IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 13, 2020, accepted October 27, 2020, date of publication November 2, 2020, date of current version November 12, 2020.

*Digital Object Identifier 10.1109/ACCESS.2020.3035251*

# Resilience Improvement With Zero Load Curtailment by Multi-Microgrid Based on System of Systems

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This work was supported by the Qatar National Library.

**ABSTRACT** This article studies the resilience and energy management in multi-microgrid system. In the proposed model, the microgrid is formed by four sub-microgrids. Based on the system of systems (SOS), these sub-microgrids pool their resources and capacities together to form a new and more complex microgrid that provides further functionality than the basic separated microgrids. One of the sub-microgrids is connected to the external grid. The tie-line connections are between all sub-microgrids. Some connections are normally-open and the rest are normally-closed. The status of normally-open connections is changed to close when the resilience or economic criteria dictate. The sub-microgrids are integrated with solar panels, wind turbines, battery energy storage (BES) and loads. All sub-microgrids are also equipped with diesel generator as emergency resource. Under normal operating condition, the proposed model optimally utilizes the resources of all sub-microgrids to minimize the cost, pools the extra resources of sub-microgrids, and optimizes the operation of batteries and diesel generators. Under faulty operating condition when some or all sub-microgrids are islanded, the model supplies the loads with zero load curtailment and minimizes the costs. In the faulty condition, the model may change the status of connections from normally-open to close when required. The simulation results on a given test system verify that the recommended model confirms optimal operation of the microgrid. Furthermore, all sub-microgrids, improves resilience, minimizes operating cost, handles the events and achieves zero load curtailment under both faulty and healthy conditions.

**INDEX TERMS** Multi-microgrid, resilience, zero load curtailment, system of systems.

## NOMENCLATURE

### *INDEX AND SETS*

| | |
|---|---|
| $i, I$ | Index and set of scenarios |
| $j, J$ | Index and set of seasons |
| $k, K$ | Index and set of time periods |
| $n, m$ | Indexes of sub-microgrids |
| $N$ | Set of sub-microgrids |

### *PARAMETERS*

| | |
|---|---|
| $C_{ns}^{n}$ | Capacity of battery (kWh) |
| $\Pi_{gr}^{j,k}$ | Price of grid electricity (\$/kWh) |
| $\Pi_{dg}^{n,j,k}$ | Price of diesel electricity (\$/kWh) |
| $P_{lo}^{n,i,j,k}$ | Load power (kW) |
| $P_{ns}^{n}$ | Power of battery (kW) |
| $P_{n,m}^{r}$ | Capacity of line between sub-microgrids (kW) |
| $P_{n}^{dg}$ | Capacity of diesel generator (kW) |
| $P_{so}^{n,i,j,k}$ | Power of solar system (kW) |
| $P_{wi}^{n,i,j,k}$ | Power of wind system (kW) |
| $Q_{sc}^{i}$ | Probability of scenario |
| $T_{ps}^{j}$ | Duration of season (day) |
| $T_{ph}^{k}$ | Duration of time period (Minute) |
| $\eta_{b}^{n,j}$ | Efficiency of battery (%) |

### *DESIGN VARIABLES*

| | |
|---|---|
| $A_{c}$ | Annual cost of microgrid (\$/year) |
| $C_{s}^{n,j,k}$ | Energy inside battery (kWh) |
| $P_{dg}^{n,i,j,k}$ | Power of diesel generator (kW) |
| $P_{ext}^{i,j,k}$ | Purchased power from the external grid (kW) |
| $P_{n,m}^{i,j,k}$ | Exchanged power between sub-microgrids (kW) |

The associate editor coordinating the review of this manuscript and approving it for publication was Flavia Grassi.

$P_{cs}^{n,j,k}$ Input power to battery (kW)
$P_{ds}^{n,j,k}$ Output power from battery (kW)

### BINARY VARIABLES

$U_{cs}^{n,j,k}$ Binary variable displaying charge
$U_{ds}^{n,j,k}$ Binary variable displaying discharge

## I. INTRODUCTION

The microgrids are one of the efficient structures to deal with issues of large-scale electric power systems where the generation and consumption centers are located far apart from each other. In the microgrids, the generation and consumption centers are located close to each other [1]. The distributed energy resources like renewables, batteries and hydrogen allow the microgrid to operate on off-grid operation mode [2]. These generation systems are directly connected to the loads which may be the linear, nonlinear, or reactive loads [3], [4].

The electric vehicle and transferable loads are also investigated in microgrids as effective resources that make impacts on both economic and technical aspects of microgrid operation [5]. The combination of these capacity resources provides a very flexible functionality and performance than the simple bulk electric power systems. The microgrids are utilized to improve the voltage, resilience, operating cost, stability, environmental pollutions and reliability in the electrical grids [6]. The microgrids can operate in the grid-connected or islanded state. The transition from grid-tied to off-grid may lead to excess generation or load demand that must be spilled or curtailed. Such operation needs optimal energy management for distributed energy resources in the microgrids. The deterministic and stochastic optimization programming are suggested to handle such issues [7]. The demand response program is also an effective tool in microgrids. The demand response may curtail the on-peak demands or fill the gap caused by the mismatch between generation and loads. The demand response program covers many topics like direct load control and load re-scheduling [8].

The multi-microgrid is a new concept in the microgrid arena. The multi-microgrid system is made by forming several sub-microgrids [9]. The independence of sub-microgrids is an important factor in the multi-microgrid systems and the better model comprises more independence of sub microgrids where each sub-system can continue its operation as a separated standalone system. It has been demonstrated that the multi-microgrid system can reduce energy losses, voltage sags, and greenhouse gases. The multi-microgrid may also be operated to decrease the energy exchange with the external grid by pooling and sharing the capacities of subsystems [10]. The multi-microgrid systems are supplied by various capacity resources such as different sorts of distributed generators (DGs), various types and configuration of energy storage systems, electric and hydrogen vehicles, and demand response programs [11]. The uncertainties of loads, generating systems and prices may also be incorporated by probabilistic indexes. One of the most common objective functions in the multi-microgrid systems is to minimize the operating cost of system [12].

The multi-microgrid operation may be conceptualized based on the well-known engineering concept namely system of systems (SOS) [13]. The SOS is a group of task-oriented systems that merge their resources and capacities together to create a more advanced system which offers higher performance over the separated systems. In the SOS, each system is capable of independent operation but they incorporate collectively to get further desired capabilities [13].

The resilience in microgrids and buildings is a very important point that has recently attracted much more attention [14]. The microgrid can improve the resilience of electric grids because of island operation capability. Such ability helps the grid to restore the critical loads following events [15]. The resilience is evaluated under cyber threats, natural disasters, windstorm and vulnerabilities [16]. The communications infrastructure is required for such advanced system. The efficient mitigation tactics may be required for pre-disaster, during-disaster, and post-disaster recovery [17]. The microgrid formation is an efficient technique for microgrid resilience improvement and load restoration. The microgrid formation converts the system into several sub-grids that operate in island mode when major faults happen in the grid [18]. The load restoration is assumed as a resilience index in the microgrids. The service restoration comprising variability and scarcity of generation units has been addressed by researchers to maximize the critical load recovery [19].

In the distribution systems, the consumers' energy management may be considered together with prosumers energy trading. In the energy management part, the efficient scheduling of the loads is addressed and in the trading part, the prosumers pool their energy to supply the local loads. Such model results in low-cost electricity consumption in the grids. In such systems, the grid is sectionalized into several sub-grids that share their energy in order to reduce the cost [20]. Current work in this article also considers a multi-microgrid system but the sub-systems pool their resources to improve the system robustness and resilience.

### A. CONTRIBUTIONS OF PAPER

The key contributions of the paper to the field and to the present knowledge are listed below;

- ✓ Both the resilience and energy management are simultaneously studied in the microgrid.
- ✓ The multi-microgrid model is developed to achieve the purposes.
- ✓ The sub-microgrids are capable of both independent and connected operations. In the connected model, the sub-microgrids pool their resources.
- ✓ The sub-microgrids are integrated with renewable resources, battery energy storage (BES) and loads.
- ✓ The diesel generator is also equipped on all sub-systems to deal with contingency conditions.

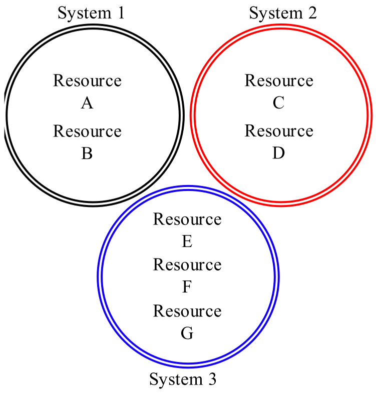

**FIGURE 1.** Regular system including three separated sub-systems.

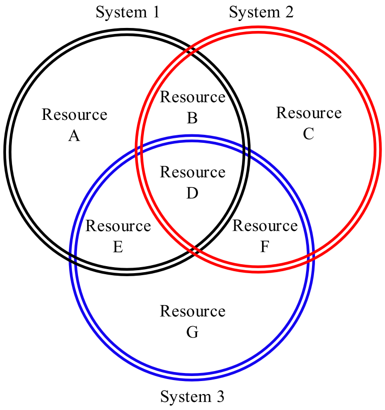

**FIGURE 2.** Three sub-systems based on system of systems.

- ✓ The sub-microgrids are connected through reserve lines and these lines can be closed when necessary.
- ✓ The defined configuration shares the resources among sub-microgrids, minimizes the operating costs and allows the sub-systems to operate under faults.
- ✓ The given model manages the sub-microgrids for zero load curtailment under both island and connected operations.
- ✓ The model finds optimal operation pattern for all resources in all sub-microgrids under both normal and faulty conditions.

## II. MULTI-MICROGRID BASED ON SYSTEM OF SYSTEMS

Figure 1 shows a regular system including three sub-systems with separated operation and resources. Figure 2 shows such system based on system of systems (SOS) [9]. In the SOS, the sub-systems share some or all resources together in order to achieve a better functionality. In the given model, resource "D" is pooled among all sub-systems and resources "E, F, B" are shared between two sub-systems. The rest of resources are not pooled. This is a typical SOS and various configurations may be developed for SOS. For instance, it is possible to share all the resources (i.e., A to G) among all sub-systems [21].

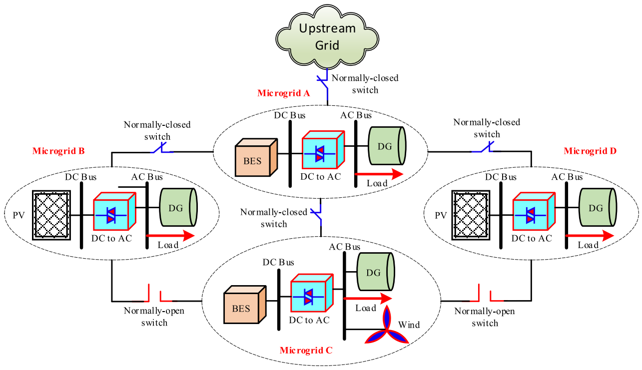

**FIGURE 3.** Multi-microgrid including for sub-systems.

According to SOS, the multi-microgrid system is designed as shown by Figure 3. The system is formed by four sub-microgrids. The microgrid "A" is connected to the upstream network as well as to microgrids "B, C, D". The normally-closed switches are located on these tie-lines. The connection between microgrids "B-C" and "C-D" is made by normally-open switches. These switches may change their status according to the network requirements which is denoted by the planner. All four microgrids are integrated with diesel generator (DG) as an emergency backup. The microgrids "A" and "C" are supported by battery energy storage (BES). The microgrids "B" and "D" are equipped with solar energy and microgrid "C" is connected by wind turbine.

The optimal operation of all microgrids under both island and connected states is achieved. The microgrids pool their resources to supply the load demand under the events such as tie-line outage and island operation. Each microgrid is able of standalone operation when the major faults happen and the system is converted to sub-systems.

## III. FORMULATION OF MULTI-MICROGRID SYSTEM

A general model is presented for multi-microgrid system includes "n" sub-microgrids. The purpose is to minimize the operating cost of multi-microgrid system with zero load curtailment under normal and faulty conditions. This cost is calculated by (1) [3], [4].

The cost given by (1) covers the cost of electricity from the external grid (i.e., first term of equation) and fuel cost of generators in each sub-microgrid (i.e., second term of equation).

$$\begin{aligned} A_c = {} & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\left(P_{ext}^{i,j,k} \times \Pi_{gr}^{j,k} \times Q_{sc}^{i} \times T_{ps}^{j}\right) \\ & + \sum_{n=1}^{N}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\left(P_{dg}^{n,i,j,k} \times \Pi_{dg}^{n,j,k} \times Q_{s}^{i} \times T_{p}^{j}\right) \end{aligned} \quad (1)$$

Each sub-microgrid is connected to the other grids. As well, one of the sub-microgrids is connected to the external grid. The power balance equation in each sub-microgrid is defined by (2). The first term of (2) shows the load demand. The second term presents the battery power which works on either chagrining or discharging state. The third term indicates the generated power in each sub-microgrid by solar, wind or diesel units. The last term models the exchanged power to the other sub-microgrids.

$$\begin{cases} \left[P_{lo}^{n,i,j,k}\right] + \\ \left[P_{cs}^{n,j,k} - P_{ds}^{n,j,k}\right] - \\ \left[P_{so}^{n,i,j,k} + P_{wi}^{n,i,j,k} + P_{dg}^{n,i,j,k}\right] + \\ \left[\sum_{n \in N}\sum_{m \in N}\left(P_{n,m}^{i,j,k}\right)\right] = 0 \end{cases}$$
$$\forall i \in I, j \in J, k \in K, n \in N, m \in N \quad (2)$$

The capacity of installed tie-line between sub-microgrids is modeled by (3). The diesel generator capacity is also given in (4).

$$\left|P_{n,m}^{i,j,k}\right| \leq P_{n,m}^{r}$$
$$\forall i \in I, j \in J, k \in K, n \in N, m \in N \quad (3)$$
$$\left|P_{dg}^{n,i,j,k}\right| \leq P_{n}^{dg}$$
$$\forall i \in I, j \in J, k \in K, n \in N, m \in N \quad (4)$$

The battery energy storage is installed and operated in some sub-microgrids. The battery operation is modeled through (5) to (7). The charging-discharging and rated powers of battery are modeled in (5). The energy and capacity of battery are modeled by (6). The battery efficiency is expressed as total discharged energy divided by total charged energy shown by (7) [22].

$$\begin{cases} U_{cs}^{n,j,k} + U_{ds}^{n,j,k} \leq 1 \\ P_{cs}^{n,j,k} \leq U_{cs}^{n,j,k} \times P_{ns}^{n} \\ P_{ds}^{n,j,k} \leq U_{ds}^{n,j,k} \times P_{ns}^{n} \end{cases}$$
$$\forall n \in N, j \in J, k \in K \quad (5)$$

$$\begin{cases} C_{s}^{n,j,k} = C_{s}^{n,j,k-1} + \begin{pmatrix} P_{cs}^{n,j,k} - \\ P_{ds}^{n,j,k} \end{pmatrix} \times T_{ph}^{k} \\ C_{s}^{n,j,k=24} = C_{s}^{n,j,k=0} \\ C_{s}^{n,j,k} \leq C_{ns}^{n} \end{cases}$$
$$\forall n \in N, j \in J, k \in K \quad (6)$$

$$\eta_{s}^{n,j} = \frac{\sum_{k=1}^{K} P_{ds}^{n,j,k}}{\sum_{k=1}^{K} P_{cs}^{n,j,k}}$$
$$\forall n \in N, j \in J \quad (7)$$

## IV. TYPICAL TEST MICROGRID

The multi-microgrid shown in Figure 3 is the typical test system. The sub-microgrids are named "A, B, C, D". The microgrid "A" is connected to the external grid. The solar, wind and energy storage of microgrids are listed in Table 1 [23], [24]. The authors have already presented some models in [23], [24]. However, those models deal with a single microgrid system that is connected to the external grid. But current model in this article comprises a multi-microgrid system including several sub-microgrids. The sub-microgrids can exchange power with each other and improve the system resilience and cost. When the upstream grid is not connected, the sub-microgrids may pool their resources to compensate the mismatch between generation and load demand. Such capabilities are not modeled and discussed by [23], [24].

The loads are also given and it is seen that the microgrid "A" which is connected to the external grid supplies the heavy load and microgrid "D" feeds the light load [25]. Two microgrids benefit from solar energy and one microgrid uses wind energy [1].

The model uses seasonal pattern for periodic modelling of energy resources. Table 2 demonstrates the periodic model for solar, wind and load energies. The short-term operation of energy resources is modeled by 30-minute time-period as shown in Figure 4 [23].

The wind and solar energies are undertaken as uncertain parameters in the system. These uncertainties are modeled by

**TABLE 1.** Resources and loads of microgrids.

| Parameter | Level |
|---|---|
| Load "A" (kW) | 30 |
| Load "B" (kW) | 10 |
| Load "C" (kW) | 15 |
| Load "D" (kW) | 5 |
| Solar panel "B" (kW) | 10 |
| Solar panel "D" (kW) | 5 |
| Wind (kW) | 10 |
| Power of BES "A" (kW) | 10 |
| Capacity of BES "A" (kWh) | 30 |
| Power of BES "C" (kW) | 5 |
| Capacity of BES "C" (kWh) | 15 |

**TABLE 2.** Cyclical model for solar, wind and load energies.

| | Solar (%) | Load (%) | Wind (%) |
|---|---|---|---|
| Season 1 | 90 | 70 | 70 |
| Season 2 | 100 | 100 | 90 |
| Season 3 | 80 | 80 | 100 |
| Season 4 | 70 | 90 | 80 |

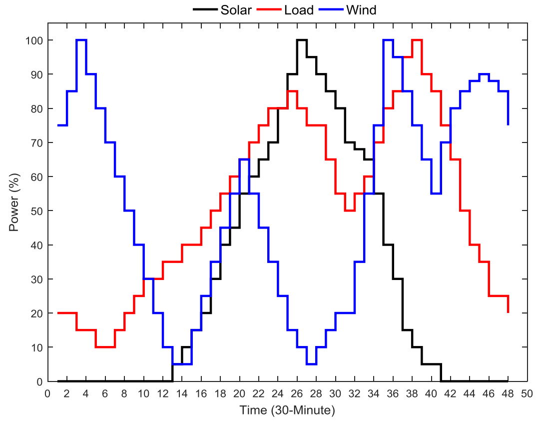

**FIGURE 4.** 30-minute time-period model of solar, wind and load powers.

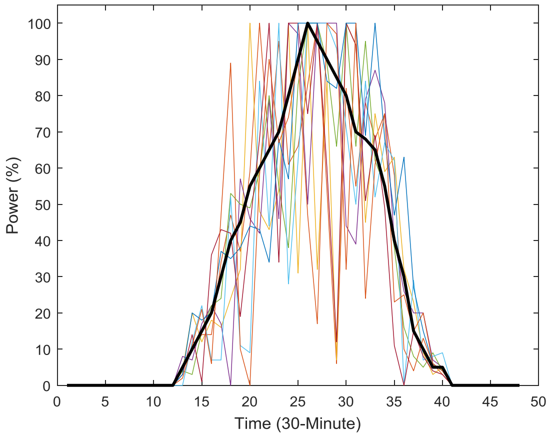

**FIGURE 5.** Solar power uncertainty and scenarios (black line: main scenario of performance).

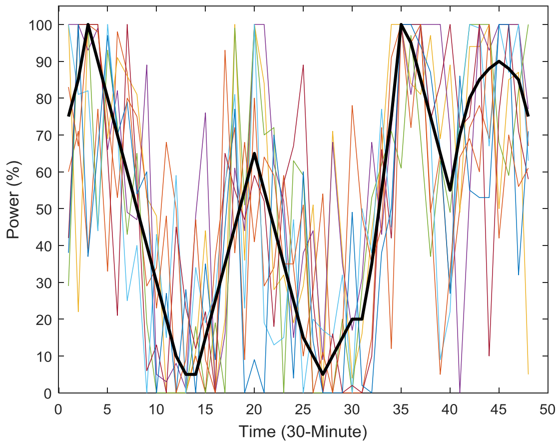

**FIGURE 6.** Wind power uncertainty and scenarios (black line: main scenario of performance).

scenarios of performance. The output power of solar system is modeled by a set of scenarios which cover the uncertainty area of solar energy. Figure 5 shows the solar energy scenarios where the black line specifies the main scenario of performance. It is seen that all possible solar energy volatilities are covered by the given scenarios. Figure 6 indicates the wind energy scenarios and the main scenario of performance is shown by black line [1]. The wind energy intermittency is modeled by a set of scenarios. The electricity price is also given in Figure 7 based on 30-minute time-period.

## V. SIMULATION RESULTS

The given multi-microgrid system is simulated in order to achieve the defined objectives. The results are categorized under normal and faulty operating conditions.

### A. NORMAL OPERATING CONDITION

In the normal operating condition, all microgrids are connected and share their resources to minimize the costs as shown in Table 3. The plan does not operate the diesel generators because they are only needed for faulty conditions.

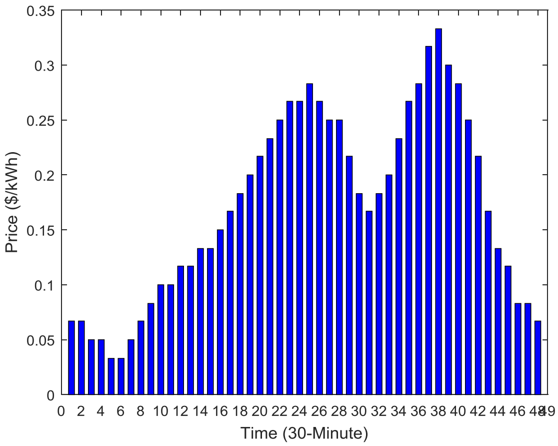

**FIGURE 7.** Electricity price based on 30-minute time-period model.

**TABLE 3.** Optimal level of variables under normal operating condition.

| Variables | Optimal level |
|---|---|
| Annual energy cost ($/year) | 60445 |
| Diesel Generator A (kW) | No operation |
| Diesel Generator B (kW) | No operation |
| Diesel Generator C (kW) | No operation |
| Diesel Generator D (kW) | No operation |
| **Load curtailment (kW)** | **Zero** |

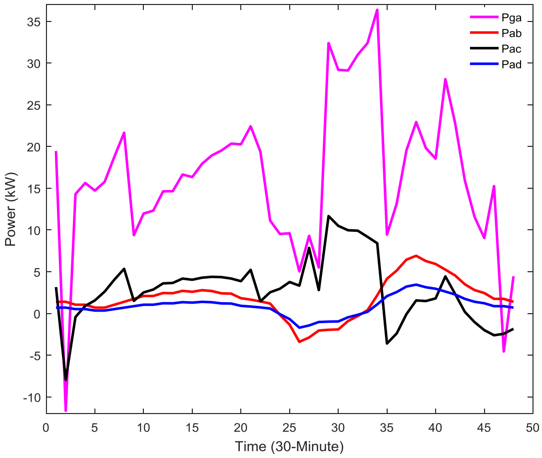

**FIGURE 8.** Exchanged power between grid and microgrid "A" and between microgirds "A-B", "A-C", "A-D" under main scenario.

In the normal operating condition, all subsystems pool their resources to fill the gap caused by mismatch between generation and load demand. The plan optimizes the operation of resources to minimize cost as 60445 ($/year). The developed model also confirms the zero-load curtailment as listed in Table 3.

Figure 8 shows the exchanged power between all subsystems. These exchanged powers are between external grid and microgrid "A", between microgrids "A-B", "A-C", and "A-D". The received power from the external grid is more than the exchanged power between the sub-microgrids. This point confirms that the sub-systems need to received power

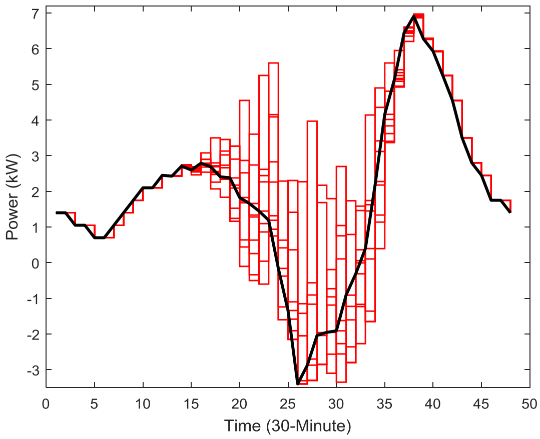

**FIGURE 9.** Exchanged power between microgirds "A-B" under all scenarios (black line: main scenario of performance).

from the external grid to supply their load demands when they do not utilize the diesel generators. The exchanged power between the sub-microgrids is negative at some time-periods that means reverse direction of power. The microgrid "B" is supplied by solar energy and during day-hours when solar energy is significant, the received power from microgrid "A" is reduced and it is negative at time-periods close to 25 which shows reverse direction of power from microgrid "B" to "A". The similar operation is seen by microgrid "D". The microgrid "C" uses wind energy and sends energy to microgrid "A" when wind energy increases at initial and last hours of the day.

The uncertainties related to wind and solar energy are properly handled by the tie-line connections. Figure 9 shows the exchanged power between microgirds "A-B" under all scenarios and the black line denotes the main scenario of performance. As it was stated, microgird "B" uses solar energy and its uncertainty is exchanged with the upstream grid through microgird "A". During day hours when solar energy rises, the extra amount of energy in microgird "B" is sent to microgird "A" where the power is negative in Figure 9. The solar energy scenarios (i.e., uncertainty) are also dealt through the tie-line connections to the upstream grid and the other sub-microgrids. The proposed model not only pools the extra energy of resources but also handles the uncertainty through multi-microgrid system and-line connections.

The batteries in microgrids "A" and "C" help the system to minimize the energy cost. These two energy storage systems have almost similar operation pattern as shown by Figure 10. They shift energy to reduce the energy cost. The energy is stored when it is inexpensive and then such energy is used when price of purchasing energy from the grid is high.

The power balance in system (all four subsystems) under on-peak load demand (time period 38) is shown in Figure 11. It is seen that the most part of load is supplied by the upstream grid and battery. The battery is operated on discharge state to produce energy. The wind and solar energy are not significant under on-peak time-period. As a result, the battery is necessary to shift energy from the off-peak time-periods to the required time-periods like on-peak time-interval.

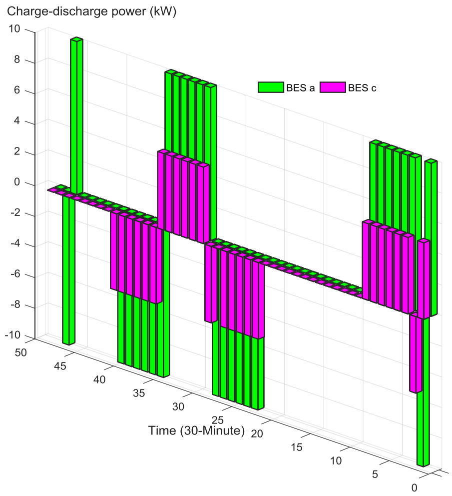

**FIGURE 10.** Operation of batteries in microgrids "A" and "C".

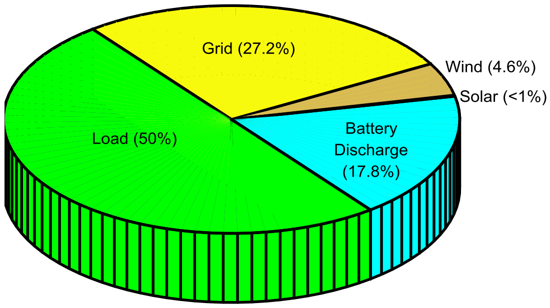

**FIGURE 11.** Power balance in the system under on-peak load demand.

**TABLE 4.** Outputs under disconnection of line between grid and microgrid "A".

| Variables | Optimal level |
|---|---|
| Annual energy cost ($/year) | 125501 |
| Diesel Generator A (kW) | Operation |
| Diesel Generator B (kW) | No operation |
| Diesel Generator C (kW) | No operation |
| Diesel Generator D (kW) | No operation |
| **Load curtailment (kW)** | **Zero** |

## *B. DISCONNECTION OF LINE BETWEEN GRID AND MICROGRIDS*

In this case, the tie-line between external grid and microgrid "A" is disconnected. The sub-microgrids are connected to each other and share their resources to handle this situation. The emergency diesel generators are also available to handle the event. The purpose is to minimize the operating cost with zero load curtailment.

Table 4 lists the outputs under island operation of system. The diesel generator "A" is operated to supply the load demand under event. The diesel operation increases the cost compared to the normal operating condition. The model completely supplies the load demand and load curtailment is zero.

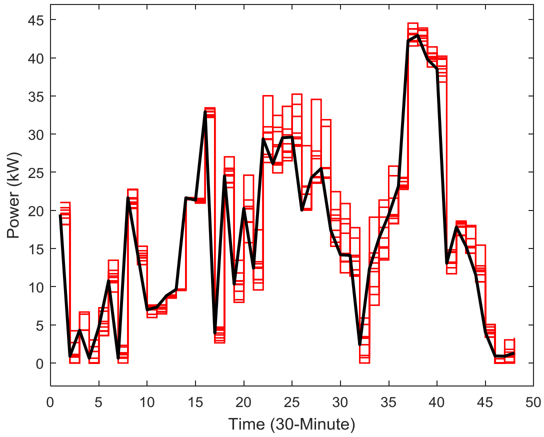

**FIGURE 12.** Produced power by diesel generator in microgird "A" under all scenarios (black line: main scenario of performance).

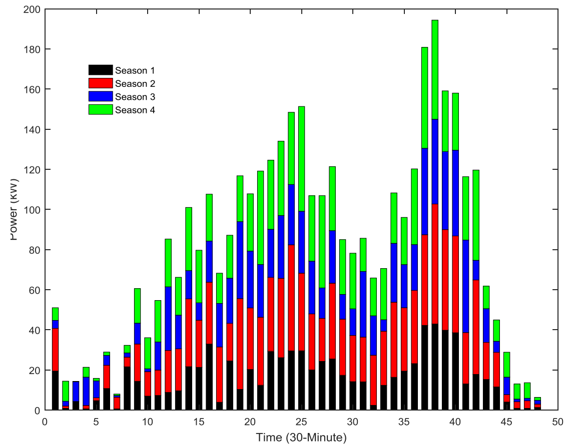

**FIGURE 13.** Produced power by diesel generator of microgird "A" on different seasons under main scenario.

The diesel generator in microgird "A" is operated to compensate shortage of energy and avoiding load curtailment. Figure 12 shows the produced power by this generator under all scenarios of performance. The operation under main scenario of performance is shown by solid black line. Under the other scenario of performance, the operation is different. The diesel generator copes with uncertainties by providing flexible operation pattern under each scenario of performance.

Figure 13 shows the diesel power on different seasons. The diesel follows almost a similar pattern under all seasons. In the summer (season 2) when the load demand increases, the diesel produces more energy to avoid load curtailment. The energy of batteries in microgrids "A" and "C" is shown in Figure 14. The battery in microgrid "A" stores energy at time periods 10 to 20 but the battery in microgrid "B" stores energy at time periods 25 to 35. These operation patterns show that the battery in microgrid "B" tries to store energy of solar unit but the other battery tries to store energy of wind energy. These energies are afterward restored to supply the load demand when the solar and wind energies are not available.

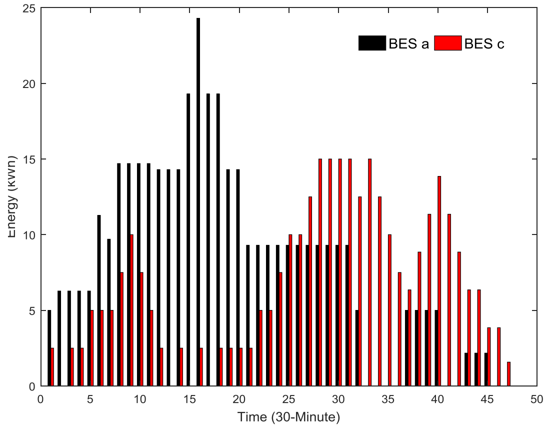

**FIGURE 14.** Energy of batteries in microgrids "A" and "C".

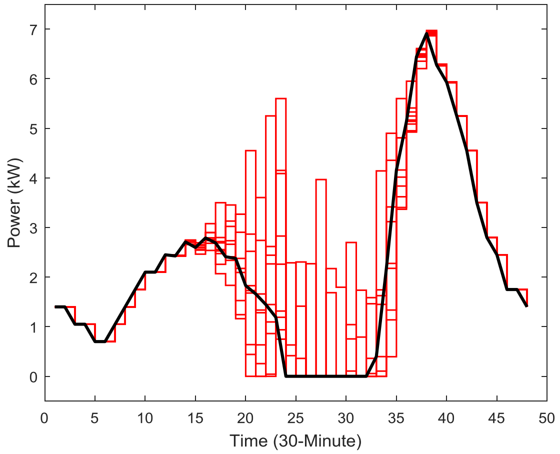

**FIGURE 15.** Produced power by diesel generator of microgird "B" under all scenarios (black line: main scenario of performance).

### *C. DISCONNECTION OF TIE-LINE BETWEEN MICROGRIDS*

When the tie-lines between sub-microgrids are disconnected, the sub-microgrids either continue their operation as island or the normally-open switches are closed to make a new connection between sub-systems. The economic option is to use the normally-open switches and making the new connection between sub-microgrids. However, if this option is not available because of consecutive faults in the system, the diesel generator is operated as a backup resource. Figure 15 depicts the produced power by diesel generator in microgird "B" when the tie-line between microgirds "A" and "B" is disconnected. In this case, the microgird "B" is standalone and supplied by diesel and solar resources. The diesel produces power when solar energy is not available. The diesel power is then set on zero when the solar energy rises.

The operation of diesel under main scenario of performance is shown by solid black line. The diesel has various operation patterns under other scenarios of performance. The diesel takes responsibility to deal with solar energy uncertainties.

The operation and power balance in microgrid "B" are evaluated in Table 5. The island operation of microgrid "B"

**TABLE 5.** Island operation of microgrid “B”.

| Time periods | Diesel (kW) | Solar (kW) | Load (kW) | Extra power (kW) |
|---|---|---|---|---|
| 1 | 1.4 | 0 | 1.4 | 0 |
| 2 | 1.4 | 0 | 1.4 | 0 |
| 3 | 1.05 | 0 | 1.05 | 0 |
| 4 | 1.05 | 0 | 1.05 | 0 |
| 5 | 0.7 | 0 | 0.7 | 0 |
| 6 | 0.7 | 0 | 0.7 | 0 |
| 7 | 1.05 | 0 | 1.05 | 0 |
| 8 | 1.4 | 0 | 1.4 | 0 |
| 9 | 1.75 | 0 | 1.75 | 0 |
| 10 | 2.1 | 0 | 2.1 | 0 |
| 11 | 2.1 | 0 | 2.1 | 0 |
| 12 | 2.45 | 0 | 2.45 | 0 |
| 13 | 2.427 | 0.022 | 2.45 | 0 |
| 14 | 2.71 | 0.09 | 2.8 | 0 |
| 15 | 2.597 | 0.203 | 2.8 | 0 |
| 16 | 2.79 | 0.36 | 3.15 | 0 |
| 17 | 2.69 | 0.81 | 3.5 | 0 |
| 18 | 2.41 | 1.44 | 3.85 | 0 |
| 19 | 2.377 | 1.823 | 4.2 | 0 |
| 20 | 1.827 | 2.723 | 4.55 | 0 |
| 21 | 1.66 | 3.24 | 4.9 | 0 |
| 22 | 1.447 | 3.802 | 5.25 | 0 |
| 23 | 1.19 | 4.41 | 5.6 | 0 |
| 24 | 0 | 5.76 | 5.6 | 0.16 |
| 25 | 0 | 7.29 | 5.95 | 1.34 |
| 26 | 0 | 9 | 5.6 | 3.4 |
| 27 | 0 | 8.123 | 5.25 | 2.873 |
| 28 | 0 | 7.29 | 5.25 | 2.04 |
| 29 | 0 | 6.503 | 4.55 | 1.953 |
| 30 | 0 | 5.76 | 3.85 | 1.91 |
| 31 | 0 | 4.41 | 3.5 | 0.91 |
| 32 | 0 | 4.162 | 3.85 | 0.312 |
| 33 | 0.397 | 3.802 | 4.2 | 0 |
| 34 | 2.177 | 2.723 | 4.9 | 0 |
| 35 | 4.16 | 1.44 | 5.6 | 0 |
| 36 | 5.14 | 0.81 | 5.95 | 0 |
| 37 | 6.447 | 0.203 | 6.65 | 0 |
| 38 | 6.91 | 0.09 | 7 | 0 |
| 39 | 6.277 | 0.022 | 6.3 | 0 |
| 40 | 5.927 | 0.022 | 5.95 | 0 |
| 41 | 5.25 | 0 | 5.25 | 0 |
| 42 | 4.55 | 0 | 4.55 | 0 |
| 43 | 3.5 | 0 | 3.5 | 0 |
| 44 | 2.8 | 0 | 2.8 | 0 |
| 45 | 2.45 | 0 | 2.45 | 0 |
| 46 | 1.75 | 0 | 1.75 | 0 |
| 47 | 1.75 | 0 | 1.75 | 0 |
| 48 | 1.4 | 0 | 1.4 | 0 |

forces the diesel to produce power when solar energy is not enough. On the other hand, at time intervals 24 to 32, the solar energy can supply the load and the diesel is switched off. At these time intervals, the solar energy exceeds the load demand and the surplus of solar energy is useless because the microgrid is not connected to the other sub-systems. The proposed model by this article successfully address this issue by using the switches between sub-microgirds. In the proposed method, the switch between microgirds “B” and “C” is connected the surplus of energy is transferred to the other sub-microgirds. As a result, the energy resilience is improved, the energy cost is reduced and the load curtailment is managed.

Tables 6 and 7 show the results under disconnection of tie-lines between sub-systems. Table 6 shows the results when the sub-systems continue their operation as island systems following event (line outage) but Table 7 lists the outputs when the substitute lines between sub-systems are connected for avoiding island operation. It is clear that all subsystems can operate under both island and connected modes. The system can use the substitute lines when the main lines are disconnected. The load curtailment is set on zero in all cases. The minimum cost is realized when all tie-lines are connected and all sub-microgrids can pool their resources. When the connection between microgrids “A-B” is opened, the diesel generator “B” is operated and increases the cost by 29%.

**TABLE 6.** Disconnection of lines and island operation of sub-systems.

| | Disconnected of Tie-Line (From-To) | | | |
|---|---|---|---|---|
| | **No Disconnection** | **From “A” to “B”** | **From “A” to “C”** | **From “A” to “D”** |
| Energy Cost ($/year) | 60445 | 78137 | 84351 | 69291 |
| Diesel A (kW) | OFF | OFF | OFF | OFF |
| Diesel B (kW) | OFF | ON | OFF | OFF |
| Diesel C (kW) | OFF | OFF | ON | OFF |
| Diesel D (kW) | OFF | OFF | OFF | ON |
| **Load curtailment (kW)** | **Zero** | **Zero** | **Zero** | **Zero** |

**TABLE 7.** Disconnection of lines and connection of substitute lines between sub-systems.

| | Disconnected of Tie-Line (From-To) | | | |
|---|---|---|---|---|
| | **No Disconnection** | **From “A” to “B”** | **From “A” to “C”** | **From “A” to “D”** |
| Connected substitute line | - | **From “B” to “C”** | **From “C” to “D”** | **From “C” to “D”** |
| Energy Cost ($/year) | 60445 | 60445 | 60445 | 60445 |
| Diesel A (kW) | OFF | OFF | OFF | OFF |
| Diesel B (kW) | OFF | OFF | OFF | OFF |
| Diesel C (kW) | OFF | OFF | OFF | OFF |
| Diesel D (kW) | OFF | OFF | OFF | OFF |
| **Load curtailment (kW)** | **Zero** | **Zero** | **Zero** | **Zero** |

## VI. CONCLUSION

This article uses the multi-microgrid system to pool the resources of separate sub-systems. The idea is based on system of systems (SOS) where the separate sub-systems pool their capacity and resources to create a more complex system with higher functionality. The purpose is to minimize the operating cost and improve the energy resilience with zero load curtailment. Under the normal operating condition, all sub-microgrids are networked and pool their resources to minimize the costs and the system does not utilize the diesel generators. The proper power is exchanged between all sub-microgrids as well as between total system and external grid. The uncertainties of wind and solar energy are properly exchanged and handled by bulk external grid. Under the disconnection of line between bulk external grid and microgrids, the sub-microgrids use the internal tie-line connection and share their resources to tackle this event. The emergency diesel generator in microgrid “A” is operated to avoid load curtailment. The diesel generator operation increases the operating cost but such cost increment is needed for zero load curtailment. Under the disconnection of tie-line between sub-microgrids, the sub-microgrids can either continue their operation as island or use the substitute lines to make new connections between sub-systems. The system can use both the options based on the economic or technical dictates. Under island operation, the operating cost is increased because the separated sub-systems have to use the diesel generators but the connection of substitute lines avoids extra costs.

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