Application of Robust Receding Horizon controller for Real-Time Energy Management of Reconfigurable Islanded Microgrids

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***Abstract*— The development of smart grid infrastructure has opened new opportunities for microgrids to operate proactively and supply their incorporated loads with local generation. This capability could be improved more efficiently through utilisation of available distributed energy resources (DERs) and modernisation of the grid characteristics. In this study, a robust rolling horizon architecture is developed for real-time energy management of islanded micogrids (IMGs), while the adaptation of network configuration is considered as a potential option for improving the system characteristics. In addition to dispatchable and non-dispatchable units, the application of plug-in electric vehicles in the grid is analysed taking into account the driving pattern of such mobile storage units. The proposed problem is modelled as mixed integer conic programming and tested on IEEE 33-bus test system using general algebraic modelling system (GAMS) software. The simulation results show the effectiveness of the proposed model in dealing with real-time energy management with lower computation time, while the significance of network reconfiguration and electric vehicles in improving the characteristics of IMGs is obvious in the outputs.**

***Index Terms*—Islanded micogrids (IMGs), network reconfiguration, real-time energy management, electric vehicles (EVs).**

NOMENCLATURE

Indices

i, j	Index of system buses
t	Index of timeslots in the operation horizon
v	Index of PEVs

Sets

Ω_b	Set of system buses
Ω_b^j	Set of buses that are not connected to the upstream network
Ω_b^s	Set of buses connected to the upstream network
$\Omega_{d/w/e}$	Set of buses to which diesel unit/WF/PEV parking lot are connected.
Ω_t	Set of time

Parameters

$(G/B)_{ij}$	Series conductance/susceptance of the line between buses i and j [pu]
$(G/B)_{ij}^{Sh}$	Shunt conductance/susceptance of the line between buses i and j [pu]
$(P/Q)_{i,\max/min}^{DU}$	Maximum/minimum active/reactive power capacity of diesel units [kW]
$\Delta D_{v,t}^{EV}$	Forecasted travel distance of PEVs [kM]
Δt	Duration of time periods [hour]
$\eta_v^{Ch/DCh}$	Charge/discharge efficiency of PEV battery [%]
η_v^{Dr}	Driving efficiency of PEV [kW/kM]
λ_t^m	Market electricity price [$/kWh]
λ_t^r	Contract price of buying electricity from WFs [$/kWh]
$\psi_{i,t}^{WF}$	Available wind power at each time interval
A_ℓ^{Max}	Branch ampacity [pu]
$E_{\max/min}^{EV}$	Maximum/minimum state of energy of PEV [kWh]
$P_{i,v,t}^{EV_{Dr}}$	Power consumed by driving of PEV [kW]
P_R^{WF}	Rated power of WFs [kW]
$R_i^{U/D}$	Ramp up/down limits of diesel units [kW]
$V_i^{\max/min}$	Maximum/minimum voltage magnitude [pu]

Variables

$(P/Q)_{i,t}^D$	Active/reactive load demand [kW/kVAr]
$(P/Q)_{i,t}^{(DU/WF)}$	Active/reactive power output of diesel units/WFs [kW/kVAr]
$(P/Q)_{ij,t}$	Active/reactive power flow between buses i and j [kW/kVAr]
$(R/T)_{ij,t}$	Variables associated with the line between buses i and j in MICP model [pu]
$\alpha_{ji,t}$	Binary variable specifying the parent bus [=1 if bus i is the parent of bus j, =0 otherwise]
$\gamma_{i,t}^{EV_{Ch}}$	Binary variables indicating the charge/discharge status of PEV battery [0,1]
$\vartheta_{ij,t}$	Binary variable representing the status of line between buses i and j [0-1]
$E_{i,t}^{EV}$	State of energy of PEV [kWh]
$P_{i,t,v}^{EV_{Ch/DCh}}$	Charge discharge power of PEV v [kW]
$U_{i,t}$	Variable associated with voltage magnitude of bus i [pu]
$U_{ij,t}$	Variable associated with the line between buses i and j in MICP model [pu]

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I. INTRODUCTION

INCREASING the utilisation of various new technologies, like plug-in electric vehicles (PEVs) and distributed generations (DGs), in the electric power system, has accelerated the process of shifting towards smart grids frameworks. Generally, distributed energy resources (DERs) can improve the techno-economic performance of the network, decrease power losses and operation cost, especially for the microgrids (MGs) that have to operate autonomously due to the operational and security reasons [1]. Accordingly, a suitable energy management strategy (EMS) is essential for MGs considering the several challenges they pose in the design and operation of the network [2]. The volatility of renewable energy based DGs, however, is a challenging problem and requires real-time control approaches so as to deal with uncertainty of output power in such units.

In addition to the DER capabilities, system operators can boost the system's characteristics (like higher efficiency or reduced operating cost) by network reconfiguration [3]. Network reconfiguration is defined as the process of changing the status of normally opened/closed switches of the grid to reach a configuration that achieves desired goal(s) while satisfying all operational constraints without isolating any network node(s) [4].

Network reconfiguration and optimal energy scheduling of DERs have previously been studied, both separately and simultaneously. The results obtained from [5] shows that 10% of photovoltaic generation capacity of MG could be exported to the main grid, with a significant reduction in carbon emission in the MG. The environmental aspects of islanded MGs (IMGs) have also been investigated in [6] with a chance constrained optimisation taking into account the various DERs such as energy storage systems, and wind farms (WFs). Increasing the penetration of DERs in the IMGs requires suitable control and optimisation methods to achieve the system operator's goals while satisfying the reliability and stability constraints [7]. In [8] the necessity of control algorithms for PEVs is analysed, with a focus on improving the system resilience. PEVs can even have positive impacts on the operational [9], and security [1] measures of the MGs. The role of PEVs in multi-vector MGs has been investigated in [10], indicating the effect of uncertainties in energy scheduling of such systems.

Despite their significance in improving the technical, economic, and environmental characteristics of the system, the volatility of the output power of renewable energy based DERs can pose challenging issues to the IMGs, especially those which supply the majority of their demand through these units. Accordingly, it is necessary to take into account the fluctuation of DER's power in energy management strategies by employing uncertainty modelling techniques. In [11], a robust architecture based on the notion of information gap decision theory (IGDT) is developed for uncertainty handling in an IMG taking into account static frequency constraints. Another approach in reducing the effect of uncertainty is utilising the real-time approaches which work mainly based on the concept of model predictive controller (MPC). Nair *et al.* [12] benefited from a real-time EMS for improving the renewable energy utilisation and reducing the operational cost. More effectively, the utilisation of real-time EMS brought about 8.5% decrease in an IMG's generated power cost in [13].

Network reconfiguration is another efficient approach for improving the performance of IMGs. The impact of network reconfiguration on small-signal stability is analysed in [14], demonstrating an effect on the active power drop coefficient through changing the line impedance between generation sources. This unique capability of network is regarded as a decisive factor in definition of probability of islanding operation [15]. Optimal changing of the configuration can even have a positive effect on optimal use of DERs in the system [16].

Although various EMS have been proposed for IMGs, taking into account different technologies, to the best of authors' knowledge, there are several important issues that have not been considered properly. Firstly, since digital control methods will be employed, the uncertainty between two successive samples can cause various problems onto the system's operation. Although real-time methods have been utilised for tracking input data, conventional methods decrease the duration of each time interval, which increase the computation time while the input data are more likely to change between timeslots. Secondly, the majority of previous works have utilised non-convex optimisation approaches. However, these methods fail to obtain a global optimal solution and demand high computation time. Finally, the papers that have considered PEV in IMGs have not taken into account PEV's driving patterns. This is a simplistic modelling of PEV behaviour since the power that is consumed in driving mode of these units is an important factor in definition of their state of charge. Accordingly, this study tries to cover the aforementioned drawbacks by proposing a robust receding horizon (RRH) approach for real-time energy management of IMGs. The proposed model introduces a mixed integer conic programming (MICP) for reconfiguration of IMGs, while optimally scheduling various dispatchable and non- dispatchable units as well as PEVs, aiming at minimising the operational cost of the system. The proposed real-time technique deals with possible errors in WFs output data, with lower computation time and a lower operational cost. The main research questions are: *"How the performance of real-time EMSs in the IMGs could be improved, and how the implementation of network reconfiguration and utilisation of PEVs can improve the techno-economic performance of such grids?"* Generally, the main contributions of this paper are:

- Developing a comprehensive MICP model for reconfiguration of IMGs.
- Introducing an RRH algorithm for increasing the robustness of real-time EMS methods.
- Investigating the influence of PEVs on the energy scheduling of IMGs, taking into account the driving pattern of PEVs.

The remainder of this paper is organised as follows. Section II describes the proposed RRH method. Section III provides the model formulation. Simulation results are given in Section IV. Finally, Section V concludes the paper.

II. Robust Rolling Horizon Controller

Thanks to its efficiency in handling process control problems, MPC has been used for real-time EMS of MGs [17]. The MPC approach, gets the input data for current time interval and optimises the problem based on the objective function, taking into account the data for the following timeslots. The result obtained for the current timeslot is implemented and the optimisation is shifted forward. Based on this shifting mechanism, this approach is also called receding horizon (RH) controller. The conventional RH methods usually increase the resolution (i.e. receiving the input every 30 minutes instead of 60 minutes). Although this approach is efficient in handling more accurate real-time EMS, it increases the computation time dramatically and requires high computational capacity. Note that in a real-time energy scheduling, the optimisation problem should be solved in the current time interval, before getting the new input data. Regardless of decreasing the resolution, the possible error between time intervals cannot be neglected. Accordingly, this study introduces a robust methodology based on the notion of IGDT technique so as to increase the robustness of RH (knowing as RRH hereafter) controller in each consecutive timeslot. The detailed explanation of IGDT method is given in [18]. An illustration example is given in Fig. 1 so as to compare the conventional (i.e Fig. 1-a) and proposed (i.e Fig. 1-b) RRH controller. As it has been shown in this figure, regardless of increasing or decreasing

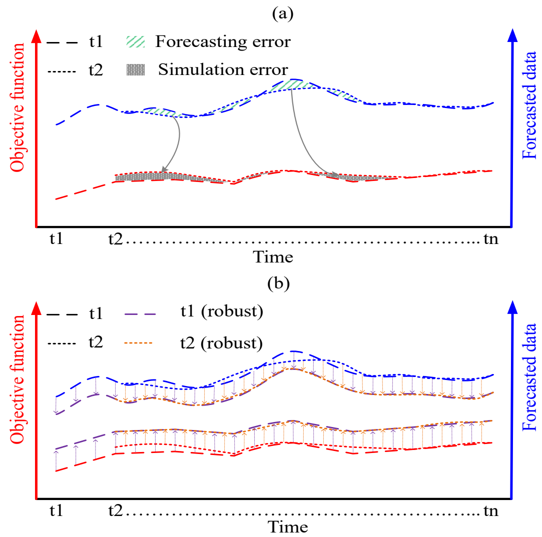

Fig. 1: Conventional RH (a) and proposed RRH (b) controller scheme.

the resolution, the conventional techniques can not guarantee robust results, considering the probability of changing the data between time intervals which can result in simulation error or inaccurate results. On the other hand, in Fig. 1-b, the proposed RRH methodology shifts the degree of fluctuation in possible errors to a specific level that could be defined by the decision maker, knowing as robustness degree. This approach boosts the robustness of real-time EMS, with lower computation requirement.

Applying the proposed RRH changes the problem to a bi-level optimisation. In this regards, for each timeslot, the model is first solved in real-time and the robustness of outputs is increased via a risk averse approach before implementing the results for the current time period.

III. Problem Formulation

This section introduces the proposed MICP optimisation problem for IMG reconfiguration in the presence of DERs and PEVs. The model is solved for a real-time EMS, aiming at minimising the operational cost. The objective function, technical, and physical constraints of the system are given in the following.

A. Objective function

As an MG scheduling problem, the objective function of the model is operational cost minimisation, including the cost of buying power from different sources including diesel units, and WFs, while PEVs pay for charging and gain from discharging to the grid. The operational cost of IMG is described as:

$$\min\ Of = \sum_{t\in\Omega_t} \Delta t \left\{ \begin{array}{l} \sum\limits_{i\in\Omega_d} \lambda_t^m P_{i,t}^{DU} + \lambda_t^r \sum\limits_{i\in\Omega_w} P_{i,t}^{WF} \\ + \sum\limits_{\substack{\in\Omega_e \\ \in\Omega_v}} \lambda_t^m \left(P_{i,v,t}^{EV_{DCh}} - P_{i,v,t}^{EV_{Ch}} \right) \end{array} \right\} \quad (1)$$

where, the first and second terms are the operational costs of purchasing power from the diesel units and WFs respectively, while the third and fourth terms are charging and discharging cost of PEVs.

B. Power Flow Constraints

In order to avoid a local optimal solution for the problem which includes the non-convex power flow constraints, the convexified version of the model is adopted, which guarantees a global optimal solution for the optimisation problem, with lower computation time. Such constraints are introduced as follows ($\forall i,j \in \Omega_b, \forall t \in \Omega_t$):

$$P_{i,t}^{DU} + P_{i,t}^{WT} + \sum_{v\in\Omega_v} P_{i,v,t}^{EV_{DCh}} - P_{i,t}^{D} - \sum_{v\in\Omega_v} P_{i,v,t}^{EV_{Ch}} = \sum_j P_{ij,t} \quad (2)$$

$$Q_{i,t}^{DU} + Q_{i,t}^{WT} - Q_{i,t}^{D} = \sum_j Q_{ij,t} \quad (3)$$

$$P_{ij,t} = \sqrt{2}\, U_{ij,t} G_{ij} - G_{ij} R_{ij,t} - B_{ij} T_{ij,t} \quad (4)$$

$$Q_{ij,t} = -\sqrt{2} \left(B_{ij} + \frac{B_{ij}^{Sh}}{2} \right) U_{ij,t} + B_{ij} R_{ij,t} - G_{ij} T_{ij,t} \quad (5)$$

$$\left\{ \begin{array}{l} \sqrt{2} \left[{G_{ij}}^2 + \left(B_{ij} + \frac{B_{ij}^{Sh}}{2} \right)^2 \right] U_{ij,t} \\ + \sqrt{2} \left[{G_{ij}}^2 + {B_{ij}}^2 \right] U_{ji,t} + 2 \left[G_{ij} \frac{B_{ij}^{Sh}}{2} \right] T_{ij,t} \\ -2 \left[{G_{ij}}^2 + B_{ij} \left(B_{ij} + \frac{B_{ij}^{Sh}}{2} \right) \right] R_{ij,t} \end{array} \right\} \leq \left(A_L^{Max} \right)^2 \quad (6)$$

$$U_{ij,t} U_{ji,t} \geq \left(R_{ij,t} \right)^2 + \left(T_{ij,t} \right)^2 \quad (7)$$

$$R_{ij,t} \geq 0 \quad (8)$$

$$\frac{\left(V_i^{\min}\right)^2}{\sqrt{2}} \leq U_{i,t} \leq \frac{\left(V_i^{\max}\right)^2}{\sqrt{2}} \quad (9)$$

$$0 \leq U_{ij,t} \leq \frac{\left(V_i^{\max}\right)^2}{\sqrt{2}} \vartheta_{ij,t} \quad (10)$$

$$0 \leq U_{ji,t} \leq \frac{\left(V_j^{\max}\right)^2}{\sqrt{2}} \vartheta_{ij,t} \quad (11)$$

$$0 \leq U_{i,t} - U_{ij,t} \leq \frac{\left(V_i^{\max}\right)^2}{\sqrt{2}} (1 - \vartheta_{ij,t}) \quad (12)$$

$$0 \leq U_{j,t} - U_{ji,t} \leq \frac{\left(V_j^{\max}\right)^2}{\sqrt{2}} (1 - \vartheta_{ij,t}) \quad (13)$$

where, (2) and (3) denote the active and reactive power injection at each bus respectively, while the power flow through the MG lines for the former is given by (4), and (5) represents the power flow for the latter. Constraint (6) is the ampacity limit of the MG branches. The relaxed conic version of quadratic constraint for branch ij is given with (7), while $T_{ij,t}$ is a free variable and $R_{ij,t}$ is a positive variable (8). The voltage magnitude of system buses is limited by (9). Constraints (10)-(13) represent the connection status for the system branches, mainly through variables $U_{ij,t}$ and $U_{ji,t}$. These variables take the values of $U_{i,t,s}$ or $U_{j,t,s}$, if the branch is closed (i.e. $\vartheta_{ij,t} = 1$), and are set to zero, otherwise (i.e. $\vartheta_{ij,t} = 0$).

C. Radial Configuration

The previous literature [19] suggested graph theory as the main condition of radiality. Based on this criterion, number of lines should be equal to the number of buses minus one so as to keep the network configuration radial. This constraint is a necessary condition for the radiality; however, it cannot guarantee the radial configuration, especially in an IMG with no access to the main grid power supply and the alternative power flow from DERs in various directions. In this regards, thanks to the spinning tree concept (given in (14)), this study introduces a set of radiality constraint for the IMGs, as follows ($\forall i, j \in \Omega_b, \forall t \in \Omega_t$):

$$\alpha_{ij,t} + \alpha_{ji,t} = \vartheta_{ij,t} \tag{14}$$

$$\sum_{j \in \Omega_b^j} \alpha_{ij,t} = 1 \tag{15}$$

$$\alpha_{ij,t} + \alpha_{ji,t} = 0 \qquad , \forall i \in \Omega_b^s \tag{16}$$

$$\alpha_{ji,t}, \vartheta_{ij,t} \ \in \{0, 1\} \tag{17}$$

$$\vartheta_{ij,t} = \vartheta_{ji,t} \tag{18}$$

where, based on (14), if node i is the parent node for j or vice versa, the branch ij is in the spanning tree, while (15) demonstrates only one parent node should exist for each node. Constraint (16) shows that for an IMG, the status of the line connecting the MG to the upstream network should be open, as shown in (16).

D. Dispatchable and Non-Dispatchable Generation Units

For an MG, especially the ones that operate autonomously, dispatchable and non-dispatchable units play a critical role in demand supply and maintaining the frequency and voltage stability. This study takes into consideration the diesel units and WFs as dispatchable and non-dispatchable generation sources respectively. For an energy scheduling problem, the power output of this units should be limited as follows ($\forall t \in \Omega_t$):

$$0 \le P_{i,t}^{WF} \le \psi_{i,t}^{WF} P_R^{WF} \quad , \forall i \in \Omega_w \tag{19}$$

$$-tg(\varphi_{lead}) P_{i,t}^{WF} \le Q_{i,t}^{WF} \le tg(\varphi_{lag}) P_{i,t}^{WF} \quad , \forall i \in \Omega_w \tag{20}$$

$$P_{i,\min}^{DU} \le P_{i,t}^{DU} \le P_{i,\max}^{DU} \quad , \forall i \in \Omega_d \tag{21}$$

$$Q_{i,\min}^{DU} \le Q_{i,t}^{DU} \le Q_{i,\max}^{DU} \quad , \forall i \in \Omega_d \tag{22}$$

$$P_{i,t}^{DU} - P_{i,t-1}^{DU} \le R_i^U \quad , \forall i \in \Omega_d \tag{23}$$

$$P_{i,t-1}^{DU} - P_{i,t}^{DU} \le R_i^D \quad , \forall i \in \Omega_d \tag{24}$$

where the active power output of WFs is limited based on the wind profile (i.e. $\psi_{i,t}^{WF}$) and rated capacity (i.e. P_R^{WF}) of WFs as shown in (19). Also, (20) limits the reactive power output of WFs. Constraints (21) and (22) show the upper and lower limits of active and reactive power of diesel units, respectively, while the ramp up and ramp down constraints are applied through (23) and (24) respectively.

E. Plug-in Electric Vehicles

In this study, a parking lot is considered as the aggregator of PEVs. Thus, in constraint (2), sum of charge/discharge power for all PEVs is considered for the IMG. The behaviour of PEVs in the system is modeled through battery of each one, with consideration for the amount of energy that is consumed on the driving sector. The mathematical description of PEVs' model is given as ($\forall t \in \Omega_t, \forall i \in \Omega_e$):

$$E_{i,t}^{EV} = E_{i,t-1}^{EV} + \Delta t. \left(P_{i,v,t}^{EV_{Ch}} \eta_v^{Ch} - P_{i,v,t}^{EV_{DCh}} / \eta_v^{DCh} - P_{i,v,t}^{EV_{Dr}} \right) \tag{25}$$

$$E_{\min}^{EV} \le E_{i,t}^{EV} \le E_{\max}^{EV} \tag{26}$$

$$0 \le P_{i,t}^{EV_{Ch}} \le \gamma_{i,t}^{EV_{Ch}} P_{\max}^{EV_{Ch}} \tag{27}$$

$$0 \le P_{i,t}^{EV_{DCh}} \le \gamma_{i,t}^{EV_{DCh}} P_{\max}^{EV_{DCh}} \tag{28}$$

$$\gamma_{i,t}^{EV_{Ch}} + \gamma_{i,t}^{EV_{DCh}} \le 1 \tag{29}$$

$$P_{i,v,t}^{EV_{Dr}} = \Delta D_{v,t}^{EV} \times \eta_v^{Dr} \tag{30}$$

where (25) represents the state of energy of PEV based on its amount in the previous time interval, charge/discharge energy, as well as the energy consumed by driving sector. Constraint (26) limits the upper and lower energy of PEV, while (27) and (28) are limits on the charging and discharging power of PEV battery respectively. Logic (29) prevents the simultaneous charge and discharge. Finally, the power consumed in driving sector is given by (30).

IV. Simulation Results

The proposed robust real-time EMS model for reconfiguration of IMGs is simulated in general algebraic modelling system (GAMS) [20] using MOSEK solver, on an Intel Core i7-3.00 GHz, 8 GB RAM personal computer. The effectiveness of the model is examined using the IEEE 33-bus system as the test IMG, considering 5 tie switches, while the line connecting the network with the upstream grid in open status as indicated in constraint (16). The single-line diagram of the IMG with the assumed buses for locating the diesel units, WFs, and PEV aggregator is shown in Fig. 2. The dotted lines are potentially open lines in the initial status of the grid. The contract price of buying electricity from WFs is assumed to be 30 *cent/kWh*. The data of system is available in [21]. The hourly load, wind, price profile is given in [22]. The rated capacity of each WF is 1000 *kW*. Minimum and maximum capacity of diesel units is assumed to be 500 *kW* and 1500 *kW* respectively, while the ramp limits are 500 *kW* per hour. The total number of 100 PEVs is considered in the grid, with five travel distance patterns. Each travel pattern is followed by 20 PEVs. All associated PEV data is taken from [23]. The degree of robustness is assumed to be 3%

The proposed model is investigated in various case studies as follows:

- Case I: Conventional RH methods.
- Case II: Proposed RRH architecture.

In addition, different sensitivity analysis are performed to show the effectiveness of the proposed RRH controller.

As a robust optimisation problem, increasing the robustness requires a specific cost. Accordingly, the obtained operational cost of the IMG scheduling in cases I and II is $2526.0 and

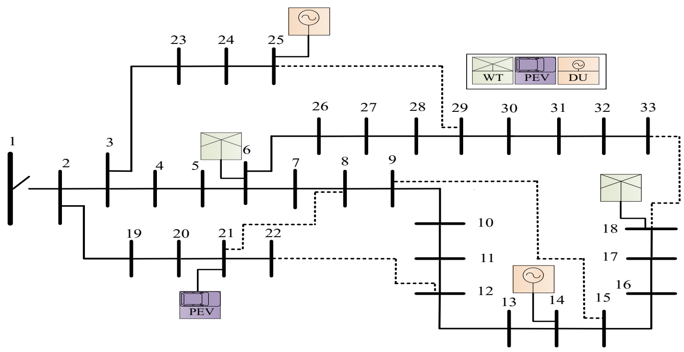

Fig. 2: The single-line diagram of the test microgrid.

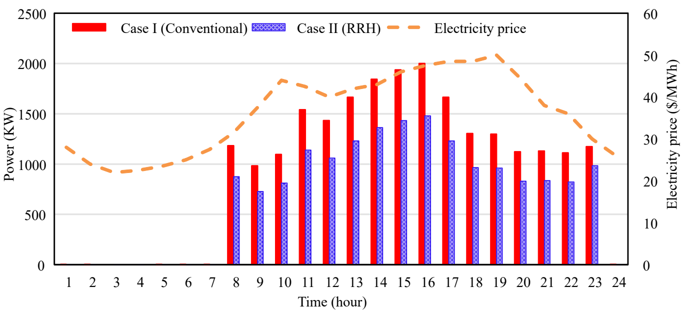

Fig. 3: The optimal output power of the WFs in different cases.

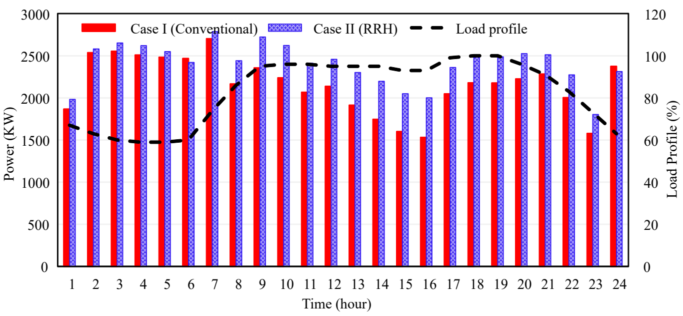

Fig. 4: The output power of diesel units in the different cases.

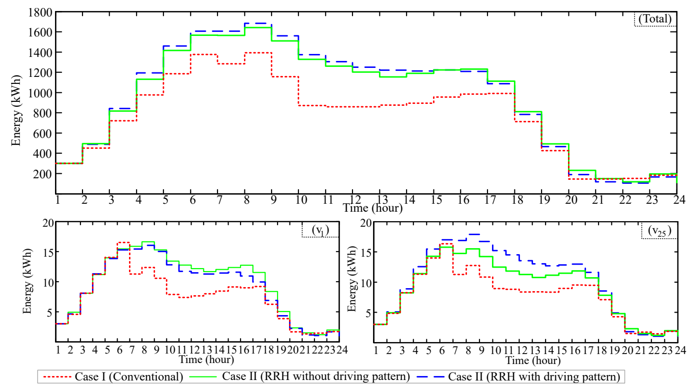

Fig. 5: The state of energy of PEVs.

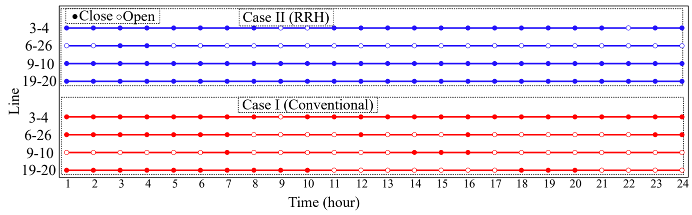

Fig. 6: The status of power lines in different cases.

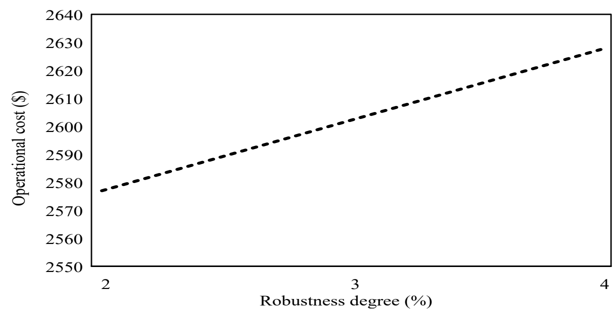

Fig. 7: Variation of operational cost over the changes in robustness degree.

$2601.8 respectively. The robustness cost equals to $75.78 (i.e 0.03 × 2526.0). The main reason for increasing the cost in RRH is that the decision maker has to increase the power output of diesel units while decreasing the penetration of WFs in a robust manner. Fig. 3 illustrates the output power of WFs over the scheduling horizon. It is evident from this figure that the injected power from WFs is declined in Case II. Besides, in the hours with the market price lower than the contract price of buying power from WFs, the system operator have not purchased power from these units. On the other hand, to boost the robustness, this decline in WF penetration should be compensated by the diesel units, as shown in Fig. 4, indicating the increase in power output of this units in Case II. The main reason is that the diesel unit output is always certain, while the WF output is more likely to change and bring about scheduling problems.

Figure 5 depicts the total state of energy of all PEVs in the network, as well as two selected PEVs (e.g. vehicle numbers 1 and 25) in different case studies. It can be seen in this figure that PEVs play their part in the proposed robust control, such that they have charged their batteries in the hours with lower electricity price, and discharged the power to the grid in the peak hours. In addition, in the proposed RRH scheme, the state of energy is higher than Case I, demonstrating the PEVs role in following the predefined robustness cost. Finally, the difference between the state of energy of vehicle numbers 1 and 25 shows the importance of driving pattern in definition of PEVs' role in the grid. Finally, in order to examine the effect of PEVs on robustness, the model is solved with and without these units, showing that the robustness degree is 0.26 for the former and 0.02 for the latter.

In order to investigate the role of network reconfiguration in improving the system robustness, the status of some candidate lines in cases I and II is depicted in Fig. 6. This figure demonstrates the fact that the long lines (e.g. from bus 9 to bus 10, and from bus 19 to 20) are closed in RRH case since the robustness improvement is the main goal in this strategy, while the cost minimisation strategy (i.e Case I) opens these lines to reduce the power loss resulting in a decrease in the operational cost. On the other hand, the status of short lines are approximately different in these two strategies. Generally speaking, the system operators can adopt the network reconfiguration in achieving their goals.

The degree of robustness could be defined by decision maker and it can affect the robustness cost. The more the robustness cost, the more robust RRH control strategy. To investigate this concept, a sensitivity analysis is performed, in which the robustness degree of RRH controller is increased from 2% to 4% and the value of operational cost is obtained, shown in Fig. 7. It is obvious that increasing the robustness degree raises the operational cost linearly.

TABLE I: Computation efficiency of different case studies.

Method (Timeslot)	Computation time (sec.)	Operational cost($)
Conventional (60min.)	7,964.16	2526.0
Conventional (30min.)	55,176.96	2625.7
Proposed RRH (60min.)	9,634.32	2601.8

Finally, in order to compare the computational efficiency of the proposed RRH and conventional methods, Table I is presented. This Table compares the computational statistics of Case I in two different resolutions with that of the proposed RRH. Note that the computation time in second column is actual for the whole operation hours. Therefore, it should be divided into the number of intervals to obtain the computation time of each timeslot. The conventional case with shorter timeslot led to 7 times higher computational time and almost 4% increase in operational cost. The RRH has a 20% increase in computational time, for a 3% increase in operational cost. However, it performs much better than the conventional method with shorter timeslot, being 5 times faster and 1% lower operational cost.

V. Conclusion

In this study, an RRH controller is introduced for real-time energy management of IMGs, with dispatchable and non-dispatchable generation units and PEVs as mobile storage units. Furthermore, a convex network reconfiguration is proposed for IMGs so as to improve the system efficiency with lower operational cost. The simulation results show that the the system operator needs to reschedule the power output of generation units and PEVs so as to make a robust energy management decision, whereas higher output from dispatchable units is required for improving the robustness. Also, the optimal system configuration changes to achieve a robust energy scheduling, while system reconfiguration can also bring about economic advantages. Generally the main conclusions of this paper are:

- The PEVs play a considerable role in improving system robustness such that solving the model without these units decreased the robustness degree by 24%.
- A robust decision making in the energy management of system requires more participation from dispatchable units and PEVs, resulting in an increase in the operational cost.
- Network reconfiguration can contribute positively in improving the system robustness.
- The RRH is an efficient controller that can produce robust results with almost 82% lower computation time compared to the conventional methods that increase the number of consecutive operation time windows so as to achieve more accurate results.

The future research questions could be investigated around the effect of PEVs' driving uncertainty on the EMS of MGs. Besides, considering the curtailment cost for the WFs and its influence on the economic issues of the model could be another problem to analyse.

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