in this topology as proposed by the researchers L. Roggia *et al.* [15]. Windings 1 and 2 are used in the full-bridge operation, and windings 1 and 3 are in the forward operation. One diode is required to be added in series with the transformer tertiary winding to avoid any current circulation via the antiparallel diode of the forward converter switch during the full-bridge converter operating mode.

6. Adaptive Droop Control

Adaptive droop control is devised for the BESS in the interconnected mode of operation, while the BESS is for keeping the voltage of a DC bus in a defined acceptable range for providing UPS service in term of an autonomous mode of operation [1].

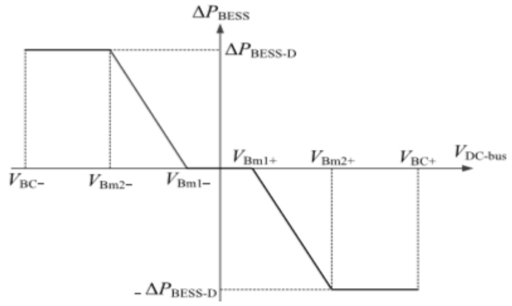

Fig. 3: The Droop control of a BESS power electronic converter to mitigate power deviations of DC microgrid in normal condition of the BESS [1]

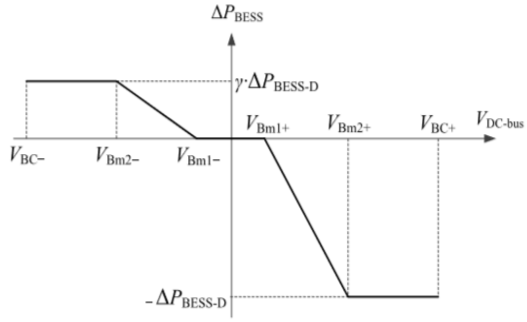

Fig. 4: Droop control of BESS power electronic converter to mitigate the power deviations of DC microgrid is lower than the schedules SOC of the BESS [1]

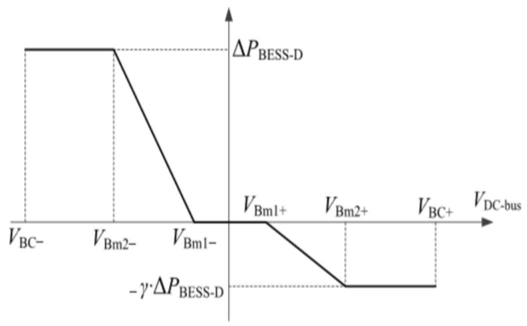

Fig. 5: Droop control of the BESS to mitigate the power deviations of DC microgrid in higher than the scheduled SOC of the BESS [1]

The second droop curve, as shown in Fig. 4, is devised for a situation in which the real-time SOC of the BESS is less than the optimized and scheduled SOC of the BESS. Thus, the BESS is contributing to stabilize the DC bus voltage by charging at the same power as shown in Fig. 3. This way, the SOC is capable of coming closer to the optimized and scheduled SOC.

The third droop as shown in Fig. 5 is devised for a situation where the real-time SOC of the BESS is higher than the optimized and scheduled SOC of the BESS. So, the BESS contributes to stabilizing the DC bus voltage by discharging at the same power as shown in Fig. 3.

7. Comparison of Results

A comparison of the results (as below) shows the importance of coordinating the droop settings with scheduling in microgrids with wind and solar power.

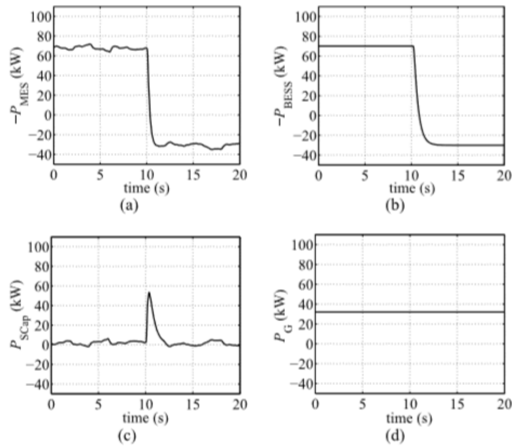

Fig. 6: Case A: Droop-control-based responses to wind fluctuation and fast charging when SOC of the battery is as scheduled: (a) Multilevel energy storage system (MES) charging power from the DC bus, (b) Battery charging power from the DC bus, (c) Supercapacitor discharging power to the DC bus, (d) Grid power to the DC bus [1]

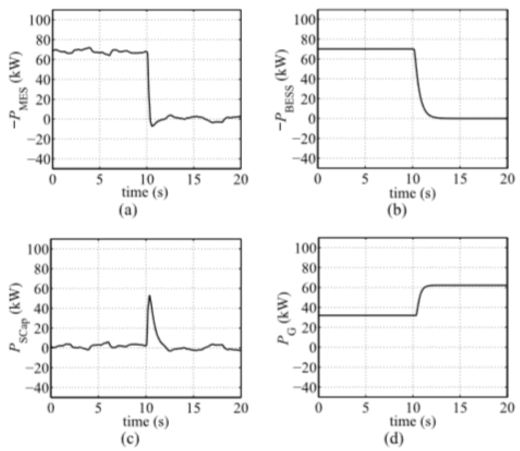

Fig. 7: Case B: Droop-control-based responses to wind fluctuation and fast charging when SOC of the battery is lower than the scheduled: (a) Multilevel energy storage system (MES) charging power from the DC bus, (b) Battery charging power from the DC bus, (c) Supercapacitor discharging power to the DC bus, (d) Grid power to the DC bus [1]

In Case A, SOC of the battery is assumed to be within the close range of the scheduled SOC, while resulting from the day ahead optimization. The simulation result of the control shown in Fig. 3 is given in Fig. 6.

In Case B, the BESS is assumed to have lower than the expected SOC compared with SOC scheduled in optimization. The simulation result of the control shown in Fig. 4 is given in Fig. 7. With the asymmetric curve of the BESS (Fig. 4), the multilevel energy storage does not provide full compensation of renewable fluctuation. Hence, droop control of the grid is activated; and from the main grid, it contributes the power demand to the fast charging.

The SOC of the battery, shown in Fig. 6, is as desired according to the scheduling, while the SOC of the battery becomes lower than the expected due to forecast uncertainty as shown in Fig. 7. In the latter case, the asymmetric droop as shown in Fig. 4, avoids further significant discharging but has full droop contribution on the charging side. On the reduced discharging side, the droop on the other power electronic converter connects to the main grid.

8. Conclusion

A DC microgrid for optimization of renewable power integration has been proposed. The operational optimization and power electronic based voltage-power droop control were developed. Microgrids are beneficial for the development of efficient and cost-effective energy storage technology.

The battery can be connected in parallel with a supercapacitor to form a multilevel energy storage. The battery plays an important role in compensating renewable power fluctuations and providing the power needed. The optimization for power exchanges and DC voltage control by using adaptive control are normally done through power electronic converters.

Nowadays, natural energy stored in fossil fuels is coming to its end. This fact will globally change the way our society manages energy. So for future developments will be based on expanding the technique into developing an optimal control algorithm of renewable energy microgrid with photovoltaic generator and wind turbine.

The usage of wind and solar energy reduces emission, free from pollution and so on, which is convenient for the citizen and resulting energy system serves local stationary, and it is a good citizen within the main grid.

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