A Novel Distributed Algorithm for Power Loss Minimizing in Smart Grid

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A Novel Distributed Algorithm for Power Loss Minimizing in Smart Grid

Chao Wei[†,‡]
Zubair Md. Fadlullah[†]
and Nei Kato[†]
[†] Graduate School of Information Sciences
Tohoku University, 980-8579, Japan
[‡] School of Information Science and Technology
Heilongjiang University, 150080, China.
Email: {weichao, zubair, kato} @it.ecei.tohoku.ac.jp

Ivan Stojmenovic
SIT, Deakin University, Melbourne, Australia
King Abdulaziz University, Jeddah, Saudi Arabia,
and SEECS University of Ottawa, Canada.
Email: stojmenovic@gmail.com

***Abstract*—Because power generation of renewable resources are unstable and demands of the customers are time-varying, the supply power and demands of the customers are always unequal. To meet the demands of the customers, power is transmitted from primary power generation to secondary power generation. It will cause high power loss. To solve this problem, a distributed algorithm is proposed in this paper. By using the algorithm, the micro-grids are able to exchange power with their neighbors so as to minimize the total power losses of the smart grid. Moreover, communication overhead (bandwidth) is reduced, comparing with centralized algorithm. Through computer simulations, we demonstrate that the proposed algorithm can lead to near-optimal result for alleviating the average power loss per micro-grid and reduce the communication overhead significantly in contrast with the centralized approach.**

***Index Terms*—Distributed algorithm, micro grid, smart grid.**

I. Introduction

Smart grid is regarded as the next-generation power grid([1]-[4]). Unlike the traditional power grid, the smart grid does not only send power to customers, but also send demands of the customers through communication technology and infrastructure. Based on the demands of the customers, the power plant could decide the quantity of power generation so as to abate waste. In other words, the emergence of the smart grid causes a revolution of power grid.

Smart meters which is an important component of smart grid, are installed in equipment of the customers. It can help the customers to save power and send demands to secondary power station (e.g., micro-grid) that they are linked. To meet the demands, the micro-grids will generate power by renewable resources (i.e., wind, solar, water and so forth). Comparing with the traditional power grid, micro-grid is more easy to control the quantity of power generation. It plays an increasingly important role in the modern power grid. Although the micro-grids possess some advantages, we cannot neglect its shortcoming. For instance, those renewable resources cannot guarantee stability of power generation. It causes that the supply of micro-grid is often not equal to demand. Hence, the micro-grids need to sell/buy power from primary power generation (e.g., macro-station) ([5]). However, the power loss between the micro-grid and the macro-station is higher than that between the micro-grids. To enhance the efficiency of the smart grid (reduce the power loss), the micro-grids hope to exchange power with other micro-grids instead of the macro-station, so as to reduce power loss. Nevertheless, if the micro-grids have more than one neighbor, which is the proper partner is the most important problem that the micro-grids have to face. To solve this problem, an algorithm is proposed to help the micro-grids to choose proper neighbors to exchange power so as to minimize the total power loss. At first, based on the demands of the customers and generation power, by using the algorithm, the current remaining powers can be calculated. If current remaining powers are not zero, the micro-grids will exchange information of the remaining power with their neighbors. Then, depending on the information each micro-grid generates and sorts the set of neighbors which are able to exchange power with, sends offer to the first element of this set and waits the response. If the "accept" response from the first element is received, the two micro-grids will exchange power. After that the first element will be deleted from the set. Additionally if the response from the first element is not received and time-out occurs, or receive "reject" response, the first element will be deleted as well. Then, the offer is sent to the "new" first element of the set if the set is not empty. At the same time, the micro-grid can receive offers from the other elements of the set when it is waiting the response from the first element. If the offer is from other elements, the offer will be "hold" and the "hold" message will be returned. For instance, if the offer from the second element, it will be hold. If the first element is deleted, this second element is the "first" element and the hold offer will be activated. Moreover, the hold offer will be deleted when time-out occurs as well. Sending offer and receiving response/offer will not stop until the neighbor set is empty or the current remaining power is zero. After exchanging power with their neighbors, the micro-grids will exchange power with the macro-station if current remaining power is not zero. If the current remaining power is zero and receive offers, the micro-grids will return "reject".

The remainder of our paper is organized as follows. The background and related works are discussed in Section II. The system model is discussed in Section III. In Section IV, distributed algorithm for micro-grids is discussed. In Section V the simulation result is presented, and the conclusion is drawn in Section VI.

II. Background and related works

In this section, we introduce several power loss reducing methods for the smart grid that exist in literature. Moreover, the drawbacks of these existing methods are delineated.

The first method is dynamic pricing strategy ([6]). It means adjusting the electricity price in different period (raising the price in high power consumption period whilst reducing the price in the low power consumption period). It will help the customers to adjust work schedule of equipment from high power consumption period (e.g., 8 PM) to low power consumption period (e.g., 2 AM). Although this kind of method could guarantee the demands of the customers, the drawbacks are evident. For instance, the customers have to pay more money than that in low power consumption period, when their electric equipment must be operated in the high power consumption period (e.g., TV). Additionally, this method could not alleviate the mount of the demands of the customers, if the schedule of equipment cannot be changed.

The other kind of method is reducing power loss ([5], [7]-[9]). If a micro-grid cannot meet the demands of the customers, it needs to obtain power from other neighboring micro-grids or the macro-station. And the power transmission causes power loss. Our previous work [5] proposed an algorithm which can help the micro-grids to form groups and exchange power with others, so as to alleviate the power loss and meet the demands of the customers. This algorithm is a centralized algorithm. For obtaining global information which could help the micro-grids to make decisions, the micro-grids will communicate with the macro-station. Compared with distributed algorithm, although its result is better than that of distributed algorithm, it costs more bandwidth than that of distributed case costed. W. Saad *et al.* [9] proposed a distributed algorithm to help micro-grid to communicate with others. In [9], by using the algorithm micro-grids will choose the nearest neighbors to exchange power so as to reduce the local power loss. Nonetheless, the authors did not consider the total power loss.

Note that the above-mentioned power loss minimization techniques described do not consider all the power losses affecting the power system comprising the macro-station and numerous micro-grids. They usually adopted a localization approach, e.g., how to propose a centralized algorithm to help micro-grids to exchange power with others, or how to exchange power with the nearest neighbors, so as to reduce the power loss. On the other hand, in our paper, we focus on a scalable total power loss minimization approach across the entire smart grid.

III. System Model

In this section, our proposed model will be considered. As shown in Fig. 1, we consider that there are three layers in our model. The primary power station (macro-station) is the first layer. It could exchange power with the secondary power station (micro-grid). For simplicity, assume that the macro-station has enough power to meet the demands of the micro-grids and receive the surplus power from the micro-grids. Following as our previous work [5], each micro-grid is linked to the macro-station directly. The micro-grids are the second layers in our model. Comparing with the macro-station, they could be deployed nearer to customers. Therefore, the customers could be linked to the micro-grids directly. The micro-grids support power to the customers so as to meet the demands of them. And they will exchange power with their neighbors or the macro-station, when supply and demand are unequal. Because they just know the location of their neighbors, a distributed algorithm is to be proposed. The algorithm could help the micro-grids to find proper partner so as to minimize the total power loss of the smart grid. The smart meters are installed in equipment of the customers. Therefore, they can send the demands of the customers to the micro-grids. Finally, the customers, who obtain power from their respective micro-grids, form the last layer of our considered system.

Let $\mathcal{N}$ denote the set of the micro-grids and $N = |\mathcal{N}|$. In the given time period (e.g., one second), for $micro\text{-}grid_i$, we define real function $D_i(t)$ as the current remaining power of $micro\text{-}grid_i$ and it can be expressed as follows:

$$D_i(t) = G_i(t) - W_i(t). \quad (1)$$

where $G_i(t)$ and $W_i(t)$ are the generation power of $micro\text{-}grid_i$ and the demands of the customers which are linked to $micro\text{-}grid_i$, respectively. It means that $micro\text{-}grid_i$ wants to obtain power to meet its demand ($D_i(t) < 0$), $micro\text{-}grid_i$ has a power surplus to sell ($D_i(t) > 0$), or its supply equals its demand ($D_i(t) = 0$). The micro-grids can be divided into two types, namely "exporters" and "importers".

TABLE I
PARAMETERS DECLARATION

Parameter	Definition
$G_i(t)$	Generation power of i^{th} micro-grid of slot t
$W_i(t)$	Demand of customers linked to i^{th} micro-grid of slot t
$D_i(t)$	Currently remaining power of i^{th} micro-grid within slot t
$Q_{0i}(t)$	Actual exchange power between i^{th} micro-grid and the macro-station of slot t
$Q_{ij}(t)$	Actual exchange power between i^{th} micro-grid and j^{th} micro-grid of slot t
α	Conversion power loss ratio
R_{ij}	Resistance between i^{th} micro-grid and j^{th} micro-grid
R_{0i}	Resistance between i^{th} micro-grid and macro-station
U_1	Voltage between i^{th} micro-grid and j^{th} micro-grid
U_0	Voltage between i^{th} micro-grid and macro-station
$PL_{ij}(t)$	Power loss when i^{th} micro-grid exchanges power with j^{th} micro-grid of slot t
$PL_{0i}(t)$	Power loss when i^{th} micro-grid exchanges power with macro-station of slot t
$PLC_i(t)$	Power loss when power is converted from U_0 to U_1 of slot t
$PLT_i(t)$	Power loss due to power transmission of slot t
$PLA_i(t)$	Total power loss of i^{th} micro-grid of slot t

The "exporters" have surplus to sell while the "importers" need additional amount of power to meet the demands of the customers. If the current remaining power of $micro\text{-}grid_i$ is zero ($D_i(t) = 0$), $micro\text{-}grid_i$ is considered to be either an "exporter" or an "importer", and it cannot affect the result. In fact, the demand of customers $W_i(t)$ and production power $G_i(t)$ are always considered as random numbers in the real smart grid networks [9]. As a consequence, the value of $D_i(t)$ is accordingly considered as a random number with a certain observed distribution.

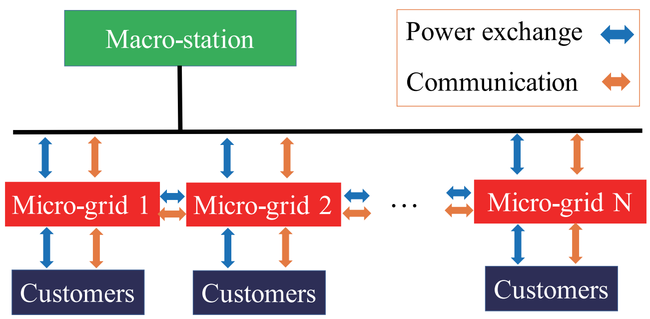


Fig. 1. The construction of considered model

When $D_i(t) \neq 0$, $micro\text{-}grid_i$ will exchange power with other micro-grids or the macro-station. It will cause power loss. For simplicity, two kinds of power losses will be considered in our model. The first one is Power Loss due to Transmission (PLT)([9]). To alleviate power loss of long-distance transmission, voltage between primary power station to macro-station is high (e.g., 50 kV [9]) while that between micro-grid and macro-station is middle (e.g., 22 kV [9]). Therefore, high voltage will be converted into middle voltage. This process will cause the other power loss named Power Loss due to Conversion (PLC).

First, the power loss between two micro-grids are considered. Based on [9], if $micro\text{-}grid_i$ transmits power to $micro\text{-}grid_j$, the power loss function $P_{ij}(t)$ can be expressed as follows.

$$P_{ij}(t) = \frac{R_{ij} Q_{ij}^2(t)}{U_1^2}, \tag{2}$$

where R_{ij} is the resistance of the distribution line between $micro\text{-}grid_i$ and $micro\text{-}grid_j$. U_1 denotes the transfer voltage between $micro\text{-}grid_i$ and $micro\text{-}grid_j$ and it is less than U_0. In this model, we do not consider the power loss of transforming between $micro\text{-}grid_i$ and $micro\text{-}grid_j$. Also, $Q_{ij}(t)$ is defined as.

$$Q_{ij}(t) = \begin{cases} \frac{Q_{ij}^2(t) R_{ij}}{U_1^2} - D_j(t) : |D_i(t)| > |D_j(t)| \\ D_i(t) \quad :otherwise. \end{cases} \tag{3}$$

If $micro\text{-}grid_i$ sells power to $micro\text{-}grid_j$, the current remaining power $D_i(t)$ will be updated as:

$$D_i(t) = D_i(t) - Q_{ij}(t). \tag{4}$$

If $micro\text{-}grid_i$ buys power from $micro\text{-}grid_j$, $D_i(t)$ will be updated as follow:

$$D_i(t) = \min\{D_i(t) + Q_{ij}(t) - PL_{ij}(t), 0\}. \tag{5}$$

After exchanging power with other micro-grids, if $D_i \neq 0$, $micro\text{-}grid_i$ will exchange power with the macro-station. In this process, we consider two kinds of power losses, namely PLT and PLC ([9]). If $micro\text{-}grid_i$ wants to sell $D_i(t)$ to the macro-station ($D_i(t) > 0$) or buy $D_i(t)$ from the macro-station ($D_i(t) < 0$), we are able to express the power loss $PL_{0i}(t)$ as follows.

$$PL_{0i}(t) = \frac{R_{0i} Q_{0i}^2(t)}{U_0^2} + \alpha Q_{0i}(t), \tag{6}$$

where R_{0i} is the distribution line resistance between the macro-station and $micro\text{-}grid_i$, the voltage of power transfer between the $micro\text{-}grid_i$ and the macro-station is U_0, and α is a fraction of power loss caused by voltage conversion. For simplicity, α is treated as a constant ([9]). $Q_{0i}(t)$ is the power that $micro\text{-}grid_i$ wants to buy or sell. The value of $Q_{0i}(t)$ is any of the following.

$$Q_{0i}(t) = \begin{cases} \frac{Q_{0i}^2(t) R_{ij}}{U_0^2} + \alpha Q_{0i}(t) - D_i(t) & : \quad D_i(t) < 0 \\ D_i(t) & : \quad otherwise. \end{cases} \tag{7}$$

Based on eqs. (2) and (6), in a given time slot t, the total power loss of the i^{th} micro-grid $PLA_i(t)$ is,

$$PLA_i(t) = PL_{0i}(t) + \sum_j \frac{PL_{ij}(t)}{2}. \tag{8}$$

If $micro\text{-}grid_i$ exchanges power with $micro\text{-}grid_j$, power loss $PL_{ij}(t)$ should not be calculated twice. Therefore, $PLA_i(t)$ includes half of $PL_{ij}(t)$.

Our research target is to minimize the total power loss. Hence, the objective function is,

$$\begin{aligned} &Minimize \sum_i PLA_i(t) \\ &s.t. \quad D_i(t) \leq G_i(t) + \eta_i(t) \quad \forall i \in \mathcal{N}, \end{aligned} \tag{9}$$

where $\eta_i(t) = sign(D_i(t))Q_{0i}(t) - PL_{0i}(t) + \sum_j (sign(D_i(t))Q_{ij}(t) - PL_{ij}(t))$, $sign(D_i(t)) = 1$ if $D_i(t) < 0$, and $sign(D_i(t)) = -1$ otherwise. Therefore, our condition is that the demand at each micro-grid does not exceed the sum of the amount of remaining produced power and the power it exchanged with other micro-grids and the macro-station.

IV. Algorithm for Power Exchange

In Section III, the model and functions are discussed. Based on these functions, the total power loss of smart grid could be calculated. However, unlike centralized algorithm, the micro-grids do not acquaint the total information. They just know the locations of one-hop neighbor(s) and exchange power with it/them.

At the beginning of time slot t, $micro\text{-}grid_i$ receives $W_i(t)$ from the customers. To meet $W_i(t)$, $micro\text{-}grid_i$ generates power $G_i(t)$. If current remaining power of $micro\text{-}grid_i$ $D_i(t) \neq 0$, $micro\text{-}grid_i$ will exchange power with its neighbor(s). The $micro\text{-}grid_i$ will exchange information of $D_i(t)$ with its neighbors. Based on the remaining power of neighbors, $micro\text{-}grid_i$ generates a set of Potential Exchange power Neighbors (PEN). This set means that if $micro\text{-}grid_j \in PEN$, $micro\text{-}grid_i$ has opportunity to exchange power to $micro\text{-}grid_j$. If PEN of $micro\text{-}grid_i$ has more than one element, it needs to choose proper neighbor to exchange power, so as to minimize the total power loss. The "Reducing power loss per Unit exchanged Power" (RUP) of $micro\text{-}grid_i$ and $micro\text{-}grid_j$ for the micro-grid pair can deal with this problem. If $micro\text{-}grid_i$ exchanges power with $micro\text{-}grid_j$, the function is expressed below,

$$RUP(Q_{ij}(t)) = \frac{PL_{0i}(t) + PL_{0j}(t) - PL_{ij}(t)}{|Q_{ij}(t)|}. \qquad (10)$$

This function represents potential extra payoffs (reducing power loss) per unit exchange power, if $micro\text{-}grid_i$ joins the coalition. $PL_{0i}(t)$ and $PL_{0j}(t)$ represent power loses if the same power $Q_{ij}(t)$ was exchanged with macro-station by both micro-grids, in the current coalition. Merging them could replace these two by power exchange between them, with power loss $PL_{ij}(t)$. Higher values of RUP mean saving power per unit power. Therefore, based on eq. (10), the micro-grids can make the best decisions to merge their coalitions.

The $micro\text{-}grid_i$ calculates RUP (eq. 10) of PEN and sorts PEN in descending order according to RUP. Then, $micro\text{-}grid_i$ considers the first element j from PEN, if PEN is not empty. $Micro\text{-}grid_i$ sends $D_i(t)$ to $micro\text{-}grid_j$, waits for the response from $micro\text{-}grid_j$ unless time-out occurs. If $micro\text{-}grid_i$ receives "accept" response from $micro\text{-}grid_j$, it will exchange power with $micro\text{-}grid_i$, based on $D_i(t)$ and $D_j(t)$, delete j from PEN, and update $D_i(t)$. $Micro\text{-}grid_j$ will be deleted when $micro\text{-}grid_i$ is waiting for the response from $micro\text{-}grid_j$ and time-out occurs, or the response is "reject". At the same time, $micro\text{-}grid_i$ receives offers from its neighbors as well. If $micro\text{-}grid_i$ is waiting the response from the first element of PEN j and receives the offer from other neighbor $k (k \neq j)$, the status of $micro\text{-}grid_k$ will be set as "hold" and the hold message is returned. The neighbor k will not be deleted until time-out occurs. The above action will not repeated until $D_i(t) = 0$ or PEN is empty. After exchanging power with one-hip neighbors, $D_i(t)$ has been updated by the quantities of exchanged powers. If $D_i(t) \neq 0$, $micro\text{-}grid_i$ will exchange power with the macro-station. For instance, assume that there are one macro-station (MS) and five micro-grids (MG1 to MG5) (2). RUP_{12}=1.2, RUP_{23}=2, RUP_{34}=3.5, and RUP_{45}=4. Based on those RUPs, MG1 will send offer to MG2, MG2 will send offer to MG3, MG3 will send offer to MG4, and MG5 will send offer to MG4. Because MG4 sends offer to MG5 and waits the response, MG4 will send "hold" to MG3. In the same manner, MG3 and MG2 send "hold" to MG2 and MG1, respectively. When MG4 receives response from MG5, they will exchange power. Because PL_{45}=0.2, Q_{45}=1.3. After that D_4=D_5=0 and MG4 sends "reject" to MG3. When MG3 receives "reject", it will activate the offer of MG2 and exchange power with MG2 (Q_{23}=3). Therefore, MG1 receives "reject" from MG2, after power transmission between MG2 and MG3 (D_2=D_3=0). Finally, MG1 will exchange power with the MS ($Q_{01} = 3.5$).

Algorithm 1 DISTRIBUTED POWER EXCHANGE ALGORITHM OF MICRO-GRIDs (Input: $W_i(t)$, $G_i(t)$, Output: $Q_{ij}(t)$, $Q_{0i}(t)$, and $PLA_i(t)$)

```
BEGIN
 for each micro-grid i
 Loop
   Calculate D_i(t), based on W_i(t), G_i(t) (eq. 1)
   While (D_i(t) ≠ 0)
    Send information of D_i(t) with its neighbors.
    Generate PEN, calculate RUP of PEN and sort PEN
    While (D_i(t) ≠ 0 and PEN is not empty)
     Get first element of PEN j
     If (j.status==hold and time-out occur)
      Delete j from PEN
     Else
      Send offer to micro-grid_j and wait response
      while (time-out does not occur)
       If (the response from j =="accept")
        exchange power with j, calculate Q_ij(t), PL_ij(t)
based on eqs. 2, 3, update D_i(t) and delete j from PEN.
       Endif
       If (receive offer from neighbor k and k ≠ j)
        k.status=hold and send "hold" to k
       Endif
      Endwhile
     Delete j from PEN
     Endif
    Endwhile
    If (D_i(t) ≠ 0)
     Calculate Q_0i(t), PL_0i(t) based on eqs. 6 and 7 and
D_i(t)=0
    Else
     If receive offer from neighbor l
      Send "reject" to the neighbor l
     Endif
    Endif
   Endwhile
 Endloop
END
```

Theorem 4.1: The solution of Algorithm 1 is Pareto Optimal.

Proof: Assume that the solution $(a_1, a_2, ..., a_N)$ is not Pareto Optimal. Therefore, there exists a micro-grid $l \in N$ least, which can adjust its action a_l to a_l^* so as to augment its utility while utilities of others will not be diminished. In other words, $u(a_l, a_{-l}) < u(a_l^*, a_{-l})$. Because the algorithm could help micro-grids to find the most proper neighbors and exchange power so as to maximize their payoff, micro-grids cannot augment their utilities through change the solution of

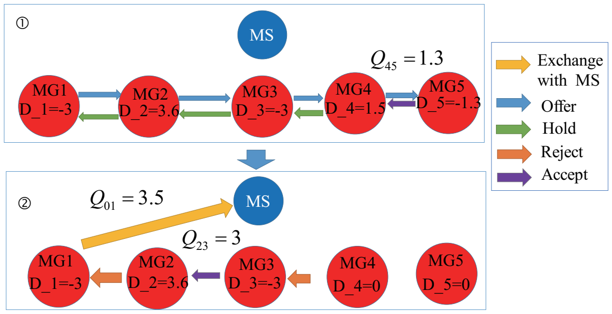


Fig. 2. A simple example showing how the algorithm 1 lead to power exchange between micro-grids and macro-station with minimized power loss.

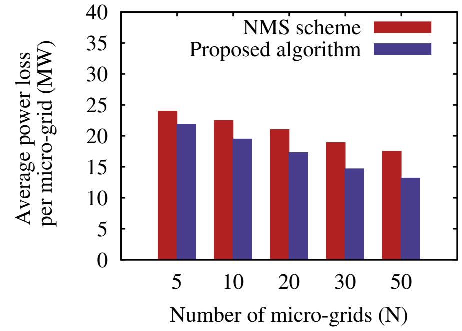


Fig. 3. Comparison of the average power loss in the NMS scheme and our proposal.

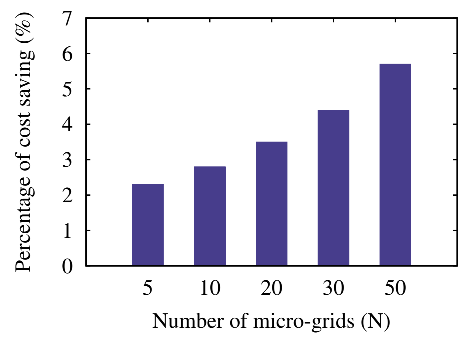


Fig. 4. The percentage of cost saving using our proposal compared with the NMS algorithm.

the algorithm. Therefore, $u(a_l, a_{-l}) \geq u(a_l^*, a_{-l}) \quad \forall a_l^* \in A_l$. This result contradicts the previous assumption that the solution is not Pareto Optimal. ■

V. Performance Evaluation

In this section, simulation results are presented to evaluate the effectiveness of our proposed algorithm. The performance of our proposed scheme is compared with that of a distributed algorithm dubbed as NMS used in [9] (The micro-grids will choose the nearest neighboring micro-grid to exchange power) and our previous centralized work GT-CFS [5]. Our considered simulation scenario comprises a power distribution grid topology, area of which $10 \times 10\ km^2$. The macro-station is placed at the center of the grid, and the micro-grids are deployed randomly in the topology. Each micro-grid is linked with its one-hop neighbouring micro-grid and the macro-station. Similar to the assumption made by [9], the power demands of the customers $W_i(t)$ of $micro\text{-}grid_i$ is derived from a Gaussian distribution between 10 MW and 316 MW. The power generation $G_i(t)$ is obtained from a Gaussian distribution between 10 MW and 316 MW. The resistance between the micro-grids is the same as that between the macro-station and any micro-grid, and its value $R = 0.2\ \Omega$ per km. The fraction number of power conversion $\alpha = 0.02$ according to the assumption in [10]. The voltage values of U_0 and U_1 are set to 50 kV and 22 kV, respectively, which represent practical values in a variety of smart grid distribution networks [10]. The prices of the each of the unit power are set as $w_1 = 1$ and $w_2 = 3$ [5]. The simulation results are presented in the remainder of this section.

Fig. 3 depicts the average power loss per micro-grid for varying number of micro-grids from 5 to 50 in case of a conventional algorithm called NMS [9] (micro-grids will find the nearest micro-grid to exchange power) and our proposed algorithm. The results in the figure indicates that when the number of micro-grids increases, the power losses decrease. However, the result of our proposed algorithm is less than that in NMS algorithm. The reason is that in our algorithm the total power loss is considered, global optimal is better than local optimal. By using out proposal, the micro-grids could find the proper one-hip neighbors to exchange power, so as to minimize the total power loss.

Fig. 4 demonstrates the percentage of cost saving using our proposal compared with the NMS algorithm. As shown in the figure, when the number of micro-grids increases, the percentage becomes bigger. This is because our proposal could help micro-grids to find proper neighbor so as to minimize the total power loss and saving the money. Hence, our algorithm will help the entire power grid to save a significant amount of money in contrast with the NMS algorithm.

Fig. 5 demonstrates that the macro-station in the NMS case needs to supply more power for the micro-girds to meet their demands than that in our proposal. The reason is that in the NMS case, micro-grids only exchange power with the nearest one-hip neighboring micro-grids and it did not consider the total power loss while by using our algorithm micro-grids could exchange power with others so as to reduce the total power loss. Higher power loss will cause higher power load from the macro-station. Therefore, the proposed algorithm helps the macro-station to decrease the peak of power generation and improve efficiency of power.

Next, let us consider the comparison in centralized algorithm and our proposal. In centralized algorithm, the micro-grids will send demands to the data center (e.g., macro-station). The macro-station will help all the micro-grids to find proper neighbors, as it knows all the information of the micro-grids. However, in distributed system, the micro-grids only know the demands of one-hip neighbors. By using our proposal, the micro-grids will send the demands to one-hip

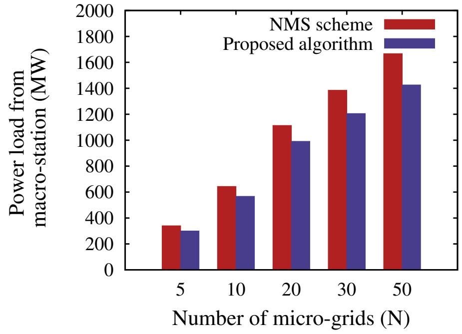
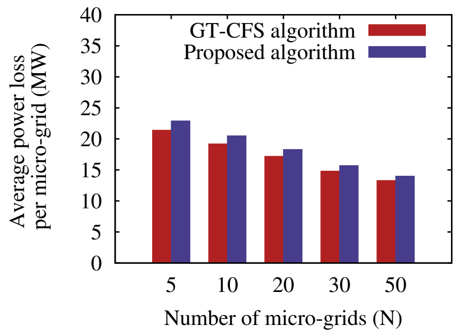
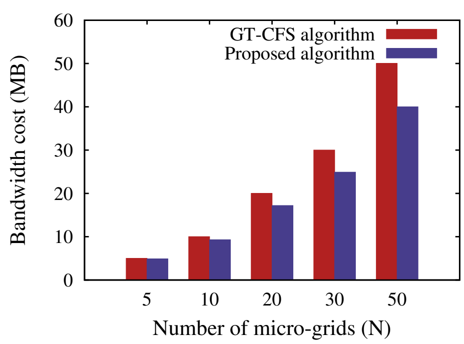


Fig. 5. The power load on the macro-station in NMS case and our proposal.



(a) Average power loss



(b) The bandwidth cost

Fig. 6. The comparison in GT-CFS and our proposal.

neighbors so as to minimize the total power loss. If the time-out occurs, the micro-grids will give up this neighbor and try to exchange power with other neighbors. And it could add power loss. Therefore, the average power loss in our proposal is sightly more than that in centralized algorithm (e.g., GT-CFS). The fig. 6(a) talks about it. In the other hand, because the micro-grids do not send information to the data center, the communication bandwidth cost in our proposal is less than that in the centralized algorithm. Therefore, from Fig. 6(b), we can see that the communication bandwidth cost in our proposal is less than that in our previous work GT-CFS. It means that by using our algorithm, more micro-grids could share the fixed bandwidth by using our proposal than that in GT-CFS.

VI. Conclusion

In this paper, we proposed a novel cooperative power exchange algorithm for the distributed micro-grids. Our proposal allows the micro-grids to form coalitions so as to minimize the total power loss, when power is transmitted from a micro-grid to other micro-grids or the macro-station. The proposed algorithm also allows the micro-grids to make decisions on whether to form or break the coalitions while maximizing their utility functions through alleviating the power loss. Through simulation results, the effectiveness of our algorithm is verified. Comparative results demonstrate its superior performance, in contrast with the conventional NMS algorithm and our previous work GT-CFS. In the future, it will be interesting to analyze the interactions of the customers with their corresponding micro-grids with power storage devices to explore possibility of formulating more effective coalitions and reduce further total power loss in the realistic power system.

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References

[1] Z. M. Fadlullah, M. M. Fouda, N. Kato, A. Takeuchi, N. Iwasaki, and Y. Nozaki, "Towards Intelligent Machine-to-Machine Communications in Smart Grid," *IEEE Communications Magazine*, vol. 49, no. 4, pp. 60-65, Apr. 2011.

[2] L. Zheng and L. Cai, "A Distributed Demand Response Control Strategy Using Lyapunov Optimization," *IEEE Trans. on Smart Grid*, vol. 5, no. 4, pp. 2075-2083, July 2014.

[3] Z. M. Fadlullah, Y. Nozaki, A. Takeuchi, and N. Kato, "A survey of game theoretic approaches in smart grid", *IEEE Wireless Communications and Signal Processing (WCSP)*, pp.1-4, 2011.

[4] Z. M. Fadlullah, D. M. Quan, N. Kato, and I. Stojmenovic, "GTES: An Optimized Game-Theoretic Demand Side Management Scheme for Smart Grid," *IEEE System Journal*, to appear (available online).

[5] Chao Wei, Z.Md. Fadlullah, N. Kato, and A. Takeuchi, "GT-CFS: A Game Theoretic Coalition Formulation Strategy for Reducing Power Loss in Micro Grids," *IEEE Transactions on Parallel and Distributed Systemacro-station*, July 13, 2013.

[6] Rongxin Lu, Xiaodong Lin, and Xuemin Shen "UDP: Usage-Based Dynamic Pricing With Privacy Preservation for Smart Grid", *IEEE Transactions on Smart Grid*, vol.4, issue 1, pp.141-150, 2013.

[7] Julio Romero Aguero, "Improving the efficiency of power distribution systems through technical and non-technical losses reduction", *Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES* , pp.1-8, 2012.

[8] L. McDonald, R.L. Storry, A. Kane, F. McNicol, G. Ault, I. Kockar, S. McArthur,E. Davidson, and M. Dolan," Minimisation of distribution network real power losses using a smart grid Active Network Management System", *Universities Power Engineering Conference (UPEC), 2010 45th International* , pp.1-6 , 2010.

[9] W. Saad, Han Zhu, and H.V. Poor, "Coalitional Game Theory for Cooperative Micro-Grid Distribution Networks", *IEEE International Conference on Communications Workshops (ICC)*, pp.1-5, 2011.

[10] J. Machowski, J.R. Bialek and J.R. Bumly, "power systems dynamics: Stability and Control", New York, USA: Wiley, 2008