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Optimal Power Flow Scheduling of Distributed Microgrid Systems Considering Backup Generators

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***Abstract*—Due to the great renewable integration capability of Microgrids (MG), reliability, resiliency and stability improvement, MGs play a crucial role in the next generation of electrical power networks. Besides, MGs provide significant potential economic and environmental benefits. However, the intermittent nature of renewable sources necessitates utilising energy storage devices, which would impose new challenges to the energy management of MGs. This paper proposes a centralised optimal power flow controller to minimise the operation cost of distributed microgrid systems while satisfying the technical constraints, considering the battery energy storage depreciation, transmission losses, and dispatchable units' characteristics. Due to the extensive computational time required to solve the nonlinear optimisation problem, the distributed microgrid system is formulated as a Mixed Integer Linear Problem. To investigate the performance and functionality of the proposed approach, it is applied to an actual case study at Griffith University, consisting of four MGs. The obtained results confirm the cost-effectiveness and applicability of the proposed model and control approach.**

Keywords—distributed microgrids, power flow optimisation, energy storage system, community microgrids, energy management system

I. INTRODUCTION

The conventional electricity generation approaches where the electricity is generated at certain locations and transported to long distances, potentially increase the probability of power outage as well as power losses in transmission lines. In contrast, integrating distributed generation where electricity production is decentralised reduces the losses and enhances the power quality as well as reliability. The Microgrid (MG) concept was introduced to overcome the aforementioned challenges and is widely used to form distributed generation networks [1].

An MG is basically a localised small scale power grid with control capability, composing of dispatchable generating units, renewable units, and loads. The ever-increasing penetration of renewables in energy systems, as well as the significant growth in demand, has posed new challenges to the control and operation of MGs. These challenges such as reliability, power quality, voltage variations, and frequency instability are primarily caused by the intermittent behaviour of renewable sources and appear when the MG is connected to the upstream grid [2-4]. In order to overcome these issues and efficiently utilise Renewable Energy Sources (RESs) to meet the dynamic load requirement, Battery Energy Storage Systems (BESSs) are employed in MGs. The availability of energy storage devices in MGs provides the capability of implementing load shifting and peak shaving functions, leading to economic and environmental benefits.

The control and management scheme of MGs is regarded as a multi-level control architecture. The objective of the primary control system is to stabilise the voltage and current at the operating point through controlling the power electronic devices. On the other hand, the secondary controller is to coordinate the power-sharing to provide reliable and economically beneficial operation of the MG. However, if the system is in grid-connected mode, the main purpose of the primary controller is to adjust the voltage and frequency deviations and synchronise the system. The tertiary control system known as Energy Management System (EMS) is to economically manage the operation of multiple MGs in conjunction with the host grid while satisfying technical operation criteria [5-7]. The focus of this paper is on the tertiary control system to achieve optimal operation of Multi Microgrid Systems (MMGS) in grid-connected mode.

There exist extensive studies in the literature about energy management systems for MGs. Authors in articles [8, 9] proposed a method to economically optimise the operation of an MG through solving a single objective unit commitment problem for BESS and distributed generators. In addition, the Matrix-Real Corded Genetic Algorithm (MRCGA) is employed to solve the optimisation problem and perform load management. Articles [10, 11] employed a rule-based control strategy to accommodate the volatile behaviour of renewables. However, this method does not provide a globally optimal solution. Paper [12] has focused on alleviating the stress and extending the lifetime of the BESS, which subsequently leads to efficiency enhancement of the system. Authors in this research used a rule-based control approach incorporated with Particle Swarm Nelder Mead (PSNM) optimisation to guarantee global optimal and efficient performance of the EMS. Furthermore, researchers in paper [13] inspect the MG cost minimisation and environmental impact reduction by implementing a Fuzzy-Logic Expert approach as the BESS scheduler and running the second stage optimiser. Considering operation cost and emission cost, a multi-objective linear optimisation problem is established to set the optimal set point of the MG components at each time instant. On the other hand, the primary objective of the developed EMS in paper [14, 15] is to improve the energy efficiency as well as to stretch the lifespan of BESS over the long term using the model predictive control strategy. To obtain the real-time optimal control signals of the developed Model Predictive Controller (MPC), the stochastic dynamic programming (SDP) approach is used. In addition, some previous studies investigated the optimal scheduling of MGs, taking the peak shaving, valley filling, and BESS operation costs into consideration as significant contributors to the MG operating cost [16-18]. Authors in [19] inspect the optimal power flow in the grid-tied MG including renewables and distributed generation units by establishing a trade-off between the economic benefit and the reliability of the system. Nevertheless, relatively less research has been carried out on the distributed optimal power-sharing in MGs. On the other hand, few other studies investigated the operation and scheduling of MGs in a distributed network considering economic, technical and environmental perspectives [6, 20-22]. Authors in [6] have conducted research on the optimal operation of multi-microgrid systems including energy storage to obtain the minimum cost while fulfilling the

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demand and technical criteria. Article [20] proposed a multi-objective optimal power flow optimisation algorithm with the aim of cost minimisation and BESS lifetime extension for an MG with distributed generation and BESS units. The objective functions are then combined and converted to a single objective with corresponding weights to determine the degree of importance of each objective. Paper [22] has addressed the operation constrains violation associated with optimal power scheduling in an MMGS by including the detailed model of the components and implementing the decentralised control concept. Furthermore, in [21] a three-stage multi-agent approach to schedule the power flow for an MG in islanding mode is introduced. The primary objective of this technique is to minimise the cost while increasing the security and reliability of the MG. However, the major drawbacks of these existing control methods are the local optimality of the solutions as in some cases such as the rule-based, MPC-based or stochastic based EMSs. Moreover, despite taking distribution topology into consideration in some of the studies in the literature, the developed approaches neglected the BESS losses, operation cost of the BESS, and the technical characteristic of the dispatchable generators.

To address the aforementioned shortcomings of the previous research and increase the penetration of renewables, this paper focuses on the EMS of a distributed microgrid system to maximise the economic profit, taking the BESS degradation, power losses and the technical operation criteria into account. The remainder of this paper is organised as follows: In Section II, the system architecture and the required EMS is described. Section III the mathematical model of the system and BESS dynamic model are developed. The simulation results and analysis of the proposed method are discussed in Section IV and finally, the conclusion is provided in Section V.

II. System Architecture

As illustrated in Fig. 1, the system understudy consists of four low voltage AC buses each one of which is connected to various generation units, BESSs, and electrical loads. In practice, the geographical location of the generation units connected to buses are different and that leads to transmission losses. The MG can be operated in either islanding or grid-tied mode. The AC bus voltage within the MG is 400 V that are interconnected based on the adopted topology. In this configuration, Bus one is only linked to the upstream grid through an 11/0.4 kV -500 kVA transformer.

The MGs that is planned to be implemented at building N34 (MG1) and N44 (MG2) consist of PV, BESS, load, and diesel generator with a backup function. The diesel generator is dispatched in the case of power deficiency in islanding mode or over during high peak demand period. On the other hand, buildings N74 (MG3) and N79 (MG4) which are connected to bus 3 and bus 4, are comprised of RES, BESS, and load. Due to the intermittency of RESs and demand, the surplus energy is stored and either shared to meet the load requirement or sold back to the grid.

III. Problem formulation

A. System Modelling

The power flow is bidirectional between the buses in the understudy distribution system and hence two variables for each bus bar are considered the injected and absorbed power of the corresponding bus.

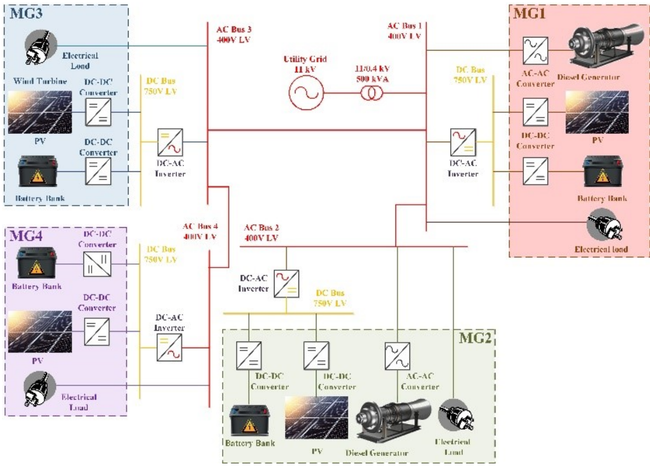

Figure 1.The architecture of a 4 bus microgrid

$$0 \le P_{i\to j}^{Imp}(t) \le \beta_{i\to j}(t).\ P_{i\to j}^{max}$$
$$\beta_{i\to j}(t) \in \{0,1\} \tag{1}$$
$$i,j \in \{1{:}4\}$$

$$0 \le P_{i\to j}^{Exp}(t) \le \left(1-\beta_{i\to j}(t)\right).P_{i\to j}^{max} \tag{2}$$

where $P_{i\to j}^{Imp}$, $\beta_{i\to j}(t)$, $P_{i\to j}^{Exp}(t)$, and $P_{i\to j}^{max}$ imply the power flowing into bus j from bus i, the binary variable corresponding to the power flow orientation, the power flowing from node i to node j, and the transmission line capacity, respectively. when a particular bus is in importing power mode, its corresponding binary variable is equal to one and zero if it is exporting power. So, defining the exchanged power of node i as in Eq. 3, the power flow vector for time instants t, $P_{exch}(t)$, is formed as follows:

$$P_i^{exch}(t) = P_i^{Imp}(t) - P_i^{Exp}(t) \tag{3}$$

$$P_{exch}(t) = [P_1^{exch}(t) \quad P_2^{exch}(t) \quad P_3^{exch}(t) \quad P_4^{exch}(t)] \tag{4}$$

The architecture of the distributed microgrid as depicted in Fig. 1 can be represented as a system configuration matrix. In this matrix, the power losses are taken into account as a transmission coefficient ε, and the linkage between buses are defined as either -1, 0, or 1 for the exported power, no connection, and imported power, respectively. Although the transmission electricity losses are a function of the power flowing through the line, the length and material characteristics of the power line, in this paper, the static power losses are only considered.

$$M_{Config} = \begin{bmatrix} (1-\varepsilon_i) & -(1-\varepsilon_i) & -(1-\varepsilon_i) & 0 \\ 0 & (1-\varepsilon_i) & 0 & 0 \\ 0 & 0 & (1-\varepsilon_i) & -(1-\varepsilon_i) \\ 0 & 0 & 0 & (1-\varepsilon_i) \end{bmatrix} \tag{5}$$

To maintain the power balance between generation and consumption at individual nodes and the system as a whole during operation, the following set of equations should be included in the model.

$$P_{dis}(i,t) - P_{ch}(i,t) + \sum_K P_{DG}^k(i,t) - P_L(i,t)$$
$$+ M_{Config}(i,t).P_{exch}(t) + \sum_R P_{RES(i,t)}^r = 0 \tag{6}$$

where $P_{dis}(i,t)$, $P_{ch}(i,t)$,and $P_L(i,t)$ respectively represent the BESS discharging power, BESS charging power and load requirement. According to these equations, the power deficiency at any node is compensated through power sharing. Furthermore, $P^r_{RES(i,t)}$ and $P^k_{DG}(i,t)$ indicate the power generated by r^{th} RES and output power of k^{th} DG at node i and time step t.

B. DG Model

The operation model of a DG is typically achieved by considering the output power constraints and power ramp limitations. The output power of each DG unit ($P^k_{DG}(i,t)$) is formulated in Eq. 7 to Eq. 10. As expressed in Eq. 10, the binary variable associated with power range limitations of the DG ($\beta^k_{DG}(i,t)$) indicates its operation status at each time instant.

$$P^k_{DG}(i,t) - P^{k,max}_{DG}(i,t).\beta^k_{DG}(i,t) \leq 0 \tag{7}$$

$$P^{k,min}_{DG}(i,t).\beta^k_{DG}(i,t) - P^k_{DG}(i,t) \leq 0 \tag{8}$$

$$\beta^k_{DG}(i,t) - P^k_{DG}(i,t) \leq 0 \tag{9}$$

$$\beta^k_{DG}(i,t) = \begin{cases} 0 & \text{DG is off} \\ 1 & \text{DG is running} \end{cases} \tag{10}$$

The dynamic thermal properties and mechanical limitations of DG units do not allow instantaneous changes in power generation, causing latency in the power production of the DG. To take this operational criterion into account, the following equations are included in the constraints of the model.

$$P^k_{DG}(i,t) \leq P^k_{DG}(i,t-1) + \theta^{k,up}_{DG}(i) \tag{11}$$

$$P^k_{DG}(i,t) \geq P^k_{DG}(i,t-1) + \theta^{k,down}_{DG}(i) \tag{12}$$

where $\theta^{k,up}_{DG}(i)$ and $\theta^{k,down}_{DG}(i)$ respectively denote the ramp-up and ramp-down limits of unit k on bus i. Apart from the technical constraints, the related operating costs of running DGs should be identified. The most significant cost factors of DGs are fuel and state transition costs. The fuel cost C_f is typically defined as a second-order function of produced power of the DG as in 13.

$$C_f(t,i) = \alpha_1.P^2_{DG}(i,t) + \alpha_2.P^2_{DG}(i,t) + \alpha_3 \tag{13}$$

where α coefficients vary depending on the type of the DG. To identify the state transition of a particular unit, the introduced binary variable of the corresponding unit is used as shown below.

$$C_{st}(i,t) = \sum_K (\emptyset^s_{k,i}.(1-\beta^k_{DG}(i,t-1)).\beta^k_{DG}(i,t) + \phi^d_{k,i}.(1-\beta^k_{DG}(i,t)).\beta^k_{DG}(i,t-1) \tag{14}$$

where $C_{ss}(i,t)$, ϕ^s_k, and ϕ^d_k denote the state transition cost, the start up and shutdown costs of unit k on bus i , respectively.

The power losses due to the employed semiconductor-based power devices and transformers are important and should be included in the model. Although these losses can be described as a dynamic function of the operating point of the device, they have a negligible impact as compared to the transmission line and other losses. Therefore, constant efficiency (η^k_i) is considered for power-electronics based devices to account for their losses.

$$P^k_{out}(i,t) = P^k_{in}(i,t).\eta^k_i \tag{15}$$

where the $P^k_{out}(i,t)$ and $P^k_{in}(i,t)$ are the output and input power of device k on i^{th} bus at time t, respectively.

The efficiency of a DG varies according to its output power. This nonlinear variation of efficiency is linearised using a stepwise function as described in [23]. Although a higher resolution of linearisation can be attained by introducing more segments, the number of required variables is accordingly increased, resulting in higher complexity and computational efficiency [24]. Assume the nonlinear function $\eta_i(P^i_{DG})$ denotes the efficiency function of the particular unit i where the dependent variable is the produced output power. The linearised efficiency function can be approximated using Eq. 16 and Eq. 17.

$$L\left(\eta_i(P^i_{DG})\right) = \sum_M \eta^i_m.U(P^i_{DG} - P^{i,m}_{DG}) \tag{16}$$

$$U(P^i_{DG} - P^{i,m}_{DG}) = \begin{cases} 1 & P^{m-1}_{DG} \leq P^i_{DG} \leq P^m_{DG} \\ 0 & otherwise \end{cases} \tag{17}$$

where η^i_m, $U(P^i_{DG} - P^{i,m}_{DG})$, and M represent the efficiency of the which DG located at bus i at m^{th} break point, the step function shifted by $P^{i,m}_{DG}$, and the total number of intervals.

C. BESS Dynamic Model

The BESSs are regarded as an indispensable component of distributed microgrids. The primary function of BESS is to store the excess energy at the time of peak generation of RESs and share this power with other buses to maintain the generation-demand balance on each node to enhance RES penetration and reduce the generation cost. The State of Charge (SOC) of BESS changes and can be described by a dynamic equation. The Eq. 18 shows the SOC level of the BESS connected to the node i at the time t ($SOC(i,t)$).

$$SOC(i,t) = SOC(i,t-\Delta T).(1-\delta(i)) + (P_{ch}(i,t-\Delta T).\eta_{ch}(i) - \frac{P_{dis}(i,t-\Delta T)}{\eta_{dis}(i)}).\Delta T \tag{18}$$

where $\delta(i)$, ΔT, $\eta_{ch}(i)$, and $\eta_{dis}(i)$ imply the energy loss rate, time step, charging and discharging efficiencies of the BESS, receptively.

The SOC of the BESS is maintained within a certain range according to the type, capacity, and application of the BESS as stated in Eq. 19. The charging and discharging power of each storage device cannot exceed the maximum charging and discharging rates. A binary variable, $\beta_{BESS}(i,t)$, is specified to prevent the simultaneous charging and discharging events as expressed in Eq. 20 and Eq. 21.

$$SOC^{min}(i) \leq SOC(i,t) \leq SOC^{max}(i) \tag{19}$$

$$\beta_{BESS}(i,t) \in \{0,1\}$$

$$0 \leq P_{ch}(i,t) \leq \beta_{BESS}(i,t).P^{max}_{ch}(i) \tag{20}$$

$$0 \leq P_{dis}(i,t) \leq (1-\beta_{BESS}(i,t)).P^{max}_{dis}(i) \tag{21}$$

In addition to the operation model, the cost associated with BESS degradation should be taken into consideration. The degradation cost is referred to as BESS operation cost and is a function of the depth of discharge (DOD) at each time instant. The DOD is defined as the ratio of the stored energy to the full capacity of the BESS after the occurrence of each charging or discharging event [25].

$$C_b(DOD) = \frac{CC_{BESS(i)}}{2.\eta_{ch}(i).\eta_{dis}(i).E_B.a.DOD^{1-b}.e^{-c.DOD}} \quad (22)$$

Applying a similar approach as that used for linear approximation of DGs' efficiency curves, a piecewise linear function with multiple criteria is replaced with the above nonlinear operation cost.

D. Optimal Power Flow Management

The primary objective of the formed optimisation problem is to obtain the operation schedule of the microgrid within a certain period of T where the operation cost is minimised, the technical constraints and meeting the load demand are satisfied. To achieve this, the operation cost components have to be identified.

The economic objective of the understudy system is composed of grid energy exchange cost, DG operation cost, and BESS degradation cost as demonstrated in Eq. 23. The energy exchange cost is calculated according to the TOU tariff and the dynamic operation cost of the BESS that corresponds to the DOD value of the battery after each time step.

$$J = \sum_{T}\left(P^G_{imp}(t).C^G_p(t) - P^G_{exp}(t).C^G_s(t)\right).\Delta t + \sum_{I}\sum_{K} P^k_{DG}(i,t).C^k_f(i,t) + \sum_{I}\left(P_{dis}(i,t) - P_{ch}(i,t)\right).C_b(t) \quad (23)$$

where I, $C^G_p(t)$, $C^G_s(t)$, and $C_b(t)$ denote the total number of buses of the distribution microgrid system, the cost of energy purchased from the grid, the profit obtained from selling electricity to the grid, and dynamic battery operation cost at the time instant t, respectively. In this paper, the developed Mixed Integer Linear Programming problem is solved employing CPLEX solver in MATLAB platform.

IV. Case Study and Simulation Results

In this section, the specifications of the understudy system are initially explained and then the performance of the proposed power flow scheduling system is evaluated in two scenarios.

The system under study consists of four buses as illustrated in Fig. 1 and four BESSs, as well as solar PV arrays, are connected to the corresponding buses. Furthermore, two diesel generators with backup function and capacity of 250 kVA are attached to bus 1 and bus 2. The parameters of the understudy system are tabulated in Table I.

The hourly output power of the PV units for a typical day in summer are collected from the data acquisition installed at Griffith University as shown in Fig. 2. Due to the different location of the MGs, the generation profiles of the PVs are different. The total PV generation during this particular day peaks at about 217 kW.

TABLE I. PARAMETERS OF THE DISTRIBUTED MICROGIRD

Description	Microgrid #	Value	Unit
Charge/discharge efficiency	-	95	%
Min depth of discharge	-	10	%
Energy storage power rating	MG1-MG2-MG3-MG4	20-20 30-20	kW
Energy Cost (Peak period)	-	10.68	¢/kWh
Energy Cost (off-Peak period)	-	5.8	¢/kWh
Diesel Generator Capacity	MG1-MG2	250	kVA
BESS Capacity	MG1-MG2-MG3-MG4	100-90 120-70	kWh
Solar PV Capacity	MG1-MG2 MG3-MG4	110-50 50-40	kW

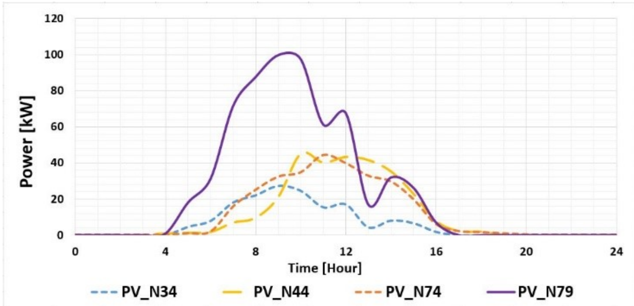

Figure 2. Solar PV arrays Generation

The electrical load profiles of the buildings vary according to their application as shown in Fig. 3. For instance, there are several laboratories equipped with measurement devices in the Science building (MG1) as well as Micro and Nanotechnology Research Centre (MG3). As the sensitive and highly accurate devices in these facilities, which require a certain operating condition, are continuously running, the fluctuations in demand are small as compared with the other two the load profiles. The total net demand in the understudy distributed microgrid system reaches to a maximum of 463 kW.

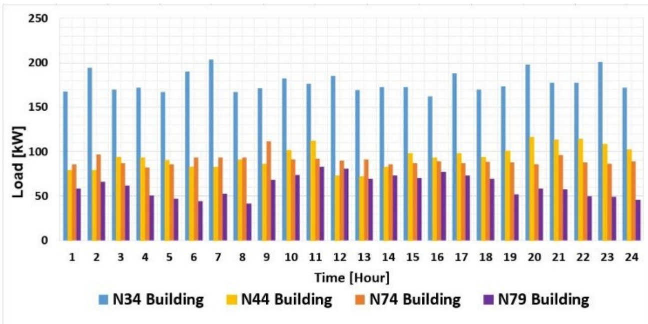

Figure 3. The dynamic loads of the facilities of the understudy case

In this paper, two case scenarios are provided to validate the proposed model and control strategy including the Normal operation and Backup operation modes.

A. Scenario A: Normal Operation

In this scenario, the control algorithm is performed on the system when the upstream grid is connected to the MG network. The generated surplus power is stored in the BESS at each line during the off-peak period and injected back to the network either during the peak-period when providing energy from the grid is not profitable or when there is a power deficit. The proposed method initially attempts to store the energy in the BEES available on the same bus, however, if the BESS is full and the load is satisfied, the excess generated power is transmitted to the node with power shortage. The energy variations in the BESSs of the system are shown in Fig. 4. In the developed model, the initial energy of the batteries should be equal to the stored energy at the end of the operation horizon. Performing the proposed control algorithm, the operating cost of the distributed system is obtained equal to $670.25.

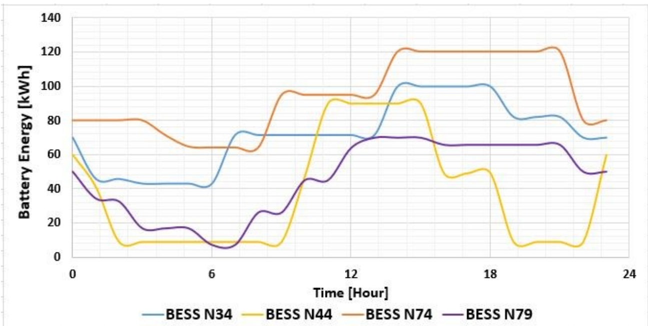

Figure 4. The energy variations of BESSs installed on the different buses

Since in this study, the power losses of the transmission lines are considered, the power flows from the node with surplus power into the node with the power deficit that results in the minimum losses. As shown in Fig. 4 due to insufficient generated power and high demand, the batteries are discharged to supply the load and reduce the power purchased from the main grid. The batteries are charged during the peak PV generation period, and once again are discharged during the peak period to decrease the operating cost.

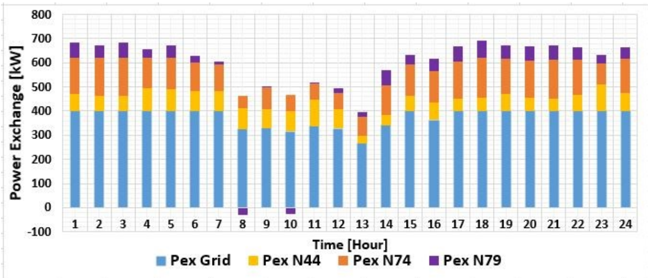

Figure 5. The power flow between different buses and the grid power

The imported and exported power of the buses at each time step is determined by different factors, including the power requirement of the buses, the RES energy production, the TOU tariff, the BESS operation cost, and the fuel cost of the backup generator. The adjacent nodes that would cause fewer power losses have a higher priority with respect to the nodes that are physically farther away. As is illustrated in Fig. 5, the imported power from the grid is approximately constant from 12 AM to 7 AM. The primary source of power to supply the load within this period is the main grid and the stored energy in the BESSs as there is a small generation. The imported power from the grid is shared among the buses depending on their distance from bus 1 (MG1). However, the excess generated power on bus 4 (MG4) is exported to other buses to mitigate the grid cost during the course of peak PV generation. In this study, the maximum RES generation is as half as the total demand and hence, the power exchange between the buses does not occur unless the energy production is higher than the demand on that bus.

B. Scenario B: Backup Operation

In this scenario, we assumed that power outage is scheduled to happen within a certain period which in this case is from 10 AM to 4 PM. However, the PV generation profile is assumed to be the same as the one considered in the normal operation.

In case of a power outage, the diesel generators serving as the backup generators are activated to compensate the power deficiency. As demonstrated in Fig. 6 during the outage period, the imported power from the grid is dropped to zero and the power generated by the backup diesel generators connected to bus 1 (MG1) and 2 (MG2) is injected to the system as shown in Fig. 7. The surplus generated PV power of the bus 4 (MG4) is exported to bus 3 (MG3).

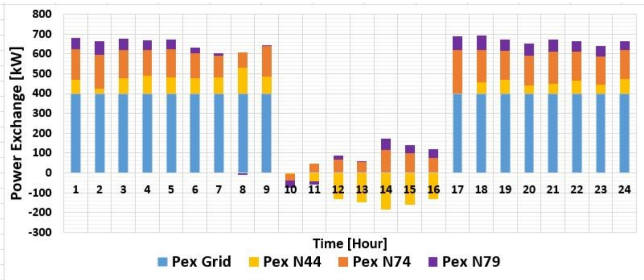

Figure 6. The power flow between different buses

The power generation pattern of the backup generators is a function of the demand on the buses. As technical specifications of the utilised DGs in this case study are the same, their operating cost is identical. Therefore, the transmission losses and power deficit would be the determinative factor in determining their power contribution to maintain the power balance in the system. The maximum power of the backup DGs located at MG1 and MG2 are optimally achieved to be equal to 150 kW and 80 kW, respectively.

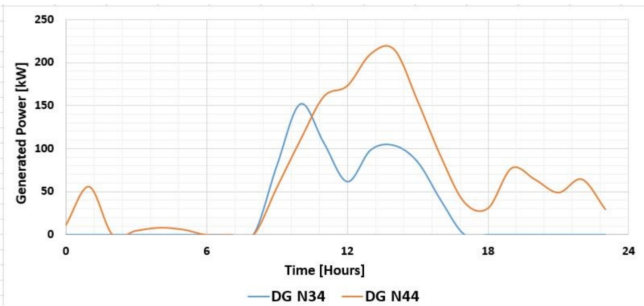

Figure 7. The optimal scheduled power of the backup generators

To further investigate the performance of the system, the obtained values at 2 PM are considered. At this point of time, the PV arrays installed at MG2 supplies about 35 kW of the corresponding demand of MG2 which is just under 86 kW. The stored energy in the BESS at MG2 and a portion of the generated power by the DG on bus 2 is utilised to meet the rest of the demand.

V. Conclusion

The integration of MGs, comprising BESS and RESs and backup generators provides an economically viable solution to reduce the cost and enhance the power stability and reliability is investigated. The optimal scheduling of the BESS and DGs in the distributed MG considering economic perspective is obtained utilising the proposed approach. In addition, the dynamic operation cost of the BESS and the variable efficiency of the DGs are approximated by a linear model. The DGs are activated when the demand exceeds the maximum capacity of the grid or the available energy in the BESSs are insufficient to meet the load requirement. The achieved results proved the effectiveness and practicality of the proposed power flow coordination algorithm to lessen the cost.

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