Decentralized Operation Framework for Hybrid AC/DC Microgrid

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***Abstract*— This paper proposes a methodology to attain the optimal generation scheduling of hybrid AC/DC microgrids. The hybrid microgrid consists of AC and DC networks with respective generation and demand resources that are connected by bi-directional AC/DC converters. The proposed methodology leverages decentralized optimization framework that uses the dispatch of the AC/DC converter to facilitate the coordinated operation of AC and DC networks. The presented framework utilizes an iterative approach to determine the optimal operation schedule for the hybrid AC/DC microgrid using distinct optimization problems. The results illustrate the effectiveness of the presented approach for operation planning of hybrid AC/DC microgrids.**

Keywords*— *hybrid AC/DC microgrid; decentralized optimization; power system economics

Nomenclature

Variables and indices

c	Index of converter
g	Index of utility grid
j,o	Index of bus
mt	Index of microturbine
$F_{c,(.)}$	Production cost function for thermal unit
$I_{i,t}$	Status indicator, 1 means ON and 0 means OFF
$I_{(.),k,t}$	Status indicator for battery storage k at hour t
k,dc,ch	Index of storage unit, discharging, and charging states
$P_{i,t}, Q_{i,t}$	Real and reactive power generation of unit i
$P_{mt,t}$	Real power generation of microturbine mt
$P_{j_{(.)},t}^{inj}$	Real power injection at bus j at hour t
$P_{j_{(.)},t}^{d}$	Served demand at bus j at hour t
$P_{c_{(.)},t}$	Exchanged power by converter c at hour t
$P_{g,t}$	Dispatched real power of the utility at hour t
$P_{w,t}$	Dispatched wind generation w at hour t
$PL_{j_{(.)},o_{(.)}}^{(.),t}$	Real power flow between buses j and o at hour t
$P_{(.),k,t}$	Charge/discharge dispatch of battery storage k at hour t
$Q_{c_{ac},t}$	Reactive power injected by converter c at hour t
$Q_{g,t}$	Dispatched reactive power of the utility at hour t
$Q_{j_{(.)},t}^{inj}$	Reactive power injection at bus j at hour t
$QL_{j_{ac},o_{ac}}^{ac,t}$	Reactive power flow in AC network at hour t
$SD_{i,t}$	Shutdown cost of unit i at hour t
$SU_{i,t}$	Startup cost of unit i at hour t
$SL_{j_{ac},o_{ac}}^{ac,t}$	Apparent power flow in AC network at hour t
$E_{k,t}$	Available energy in battery storage k at hour t
w	Index of wind unit
$V_{j_{(.)}}^{t}, \theta_{j_{(.)}}^{t}$	Voltage magnitude and angle at bus j at hour t

Constants

$B_{j,o}, G_{j,o}$	Imaginary and real part of the admittance matrix
$D_{j_{(.)}}^{(.)}$	Set of components that are connected to bus j
NT	Number of hours under study
$P_{j_{(.)},t}^{D}$	Demand at bus j at hour t
$P_{(.)}^{\min}$	Minimum real power of a unit
$P_{(.)}^{\max}$	Maximum real power of a unit
$P_{f,w,t}$	Forecasted wind generation of unit w at hour t
$P'_{c_{(.)},t}$	Exchanged power for converter c at hour t
$Q_{(.)}^{\min}, Q_{(.)}^{\max}$	Minimum and maximum capacity of a component
$SL_{j_{(.)},o_{(.)}}^{\max}$	Capacity of the line between buses j and o
α, β	Weights for the mismatches
$\varepsilon_1, \varepsilon_2$	Convergence tolerance
ρ^{t}	Hourly price of electricity
η_{ch}, η_{dc}	Charging, discharging efficiency

I. INTRODUCTION

The increase in the installed capacity of distributed energy resources (DERs) improves the reliability and quality of service for the demand in the distribution networks. Such resources are categorized as distributed generation and distributed storage (DS) facilities [1]. The emerging control on DERs to improve the economics, reliability and resilience of energy supply has led to the formation of microgrids in distribution networks [2]. Microgrids operate in grid-connected or island mode and can switch from one mode to another seamlessly. DERs are typically equipped with fast response power electronic interfaces (PEI) that improve the flexibility of energy resources in microgrids [3]. The proximity of generation and demand entities improves the power quality and reliability, reduces the power transmission loss, and improves the voltage profile in the distribution networks [4]. Microgrids also facilitate seamless integration of non-dispatchable renewable resources in distribution networks. Coordination between dispatchable generation assets such as energy storage units and conventional thermal generation resources improves the dispatchability and control on non-dispatchable renewable resources [5]-[6]. Most renewable energy resources utilize technologies that provide DC power to the consumers. Fuel cells, photovoltaic arrays (PV), batteries and wind generation units are examples of such technologies. Moreover, most types of loads involve DC power somewhere in their supply path. The inherently DC demand resources such as electronic lighting, consumer electronics including audio/video and information technology (IT) facilities, Heating Ventilation and Air Conditioning (HVAC) actuators, security and safety facilities and electric vehicles (EVs), require DC power supply. Using DC power to serve such demands reduces the number of conversion steps and respective energy losses. Moreover, reduction in the number of converters decreases the number of points of failure and improves the reliability and interruption indices. Hence, forming DC networks potentially eliminates the energy conversion loss and corresponding heat dissipation, and provides higher power quality and reliability for the demands [7]. Using the DC power supply with minimal DC to AC conversion requires a complete DC system with generation, distribution and load. The advantages of DC systems over AC systems are: 1) increase in system efficiency, once the supply and demand are both DC powered, 2) no grid synchronization concerns in DC networks, and 3) less vulnerability to disturbances at the utility side (e.g. voltage sags and swells) and improved fault-ride-through capability. DC networks cover areas as large as a building or several buildings depending on the voltage level of the distribution system [8]. Medium voltage DC distribution networks were developed to facilitate the coupling between power distribution networks with different characteristics by regulating the power flow (import/export), and controlling the voltage by providing reactive power in the DC/AC coupling points [9]. While DC systems accommodate the DC generation and demand resources effectively [10]-[11], AC systems were developed to supply the conventional AC loads [12]-[13]. In order to take the advantage of both AC and DC systems, a hybrid AC/DC microgrid is proposed as shown in Fig. 1. Here, the DC systems accommodate generation and demand resources with inherently DC power supply such as PV arrays, microturbines (MT), battery storage, electric vehicles (EVs), LED lighting, data centers and IT facilities. The AC system captures the generation and demand resources with inherently AC power supply such as synchronous and asynchronous generators and motors, and heat loads. The AC/DC bi-directional converters within the hybrid microgrid will link the AC and DC networks. The increase in the number of AC/DC converters will result in a more complicated system which increases the complexity of the control and energy management. Earlier, a decentralized approach is employed to determine the exchanged power between the transmission network and active distribution networks [14] as well as between distribution network and microgrids [15], [16]. In this paper, a decentralized optimization framework is applied to determine the operation scheduling of hybrid AC/DC microgrid. The rest of paper is organized as follows: Section II presents the problem formulation and solution methodology. Section III presents a case study to show the effectiveness of the proposed approach and section IV presents the conclusion.

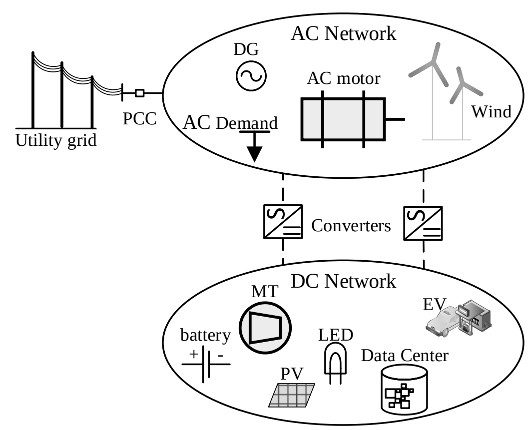

Fig.1. Hybrid AC/DC microgrid

II. PROBLEM FORMULATION AND SOLUTION METHODOLOGY

In this section, a decentralized decision-making framework is proposed to solve the generation scheduling problem in hybrid AC/DC microgrid. Here, the overall optimal scheduling problem is divided into two optimization problems for AC and DC networks. The generation scheduling problems for AC and DC networks are Mixed-integer Quadratic Programming (MIQP) problems with a vector of shared variable which determines the amount of energy exchanged between AC and DC networks via AC/DC converters. The objective in each optimization problem is to minimize the operation cost of the microgrid considering the quadratic penalty function that targets to diminish the mismatch in the exchanged power of the converters. In this section, first, a decentralized decision-making framework is presented and later, the optimal scheduling problems for AC and DC networks are formulated.

A. The Decentralized Optimization Framework

Fig. 2 shows the flowchart of the proposed methodology. As shown in this figure, the generation scheduling problem for hybrid AC/DC microgrid is decomposed into two problems: i.e. the generation scheduling problem for the AC network and the generation scheduling problem for the DC network. The vector of the real power of the AC/DC converters is represented as the common variable vector between these two generation scheduling problems. The exchanged power mismatch is minimized in the two-stage iterative procedure as shown in Fig. 2.

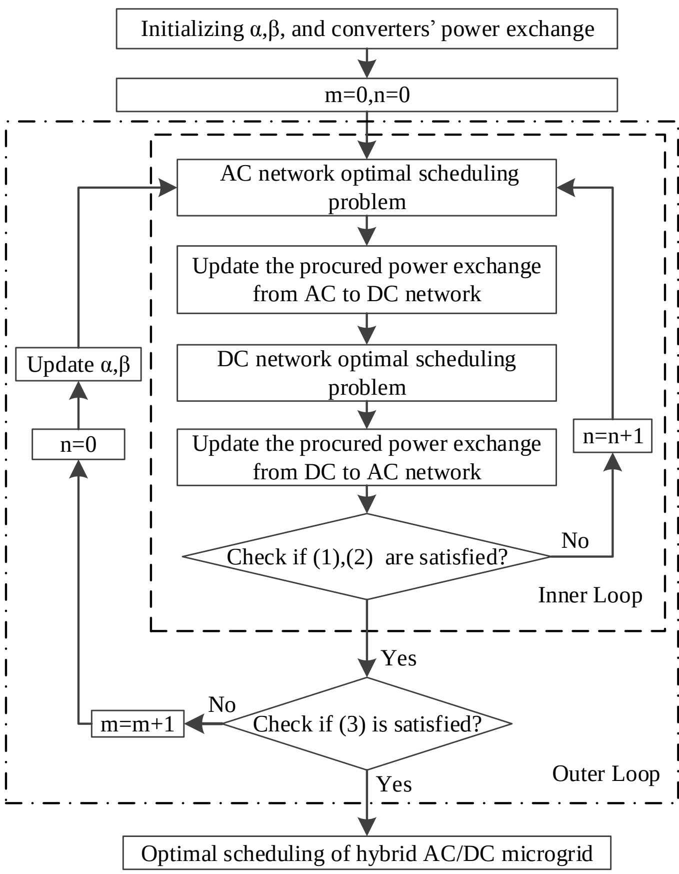

Fig. 2. Flow chart of the proposed approach

In the first step, the exchanged power between AC and DC networks and the weights of mismatches are initiated. Next, the optimal scheduling problem for AC network is solved and the exchanged power among AC and DC networks is determined. In the next step, the generation scheduling problem for the DC network is formulated to minimize the operation cost of the DC network as well as the mismatch between the exchanged power with the AC network and the exchanged power with the DC network that is procured in the generation scheduling problem for the AC network. Similarly, the determined exchanged power at this stage is passed to the generation scheduling problem for AC network and this iterative process continues until the procured solutions for AC and DC networks do not change during the iterations as stated by conditions (1) and (2). Here, (1) checks if the procured exchanged power that is passed from the generation scheduling problem for AC network to the generation scheduling problem for the DC network is close to its previous iteration. Similarly, (2) ensures that the procure solution for the generation scheduling of the DC network is converged to a certain value. Once this iterative process (i.e. the inner loop shown in the flowchart) converged, the dispatch of the converter in the AC network problem is compared with that in the DC network problem. Here, (3) checks, if the procured exchanged power in AC network, is close to the determined exchanged power in the DC network. If condition (3) is satisfied, the process terminates. Otherwise, the weights for mismatches are updated using (4) and (5) and the generation scheduling problem for AC microgrid is solved again as shown in the outer loop in Fig. 2. Here, γ is a parameter that accelerates the convergence.

$$\left| P'^{n}_{c_{ac},t} - P'^{n-1}_{c_{ac},t} \right| \le \varepsilon_1 \tag{1}$$

$$\left| P'^{n}_{c_{dc},t} - P'^{n-1}_{c_{dc},t} \right| \le \varepsilon_1 \tag{2}$$

$$\left| P'^{m}_{c_{ac},t} - P'^{m}_{c_{dc},t} \right| \le \varepsilon_2 \tag{3}$$

$$\alpha^{m+1}_{c,t} = \alpha^{m}_{c,t} + 2\beta^{m}_{c,t}(P'^{m}_{c_{ac},t} - P^{m}_{c_{dc},t}) \tag{4}$$

$$\beta^{m+1}_{c,t} = \gamma(\beta^{m}_{c,t}) \tag{5}$$

B. Operation scheduling in AC network

The generation scheduling problem for AC network is shown in (6)-(23). The operation cost of the AC network is minimized considering the penalty for the curtailed demand and the quadratic penalty function that captures the mismatch between the dispatch of the AC/DC converters in this problem and the dispatch of the AC/DC converters procured from the generation scheduling problem for the DC network. The objective function of this problem is shown in (6). The operation cost of the AC network is composed of the cost of purchasing electricity from the utility, the operation cost of conventional thermal generation units considering the startup and shutdown costs, the penalty for the lost load in AC network, and the quadratic penalty function representing the mismatch of the exchanged power in the AC/DC converter. In AC network, no operation cost is associated with wind generation. The constraints (7) and (8) show the startup and shutdown costs of the conventional thermal generation technologies. The minimum and maximum real and reactive power of thermal generation are stated by (9) and (10), respectively. The limitation on wind generation dispatch is shown in (11). Here, the dispatched wind generation is equal to or lower than the forecasted wind generation at each hour. The injected real and reactive power on each bus in AC network are shown in (12)-(13), respectively. The limitations on injected real and reactive power of the AC/DC converters are shown in (14)-(15). Similar constraints are considered for the real and reactive power from the utility grid as shown in (16)-(17). The net injected real and reactive power at each bus in AC network is shown in (18) and (19), respectively. The real and reactive power that flows through the distribution lines in AC network is shown in (20) and (21), respectively. The apparent power transmitted through the distribution line is shown in (22). Here, ξ is an auxiliary parameter, which is dependent on the demand power factor as calculated in [17]. The apparent power transmitted by the distribution lines in AC network is limited by (23).

$$Min\sum_t \begin{pmatrix} \rho^t \cdot P_{g,t} + \sum_i \left(F_{c,i}(P_{i,t}) + SU_{i,t} + SD_{i,t} \right) + \\ VOLL^{ac} \cdot (\sum_{j_{ac}} \left| P^D_{j_{ac},t} - P^d_{j_{ac},t} \right|) + \sum_c \alpha_{c,t} (P_{c_{ac},t} - P'_{c_{dc},t}) + \\ \sum_c \left(\left\| \beta_{c,t} \cdot (P_{c_{ac},t} - P'_{c_{dc},t}) \right\|_2^2 \right) \end{pmatrix} \quad (6)$$

s.t.

$$SU_{i,t} \geq CS_i \cdot (I_{i,t} - I_{i,t-1}) \quad (7)$$

$$SD_{i,t} \geq CD_i \cdot (I_{i,t-1} - I_{i,t}) \quad (8)$$

$$P_i^{\min} \cdot I_{i,t} \leq P_{i,t} \leq P_i^{\max} \cdot I_{i,t} \quad (9)$$

$$Q_i^{\min} \cdot I_{i,t} \leq Q_{i,t} \leq Q_i^{\max} . I_{i,t} \quad (10)$$

$$0 \leq P_{w,t} \leq P_{f,w,t} \quad (11)$$

$$\sum_{g \in D^g_{j_{ac}}} P_{g,t} + \sum_{i \in D^i_{j_{ac}}} P_{i,t} + \sum_{w \in D^w_{j_{ac}}} P_{w,t} - \sum_{c \in D^c_{j_{ac}}} P_{c_{ac},t} - P^d_{j_{ac},t} = P^{inj}_{j_{ac},t} \quad (12)$$

$$\sum_{g \in D^g_{j_{ac}}} Q_{g,t} + \sum_{i \in D^i_{j_{ac}}} Q_{i,t} + \sum_{c \in D^c_{j_{ac}}} Q_{c_{ac},t} - Q^d_{j_{ac},t} = Q^{inj}_{j_{ac},t} \quad (13)$$

$$P_c^{min} \leq P_{c_{ac},t} \leq P_c^{max} \quad (14)$$

$$Q_c^{min} \leq Q_{c_{ac},t} \leq Q_c^{max} \quad (15)$$

$$P_g^{min} \leq P_{g,t} \leq P_g^{max} \quad (16)$$

$$Q_g^{min} \leq Q_{g,t} \leq Q_g^{max} \quad (17)$$

$$P^{inj}_{j_{ac},t} = \left(2V_j^t - 1\right) G_{j,j} + \sum_{o(o \neq j)} \left(G_{j,o} \left(V^t_{j_{ac}} + V^t_{o_{ac}} - 1 \right) + B_{j,o} \left(\theta^t_{j_{ac}} - \theta^t_{o_{ac}} \right) \right) \quad (18)$$

$$Q^{inj}_{j_{ac},t} = -\left(2V_j^t - 1\right) B_{j,j} + \sum_{o(o \neq j)} \left(-B_{j,o} \left(V^t_{j_{ac}} + V^t_{o_{ac}} - 1 \right) + G_{j,o} \left(\theta^t_{j_{ac}} - \theta^t_{o_{ac}} \right) \right) \quad (19)$$

$$PL^{ac,t}_{j_{ac},o_{ac}} = -G_{j,o}(V^t_{j_{ac}} - V^t_{o_{ac}}) + B_{j,o}(\theta^t_{j_{ac}} - \theta^t_{o_{ac}}) \quad (20)$$

$$QL^{ac,t}_{j_{ac},o_{ac}} = B_{j,o}(V^t_{j_{ac}} - V^t_{o_{ac}}) + G_{j,o}(\theta^t_{j_{ac}} - \theta^t_{o_{ac}}) \quad (21)$$

$$SL^{ac,t}_{j_{ac},o_{ac}} = PL^{ac,t}_{j_{ac},o_{ac}} + \xi . QL^{ac,t}_{j_{ac},o_{ac}} \quad (22)$$

$$\left| SL^{ac,t}_{j_{ac},o_{ac}} \right| \leq SL^{\max}_{j_{ac},o_{ac}} \quad (23)$$

C. Operation scheduling in DC network

The operation scheduling problem in DC network is shown in (24)-(35). The objective in this problem is to minimize the operation cost, by minimizing the curtailed demand and the mismatch between the dispatch of the AC/DC converter, and the dispatch of the AC/DC converter procured from the generation scheduling problem for AC network. The quadratic penalty function introduced in the objective function diminishes the mismatch in the exchanged power between AC and DC networks as shown in (24). The limitations on charging and discharging dispatch for the storage unit are shown in (25) and (26), respectively. The minimum and maximum real power of microturbine is shown in (27). The charging and discharging states of the storage units are mutually exclusive as shown in (28). The available energy in the storage unit at each hour is shown in (29). The minimum and maximum limits for stored energy in battery storage are shown in (30). Constraint (31) indicates that the stored energy in the battery at the end of the operation period is equal to the initial energy stored. The real power transmitted by the DC line is approximated by (32), assuming that the voltage is maintained at 1 p.u in the DC network. The power transmitted by DC line is limited by the capacity of the line as shown in (33). The injected power on each bus in the DC network is shown in (34). The real power dispatch of the AC/DC converter is limited by (35).

$$Min\sum_t \begin{pmatrix} \sum_{mt} \left(F_{c,mt}(P_{mt,t}) \right) + VOLL^{dc} . (\sum_{j_{dc}} \left| P^D_{j_{dc},t} - P^d_{j_{dc},t} \right|) \\ + \sum_c \left(\alpha_{c,t} (P'_{c_{ac},t} - P_{c_{dc},t}) + \left\| \beta_{c,t} \cdot (P'_{c_{ac},t} - P_{c_{dc},t}) \right\|_2^2 \right) \end{pmatrix} \quad (24)$$

$$I_{ch,k,t} \cdot P^{\min}_{ch,k} \leq P_{ch,k,t} \leq I_{ch,k,t} \cdot P^{\max}_{ch,k} \quad (25)$$

$$I_{dc,k,t} \cdot P^{\min}_{dc,k} \leq P_{dc,k,t} \leq I_{dc,k,t} \cdot P^{\max}_{dc,k} \quad (26)$$

$$P^{\min}_{mt} \leq P_{mt,t} \leq P^{\max}_{mt} \quad (27)$$

$$I_{dc,k,t} + I_{ch,k,t} \leq 1 \quad (28)$$

$$E_{k,t} = E_{k,t-1} - \left(\frac{P_{dc,k,t}}{\eta^k_{dc}} - \eta^k_{ch} \cdot P_{ch,k,t} \right) \quad (29)$$

$$E^{\min}_k \leq E_{k,t} \leq E^{\max}_k \quad (30)$$

$$E_{k,0} = E_{k,NT} \quad (31)$$

$$PL^{dc,t}_{j_{dc},o_{dc}} = \left(\frac{V_{j_{dc},t} - V_{o_{dc},t}}{R_{dc,j_{dc}o_{dc}}} \right) \quad (32)$$

$$\left| PL^{dc,t}_{j_{dc},o_{dc}} \right| \leq SL^{\max}_{j_{dc},o_{dc}} \quad (33)$$

$$\sum_{k \in D^k_{j_{dc}}} \left(P_{dc,k,t} - P_{ch,k,t} \right) + \sum_{mt \in D^{mt}_{j_{dc}}} P_{mt,t} + \sum_{c \in D^c_{j_{dc}}} P_{c,t} - P^d_{j_{dc},t} = \sum_{o_{dc}} PL^{dc,t}_{j_{dc},o_{dc}} \quad (34)$$

$$P_c^{min} \leq P_{c_{dc},t} \leq P_c^{max} \quad (35)$$

III. Case Study

In this section, a stand-alone hybrid AC/DC microgrid, which is composed of an AC network with 6 buses and a DC network with 5 buses, is considered. The AC and DC networks are connected by two AC/DC converters as shown in Fig. 3. The generation unit characteristics including the coefficients of the quadratic operation cost function, the minimum and maximum power capacity and the startup and shutdown costs are shown in Table I. The Diesel Generator (DG) and wind generation unit are connected to the AC network while the battery storage and battery storage are connected to the DC network. The formulated operation scheduling problems for AC and DC networks are solved using CPLEX v12.6.0.

The demand and DER units with inherently DC and AC characteristics are placed on respective networks. The hourly operation scheduling of hybrid AC/DC microgrid is determined for a day-ahead operation horizon. Here, γ is 1.4, the power loss in AC/DC converter is ignored, and the limits on the injected real power for AC/DC converters C_1 and C_2 are 50 kW and 100 kW respectively.

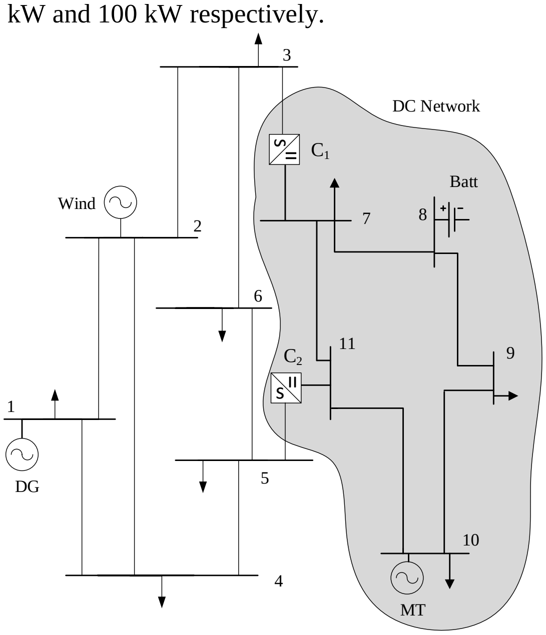

Fig. 3. Hybrid AC/DC microgrid

TABLE I
GENERATION UNITS' CHARACTERISTICS

Unit	a (¢/kWh^2)	b (¢/kWh)	c (¢/h)	P_{min} (kW)	P_{max} (kW)	SU ($)	SD ($)
DG	0.033	27.5	0	10	300	10	8
MT	0.0102	7.128	5.35	10	250	-	-

The total operation cost of hybrid AC/DC microgrid is $4,631 which is composed of the operation cost of the AC network is $3,810, and the operation cost of the DC network is $821. The demand curtailment is zero in both AC and DC networks. The dispatches of converters C_1 and C_2 for 24-hour operation period are shown in Table II. Table II also provides the generation dispatches of DG unit and wind generation unit in AC network as well as the MT and battery storage unit in DC network. The total demand of hybrid AC/DC microgrid is listed in Table II. The demand in AC and DC networks are 75% and 25% of the total demand respectively. The positive values for power dispatch of the battery storage unit indicate the discharging power and the negative values represent the charging power. The positive values for power dispatch in bi-directional AC/DC converters represent the AC to DC power conversion and the negative values represent the DC to AC power conversion. As shown in this table, MT provides the maximum generation dispatch during the operation period because its marginal cost is smaller than that of DG.

At hour 12, the battery discharges to serve the peak demand, and the power flows from DC network to AC network. At hour 3, the total demand is 1443.2 kW and the wind generation is 199 kW, while the battery is in charging mode and stores 41.2 kW. At hour 4, the total demand increased to 1544 kW and the wind generation decreased to 125.2 kW, while the battery storage discharges 42.6 kW. At this hour, the power exchange between AC and DC networks is decreased from 102 kW at hour 3 to 43.3 kW at hour 4. This indicates that the battery storage served the increased demand in DC network and eventually reduced the exchanged power between the AC and DC networks.

TABLE II
THE DISPATCH OF COMPONENTS IN AC/DC MICROGRID

Hour	C_1 (kw)	C_2 (kw)	Wind (kw)	Battery (kw)	DG (kw)	MT (kw)	Total Demand (kw)
1	19.6	59.7	169.1	-44.7	932.6	300	1338.4
2	19.7	59.7	212.9	-58	831.3	300	1285.6
3	31	71	199	-41.2	986	300	1443.2
4	8.7	34.6	125.2	42.6	1076.7	300	1544
5	13.5	46.6	123.4	19.8	1076.6	300	1519.2
6	32	72	152.2	-41.2	1040.8	300	1451.2
7	19.7	59.7	169.4	-62.5	861	300	1267.2
8	19.7	59.7	185.2	-64.7	838.6	300	1258.4
9	19.7	59.7	176.9	-48.9	894.2	300	1321.6
10	30.8	68	244.2	-10	1021.6	300	1555.2
11	28.9	68.9	241.8	-23	981.1	300	1499.2
12	-2.1	10.9	297.2	120.3	999.9	300	1716.8
13	1.6	16.5	300	108.5	998.5	300	1706.4
14	27.8	63.9	300	10	995.9	299.4	1604.8
15	29.9	69.9	300	-23	930.8	300	1507.2
16	19.9	59.9	300	-55.5	753.7	300	1297.6
17	35.7	75.7	300	-23	977.2	300	1553.6
18	30.8	70.8	300	-41.2	883.4	300	1441.6
19	25	56.3	300	23.8	996.9	300	1620
20	14.2	35.8	300	65.8	998	300	1663.2
21	12.5	33.3	300	71.4	998	300	1668.8
22	5.1	21.9	300	96.7	998.3	300	1694.4
23	31.7	71.7	282.2	-41.2	908.4	300	1448.8
24	31	71	300	-41.2	885	300	1443.2

IV. Conclusion

The increasing penetration of DC demands, as well as the increase in the number of inherently DC DERs, promote DC distribution networks. Hybrid AC/DC microgrids with distinct AC and DC networks are proposed to serve the demand with inherently AC and DC characteristics. These microgrids provide improved economic and reliability measures in the distribution networks. This paper addressed a decentralized optimization framework to determine the optimal operation scheduling of hybrid AC/DC microgrid. The presented solution framework decomposes the operation scheduling problem of hybrid AC/DC microgrid into two operation scheduling problems for AC and DC networks with shared variables that represent the dispatch of the bi-directional AC/DC converters. Each operation scheduling problem is formulated as an MIQP optimization problem. The effectiveness of the proposed approach is shown by a case study.

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