

FLC BASED DC MICROGRID FOR WIND AND SOLAR POWER INTEGRATION

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Abstract- Several operational controls are designed to support the integration of renewable energy sources within microgrids. An aggregated model of renewable wind and solar power generation forecast is proposed to support the quantification of the operational reserve for day-ahead and real-time scheduling. Then, a droop control for power electronic converters connected to battery storage is developed using fuzzy logic controller and tested. Compared with the existing droop controls, it is distinguished in that the droop curves are set as a function of the storage state-of-charge (SOC) and can become asymmetric. The adaptation of the slopes ensures that the power output supports the terminal voltage while at the same keeping the SOC within a target range of desired operational reserve. This is shown to maintain the equilibrium of the microgrid's real-time supply and demand. The controls are implemented for the special case of a dc microgrid that is vertically integrated within a high-rise host building of an urban area. Previously untapped wind and solar power are harvested on the roof and sides of a tower, thereby supporting delivery to electric vehicles on the ground. The microgrid vertically integrates with the host building without creating a large footprint.

Index Terms—Distributed energy resources, droop control, electric vehicle (EV), microgrid, multilevel energy storage, fuzzy logic controller, power electronic conversion, solar power, wind power.

I. INTRODUCTION

Wind is abundant almost in any part of the world. Its existence in nature caused by uneven heating on the surface of the earth as well as the earth's rotation means that the wind resources will always be available. The trend has been toward increasingly larger turbine sizes, culminating in the installation of off-shore wind parks that are located far from the load centers [2]. This can lead to rather large distances between generation and load in the electricity sector. The transportation sector reveals an even larger disconnect between the locations of fuel

production and consumption. The energy system proposed in this paper seeks to address both issues related to electricity and transportation sectors. One potential solution is a microgrid that can be vertically integrated with a high-rise building as frequently encountered in urban areas. The harvesting of renewable wind and solar energy occurs at the top of the building. The rooftop generation connects to the ground level via a microgrid where electric vehicle (EV) charging stations are supplied, and a battery supports maintaining the balance of supply and demand. The potential value of an urban integration within buildings as considered here comes from the usage of rooftop energy resources, the storage of the latter for offering EV fast charging at the ground level, the contribution to emission-free EV transportation in urban areas, the co-location and integration of generation and load in urban areas, and the grid-friendly integration of the microgrid with the rest of the power system main grid.

The combination of wind and solar energy resources on a rooftop was also investigated in [3]. It was verified that the combination of wind and solar energy leads to reduced local storage requirements [4]. The combination of diverse but complementary storage technologies in turn can form a multilevel energy storage, where a super capacitor or flywheel provides cache control to compensate for fast power fluctuations and to smoothen the transients encountered by a battery with higher energy capacity [5], [6]. Microgrids or hybrid energy systems have been shown to be an effective structure for local interconnection of distributed renewable generation, loads, and storage [7]–[12].

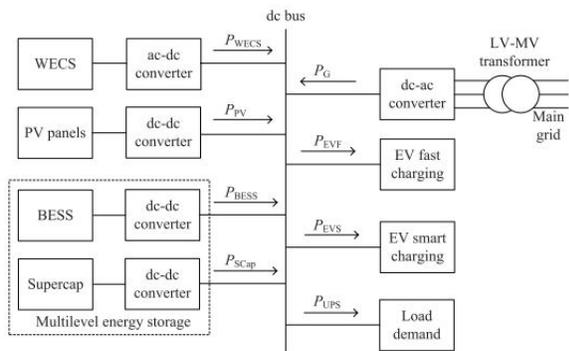


Fig.1. Layout of the dc microgrid

Recent research has considered the optimization of the operation on one hand [13]–[15] and the usage of dc to link the resources on the other [16]–[18]. The dc link voltage was shown to be maintained by a droop control that relates the dc link voltage to the power output of controllable resources. In this paper, it is proposed to set the droop as a function of the expected state of charge (SOC) of the battery according to its operational optimization set point versus the actual real time SOC. The proposed operational optimization is further distinguished in that it quantifies the uncertainty associated with renewable generation forecast, emission constraints, and EV fast charging.

Following this introduction, an outline of the principle of a dc micro grid is given in Section II. In Section III, a method is developed for quantifying the aggregated wind and solar power forecast uncertainty, the resulting required SOC of the battery, and the operational optimization.

II. OUTLINE OF DC MICROGRID

A schematic of the dc microgrid with the conventions employed for power is given in Fig. 1. The dc bus connects wind energy conversion system (WECS), PV panels, multilevel energy storage comprising battery energy storage system (BESS) and super capacitor, EV smart charging points, EV fast charging station, and grid interface. The WECS is connected to the dc bus via an ac–dc converter. PV panels are connected to the dc bus via a dc–dc converter. The BESS can be realized through flow battery technology connected to the dc bus via a dc–dc converter. The super capacitor has much less energy capacity than the BESS. Rather, it is aimed at compensating for fast fluctuations of power and so provides cache control as detailed in [19].

Thanks to the multilevel energy storage, the intermittent and volatile renewable power outputs can be managed, and a deterministic controlled power to the main grid is obtained by optimization. Providing

uninterruptible power supply (UPS) service to loads when needed is a core duty of the urban micro grid. EV fast charging introduces a stochastic load to the micro grid. The multilevel energy storage mitigates potential impacts on the main grid.

In building integration, a vertical axis wind turbine may be installed on the rooftop as shown in Fig. 2. PV panels can be co-located on the rooftop and the

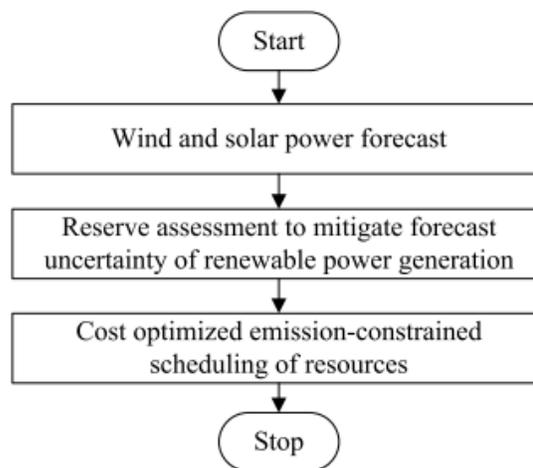


Fig.2. Overview of optimized scheduling approach

facade of the building. Such or similar configurations benefit from a local availability of abundant wind and solar energy. The fast charging station is realized for public access at the ground level. It is connected close to the LV–MV transformer to reduce losses and voltage drop. EVs parked in the building are offered smart charging within user-defined constraints.

III. OPERATIONAL OPTIMIZATION OF MICROGRID FOR RENEWABLE ENERGY INTEGRATION

The algorithm for optimized scheduling of the micro grid is depicted in Fig. 2. In the first stage, wind and solar power generation are forecast. The uncertainty of the wind and solar power is presented by a three-state model. An example of such a forecast

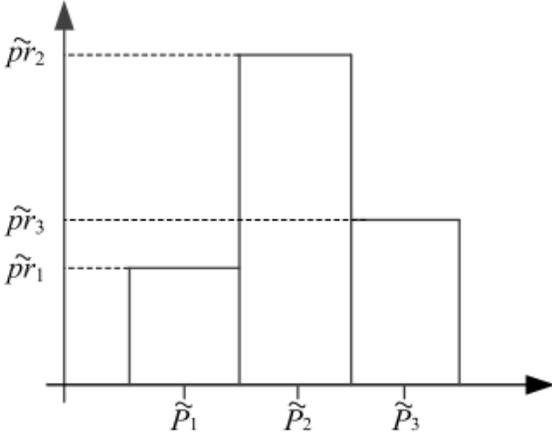


Fig.3. Wind or solar power forecast uncertainty for 1h

is shown in Fig. 3. State 1 represents a power forecast lower than the average power forecast. This state is shown by the power forecast of \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 power forecasts are aggregated to produce the total renewable power forecast model.

TABLE I
WIND AND SOLAR POWER FORECAST DATA

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

This aggregation method is formulated in Section III-A. The aggregated power generation data are used to assign hourly positive and negative energy reserves to the BESS for the microgrid operation. The positive energy reserve of the BESS gives the energy stored that can be readily injected into the dc bus on demand. The negative energy reserve gives the part of the BESS to remain uncharged to capture excess power on demand. Energy reserve assessment is performed according to the aggregated renewable power generation forecast. In order to compensate for the uncertainty

of the forecast, a method is devised to assess positive and negative energy reserves in Section III-B. Finally, the emission constrained cost optimization is formulated to schedule the microgrid resources for the day-ahead dispatch. The optimized scheduling is formulated in Section III-C.

A. Aggregated Model Of Wind And Solar Power Forecast

Wind and solar power generation forecast uncertainty data are made available for the urban micro grid. Specifically, as shown in Fig. 3, the output power state and the probability assigned to that state are available. In the three-state model, the number of individual states is $K = 3$. A sample of forecast data of the wind and solar power generation is provided for 1 h, as shown in Table I. For example, at a probability of 50% the wind power will be 50 kW in state 2.

The aggregation of output power states of the wind and solar power is formed as follows. As the microgrid has two generation resources with three individual states, $K = 3$, the number of combined states is $N = K^2$, which is equal to nine in this case. The combined states in the forecast uncertainty model of wind and solar power are shown in Fig.4. In each combined state, the power of those individual states is summed up, and the probability of a combined state is the product of the probabilities in individual states assuming that the individual states are not correlated.

TABLE II
Combined States Of Wind And Solar Power Forecast

Combined state n	Count	Aggregated state m	Power output $\tilde{P}_{1,m}$ (kw)	Probability $\tilde{P}_{r_{1,m}}$
1	1	1	40+15=55	
2	2	1	40+20=60	
3	1	2	40+25=65	
4	2	2	50+15=65	
5	3	2	50+20=70	
6	4	2	50+25=75	
7	5	2	60+15=75	
8	1	3	60+20=80	
9	2	3	60+25=85	

For the wind and PV power forecast shown in Table I, nine combined states are defined. Those states are provided in Table II. The combined states, as shown by the example in Table II, should be reduced to fewer representative states. To aggregate the combined states, M aggregated states are defined. In this example $M = 3$. Those states are shown in Table II and denoted by m . The borders between aggregated states are determined based on

the borders between individual states in Table I. The average renewable power of individual states 1 and 2 is 62.5 kW and gives the border between aggregated states 1 and 2. Likewise, the average renewable power of individual states 2 and 3 gives the border between aggregated states 2 and 3.

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

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

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 combined state l within the aggregated state m . The average power of each aggregated state is calculated by the average weighting of all power outputs in the aggregated state m

$$\widetilde{P}_{A,m} = \frac{\sum_{l=1}^L \widetilde{Pr}_{l,m} \times \widetilde{P}_{l,m}}{\widetilde{Pr}_{A,m}} \quad (2)$$

where $\widetilde{P}_{A,m}$ is the power forecast of renewable at the aggregated state m , and $\widetilde{P}_{l,m}$ is the power forecast at the combined state l within the aggregated state m .

In the example shown in Table II, the combined model is reduced to a three-state wind and solar power forecast model. Employing (1) and (2), the calculation is shown for aggregated state 1 in the following:

$$\widetilde{Pr}_{A,1} = 0.0625 + 0.1250 = 0.1875$$

$$\widetilde{P}_{A,1} = \frac{55 \times 0.0625 + 60 \times 0.1250}{0.1875} \text{ kW} = 58.33 \text{ kW}$$

A summary of the aggregated three-state model for the renewable power generation is provided in Table III. In this table, the power output at state 2 represents the average renewable energy source power forecast and is used for optimized scheduling. This three-state model is chosen as an illustrative example because it is the minimum model to represent power generation forecast uncertainty. More states may be used if deemed appropriate.

The aggregated output power states are employed to calculate required hourly positive and negative energy reserves in the BESS for operation of the urban microgrid. An example on how to use the aggregated three-state power forecast model to determine hourly positive and negative energy reserves in the BESS is provided in the following.

B. Energy Reserve Assessment for Operation of Microgrid

Taking into account the aggregated wind and solar power forecast model developed above, an illustrative example is provided to show how the energy reserve is assessed. In Table IV, an aggregated three-state power forecast model for three continuous hours is assumed. The aggregated power forecast for hour 1 is taken from the example solved in Section III-A. The aggregated power forecast of hours 2 and 3 is calculated by the same method.

As shown in Table IV, the probability of having real-time power output at state 1 in three continuous hours is equal to the product of the probabilities in state 1 for those three hours. This probability is thus equal to $0.18753 = 0.00659$. This is also the same probability for having state 3 in three continuous hours. The probability is very small. Therefore, the BESS has enough negative energy reserve to cover for uncertainty for three successive hours if the following condition is met:

$$\begin{aligned} EC_{NR-3h} &= (81.67 - 70) \text{ kWh} + (127.33 - 110) \text{ kWh} \\ &+ (40.83 - 35) \text{ kWh} \\ &= 34.83 \text{ kWh} \end{aligned}$$

Power at aggregated state 3 represents the power forecast higher than average, state 2. Therefore, the negative reserve that is used to capture excess energy is calculated by summation of the energy pertaining to state 3 minus the energy pertaining to state 2 in a 3-h window. This means that the micro grid has, at the high probability of $1 - 0.18753$, the free capacity in the BESS to capture the excess of renewable energy for a 3-h window.

Similar to the negative energy reserve assessment, the positive energy reserve is assessed. In order to calculate the positive energy reserve for the example shown in Table IV, energy of state 2 is subtracted from energy of state 1 for all three hours, and the results are summed up. Positive energy reserve is the stored energy in the BESS ready to be injected into the dc bus to mitigate less renewable power generation than expected

$$\begin{aligned} EC_{PR-3h} &= (70 - 58.33) \text{ kWh} + (110 - 92.67) \text{ kWh} \\ &+ (35 - 29.17) \text{ kWh} \\ &= 34.83 \text{ kWh} \end{aligned}$$

Similar to the example solved for 1 h in Table III, the aggregated model should be developed for the whole dispatch period. For instance, if the scheduling horizon is 24 h, a window sweeps the horizon in 24/3 blocks. Thus, eight blocks of reserve will be determined.

Both positive and negative energy reserves are considered in the BESS energy constraint. Based on the operation strategy, BESS storage capacity allocation is shown in Fig. 6. The depth of discharge

TABLE III

Single Hour Of Aggregated Three-State Power Forecast Model

Aggregated state m	1	2	3
Probability $\bar{p}r_{A,m}$	0.1875	0.625	0.187
Power output $P_{A,m}$ (kw)	58.33	70	81.67

(DOD), positive energy reserve (PR), operational area, and negative energy reserve (NR) are allocated in the BESS. The BESS can only be charged and discharged in the operation area in normal operation mode, which is scheduled by optimization. The BESS may operate in positive and negative energy reserve areas in order to compensate the uncertainties of power generation and load demand in real time operation.

TABLE IV

Three Hours Of Aggregated Three-S Tate Power Forecast Model

Aggregated state m	1	2	3
Probability $\bar{p}r_{A,m}$	0.1875	0.6250	0.1875
Power $\bar{p}_{A,m}$ (kw) at t=1h	58.33	70	81.67
Power $\bar{p}_{A,m}$ (kw) at t=1h	92.67	110	127.33
Power $\bar{p}_{A,m}$ (kw) at t=1h	29.17	35	40.83

C. Formulation of Optimized Scheduling of Microgrid

The objective of the optimization is to minimize operation cost of the microgrid in interconnected mode and provide UPS service in the autonomous mode. These objectives can be achieved by minimization of the following defined objective function:

$$F(P_G, P_{EVS}) = \sum_{i=1h}^T C_{1kwh}(i) \times P_G(i) \times \tau_h + \sum_{i=1h}^T C_{1kwh}(i) \times P_{EVS}(i) \times \tau_h + \sum_{i=1h}^T EPBF \times EMS \times P_G(i) \times \tau_h \quad (3)$$

where F is the objective function to be minimized, T is the scheduling horizon of the optimization, τ_h is the optimization time step which is 1 h, C_{1kWh} is the energy cost for 1 kWh energy, P_G is the incoming power from the grid, P_{EVS} is the smart charging power for EVs, $EPBF$ is the emission penalty-bonus factor for CO₂, and EMS is the average CO₂ emission of 1 kWh electrical energy in the power system outside the microgrid. In this objective function, P_G and P_{EVS} are to be determined by optimization. The first term in the objective function

above expresses the energy cost, the second term defines the cost of EV smart charging, and the third term describes the emission cost.

As shown in Fig. 1, for positive values of P_G , the microgrid draws power from the main grid, and for negative values of P_G the microgrid injects power into the main grid. The emission term penalizes power flow from the main grid to the microgrid. If the microgrid draws power from the main grid, the microgrid would contribute to emissions of the power system. On the other hand, as the microgrid has no unit that produces emission, when the microgrid returns power to the main grid, it contributes to emission reduction. The optimization program determines a solution that minimizes the operation cost of the dc microgrid. Thus, a monetary value is assigned to emission reduction by this approach. This objective function is subject to the constraints as follows.

1) Power limitation of the grid interface introduces a boundary constraint to the optimization

$$P_{G-} \leq P_G(t) \leq P_{G+} \quad \forall t \in T \quad (4)$$

where P_{G-} is the lower boundary of the grid power, and P_{G+} is the upper boundary of the grid power.

2) The BESS power has to be within the limits

$$P_{BESS-} \leq P_{BESS}(t) \leq P_{BESS+} \quad \forall t \in T \quad (5)$$

where P_{BESS-} is the lower boundary of the outgoing power from the BESS to the dc bus, P_{BESS+} is the BESS power to the dc bus, and P_{BESS+} is the upper boundary of the BESS power.

3) The availability of EV and charging power limits should be met

$$0 \leq P_{EVS}(t) \leq P_{EVS+} \quad \forall t \in T_{EVS} \quad (6)$$

where P_{EVS} is the EV charging power, P_{EVS+} is the upper boundary of the EV charging power, and T_{EVS} gives the hours in which EVs are available for smart charging.

4) The power balance equation has to be valid at all simulation time steps

$$\bar{P}_{A,2}(t) + P_{BESS}(t) + P_G(t) - \bar{P}_{EVF}(t) - P_{EVS}(t) = 0 \quad \forall t \in T \quad (7)$$

where $\bar{P}_{A,2}$ is the average power forecast of renewable energy sources wind and solar at aggregated state 2, and P_{EVF} is the EV fast charging power forecast.

5) The objective function is also subject to a constraint of the SOC of the BESS. In order to include UPS service, the formulation of the optimization is modified. The key application is supplying loads by the microgrid for a defined time span in the case of a contingency. It is devised so that the microgrid provides backup power for a commercial load such as a bank branch or an office

during working hours. According to the system layout shown in Fig. 1, this constraint can be defined as follows:

$$E_{BESS-}(t) \leq E_{BESS-0} - \sum_{j=1}^t \Delta E_{BESS}(j) \leq E_{BESS+}(t) \quad \forall t \in T \quad (8)$$

where E_{BESS-} is the lower boundary of energy capacity of the BESS, E_{BESS-0} is the SOC of the BESS at the beginning of the optimization, E_{BESS} is the discharged energy from the BESS to the dc bus at every minute, and E_{BESS+} is the upper boundary of energy capacity of the BESS. The SOC of the battery at all time steps should be in the operation zone of the BESS. Therefore, in this equation, the SOC of the battery is calculated and checked to be within the upper and lower SOC limits. Quantities E_{BESS-} , E_{BESS+} , and E_{BESS} are calculated as follows:

$$E_{BESS-}(t) = EC_{BESS} \times (1 - DOD) + EC_{PR-3h}(t) + EC_{UPS}(t) + \bar{EC}_{EVF}(t) \quad \forall t \in T \quad (9)$$

where E_{BESS-} is the lower boundary of BESS SOC, EC_{BESS} is the energy capacity of the BESS, DOD is the depth of discharge of the BESS, EC_{PR-3h} is the positive energy reserve of the BESS to cover power forecast uncertainty, EC_{UPS} is the energy capacity allocated in the BESS for the UPS service of the loads, and EC_{EVF} is the energy capacity forecast for fast charging demand. The first term in the equation takes into account the possible depth of discharge.

The BESS cannot be charged up to the full capacity because negative energy reserve is scheduled in the BESS to capture potential excess renewable power as calculated in Section III-B. This boundary constraint is expressed by

$$E_{BESS+}(t) = EC_{BESS} - EC_{NR-3h}(t) \quad \forall t \in T \quad (10)$$

where E_{BESS+} is the upper boundary of BESS SOC, EC_{BESS} is the energy capacity of the BESS, and EC_{NR-3h} is the negative energy reserve of the BESS.

The discharged energy from the BESS to the dc bus is calculated by

$$E_{BESS}(t) = \begin{cases} \frac{P_{BESS}(t)}{\eta_{dis}} \times \tau_{min}, & P_{BESS} \geq 0 \\ P_{BESS}(t) \times \eta_{ch} \times \tau_{min} & \end{cases} \quad (11)$$

where E_{BESS} is the discharged energy from the BESS to the dc bus in every minute, η_{dis} is the discharging efficiency of the BESS, η_{ch} is the charging efficiency of the BESS, and τ_{min} is the time step size equal to 1 min.

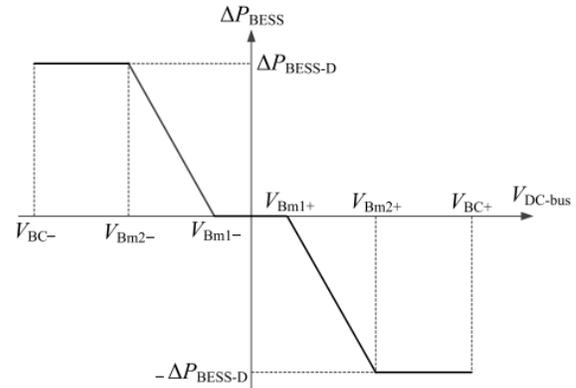


Fig.4. Droop control of BESS power electronic converter to mitigate power deviations of dc microgrid in normal SOC of the BESS.

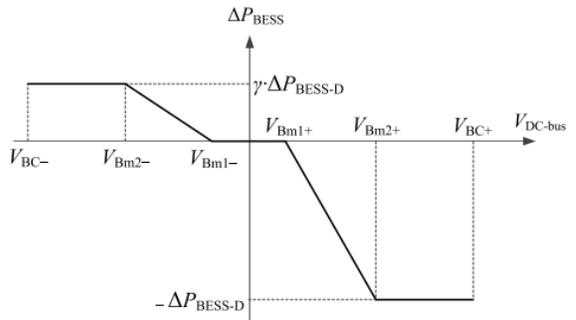


Fig.5. Droop control of BESS power electronic converter to mitigate power deviations of dc microgrid in lower than the scheduled SOC of the BESS.

6) The total required EV smart charging energy for the day-ahead scheduling is to be met. This is defined by an equality constraint

$$\sum_{i=1}^{T_{EVS}} P_{EVS}(i) \times \tau_h = \bar{EC}_{CVS-Ch} \quad (12)$$

where T_{EVS} is the time that EVs are available for smart charging by the micro grid, P_{EVS} is the smart charging power of EVs, and \bar{EC}_{CVS-Ch} is the total EV smart charging energy forecast for the day-ahead scheduling.

IV. ADAPTIVE DROOP CONTROL OF BESS

In this section, the real-time operation of the micro grid in the interconnected and autonomous modes is studied. In the interconnected mode of operation, an adaptive droop control is devised for the BESS. The adaptive droop characteristic of the BESS power electronic converter is selected on the basis of the deviation between the optimized and real-time SOC of the BESS, as calculated in Section III. Details of the method are provided in Section IV-A. In

autonomous mode of operation, the BESS is responsible for keeping the voltage of the dc bus in a defined acceptable range for providing UPS service. The autonomous mode of operation of the microgrid is described in Section IV-B.

A. DC Voltage Droop Control in Interconnected Mode

The devised droop controls of the BESS are depicted in Figs. 4–6. The change of the battery power P_{BESS} is modified as a function of the dc voltage. It can be noted that two of the three devised droop characteristics are asymmetric. The first droop curve, as shown in Fig. 4, is devised for a case where the real-time SOC of the BESS is within close range of the optimized SOC of the BESS from the scheduling calculated in Section III-C. The acceptable realtime

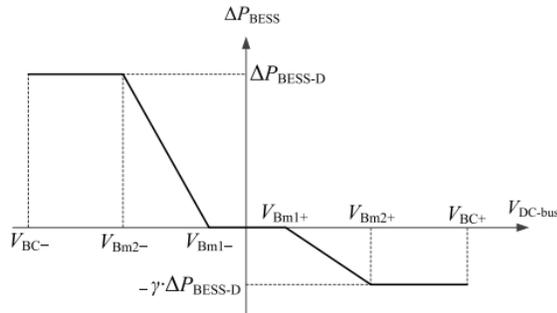


Fig.6. Droop control of BESS power electronic converter to mitigate power deviations of dc microgrid in higher than the scheduled SOC of the BESS.

SOC is determined through definition of upper and lower boundaries around the optimized SOC. If the real-time SOC is within these boundaries, the droop control of the BESS power electronic converter is selected as shown in Fig.4 to support the dc voltage. In this case, the upper boundary and the lower boundary lead to a symmetrical droop response. In the voltage range between V_{Bm1-} and V_{Bm1+} , battery storage does not react to the voltage deviations of the dc bus. In the voltage range from V_{Bm1-} to V_{Bm2-} and also from V_{Bm1+} to V_{Bm2+} , the droop control of the BESS reacts. Therefore, P_{BESS} modifies the power output P_{BESS} to mitigate the voltage deviation of the dc bus. Finally, in the voltage range from V_{Bm2-} to V_{BC-} and also from V_{Bm2+} to V_{BC+} , the droop curve is in a saturation area, and thus the BESS contribution is at its maximum and constant.

The second droop curve as shown in Fig.5 is devised for a situation where the real-time SOC of the BESS is lower than the optimized and scheduled SOC of the BESS. Therefore, the BESS contributes

to stabilizing the dc bus voltage by charging at the same power as shown in Fig. 4. However, the upper boundary of the BESS droop response is reduced by the factor γ , and it is equal to $\gamma \cdot P_{BESS-D}$. This way, the SOC can come closer to the optimized and scheduled SOC.

The third droop curve as shown in Fig. 9 is devised for a situation where the real-time SOC of the BESS is higher than the optimized and scheduled SOC of the BESS. Therefore, the BESS contributes to stabilizing the dc bus voltage by discharging at the same power as shown in Fig.4. However, the lower boundary of the BESS droop response is modified by the factor γ , and it is equal to $-\gamma \cdot P_{BESS-D}$.

The dc-ac converter connected to the main grid is also controlled by a droop, as shown in Fig. 7. The droop parameters are adjusted to support the droop control of the storage. The boundaries must respect the capacity of the converter.

In real-time operation and interconnected mode, the SOC of the BESS is measured and compared against the optimized SOC of the BESS, and the proper droop will be selected as described above. A summary of the droop selection for the BESS in interconnected operation mode is shown in Table V.

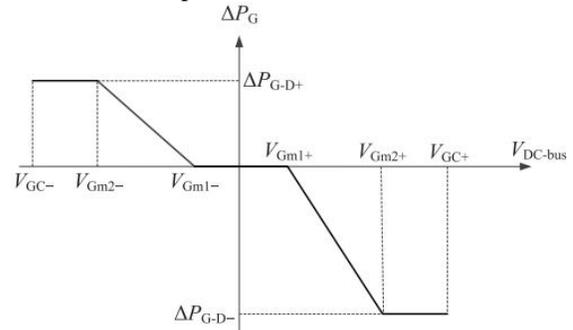


Fig.7. Droop control of the grid power electronic converter in interconnected operation mode of dc micro grid.

TABLE V

Adaptive Droop S Election For The Bess

SOC of the BESS in real-time	Droop curve
Close to the optimized scheduling	BESS droop 1(Fig.7)
Lower than in optimized scheduling	BESS droop 2(Fig.8)
Higher than in optimized scheduling	BESS droop 3(Fig.9)

B. Dc Voltage Droop Control In Autonomous Mode

In the autonomous mode, the main grid is disconnected. Then, the fast charging service has less priority compared with the supply of other loads. The control of the BESS converter is also defined by the voltage–power droop as discussed. The BESS so supports the voltage of the dc bus.

FUZZY LOGIC CONTROLLER

The error value of the dc-bus voltage $\Delta v_{dc} = v_{dc}^* - v_{dc}$ is passed through a Fuzzy-type compensator to regulate the voltage of dc bus (v_{dc}) at a fixed value. The operation of FLC is as follows. FLC contains three basic parts: Fuzzification, Base rule, and Defuzzification. FLC has two inputs which are: error and the change in error, and one output. The Fuzzy Controller structure is represented in fig.6. The role of each block is the following:

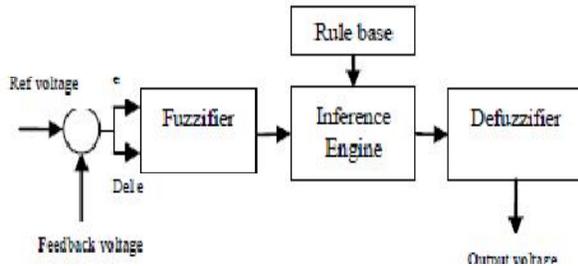


Fig.8. The general structure of Fuzzy Logic Controller

Fuzzifier converts a numerical variable into a linguistic label. In a closed loop control system, the error (e) between the reference voltage and the output voltage and the rate of change of error (Δe) can be labeled as zero (ZE), positive small (PS), negative small (NS), etc. In the real world, measured quantities are real numbers (crisp). The FLC takes two inputs, i.e., the error and the rate of change of error. Based on these inputs, The FLC takes an intelligent decision on the amount of field voltage to be applied which is taken as the output and applied directly to the field winding of generator. Triangular membership functions were used for the controller.

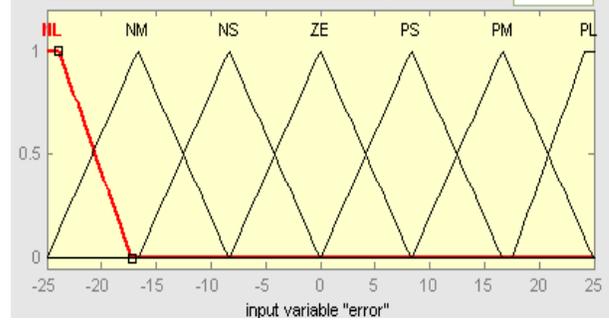


Fig .7. Membership function of voltage

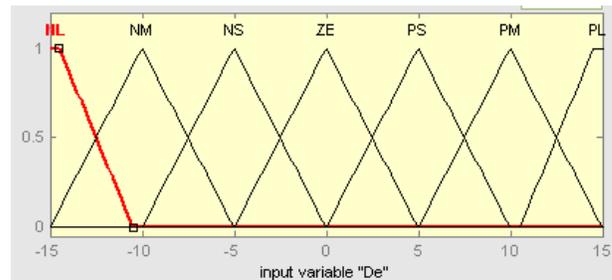


Fig.9. Membership function of voltage error

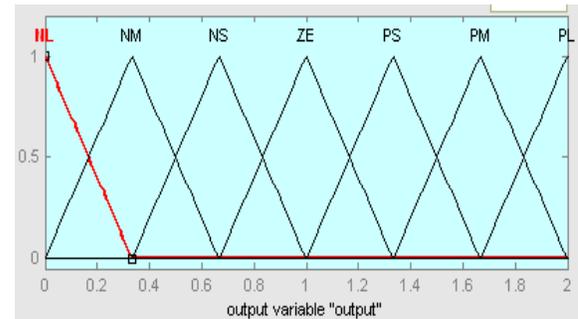


Fig .10. Membership function of output field voltage

Rule base stores the data that defines the input and the output fuzzy sets, as well as the fuzzy rules that describe the control strategy. Mamdani method is used in this paper. Seven membership functions were used leading to 49 rules in the rule base.

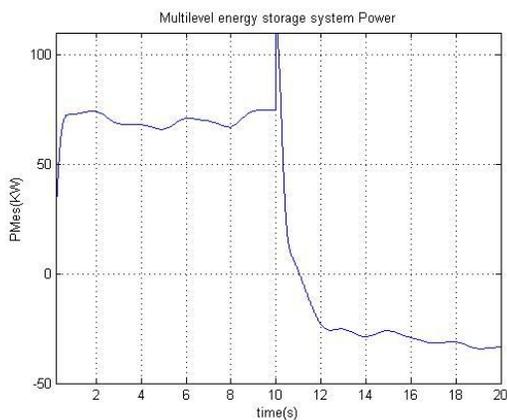
Table: Rule base for fuzzy controller

ΔE \ E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

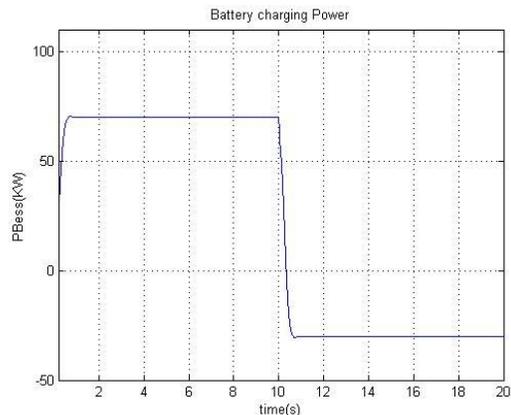
Inference engine applies the fuzzy rules to the input fuzzy variables to obtain the output values. Defuzzifier achieves output signals based on the output fuzzy sets obtained as the result of fuzzy reasoning. Centroid defuzzifier is used here.

V. VERIFICATION BY SIMULATION

The proposed operational method of the urban micro grid in day-ahead scheduling and real-time operation is verified by simulation. For the day-ahead scheduling, the method introduced in this paper is implemented in MATLAB and simulated for a case study. The real-time operation of the urban microgrid is verified by simulation in PSCAD [20]



(a)



(b)

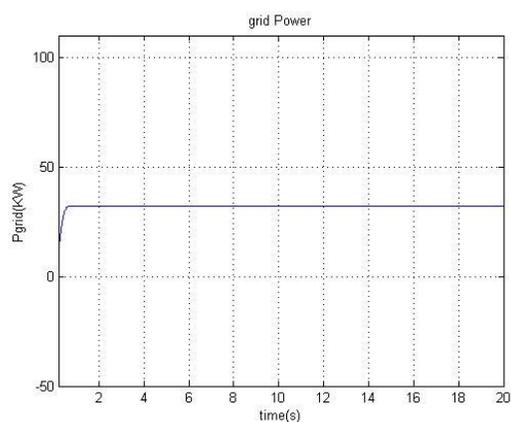
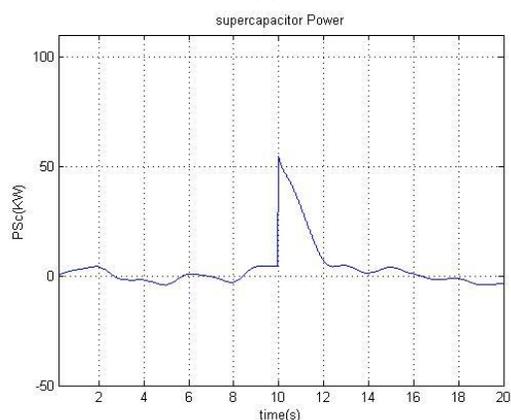


Fig.11. Case A: Droop-control-based responses to wind fluctuation and fast charging when SOC of battery is as scheduled. (a) Multilevel energy storage system (MES) charging power from the dc bus. (b) Battery charging power from the dc bus. (c) Super capacitor discharging power to the dc bus. (d) Grid power to the dc bus.

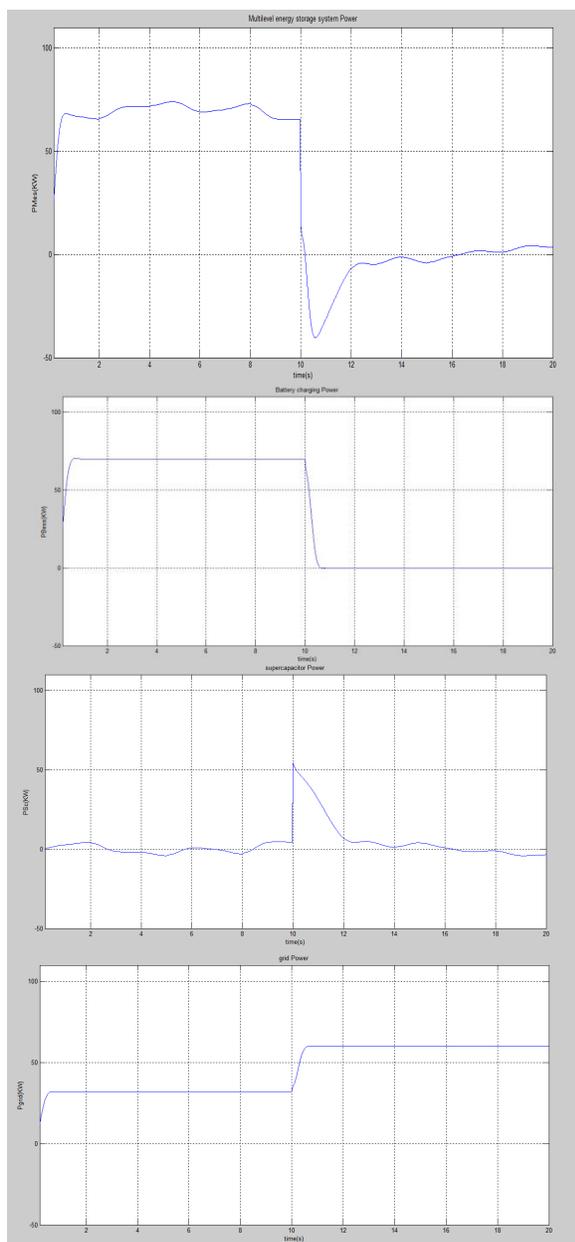


Fig.12.Case B: Droop-control-based responses to wind fluctuation and fast charging when SOC of battery is lower than scheduled. (a) Multilevel energy storage system (MES) charging power from the dc bus. (b) Battery charging power from the dc bus. (c) Super capacitor discharging power to the dc bus. (d) Grid power to the dc bus.

VI. CONCLUSION

A dc micro grid for renewable power integration has been proposed. The operational optimization and power-electronics based voltage–power droop control was developed, and the functioning was

demonstrated through simulation. Interaction with the main grid was controlled as a result of an operational optimization that seeks to minimize cost and emissions. A method to quantify the uncertainty affiliated with the forecast of aggregated wind and PV-based power generation was created and used to quantify the energy reserve of the battery energy storage system. The battery is parallel-connected with a super capacitor to form a multilevel energy storage. The latter plays a critical role in compensating renewable power fluctuations and providing the power needed when EVs stop by for fast charging. In accordance with the micro grid paradigm, operation is also supported in autonomous mode to support UPS when the connection to the main grid is unavailable. During such periods, fast charging is not supported, as the priority shifts to supplying critical local loads.

Power electronics is a key enabling technology in connecting all energy resources to the dc bus. The converters support the dc voltage through a droop control scheme. The control proposed here is adaptive in that the voltage–power droop curves are modified depending on the outcome of the operational optimization. As a novelty, asymmetric droop curves were proposed for the converters connected to the storage so as to also support the objective of bringing the actual battery SOC close to the desired one as scheduled. This ensures, in particular for the multilevel energy storage, that the contribution toward dc voltage control does not compromise its role in providing adequate energy reserve.

For the special case of an urban location, the vertical integration within a tower building offers renewable wind and solar power harvesting on the top and energy delivery at the bottom on the ground level, for example for EV charging. The structure contributes to closely co-locating renewable power generation and delivery to local stationary and mobile EV energy resources.

In sum, this paper contributes to the microgrid paradigm by a novel droop control that takes into account storage SOC when adaptively setting the slopes of the voltage–power droop curves; the proposed forecast based on aggregation of renewable power generation contributes to quantifying energy reserve. In an urban setting, a tower-integrated installation to co-locate harvesting of wind energy and local delivery of clean energy is an alternative. The optimization for power exchanges and dc voltage control using adaptive control are performed through power electronic converters that serve as interfaces to all resources. The resulting energy system serves local stationary and EV-based mobile consumers, and

it is a good citizen within the main grid as it reduces emissions by local usage of wind and solar energy.

REFERENCES

[1] "Global wind report: Annual market update 2012," Global Wind Energy Council, Brussels, Belgium, Tech. Rep., 2012.

[2] H. Polinder, J. A. Ferreira, B. B. Jensen, A. B. Abrahamsen, K. Atallah, and R. A. McMahon, "Trends in wind turbine generator systems," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 1, no. 3, pp. 174–185, Sep. 2013.

[3] F. Giraud and Z. M. Salameh, "Steady-state performance of a gridconnected rooftop hybrid wind-photovoltaic power system with battery storage," *IEEE Trans. Energy Convers.*, vol. 16, no. 1, pp. 1–7, Mar. 2001.

[4] B. S. Borowy and Z. M. Salameh, "Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system," *IEEE Trans. Energy Convers.*, vol. 11, no. 2, pp. 367–375, Mar. 1996.

[5] M. Cheng, S. Kato, H. Sumitani, and R. Shimada, "Flywheel-based AC cache power for stand-alone power systems," *IEEE Trans. Electr. Electron. Eng.*, vol. 8, no. 3, pp. 290–296, May 2013.

[6] H. Louie and K. Strunz, "Superconducting magnetic energy storage (SMES) for energy cache control in modular distributed hydrogenelectric energy systems," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 2361–2364, Jun. 2007.

[7] A. L. Dimeas and N. D. Hatziargyriou, "Operation of a multiagent system for microgrid control," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1447–1455, Aug. 2005.

[8] F. Katiraei and M. R. Iravani, "Power management strategies for a microgrid with multiple distributed generation units," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1821–1831, Nov. 2006.

[9] A. G. Madureira and J. A. Pecos Lopes, "Coordinated voltage support in distribution networks with distributed generation and microgrids," *IET Renew. Power Generat.*, vol. 3, no. 4, pp. 439–454, Dec. 2009.

[10] M. H. Nehrir, C. Wang, K. Strunz, H. Aki, R. Ramakumar, J. Bing, *et al.*, "A review of hybrid renewable/alternative energy systems forelectric power generation: Configurations, control, and applications," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 392–403, Oct. 2011.

[11] R. Majumder, B. Chaudhuri, A. Ghosh, R. Majumder, G. Ledwich, and F. Zare, "Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop,"

IEEE Trans. Power Syst., vol. 25, no. 2, pp. 796–808, May 2010.

[12] D. Westermann, S. Nicolai, and P. Bretschneider, "Energy management for distribution networks with storage systems—A hierarchical approach," in *Proc. IEEE PES General Meeting, Convers. Del. Electr. Energy 21st Century*, Pittsburgh, PA, USA, Jul. 2008.

[13] A. Chaouachi, R. M. Kamel, R. Andoulsi, and K. Nagasaka, "Multiobjective intelligent energy management for a microgrid," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1688–1699, Apr. 2013.

[14] R. Palma-Behnke, C. Benavides, F. Lanas, B. Severino, L. Reyes, J. Llanos, *et al.*, "A microgrid energy management system based on the rolling horizon strategy," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 996–1006, Jun. 2013.

[15] R. Dai and M. Mesbahi, "Optimal power generation and load management for off-grid hybrid power systems with renewable sources via mixed-integer programming," *Energy Convers. Manag.*, vol. 73, pp. 234–244, Sep. 2013.

[16] H. Kakigano, Y. Miura, and T. Ise, "Low-voltage bipolar-type DC microgrid for super high quality distribution," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 3066–3075, Dec. 2010.

[17] D. Chen, L. Xu, and L. Yao, "DC voltage variation based autonomous control of DC microgrids," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 637–648, Apr. 2013.

[18] L. Roggia, L. Schuch, J. E. Baggio, C. Rech, and J. R. Pinheiro, "Integrated full-bridge-forward DC-DC converter for a residential microgrid application," *IEEE Trans. Power Electron.*, vol. 28, no. 4, pp. 1728–1740, Apr. 2013.

[19] K. Strunz and H. Louie, "Cache energy control for storage: Power system integration and education based on analogies derived from computer engineering," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 12–19, Feb. 2009.

[20] "EMTDC transient analysis for PSCAD power system simulation version 4.2.0," Manitoba HVDC Research Centre, Winnipeg, MB, Canada, Tech. Rep., 2005.

[21] "Carbon dioxide emissions from the generation of electric power in the United States," Dept. Energy, Environmental Protection Agency, Washington, DC, USA, Tech. Rep., 2000.

[22] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems*. New York, NY, USA: Wiley, 2010.

[23] E. Tara, S. Filizadeh, J. Jatskevich, E. Dirks, A. Davoudi, M. Saeedifard, *et al.*, "Dynamic average-value modeling of hybrid-electric vehicular power



systems,” *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 430–438, Jan. 2012.