

A Strategy for Optimal Operation of Hybrid AC/DC Microgrid under Different Connection Failure Scenarios

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Abstract

This paper proposes an operation strategy to optimize the day-ahead scheduling of hybrid AC/DC microgrid (MG). The strategy schedules its resources, such as distributed generators, AC/DC battery energy storage systems to minimize the operation cost while increasing the system reliability. Moreover, an energy management system (EMS) is developed based on centralized optimization framework, which is used to optimize the MG operation in grid-connected mode. On the other hand, the EMS aims to minimize the load shedding amount in both AC and DC sides in islanded mode. In this study, the operation of hybrid MG under different connection failure scenarios is also represented. The results illustrate the effectiveness of the strategy for different operation modes of hybrid AC/DC MG.

Keywords: *Energy management system, hybrid AC/DC microgrid, mixed integer linear programming, optimal microgrid optimization.*

1. Introduction

The increasing use of renewable distributed generations (RDGs) in low voltage AC distribution network is studied due to environmental issues. In order to integrate RDGs in the distributed system, the concept of microgrid (MG) which is defined as a small-scale power system has been developed in many countries [1, 2]. Nowadays, the use of DC resources such as photovoltaics (PV) and fuel cells (FCs) have been increased in recent years, which supplies DC power to consumers. The DC/AC converters are required to connect these resources into conventional AC system. Besides, more and more DC loads are introduced in the conventional AC grid such as electronic lighting, electric vehicles (EVs), and information technology (IT) facilities, which results in the installation of the AC/DC converters to serve DC loads. Therefore, the integration of DC resources, DC loads in the conventional AC MG, which leads to the increase in the number of DC/AC, AC/DC converters. It will result in a more complicated system and increase the number of point of failure, the operation losses. However, the conventional AC demands also require the existing AC resources. In order to take the advantage of DC and AC systems, the concepts of hybrid AC/DC MG have been developed recently. Like the conventional AC MG, hybrid MG can operate in both grid-connected and islanded modes. In grid-connected mode, loads can be fulfilled continuously by its resources and the buying/selling power from/to the utility grid [3]. However, the MG has to fulfil its loads by its own resources in islanded mode. Load shedding strategy is implemented due to the unbalancing between supply and demands in this mode. The impacts of island load shedding strategies in autonomous MG have been analyzed in [4, 5]. In hybrid system, the AC and DC subgrids are developed along with an interlinking converter which is used to transfer power to each other. It can directly supply both AC and DC loads. In [6], a hybrid AC/DC MG model considering the integration of RESs and plug-in hybrid electric

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vehicles (PHEVs) has been suggested. The investigations into power-sharing issues of a hybrid MG have been introduced by [7, 8]. However, the above researches did not propose the day-ahead scheduling under connection failure states such as grid-connected, islanded modes, and the failure of interlinking converter. Therefore, this study forces on the impacts of connection failures to the day-ahead scheduling of hybrid MG. The operation mode of battery energy storage systems (BESSs), interlinking converter, the amount of load shedding, and the amount of buying/selling power are proposed in each case to operate MG in economic way.

In order to implement the proposed operation strategy for hybrid MG, an EMS is developed to operate the MG for maintaining the power balance with minimization of operation cost. The EMS architectures are grouped into centralized, decentralized, or hybrid EMS [9, 10]. The centralized EMS architectures have been introduced by several researches. A centralized EMS (C-EMS) based on predictive control approach has been suggested by [11] for isolated MGs. In [12], a multi-stage optimization-based C-EMS for MG operation in islanded mode has been proposed. An operation strategy for optimal MGs operation in difference policies of a real-time market has been suggested by [13] based on a centralized controller. A hierarchical EMS has been proposed by [14] based on multi-agent system for multi-microgrids (MMGs) operation whereas [15] presents a nested EMS for day-ahead scheduling of MMGs. Each of EMS has its advantages and disadvantages. According to [15], centralized energy management is the most cost efficient EMS. Therefore, in this paper, a mix integer linear program (MILP)-based model for centralized energy management has been developed for optimal hybrid MG operation. The developed model aims to minimize the operation cost. Moreover, four different connection failure scenarios are analyzed to propose the best case for normal operation while the system can operate in the worst case.

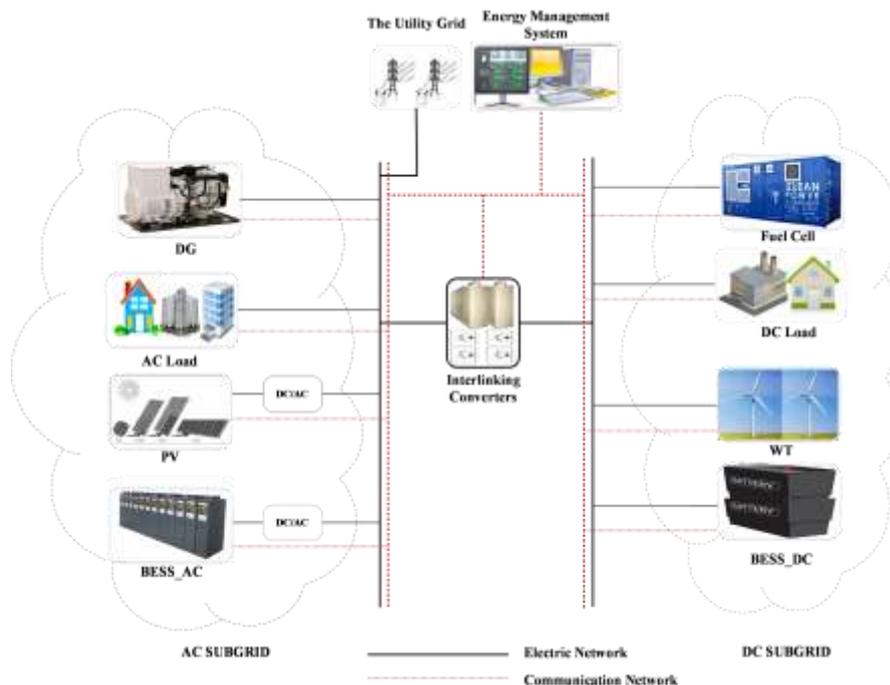


Figure 1. Test Architecture of Hybrid AC/DC Microgrid

2. Hybrid AC/DC Microgrid Model

2.1. Configuration and Components of Hybrid AC/DC Microgrid

Figure 1 depicts an architecture of hybrid AC/DC MG. It comprises of an AC subgrid, a DC subgrid, and interlinking converters. In the AC subgrid, it is composed of DGs, PV, BESS, and AC loads. Similarly, the DC subgrid is composed of FCs, wind turbine (WT), BESS, and DC loads. In order to link AC/DC subgrids, an interlinking converter system is used. Therefore, the surplus/shortage power in both AC/DC sides can be shared to each other by using the converter system. The hybrid MG can be operated in both grid-connected and islanded modes. In normal operation, the hybrid microgrid is operated in grid-connected model. In this mode, the system can buy/sell power from/to the utility grid. On the other hand, the system has to be maintained power balance in both AC and DC sides by using its own supplies in islanded mode. Moreover, load shedding strategy could be performed to ensure the power balance in the entire system.

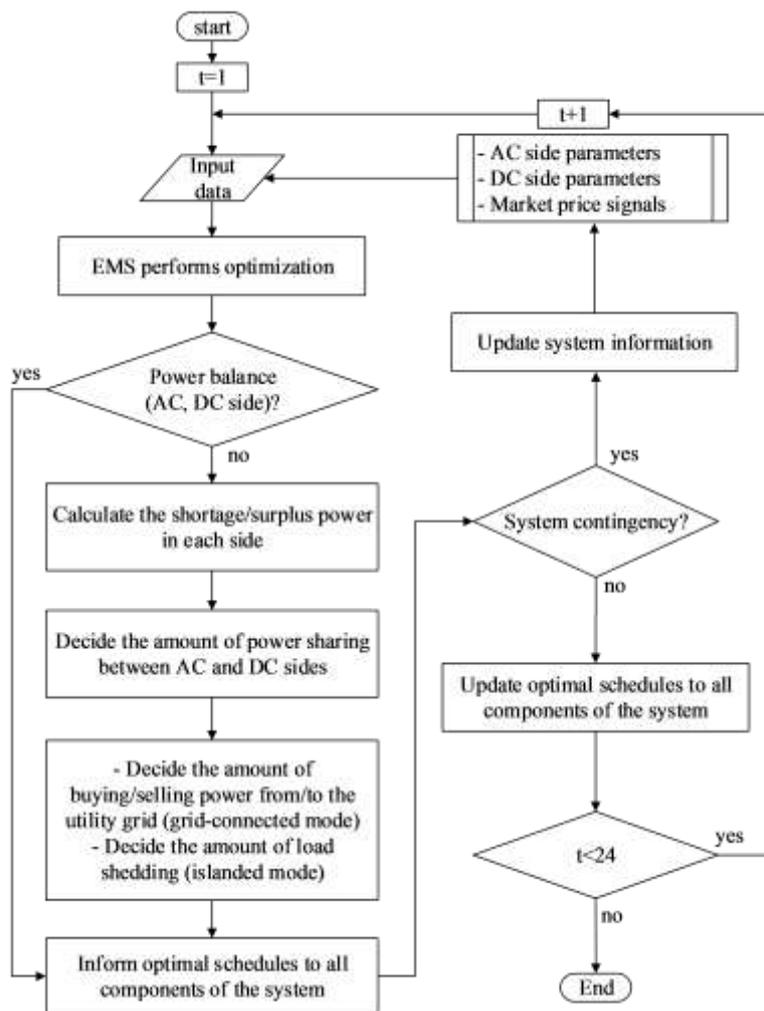


Figure 2. Proposed Operation Strategy of AC/DC Microgrid

A centralized EMS is developed to implement the operation strategy. It gathers all information from each component by using communication network. In each interval of time, the EMS decides the operation of each component in the system, the amount of purchasing/selling power from/to the utility grid, and the amount of power sharing

between AC and DC sides. The objective of the EMS is to maintain the power balance in both of AC and DC sides while ensuring the minimization of total operation cost of the entire system.

2.2. System Operation Algorithm

Figure 2 depicts the flow chart related to operation of hybrid AC/DC MG. The proposed algorithm operation aims to operate entire MG along with minimization of operation cost. Firstly, the information from all components are sent to EMS via communication network, which is taken as inputs. EMS performs optimization with its received information. The amount of shortage/surplus power is determined by checking power balance in each side. In grid-connected, the shortage/surplus power is considered to exchange with other sides or the utility grid based on market price signals. On the other hand, in islanded mode, the system is operated without the utility grid. Therefore, the demand has to be fulfilled by its own supplies. In peak-time, all supplies cannot fulfil their loads. Therefore, EMS has to decide the amount load shedding to maintain the power balance in the system. Finally, the optimal operation values are informed to all participating components.

In normal operation, the MG is operated based on the receiving information from EMS during one interval of time period. Whenever any failure of connections are detected and informed to EMS. The system information will be updated in EMS. Similarly, EMS reschedules considering updated data and informs all components along with new schedules. Figure 2 summarizes the step-by-step procedure to carry out one round of optimization.

2.3. Mathematical Model of hybrid MG

This section describes the developed MILP-based mathematical model of hybrid AC/DC MG. The proposed model aims to minimize the operation cost of entire MG. The cost objective function is described by (1), which includes costs associated with fuel consumption, start-up, shut-down, and power exchange.

$$\begin{aligned} \min \sum_{i \in I} \sum_{t \in T} & \left(C_i^{DG} \cdot P_{i,t}^{DG} + x_{i,t} \cdot C_i^{SUDG} + y_{i,t} \cdot C_i^{SDDG} \right) + \sum_{j \in J} \sum_{t \in T} \left(C_j^{FC} \cdot P_{j,t}^{FC} + z_{j,t} \cdot C_j^{SUFC} + k_{j,t} \cdot C_j^{SDFC} \right) \\ & + \sum_{t \in T} \left(PR_t^{Buy} \cdot P_t^{Buy} - PR_t^{Sell} \cdot P_t^{Sell} \right) + \sum_{t \in T} \left(pen_t^{ShedAC} \cdot P_t^{ShedAC} + pen_t^{ShedDC} \cdot P_t^{ShedDC} \right) \end{aligned} \quad (1)$$

The first term of (1) represents the cost of DGs that is composed of operated, start-up, and shut-down costs of all DGs in AC grid. The second term describes the cost of FCs in DC grid. The third term demonstrates the cost/benefit of purchasing/selling electricity from/to the utility grid. The last term represented the penalty of shedding load in AC and DC subgrids.

These constraints of hybrid AC/DC MG that are grouped into AC grid constraints, DC grid constraints, and interlinking converter constraints. These constraints are explained in the following sections.

2.3.1. Constraints for AC Side

The operated bounds and on-off mode of DGs are represented by (2), (3). Start-up status and shut-down status of DGs are defined by (4), (5), respectively.

$$u_{i,t} \cdot P_i^{DG_{\min}} \leq P_{i,t}^{DG} \leq u_{i,t} \cdot P_i^{DG_{\max}} \quad \forall i \in I, t \in T \quad (2)$$

$$u_{i,t} \in \{0,1\} \quad \forall i \in I, t \in T \quad (3)$$

$$x_{i,t} = \max \left\{ (u_{i,t} - u_{i,t-1}), 0 \right\} \quad \forall i \in I, t \in T \quad (4)$$

$$y_{i,t} = \max \left\{ (u_{i,t-1} - u_{i,t}), 0 \right\} \quad \forall i \in I, t \in T \quad (5)$$

The balance of supply and demand is given by (6):

$$P_t^{PV} + \sum_{i \in I} P_{i,t}^{DG} + P_t^{Buy} + P_t^{B_{AC}^-} + P_t^{Rec_{DC}} + P_t^{Shed_{AC}} = P_t^{Load_{AC}} + P_t^{Sell} + P_t^{B_{AC}^+} + P_t^{Send_{DC}} \quad \forall t \in T \quad (6)$$

The constraints associated with AC-BESS include the following:

$$0 \leq P_t^{B_{AC}^+} \leq P_{B_{AC}}^{Cap} \cdot \left(1 - SOC_{t-1}^{B_{AC}} \right) \cdot \frac{1}{1 - L_{B_{AC}}^+} \quad \forall t \in T \quad (7)$$

$$0 \leq P_t^{B_{AC}^-} \leq P_{B_{AC}}^{Cap} \cdot SOC_{t-1}^{B_{AC}} \cdot (1 - L_{B_{AC}}^-) \quad \forall t \in T \quad (8)$$

$$SOC_t^{B_{AC}} = SOC_{t-1}^{B_{AC}} - \frac{1}{P_{B_{AC}}^{Cap}} \cdot \left(\frac{1}{1 - L_{B_{AC}}^-} \cdot P_t^{B_{AC}^-} - P_t^{B_{AC}^+} \cdot (1 - L_{B_{AC}}^+) \right) \quad \forall t \in T \quad (9)$$

$$0 \leq SOC_t^{B_{AC}} \leq 1 \quad \forall t \in T \quad (10)$$

Constraint (7) and (8) represent the maximum charging/discharging of AC-BESS. The SOC is updated in each interval of time according to (9). Constraint (10) enforces operated bounds of AC-BESS.

2.3.2. Constraints for DC Side

Similarly, the constraints for operated bounds, on-off mode, and start-up/shut-down status of FCs are represented by (11)-(14), respectively.

$$v_{j,t} \cdot P_j^{FC_{min}} \leq P_{j,t}^{FC} \leq v_{j,t} \cdot P_j^{FC_{max}} \quad \forall j \in J, t \in T \quad (11)$$

$$v_{j,t} \in \{0,1\} \quad \forall j \in J, t \in T \quad (12)$$

$$z_{j,t} = \max \left\{ (v_{j,t} - v_{j,t-1}), 0 \right\} \quad \forall j \in J, t \in T \quad (13)$$

$$k_{j,t} = \max \left\{ (v_{j,t-1} - v_{j,t}), 0 \right\} \quad \forall j \in J, t \in T \quad (14)$$

Constrain (15) is power balancing for DC subgrid:

$$P_t^{WT} + \sum_{j \in J} P_{j,t}^{FC} + P_t^{B_{DC}^-} + P_t^{Rec_{AC}} + P_t^{Shed_{DC}} = P_t^{Load_{DC}} + P_t^{B_{DC}^+} + P_t^{Send_{AC}} \quad \forall t \in T \quad (15)$$

Maximum charge/discharge rate constraint of DC-BESS is given by (16), (17):

$$0 \leq P_t^{B_{DC}^+} \leq P_{B_{DC}}^{Cap} \cdot (1 - SOC_{t-1}^{B_{DC}}) \cdot \frac{1}{1 - L_{DC}^+} \quad \forall t \in T \quad (16)$$

$$0 \leq P_t^{B_{DC}^-} \leq P_{B_{DC}}^{Cap} \cdot SOC_{t-1}^{B_{DC}} \cdot (1 - L_{DC}^-) \quad \forall t \in T \quad (17)$$

The amount of SOC in each interval of time is calculated by (18). Constraint (19) represents operated bounds of DC-BESS.

$$SOC_t^{B_{DC}} = SOC_{t-1}^{B_{DC}} - \frac{1}{P_{B_{DC}}^{Cap}} \cdot \left(\frac{1}{1 - L_{DC}^-} \cdot P_t^{B_{DC}^-} - P_t^{B_{DC}^+} \cdot (1 - L_{DC}^+) \right) \quad \forall t \in T \quad (18)$$

$$0 \leq SOC_t^{B_{DC}} \leq 1 \quad \forall t \in T \quad (19)$$

2.3.3. Constraints for Interlinking Converters

The role of interlinking converter is to share power between AC and DC sides. Equation (20) presents the constraint of maximum operation of converter. The power balance in converter is enforced by (21), (22).

$$0 \leq P_t^{Rec_{DC}}, P_t^{Send_{DC}}, P_t^{Rec_{AC}}, P_t^{Send_{AC}} \leq P_{Converter}^{Cap} \quad \forall t \in T \quad (20)$$

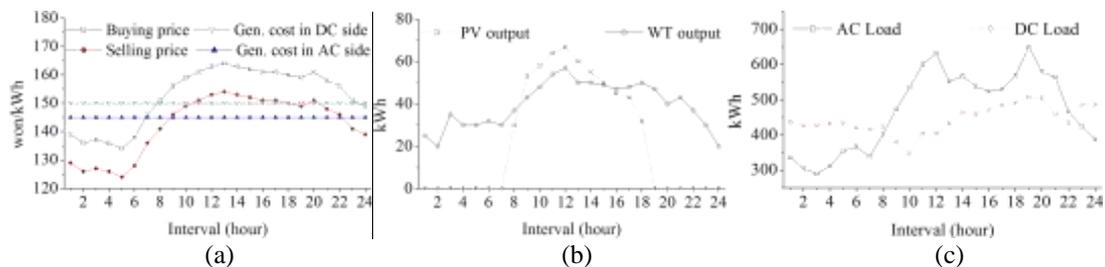
$$0 \leq P_t^{Rec_{DC}} = \eta_{Converter} \cdot P_t^{Send_{AC}} \quad \forall t \in T \quad (21)$$

$$0 \leq P_t^{Rec_{AC}} = \eta_{Converter} \cdot P_t^{Send_{DC}} \quad \forall t \in T \quad (22)$$

3. Numerical Results

3.1. Input Data

In this study, the proposed MILP-based model is demonstrated on a test hybrid AC/DC MG. In this system, the AC bus has 1 PV, 1 DG, 1 BESS and AC loads. Besides, DC bus has 1 WT, 1 FC, 1 BESS and DC loads. The analysis is conducted for a 24-hour scheduling horizon and each time of interval is set to be 1 hour. The market price signals, RDG outputs, and load profiles are depicted in Figure 3.



**Figure 3. (a). Market Price Signals and AC/DC Side Generation cost
(b). Output Power of Renewable Distributed Generations
(c). AC/DC Loads**

The parameters of DG, FC, and AC/DC BESSs are tabulated in table 1, 2, respectively. The capacity of interlinking converter is 500 kWh along with 2% of transferred loss. All numerical simulation results are coded in Java and solved using the MILP solver CPLEX 12.3 [16].

Table 1. Generator Parameters

Parameters	AC Side	DC Side
	Diesel Generator	Fuel Cell
Min. (kWh)	0	0
Max. (kWh)	500	400
Start-up cost (KRW)	300	250
Shut-down cost (KRW)	200	200
Operation cost (KRW)/kWh	145	150

Table 2. AC/DC BESSs Parameters

Subgrid	BESS parameters				
	Min. (kWh)	Capacity (kWh)	Initial (kWh)	Char. Loss (%)	Dis. Loss (%)
AC	0	200	50	5	5
DC	0	150	50	5	5

Four scenarios have been considered and compared in this study as follows:

- a. *Normal operation (case 1)*: the system is in normally operation with grid-connected mode.
- b. *Islanded mode (case 2)*: the system is operated in islanded mode.
- c. *Failure of interlinking converters (case 3)*: there is no power sharing between AC and DC sides. However, AC bus can exchange power with the unity grid.
- d. *Failure of interlinking converters and islanded mode (case 4)*: This is the worst case. The system is separately divided into AC, DC grids. These grids are independently operated in islanded mode.

The operation of 4 scenarios will be analyzed and compared in the following sections.

3.2. Hybrid AC/DC MG in Normal Operation

In this mode, a day-ahead scheduling of the hybrid AC/DC MG has been proposed with minimization of total operation cost. In each interval of time, the output power of RDG units are firstly used for reducing the operation cost. The generation power are determined based on the comparison of generation costs and market price signals. Interval 1-6, the generation cost is less than market price, the system will buy electricity from the utility grid instead of operating generators. On the other hand, the system will sell surplus power with high marker price such as interval 10, 13. Charging/discharging amount of AC/DC BESSs are decided to maximize the benefit in the system. Interval 5, in low price interval the power is fully charged to BESS and discharged on higher price intervals (10-14, 17-20). Finally, the amount of purchasing/selling power is determined to fulfill loads in the system. In this mode, the interlinking converter is used to share the cheaper resources between AC and DC sides. The day-ahead schedules for all components are summarized by Figure 4.

Table 3. Load Shedding in the System for Difference Scenarios

t	Load shedding in AC side				Load shedding in DC side			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0	0	36	0	0	0	0
12	0	0	0	15.36	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	10.38	0	12	0	14	14	14
15	0	0	0	0	0	0	10	10
16	0	0	0	0	0	1.42	22	0
17	0	0	0	0	0	23.26	36	0
18	0	36	0	36	0	38.5	22.5	0
19	0	103	0	103	0	0	0	16.5
20	0	0	0	0	0	0	0	64
21	0	0	0	0	0	0	16	16
22	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	56	53.29
24	0	0	0	0	0	0	63.29	66

3.3. Hybrid AC/DC MG Operation under Different Connection Failure Scenarios

In this section, a comparison of the mentioned scenarios is represented. The load shedding amount, the operation of AC/DC BESSs, and the amount of power sharing are determined and compared in each case.

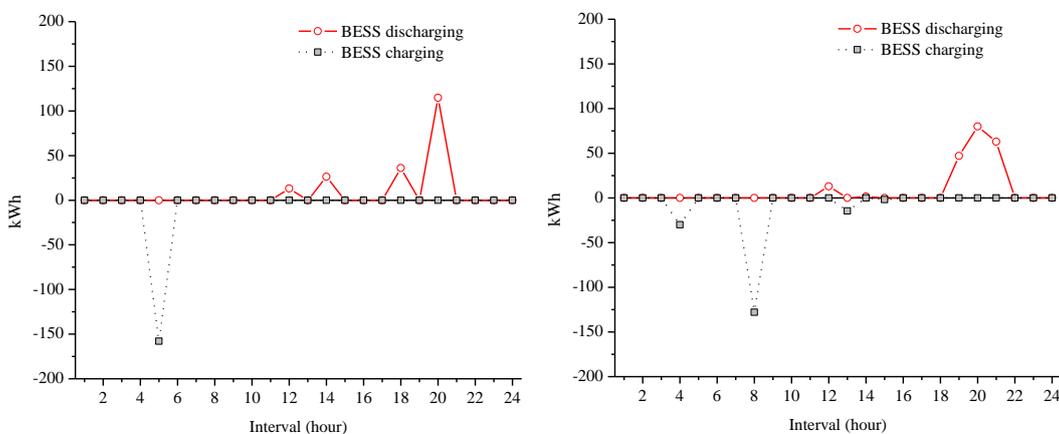
3.3.1. Load Shedding in MG

In islanded mode, in order to balance supply and demand, the load shedding is necessary to make power balance. This study proposed the operation strategy to minimize the amount of load shedding in AC and DC sides. The amount of load shedding in the cases are shown in table 3. In case 1, the system operates in grid-connected mode. Hence, there is no load shedding. However, in case 2, 3, and 4, in peak-hours the system cannot fulfill its loads by its own supplies. In these cases, load shedding algorithm has to be performed to ensure power balance. As can be obtained from table 3, case 4 is the worst case for operation of the system. The amount of load shedding are decreased in case 2, 3 due to power exchange with external grids.

3.3.2. AC/DC battery Energy Management System Operations

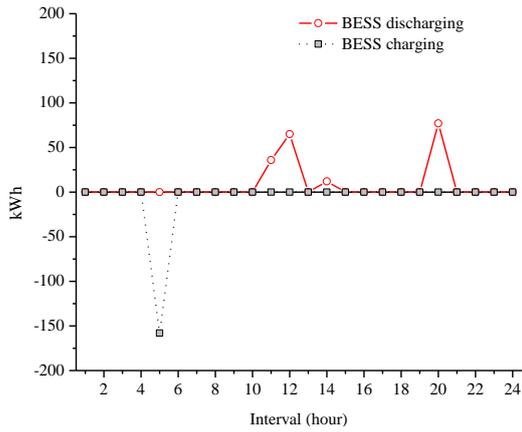
The AC side BESS operation for the 4 cases are depicted by Figure 5. It can be observed from Figure 5 that BESS has been fully charged in lower price intervals. Case 1 and 3, the AC bus is operated in grid-connected mode. Therefore, the BESS is operated in economic way to maximize the system benefit, as shown in Figure 5 (a), (c). On the other hand, case 2, 4, BESS is operated in islanded mode. In these cases, BESS aims to minimize the total load shedding amount, as shown in Figure 5 (b), (d). In peak-hour (interval 18-22), the demand cannot be fulfilled by using its own generators. Therefore, BESS is charged surplus power from off-peak intervals (13-17) and discharged to peak intervals.

Similarly, the operation of DC-BESS is demonstrated in Figure 6. In case 1 and 2, DC bus is connected to AC bus by using interlinking converter. The DC bus can sell/buy the surplus/shortage power to/from AC bus for minimization of operation cost. Charging/discharging amount of BESS is depicted in Figure 6 (a), (b). In case 3, 4, the DC bus is in autonomous mode. The BESS is operated to maintain the power balance in the DC grid. Charging/discharging amount of BESS is shown in Figure 6 (c), (d).

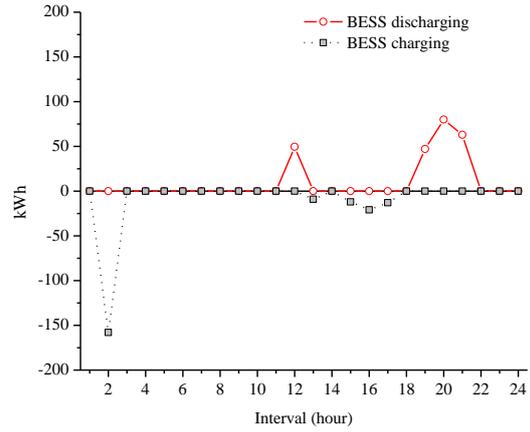


(a) Case 1

(b) Case 2

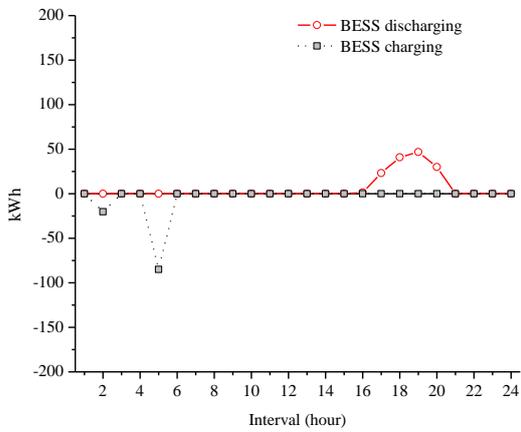


(c) Case 3

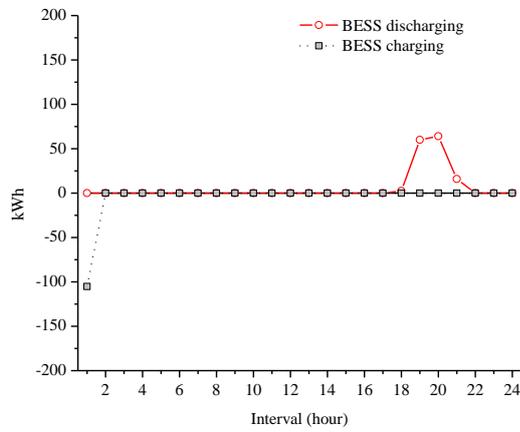


(d) Case 4

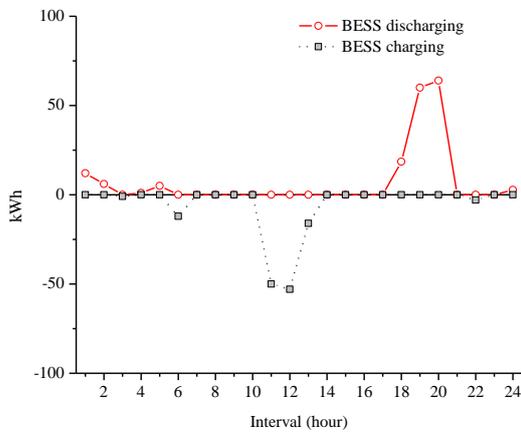
Figure 5. AC Side Battery Energy Management System Operation



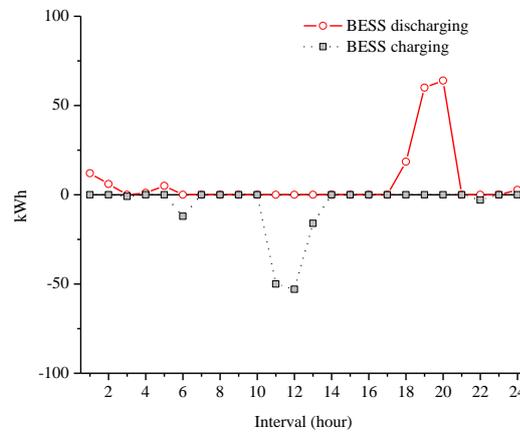
(a) Case 1



(b) Case 2



(c) Case 3



(d) Case 4

Figure 6. DC Side Battery Energy Management System Operation

3.3.3. Power Sharing by Using Interlinking Converters

The amount of power sharing is shown in Figure 7. In grid-connected mode (case 1), the amount of power sharing is decided to share the cheaper resources for minimization of total operation cost. In case 2, the hybrid AC/DC MG is operated in islanded mode. The system cannot exchange power with the utility grid. Therefore, the amount of power sharing is decreased to minimize the load shedding amount as well as operation cost, as illustrated in Figure 7 (b). In case 3 and 4, the connection between AC and DC sides is broken. Hence, the amount of power sharing is zero, as shown in Figure 7 (c).

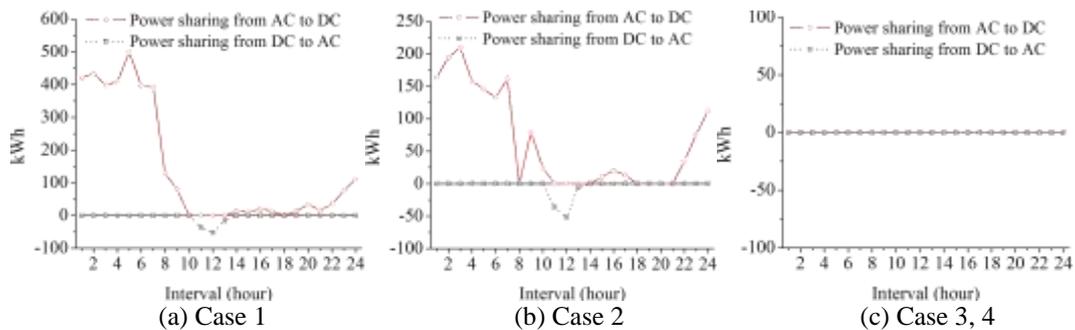


Figure 7. Power Sharing by Using Interlinking Converter

4. Conclusion

In this study, a strategy for optimal energy management in hybrid AC/DC MG has been proposed. In grid-connected mode, the test system is capable of trading surplus/deficit of electricity with the utility grid. The AC and DC subgrids can share their resources by using interlinking converters. The developed EMS is to minimize the operation cost of the entire network while reducing the amount of load shedding in islanded mode. Moreover, the effects on the system of different connection failures have also been analyzed and compared. The amount of load shedding, the AC/DC BESS operations, and the amount of power sharing are compared in each case of failure. By the comparison of four different scenarios, the best operation mode is chosen for normal operation. In failure cases, the operation mode of BESSs and interlinking converters are proposed for minimization of operation cost as well as the amount of load shedding. Finally, the results indicated that the system are able to operate even in the worst case in economic way by using the proposed operation strategy.

Nomenclature

Sets

T	Set of time intervals.
I	Set of diesel generations.
J	Set of fuel cells.

Constants

C_i^{DG}, C_j^{FC}	Production cost of DG unit i, FC unit j.
$C_i^{SU_{DG}}, C_j^{SU_{FC}}$	Start-up cost of DG unit i, FC unit j.
$C_i^{SD_{DG}}, C_j^{SD_{FC}}$	Shut-down cost of DG unit i, FC unit j.
PR_t^{Buy}, PR_t^{Sell}	Buying/selling price at t.
P_t^{PV}, P_t^{WT}	Forecasted output of PV cell & wind turbine.
$P_t^{Load_{AC}}, P_t^{Load_{DC}}$	AC, DC load amount at t.
$pen_t^{shed_{AC}}, pen_t^{shed_{DC}}$	Penalty for AC, DC load shedding amount at t.
L_{AC}^{B+}, L_{AC}^{B-}	Losses for charging/discharging of AC BESS.
L_{DC}^{B+}, L_{DC}^{B-}	Losses for charging/discharging of DC BESS.
$P_{B_{AC}}^{Cap}, P_{B_{DC}}^{Cap}$	Capacity of AC and DC BESSs
$P_{Converter}^{Cap}$	Capacity of interlinking converters
$\eta_{Converter}$	Efficiency of interlinking converters

Variables

$u_{i,t}, v_{j,t}$	On or off mode of DG unit i and FC unit j at t.
$P_{i,t}^{DG}, P_{j,t}^{FC}$	Generation amount of DG unit i and FC unit j at t.
P_t^{Buy}, P_t^{Sell}	Buying/selling power from/to the utility grid at t.
$P_t^{B_{AC}^+}, P_t^{B_{AC}^-}$	Charging/discharging power of AC BESS at t.
$P_t^{B_{DC}^+}, P_t^{B_{DC}^-}$	Charging/discharging power of DC BESS at t.
$P_t^{Rec_{DC}}, P_t^{Send_{DC}}$	Receiving/sending power from/to DC subgrid at t.
$P_t^{Rec_{AC}}, P_t^{Send_{AC}}$	Receiving/sending power from/to AC subgrid at t.
$P_t^{Shed_{AC}}, P_t^{Shed_{DC}}$	Load shedding amount in AC and DC subgrids at t.
$SOC_t^{B_{AC}}, SOC_t^{B_{DC}}$	State of charge for AC BESS and DC BESS at t.

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