Regulating power management in interconnected microgrids

Mohammad Fathi, and Hassan Bevrani

Published (to be published) in: American Institute of Physics

(Expected) publication date: March 2019

Citation format for published version:

Copyright policies:
- Download and print one copy of this material for the purpose of private study or research is permitted.
- Permission to further distributing the material for advertising or promotional purposes or use it for any profit-making activity or commercial gain, must be obtained from the main publisher.
- If you believe that this document breaches copyright please contact us at smgrc@uok.ac.ir providing details, and we will remove access to the work immediately and investigate your claim.
Regulating power management in interconnected microgrids
Mohammad Fathi, and Hassan Bevrani

Citation: Journal of Renewable and Sustainable Energy 9, 055502 (2017); doi: 10.1063/1.5003003
View online: http://dx.doi.org/10.1063/1.5003003
View Table of Contents: http://aip.scitation.org/toc/rse/9/5
Published by the American Institute of Physics

Articles you may be interested in
Modeling of wind turbine vortex generators in considering the inter-effects between arrays
Journal of Renewable and Sustainable Energy 9, 053301 (2017); 10.1063/1.4997039

Study and comparison between two DTC strategies of induction machine fed by direct matrix converter
Journal of Renewable and Sustainable Energy 9, 055501 (2017); 10.1063/1.5002769
Regulating power management in interconnected microgrids

Mohammad Fathi and Hassan Bevrani
Smart/Micro Grids Research Center (SMGRC), University of Kurdistan, Sanandaj, Iran
(Received 15 April 2017; accepted 28 August 2017; published online 19 September 2017)

An effective regulating power management is needed in next generation interconnected microgrids to mitigate the effect of load-generation imbalance in the system. The objective of this paper is to present a two-stage regulating power management scheme in an interconnected microgrid (MG) system. First, in a day-ahead power management, the power generation set-points are determined in the individual MGs considering predicted demand and power from renewable energy sources. Second, in a real-time regulating power management, a network operator establishes a set of power flow interactions among MGs to mitigate the load-generation imbalances in MGs. These interactions are obtained using a convex multi-constraint optimization problem and a cooperative developed algorithm. A simple suboptimal greedy solution is also proposed. Numerical results demonstrate the effectiveness of the proposed real-time regulating power management in cooperation with day-ahead scheduling to reduce the system load-generation imbalance, in comparison with conventional power resources.

I. INTRODUCTION

Distributed power generation is a key concept in the next generation of power systems. Small scale generators and renewable energy sources can be collected together to supply heterogeneous power demands. Because of its distributed structure, the system is more reliable in terms of maintenance and services, as well as is more flexible in using renewable energy sources.

Integrating distributed power units into a framework, using information and communication technologies, is known as a smart power grid. This grid, characterized by power flexibility and reliability, enables the incorporation of various components such as renewable power resources and distributed micro-generators. A unit of the grid, known as a microgrid (MG), is a group of small generators and loads connected to the grid in multiple points. As a considerable capability, each MG can operate in islanded and grid-connected operation modes. In the grid-connected operation mode, each MG interacts with other MGs to establish a set of regulating power flows in the grid. As a result of this regulation, a grid-wide balance between supply and demand is provided and results in low operational cost.

For reliable operation of a power system, power balancing between generation and consumption needs to be maintained instantaneously. This balancing is challenging in the presence of intermittent renewable sources and uncertain load demands. In the day-ahead MG operation, MG commitments including buy/sell power quantities are submitted to power markets several hours before the operating day. During the operation day, actual conditions often deviate from the day-ahead schedule as a result of generation/demand uncertainty. To compensate this deviation and to mitigate grid-wide imbalance powers, the MGs then participate in real-time ancillary services or regulating power management. This management can mitigate the existing gap between actual power generation and load demand and can be considered as a critical component in future distribution power networks with numerous connected MGs.

Electronic addresses: mfathi@uok.ac.ir and bevrani@ieee.org

Published by AIP Publishing.
Similar to the conventional power systems, in a distribution network, the regulating power or spinning reserve is provided chiefly by energy storage systems, pumped-storage stations, gas turbines, and small thermal power stations operating at less than full power capacity. The power reserves are automatically activated by the network or market operator. Always, the market operator needs to ensure that there is enough reserved capacity for potential future occurrences. In Ref. 10, an electricity aggregator schedules the charging of energy storages of its consumers to maximize its potential for participating in the reserve market. An energy storage system is also used in Ref. 11 to control ancillary voltage for a distribution feeder.

To increase reliability in the overall interconnected network, the MGs must be able to show proper performance in the connected operation mode. In the presence of the main distribution grid, it is assumed that the main distribution grid is responsible for regulating and maintaining the power network in desired conditions using the available regulating/spinning power. In other words, the set-points of the regulating participant microsources in the connected MGs are to be adjusted by the given references from the main grid. In Refs. 13 and 14, the operation optimization of a MG is done using a two-stage stochastic program. In the first stage, MG day-ahead bids including hourly power quantities and source commitments are optimized and are submitted to the market. Real-time power scheduling with the market operator is then decided in the second stage. A power flow method is also proposed in Ref. 15 to address the power flow solution for an unbalanced distribution network. In Ref. 16, an optimization framework has also been proposed to maximize the overall MG profit from selling energy to the grid while satisfying all network constraints. Model predictive control is used for handling uncertainty in renewable generation and load.

Regulating power management using demand responses in distinct MGs has also been investigated in the literature. A coordination framework between dynamics of regulating power and demand responses is done using model predictive control in Ref. 18. A bi-level interaction scheme is also proposed in Ref. 19. At one level, power generation of thermal power units is economically dispatched, and at the other level, user consumption behavior is determined. In Refs. 20 and 21, distributed power dispatching and demand response are also done using a dual decomposition method. The participation of electric vehicle batteries in ancillary services and regulating energy markets has been considered in Ref. 22–24. An aggregation of electric vehicles is needed for the aim of reliably regulating the power.

The present paper addresses regulating power management in a distribution network of interconnected MGs as shown in Fig. 1. Due to the high diversity of generation and load, an interconnected network exhibits high nonlinearities, changing dynamics, and uncertainties that require control and optimization strategies coordinated by the network operator (NO). The MGs contribute to regulating power management by injecting their surplus active/reactive powers. The NO has responsibility to manage the regulating power in the operation of the electric grid in which more than one MG may exist. The NO allows the connected MGs to interchange

![Diagram](attachment:image.png)  
*FIG. 1. Interconnected MG system.*
regulating power at an economic optimum, and it organizes the power flow interactions between the connected MGs.\textsuperscript{26}

The aim of the given approach in this paper is to optimally manage the spinning reserves provided by distributed power producers to reduce cost and to smooth the transient states due to switching from regulating power producer to another one. This approach is different from those in the literature in that there is no need for the presence of the main grid in the network. Moreover, as noted previously, regulating power in the literature is mainly supplied by the main grid, storage stations, small thermal power stations, demand response, or vehicle batteries. However, in this approach, the surplus power of a number of MGs is to be used as the regulating power for other MGs. The operation optimization on regulating power management/scheduling is summarized in two stages as depicted in Fig. 2 and is stated in the following.

(1) In a day-ahead scheduling, it is assumed that there is a way of predicting day-ahead demand and power from renewable power sources. Considering this prediction and generation constraints from conventional sources, each MG determines the power to be generated from its conventional sources over a set of dispatching intervals, indexed by \( t \). Due to the uncertain behavior of renewable power resources and demand that cause prediction error on realized values, there might be some supply-demand imbalances within MGs. Other causes of these imbalances are power generation constraints such as the ramp rate constraint and the maximum achievable power limit.

(2) In a real-time scheduling at the beginning of each dispatching interval, the NO performs regulating power management. Considering supply-demand imbalances within the MGs as a result of the first stage scheduling, the NO formulates grid-wide balance between supply and demand as an optimization problem. As a result of this problem, a set of regulating power flow interactions is established in the grid, and accordingly, a regulating power management scheme is proposed. To demonstrate the effectiveness of this scheme, a case study is considered and some simulations are performed.

The rest of this paper is organized as follows: In Sec. II, the power regulation problem in an interconnected MG system is briefly explained. Then, the problem is formulated as a convex

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{regulated_power.png}
\caption{Regulating power management flow chart.}
\end{figure}
multi-constraint optimization expression in Sec. III, and an effective algorithm is developed for cooperative power management. In addition to the discussion of the optimal solution of the problem in Sec. III, a greedy solution is also proposed in Sec. IV. In Sec. V, to verify the capability of the proposed method, a number of numerical examples are given. Finally, this paper is concluded in Sec. VI.

II. REGULATING POWER: PROBLEM STATEMENT

In a MG-based distribution system, as shown in Fig. 3, each MG uses a MG central controller (MGCC) to facilitate a high level management of the MG operation by means of technical and economical functions. Microsource controllers (MCs) control the microsources and the energy storage systems. Finally, the controllable loads are controlled by load controllers (LCs). The MGCC interfaces between a MG and other connected MGs. The NO located in the application layer of the network management system (NMS) acts at an economical-based energy management level between each MG and the neighboring MGs similar to the existing supervisors for power exchanges and economic dispatch in a conventional multi-area power system.

In the mentioned interconnected network, identifying the optimal consumption/generation schedule to minimize production costs and balancing the demand and supply which comes from the MGs, as well as online assessment of the overall network security and reliability, are the responsibilities of the NO unit. The NO together with the MGCCs supervises the MG market activities such as buying and selling regulation power to the grid and possible network congestions. The mentioned global task for an interconnected power network should be implemented through the cooperation of its various MGs, on the basis of communication and collection of information about distributed energy systems and control commands. This could

FIG. 3. MG-based distribution system.
be deployed by optimizing the power exchanged between different MGs, thus maximizing the grid production depending on the market prices and reliability/security constraints.

In order to have a reliable and secure operation, enough regulating power reserve should be available within the network. Power reserves insure that capacity is available when needed to maintain secure power system operations following an imbalance in the system load-generation. In a power market, the reserves must be carefully planned and purchased so that the NO is able to use them when required. The NO guarantees the effective use of assets, including the dispatch of energy and the dispatch of spinning (regulation) reserves, and organizes the energy and ancillary service markets. The system operator must activate these power reserves to meet the standard performance indices in a timely and economically manner.

In an interconnected MG network, the reserves must be carefully planned and purchased so that the NO is able to use them when required. The NO guarantees the effective use of assets, including the dispatch of energy and the dispatch of spinning (regulation) reserves, and organizes the energy and ancillary service markets. In order to determine the sufficient amount of regulation power for proper load-generation balance with acceptable reliability, it is necessary to refer to the existing reliability standards and assigned performance indices by the relevant technical committees. The amount of required power reserve depends on several factors including the type and size of imbalance (load/generation variation) in the network.  

III. PROBLEM FORMULATION AND SOLUTION

Consider a distributed power grid consisting of a set \(N \triangleq \{n : n = 1, \ldots, N\}\) of MGs interconnected through a power transmission infrastructure. These MGs are to be scheduled over a set \(T = \{t : t = 1, \ldots, T\}\) of dispatching intervals in a two stage power management. The first stage that is done a day-ahead of this time horizon in individual MGs determines the power generation set-points in each MG. The second stage is done by the NO in a real-time manner at the beginning of each dispatching interval \(t\). It determines the regulating power flow interaction among MGs. Each MG uses a MGCC to handle a high level operation of management. Nomenclature lists the notations that are used in Secs. III A and III B.

A. First stage: Day-ahead power management in MGs

Within each MG, there are a set of conventional sources and a set of renewable power resources to supply a time-varying demand. Due to the lower operational cost of renewable resources in comparison with conventional sources, the MG preferably utilizes the power generated from renewable power resources to supply the demand at each dispatching interval \(t\). It then uses power from conventional sources if more power is needed, based on the following minimization problem.

For MG\(_n\), given \(r_n(t)\) as the predicted power from renewable resources and \(d_n(t)\) as the predicted demand, the MG\(_n\) determines \(g_n(t)\) as the power from conventional sources. The objective in this determination is to minimize the squared imbalance power of the MG, i.e., the squared difference between the achieved and consumed powers, as

\[
\min_{g_n(t)} \left| g_n(t) + r_n(t) - d_n(t) \right|^2, \quad (1a)
\]

s.t. \(\left| g_n(t) - g_n(t-1) \right| \leq R\),

\[0 \leq g_n(t) \leq P_{n}^{\text{max}}. \quad (1c)\]

Constraint (1b) forces the conventional sources to operate in their ramp rate restriction \(R\). \(P_{n}^{\text{max}}\) is the maximum allowed generated power. Forecasting or estimating renewable resource power and demand during the dispatching intervals is beyond the scope of this paper. They are assumed as known values in this problem.
The feasible region of problem (1) is the intersection of constraints (1b) and (1c), which can be written as
\[ \max(g_n(t-1) - R, 0) \leq g_n(t) \leq \min(g_n(t-1) + R, P_n^{\text{max}}), \] (2)
which is a convex region. To find the optimal solution, consider the derivation of the objective function with respect to the optimization variable as
\[ \frac{\partial (g_n(t) + r_n(t) - d_n(t))}{\partial g_n(t)} = 0, \]
that results in \( g_n(t) = d_n(t) - r_n(t) \). Projecting this value into the feasible region, the optimal solution is achieved as
\[ g_n^*(t) = \left\lfloor d_n(t) - r_n(t) \right\rfloor_{\max(g_n(t-1) + R, P_n^{\text{max}})}^{\min(g_n(t-1) - R, 0)}, \] (3)
where \( y = [x]_a^b \) returns to the nearest value to \( x \) between \( a \) and \( b \).

If the optimal solution lies at the interior point of the feasible region, demand is fully supplied. There is neither power shortage nor power surplus within MGs. However, due to the stochastic nature of renewable resources and demand, this is not the case in all dispatching intervals. The ramp rate constraint prevents the conventional sources to be adapted with large variations of renewable resources and demands. Therefore, while some MGs face power shortage, some MGs have surplus power. Both cases incur operational cost in the grid. These imbalances are addressed and treated using cooperative interactions among individual MGs in Subsec. III B.

B. Second stage: Real-time regulating power management

Given \( g_n^*(t) \) as the decided power to be generated by conventional sources in MG \( n \) in the first stage, the imbalance power within the MG at dispatching interval \( t \) is denoted by
\[ \Delta_n(t) = g_n^*(t) + r_n^*(t) - d_n^*(t). \] (4)
where \( r_n^*(t) \) and \( d_n^*(t) \) are the realized power from renewable resources and realized demand at dispatching interval \( t \), respectively. Based on the sign of imbalances, we partition MGs into two distinct sets
\[ A_1 = \{ i \in \mathcal{N} : \Delta_i(t) > 0 \}, \] (5)
and
\[ A_2 = \{ j \in \mathcal{N} : \Delta_j(t) < 0 \}, \] (6)
where \( A_1 \) is the set of MGs with excess supply and \( A_2 \) is the set of MGs with shortage supply. To mitigate these imbalances throughout the grid, the NO establishes a set of regulating power flows \( S(t) = \{ s_{ij}(t) \}_{i \in A_1 \atop j \in A_2} \) between MGs in \( A_1 \) and \( A_2 \). Let \( s_{ij}(t) \geq 0 \) be the power flow from MG \( i \) to MG \( j \) at dispatching interval \( t \). Due to random variations of renewable resources and demand, and accordingly imbalance powers, power flows within \( S(t) \) should be regulated adaptively dispatching intervals \( T \).

The objective of the NO is to determine power flows \( S(t) \) to minimize the aggregated grid imbalance power as
\[
\min_S \sum_{i \in A_1} \left( \Delta_i(t) - \sum_{j \in A_2} s_{ij}(t) \right)^2 + \sum_{j \in A_2} \left( \Delta_j(t) + \sum_{i \in A_1} s_{ij}(t) \right)^2, \] (7a)
s.t. \[ \sum_{j \in \mathcal{A}_2} s_{ij}(t) \leq \Delta_i(t) \quad \forall i \in \mathcal{A}_1, \forall t \in T, \] (7b)

\[ \sum_{i \in \mathcal{A}_1} s_{ij}(t) \leq |\Delta_j(t)| \quad \forall j \in \mathcal{A}_2, \forall t \in T, \] (7c)

\[ 0 \leq s_{ij}(t) \leq c_{ij} \quad \forall i \in \mathcal{A}_1, j \in \mathcal{A}_2, \forall t \in T. \] (7d)

The objective function is the sum of squared imbalance powers in the grid after injecting regulating power flows. It can also be considered as an economic measure. The constraint (7b) states that the aggregated output power from the MG with surplus power, i.e., \( \Delta_i(t) > 0 \), should not exceed its surplus value. Similarly, the aggregated input power for the MG with shortage power, i.e., \( \Delta_j(t) < 0 \), should not exceed its shortage value, as stated in constraint (7c). There is always a maximum power transmission capacity \( c_{ij} \) between MG \( \mathcal{A}_1 \) and MG \( \mathcal{A}_2 \). Constraint (7d) restricts each power flow \( s_{ij} \) to be smaller than \( c_{ij} \) and at the same time to be non-negative.

Problem (7) is a quadratic problem with linear constraint functions. The quadratic objective function is a convex composition of affine expressions which is positively semi-definite. Accordingly, the problem is convex and can be solved using efficient algorithms such as the interior point method.\(^29\)

Given the solutions of aforementioned problems (1) and (7), a cooperative regulating power management (CRPM) algorithm at each dispatching interval is summarized in Algorithm 1. It consists of two stages. In stage 1, individual MGs estimate demand and achieved power from renewable resources and accordingly compute their own generation power from conventional sources. They then report their imbalance powers \( \Delta_n(t) \) to the NO. In stage 2, the NO optimizes regulating power flow interactions among MGs.

### Algorithm 1. The developed CRPM scheme.

1. **Stage 1: Power Management in MGs**
   2. for \( n \in \mathcal{N} \) do
      3. Estimate \( r_n(t) \) and \( d_n(t) \) during dispatching interval \( t \).
      4. Obtain \( g_n^*(t) \) using (3).
      5. Report \( \Delta_n(t) = g_n^*(t) + r_n(t) - d_n(t) \) to the NO.
   6. end for

7. **Stage 2: Regulating Power Management by the NO**
   8. Given \( \Delta_n(t) \) from all MGs, obtain optimal power flows \( \{s_{ij}(t)\}_{i,j \in \mathcal{A}} \) using the solution of (7).

The solution of regulating power management in the second stage can be obtained efficiently using state-of-art solvers. In the present work, the CVX\(^30\) is used to find the optimal solution of power flows in stage 2, which is referred to as the optimal solution in the rest of this paper. In addition to this solution, we are also interested in a low complex but suboptimal greedy solution that is discussed in Sec. IV.

### IV. GREEDY SOLUTION

Unlike day-ahead power sharing that is scheduled offline, regulating power management should be decided in a real time manner at the beginning of each dispatching interval \( t \). Consequently, a low complex but suboptimal management scheme is desired. Having this in mind, we propose a Greedy solution for the second stage of the CRPM scheme. The main idea is to supply MGs with negative imbalance values in \( \mathcal{A}_2 \) using MGs with positive imbalance values in \( \mathcal{A}_1 \). The preference is going to the highest imbalance absolute values in either side. The proposed methodology is summarized in Algorithm 2.
In the beginning, all power flows are set to zero and a temporary imbalance vector $\tilde{\Delta}$ is initialized by the imbalance vector $\Delta$. This temporary vector is updated upon any power flow assignment during the algorithm.

The algorithm consists of two loops: the outer loop from lines 4 to 18 and the inner loop from lines 9 to 16. In the beginning of the outer loop, the MG $I \in A_2$ with the highest absolute imbalance power value is chosen. Imbalance power in this MG is going to be compensated by MGs in $A_1$ in the inner loop. Prior to this, the feasible power flows between MG and MGs in $A_1$ are found in line 6. The feasible flow between MG and any MG is the minimum value of available power in MG, i.e., $\Delta_i$, and the capacity of the transmission line between these two MGs, i.e., $c_{ij}$. The feasible power flows stored in vector $V$ are then sorted in a descending order to form vector $V^*$, as in line 7. The sorted indexes are also saved in set $I$. In other words, the MGs to be used for imbalance power compensation of MG appear in $I$ in order.

In the inner loop, the imbalance power value in MG is going to be compensated by MGs indicated in $I$ and indexed by $k$, consecutively. This loop repeats until either the imbalance value in MG is fully compensated or the whole MGs in $A_1$ are looked for power interaction. At each iteration of the inner loop, the MG $I(k) \in A_1$ is chosen for power flow interaction with MG, as in line 10. In lines 11 and 12, the values of imbalance powers of outflow and inflow MGs in $\Delta$ are updated. Finally, in line 17, MG is removed from the set of MGs to be compensated in the next rounds of the algorithm.

The outer loop repeats until there would be no MG in $A_2$ for power flow interaction. The computational complexity of the Greedy algorithm depends on the number of iterations of aforementioned outer and inner loops. This can be approximated as $O(|A_1||A_2|)$. In a network with $|A_1|+|A_2|=N$ MGs, the worst complexity is $O\left(\frac{N}{2} \times \frac{N}{2}\right)$ or $O\left(\frac{N^2}{4}\right)$. This polynomial complexity is absolutely much smaller than the exponential complexity of the optimal solution of problem (7). Consequently, it is worth taking advantage of the low complexity Greedy algorithm in real-time regulating power management schemes.

V. NUMERICAL RESULTS

To illustrate the functionality of the proposed CRPM scheme, two simple power grid examples including 2 and 4 MGs are considered. Then, to show the effectiveness of the proposed optimal power regulating methodology, clearly, a new regulation index is introduced.
A. 2-MG power grid

Consider a power grid of two MGs with $P_{\text{max}} = 30$ and a ramp rate of $R = 5$ in $T = 25$ dispatching intervals within a day. The renewable power in the MGs is assumed to follow a uniform density function with a mean of 25, i.e., $U(0, 50)$. To illustrate power interactions between MGs, MG1 and MG2 are assumed to be low and high demand MGs, respectively. For instance, demand in MG1 is assumed to be a uniform density function with a mean of 5, and demand in MG2 is assumed to be a uniform density function with a mean of 45. In other words, demands in MG1 and MG2 are assumed as $U(0, 10)$ and $U(0, 90)$, respectively. The realized renewable power and demand and the corresponding generation power from conventional sources in the first stage of CRPM are shown in Fig. 4. Due to low demand, the power generated in MG1 is mostly zero except for some dispatching intervals. This is due to the fact that the low demand in this MG is totally supplied by the renewable power. However, due to the high demand, MG2 needs to mostly utilize its conventional sources.

As stated in Sec. III A, due to possible large variations of renewable power and demand, as well as the ramp constraint of conventional sources, there is imbalance power within MGs. In particular, the imbalance power value within a MG is the difference between the achieved power, i.e., renewable power plus generated power, and the demand in that MG. In the aforementioned setup, imbalance power values after the first stage of power management are shown in the upper part in Fig. 5. While MG1 has a power surplus, MG2 has a power shortage. Regulating power interaction between these MGs managed by the NO in the second stage results in lower imbalance values, which is shown in the middle and lower parts in Fig. 5. The middle and lower parts contain imbalance power values resulted from the optimal and the Greedy solutions, respectively, in the second stage of the CRPM scheme. As shown, the power shortage in MG2 is mostly compensated by MG1 as much as there is power surplus, in both solutions. Absolutely, this would result in low operational cost in comparison with no regulating power.

B. 4-MG power grid

To get more insight into the performance of the proposed CRPM scheme, consider a power system of $N = 4$ MGs with demand profiles $U(0, 10)$, $U(0, 30)$, $U(0, 70)$, and $U(0, 90)$ from MG1 to MG4, respectively, and a renewable power profile of $U(0, 50)$ for all MGs. As in the aforementioned setup, renewable, demand, and generation power of conventional sources within MGs, in the first stage, are shown in Fig. 6. The corresponding imbalance power values in the first stage are shown in the upper part of Fig. 7. The middle and lower parts are imbalance power values resulted from the optimal and the Greedy solutions in the second stage of the CRPM scheme.
CRPM scheme. Once again, the power shortage of high demand MGs has been mostly provided by power surplus of low demand MGs.

C. Regulation index and discussion

To quantify the improvement of imbalance power values in the second stage of the CRPM scheme, specifically for a power grid with numerous MGs, a suitable measurement index is necessary. Here, to indicate the regulating performance, we define a regulation measure (RM) as

$$RM = \sqrt{\frac{\sum_{i=1}^{N} \sum_{t=1}^{T} \delta_i^2(t)}{TN}},$$

where $\delta_i(t) = \Delta_i(t)$ in the first stage of the CRPM scheme and $\delta_i(t) = \Delta_i(t) - \sum_{j=1}^{N} s_j^2(t)$ in the second stage, after applying power flow interactions in the optimal and Greedy solutions. Indeed, the regulation measure can be interpreted as the imbalance power per MG per dispatching interval. In other words, a lower regulation measure reveals more balance between supply and demand in the grid and the corresponding lower operational cost.
It is shown that the transmission line capacity plays an important role in the grid power management performance. Here, to perform a comparison in terms of regulation measure, first, we are interested in the variation of this measure against the transmission line capacity between MGs. Toward this, consider a power system of $N=8$ MGs with the same renewable power profile of $U(0, 50)$. A half of MGs are assumed to be low demand MGs with demand profile $U(0, 20)$ and another half are high demand MGs with demand profile $U(0, 80)$. The variation of the system regulation measure versus the variation of the transmission line capacity between MGs is shown in Fig. 8. In the first stage of the CRPM scheme, there is no power flow interaction between MGs, and accordingly, regulation measure values are independent of line capacities. However, with power flow interactions of the optimal and Greedy solutions in the second stage, regulation measure values become smaller as the line capacities increase. This is due to the fact that high line capacities allow high power flow interactions between MGs. As a notable point, regulation measure values become converged for high line capacities. In other words, by increasing the line capacity beyond a certain value, there is no gain in the regulation measure reduction.

In addition to the line capacities, another effective parameter in the regulation measure is the number of MGs in a power system. Toward this, consider a system of MGs, in which renewable power in all MGs follows $U(0, 50)$. Similar to the aforementioned setup, a half of
MGs are assumed as low demand MGs with profile $U(0, 20)$ and another half are assumed as high demand MGs with profile $U(0, 80)$. Transmission line capacity between any two MGs is assumed to be a constant of $c = 10$. The regulation measure when the number of MGs is varied is shown in Fig. 9. At each instant, the regulation measure is computed over a duration of $T = 250$ dispatching intervals. As shown, the regulation measure of the system has been improved as a result of power flow interactions in the performed optimal and Greedy solutions of the second stage power regulation management. More importantly, the regulation measure is improved when the number of MGs is increased. This is due to the fact that the power shortage of a MG is more likely to be compensated by the power surplus of another MG as the number of participating MGs increases.

VI. CONCLUSION

The regulating power management in a MG-based distribution system is totally different from the same issue in a conventional power system, mostly due to high diversity in generations and loads as well as fast dynamics of the grid. In this paper, a two-stage regulating power management scheme has been developed to mitigate the load-generation imbalance in the context of interconnected MGs. The optimal and greedy solutions of the resulting problem result in a set of regulating power flows among MGs at each dispatching interval. This indicates the improvement of the defined imbalance index in comparison with cases with no regulating power management. The study in this paper highlights the use of power flow interactions among interconnected MGs for the purpose of regulating power instead of conventional sources such as the main grid, storage stations, and small thermal power stations. Power of renewable resources and demand profiles in this work have been assumed to follow uniform probability density functions, which might not be valid in practice. As a future scope of this paper, the proposed scheme can be examined using realistic probability density functions in the literature.

ACKNOWLEDGMENTS

This work was financially supported by the research office at the University of Kurdistan.

NOMENCLATURE

$A_1$ The set of MGs with excess supply
$A_2$ The set of MGs with shortage supply
\( c_{ij} \)  
Transmission capacity between MG_i and MG_j  

\( d_n(t) \)  
Predicted demand of MG_n at time t  

\( g_n(t) \)  
Power from conventional sources of MG_n at time t  

\( N = \{ n : n = 1, \ldots, N \} \)  
The set of MGs  

\( \rho_{\text{max}}^n \)  
Maximum allowed generated power at MG_n  

\( R \)  
Ramp rate restriction  

\( RM \)  
Regulation measure  

\( r_n(t) \)  
Predicted power from renewable resources of MG_n at time t  

\( S(t) = \{ s_j(t) \}_{j \in A^1} \)  
The set of regulating power flows  

\( T = \{ t : t = 1, \ldots, T \} \)  
The set of time dispatching intervals  

\( \Delta_n(t) \)  
Power imbalance of MG_n at time t


