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On Optimally Reducing Power Loss in Micro-Grids with Power Storage Devices

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***Abstract*—Smart micro-grids can produce "renewable" energy and store them in power storage devices. Power loss, however, is a significant problem in power exchange among the micro-grids, and also between the macro-station and individual micro-grids. To optimally reduce the total power losses in such a power grid system, in this paper, a greedy coalition formation algorithm is proposed, which allows the macro-station to coordinate mutual power exchange among the micro-grids and between each micro-grid and macro-station. Our algorithm optimizes the total power losses across the entire power grid, including the cost of charging and discharging power storage devices, and power losses due to power transfers. The algorithm creates exchange pairs among the micro-grids giving priority to pairs with higher power loss reduction per exchanged power unit. Through computer-based simulations, we demonstrate that the proposed approach significantly reduces the average power loss compared with the conventional non-cooperative method. The simulations also demonstrates that the communications overhead of our proposal (due to negotiations aimed at forming coalitions) does not significantly affect the available communication resource.**

***Index Terms*—power storage devices, micro grid, smart grid, greedy algorithm.**

I. Introduction

THE next-generation smart power grid concept [1] makes use of bi-directional communication driven demand-response based power generation scheduling at the macro-station [2], [3]. It can be enhanced by distributed (e.g., community-specific) micro-grids, which may locally generate, distribute, and regulate the flow of electricity to consumers. Smart micro-grids integrate renewable resources on the community level and allow for customers' participation in the electricity enterprise [4]. In this paper, we specifically focus on the next-generation power system comprising micro-grids.

A micro-grid delivers power to residential consumers, companies, schools, hospitals, and so on. The demands of these users, however, are subject to variation during each day [5][6][7], e.g., during peak periods when the total demand may approach/exceed the supply power. To meet the demands of the users, micro-grids may purchase additional power from the macro-station and/or from other micro-grids. Micro-grids can also exploit power storage devices (e.g., batteries, plug-in hybrid electric vehicles (PHEVs), etc.,) which could be charged during the off-peak hours and discharged during the peak period to meet the demands of the users. However, both techniques increase the power losses. There are different kinds of power losses during the power exchange. When power is transmitted, heated power distribution lines cause transmission power loss. Also, storage power loss occurs during charging and discharging process. Additionally, transmission power loss caused by obtaining power from a nearby micro-grid is lower than that from a distant micro-grid. Therefore, there is a need to design an efficient algorithm to optimally reduce the total power losses in a smart micro-grids-based power system.

In this paper, we aim to explore a game-theoretic method to allow micro-grids' coalitions formation to minimize the total power losses in the micro-grids having power storage devices. Toward this target, our main challenge is how to encourage the micro-grids to form coalitions while minimizing power losses.

The main idea in our proposed solution is to communicate power exchange needs from micro-grids to the macro-station. The macro-station will calculate reduced power losses per power unit for each pair of micro-grids, sort them, and create exchange pairs by a greedy algorithm (following sorted order and making updates) until all demands are met. By forming coalition and exchanging power among the micro-grids, the total power loss will be reduced, which directly generates additional monetary payoffs. The extra payoff will be distributed by power exchanging among the micro-grids (where both of seller and buyer save power).

The remainder of our paper is organized as follows. The background and related works are discussed in Section II. Our problem statement and considered micro-grids based power system model are presented in Section **??**. In Section IV, our coalition formation algorithm for the micro-grids is proposed. We prove that our proposed approach is stable and convergent. In Section V, computer-based simulation results are presented to evaluate the performance of our proposal. Conclusion is drawn in Section VI.

II. Background and Related Works

Energy management in the smart grid received a lot of attention recently, e.g., in sensor network controlled lighting systems [8]. Arefifar *et al.* presented systematic and optimized approaches, with optimized self-adequacy, for the power distribution system containing a set of micro-grids [9]. Niyato *et al.* [10] proposed an algorithm, which optimizes the transmission strategy to minimize the total cost. The problem of minimizing power losses in distribution networks has been traditionally investigated by using a single, deterministic demand level. Also, power loss issues were addressed in [12]-[16].

In [4], a game theoretic coalition formulation strategy, named GT-CFS, for reducing power loss in micro-grids was proposed. The work in [4] allowed the micro-grids to form coalitions and exchange power with other micro-grids and/or

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the macro-station. However, in that model, the considered micro-grids were not assumed to use power storage devices. Recently, micro-grid developers and operators reported that lithium-ion batteries and flow batteries are quite capable of providing exceptional renewable energy integration services in micro-grids based power systems [11]. Power storage might lead to improved power management in micro-grids exploiting renewable energy sources [17]-[19]. The storage devices match energy generation to consumption, facilitating a smooth and robust energy balance within the micro-grid. Particularly, Ahn *et al.* [17] focused on an optimal control of the micro-grids' power storage devices. Whereby stored energy was controlled to balance power generation of renewable sources to optimize the overall power consumption at the micro-grid.

Existing power loss minimization and power storage techniques do not encompass all the power losses affecting the power system comprising the macro-station, numerous micro-grids and power storage devices. Usually they only discuss how to reduce the power loss within an individual micro-grid, or how to charge or discharge power within individual power storage devices. On the other hand, in this paper, we focus on a envisioning total power loss minimization approach across the entire smart grid that is managed centrally by the macro-station.

III. System Model and Problem Statement

The parameters used in this paper are presented in Tab.I.

TABLE I
PARAMETERS DECLARATION

Parameter	Definition
$G_i(t)$	Generation power of i^{th} micro-grid of slot t
$U_i(t)$	Actual supply power of i^{th} micro-grid of slot t
β_i	Storage power loss ratio of i^{th} micro-grid
$S_i(t)$	Currently stored power of i^{th} micro-grid within slot t
$S0_i(t)$	Stored power of i^{th} micro-grid at the beginning of slot t
$D_i(t)$	Demand of users linked to i^{th} micro-grid of slot t
$W_i(t)$	Currently remaining power of i^{th} micro-grid within slot t
$B_{0i}(t)$	Actual exchange power between i^{th} micro-grid and the macro-station of slot t
$\delta_i(t)$	Power that i^{th} micro-grid wants to sell or buy from the macro-station of slot t
$B_{ij}(t)$	Actual exchange power between i^{th} micro-grid and j^{th} micro-grid of slot t
α	Conversion power loss ratio
θ_i	Generation power loss ratio of i^{th} micro-grid
θ_0	Generation power loss ratio of macro-station
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
$PLG_i(t)$	Power loss due to power generation 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
$PLS_i(t)$	Power loss due to power storage of slot t
$PLA_i(t)$	Total power loss of i^{th} micro-grid of slot t
S_{max}	Maximum of power storage devices

There are three layers in our considered system model, as depicted in Fig. 1. The first layer is the macro-station. It can sell power or buy the power surplus from the micro-grids, using power distribution lines between them. The second layer comprises the micro-grids, which are capable of generating power by using various renewable resources such as wind farm, solar panel, PHEVs, and so on. The generated power can be transmitted from the micro-grids to the end-users according to their demands. Additionally, the micro-grids are assumed to have power storage devices (e.g., batteries, PHEVs, flywheels, and so forth). Although their initial deployment may be relatively expensive, power storage devices in the micro-grids can save the power in off-peak time and use it during the peak time, and minimize the total power loss while meeting the users' demands. Finally, the users, who obtain power from their respective micro-grids, form the last layer of our considered system.

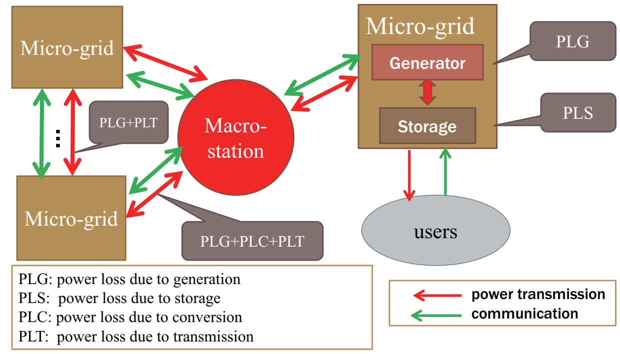


Fig. 1. Micro-grids based power delivery system and different types of power losses that affect it.

Let $\mathcal{N}$ denote the set of micro-grids $micro\text{-}grid_i$ $(1 \leq i \leq N)$, and $N = |\mathcal{N}|$. Power generation, storage, and transmission will cause power losses. Compared with the generated, saved and delivered power, the total power losses across the considered system are typically not negligible. We will consider four kinds of power losses, due to generation (PLG) (see [20]), storage (PLS) [21], transmission (PLT) and conversion (PLC) [4]. The other types of power losses are assumed to be negligible. This includes also power loss solely due to storage over time; that is, we only consider storage loss due to charging and discharging processes.

We assume that time is slotted and discretized, and normalized to $t = 0, 1, \ldots$ which conveniently may refer to the status at the beginning of the slot or during the slot before the next one starts. At the beginning of slot t, $micro\text{-}grid_i$ stores power $S0_i(t) = S_i(t-1)$. $S_i(t)$ denotes stored power during slot t and is a variable amount, affected by charging and discharging during the time slot; when slot t starts, the last value of $S_i(t-1)$ at the previous slot is the value for $S0_i(t)$ at the beginning of new slot.

At the beginning of time slot t, to minimize the total power loss, $micro\text{-}grid_i$ needs to know, as input, the total demand $D_i(t)$ from users who are linked to it, stored power $S0_i(t)$, and generated power $G_i(t)$.

$G_i(t)$ and $D_i(t)$ distributions were studied in [22]. The power loss $PLG_i(t)$ associated with $G_i(t)$ is:

$$PLG_i(t) = \theta_i G_i(t), \tag{1}$$

where θ_i is generation power loss ratio of i^{th} micro-grid. Therefore, the actual supply power $U_i(t)$ is:

$$U_i(t) = (1 - \theta_i)G_i(t). \tag{2}$$

$Micro\text{-}grid_i$ will first act on its own input and make some decisions to respond to the received demand directly. It will use newly generated power first, if possible, to fully meet the requested demand from users. In that case, $U_i(t) > D_i(t)$ and stored power will not be affected ($S_i(t) = S0_i(t)$). This power surplus could be exchanged to other micro-grids or the macro-station. The power $W_i(t)$ remaining for exchange is

$$W_i(t) = (1 - \beta_i)S0_i(t) + U_i(t) - D_i(t). \tag{3}$$

Further, demand is changed to $D_i(t) = 0$, while the current remaining power is reduced $W_i(t) = U_i(t) - D_i(t)$.

If not, user demand could be met with the help of stored power. If $(1 - \beta_i)S0_i(t) + U_i(t) \le D_i(t)$ then all generated power and all power storage will be used, and afterwards $W_i(t) = D_i(t) - U_i(t) - (1-\beta_i)S0_i(t)$, $U_i(t) = 0$, and $S_i(t) = 0$. β_i is the storage power loss ratio of $micro\text{-}grid_i$. The remaining power demand $W_i(t)$ is given by the same equation above. $W_i(t) < 0$ in this case indicates that $micro\text{-}grid_i$ needs to buy power from other micro-grids or the macro-station.

In the remaining case, newly generated power $U_i(t)$ and stored power $S0_i(t)$ suffice to meet the demand. We decide that newly generated power is used in full and is helped with the portion of storage needed. The remaining stored power is then $S_i(t) = S0_i(t) - (D_i(t) - U_i(t))/(1 - \beta_i)$. Further, demand and generation are changed to $D_i(t) = 0$ and $U_i(t) = 0$, respectively. In this case, $W_i(t) \ge 0$. If $W_i(t) = 0$, the micro-grid does not participate in the power exchange.

The corresponding power loss $PLS_i(t)$ is expressed as

$$PLS_i(t) = \begin{cases} 0: \quad U_i(t) > D_i(t) \\ \beta_i S0_i(t) : (1 - \beta_i)S0_i(t) + U_i(t) \le D_i(i) \\ \frac{\beta_i}{1-\beta_i}(D_i(t) - U_i(t)) : otherwise. \end{cases} \tag{4}$$

However, power losses (in all three cases) are not considered in the optimization formula, because they occurred internally in micro-grid, before it contacted macro-station. They are, for simplicity, treated as natural losses in each micro-grid. The optimization formula makes use of power storage loss $PLS_i(t)$ due to storage charging or discharging process as part of power exchange.

To minimize the total power loss, the micro-grids will consider selling/buying power from other micro-grids when the power losses between them are less than those between the micro-grids and the macro-station. To minimize the total power loss, the macro-station receives the following information from $micro\text{-}grid_i$: $W_i(t)$ and $S_i(t)$. $PLG_i(t)$ and $PLS_i(t)$ (the portion already experienced) could be also communicated so that macro-station can calculate the total power losses in the system, but are not needed to macro-station in the optimization process for power exchanging decisions. $PLG_i(t)$ is the percentage of generated power and the loss occurs in the micro-grid alone. $PLS_i(t)$ is partially experienced before contacting macro-station, and partially derived by macro-station as the outcome of the optimization process.

When the macro-station receives the information, it helps $micro\text{-}grid_i$ to find proper neighbor j to exchange power $B_{ij}(t)$. It calculates the corresponding power loss is $PL_{ij}(t)$. The value of $W_i(t)$ will be updated based on $B_{ij}(t)$. The exchange pair $(i,\ j)$ is generated. The action will continue until $W_i(t)$=0 or no proper neighbor exists (e.g., when power loss between available micro-grids is more than between micro-grid and the macro-station). Afterwards, the value of $W_i(t)$ has been updated. Power exchange between micro-grid and macro-station causes power loss $P_{0i}(t)$. The macro-station will calculate $B_{ij}(t), B_{0i}(t)$, update $S_i(t)$ and inform $micro\text{-}grid_i$. $Micro\text{-}grid_i$ will follow and exchange power with $micro\text{-}grid_j$ and/or the macro-station, and discharge or charge accordingly. Additionally, if power is charged or discharged, $S_i(t)$ and $PLS_i(t)$ will be updated in the micro-grid.

Overall, the input of algorithm are $G_i(t)$ and $D_i(t)$ at each micro-grid, and the outputs are the exchange power pairs $(i,\ j)$ ($micro\text{-}grid_i$ should exchange power with $micro\text{-}grid_j$), corresponding power $B_{ij}(t)$, $B_{0i}(t)$, $S_i(t)$, and the sum of power losses $\sum_i PLA_i(t)$.

The macro-station will decide how much power $B_{ij}(t)$ should be exchanged among micro-grids, how much power should be discharged or charged, and how much power $B_{0i}(t)$ to exchange itself with corresponding micro-grid, based on $W_i(t)$ and $S_i(t)$. In a given time slot t (e.g., one hour), the total power loss of the i^{th} micro-grid $PLA_i(t)$ is,

$$PLA_i(t) = PLG_i(t) + PLS_i(t) + PL_{0i}(t) + \sum_j \frac{PL_{ij}(t)}{2}. \tag{5}$$

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

When the micro-grids exchange power with others, they will belong to the same coalition. If a micro-grid does not exchange power with other micro-grids, it is a sole micro-grid in its coalition. The power loss function $v(C_l)$ of coalition C_l is,

$$v(C_l) = -\sum_{i \in C_l} PLA_i(t). \tag{6}$$

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

$$\begin{aligned} &\textit{Maximize} \sum_l v(C_l) \\ &s.t. \quad D_i(t) \le U_i(t) + (1 - \beta_i)S_i(t) + \eta_i(t) \quad \forall i \in \mathcal{N}, \end{aligned} \tag{7}$$

where $\eta_i(t) = sign(W_i(t))B_{0i}(t) - PL_{0i}(t) + \sum_j (sign(W_i(t))B_{ij}(t) - PL_{ij})(t)$, $sign(W_i(t)) = 1$ if $W_i(t) < 0$, and $sign(W_i(t)) = -1$ otherwise. Therefore, our condition is that (after the preliminary step of meeting own demands first when possible) the demand at each micro-grid does not exceed the sum of the amount of remaining produced power, and stored power, and the power it exchanged with other micro-grids and macro-station. Therefore it allows for a non-negative balance to be stored in its power storage for the next time period.

Consider the power loss among the micro-grids. Because the voltage among the micro-grids are medium level voltage, the conversion power loss can be neglected [23]. Power transmission will cause PLT. Based on [23], if $micro\text{-}grid_i$ sells power to $micro\text{-}grid_j$, the power loss function $PL_{ij}(t)$ can be expressed as

$$PL_{ij}(t) = \frac{R_{ij} B_{ij}^2(t)}{U_1^2}, \quad (8)$$

where

$$B_{ij}(t) = \begin{cases} \frac{B_{ij}^2(t) R_{ij}}{U_1^2} - W_j(t) : |W_i(t)| > |W_j(t)| \\ W_i(t) \quad :otherwise. \end{cases} \quad (9)$$

This is quadratic equation in $B_{ij}(t)$ and therefore the optimal power exchanged between two micro-grids in not necessarily equal to the lower amount among them. The difference, however, is the power loss $PL_{ij}(t)$ due to the exchange. The "buyer" $micro\text{-}grid_j$ will receive all its needed power $W_j(t)$ if possible, and quadratic equation will only decide how much power the "seller" $micro\text{-}grid_i$ needs to send. Otherwise $micro\text{-}grid_i$ (the "seller") cannot meet the demand of $micro\text{-}grid_j$ (the "buyer"), and the seller only sells $W_i(t)$ to $micro\text{-}grid_j$. If $micro\text{-}grid_i$ sells power to $micro\text{-}grid_j$, the current remaining power $W_i(t)$ will be updated as:

$$W_i(t) = W_i(t) - B_{ij}(t). \quad (10)$$

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

$$W_i(t) = \min\{W_i(t) + B_{ij}(t) - PL_{ij}(t), 0\}. \quad (11)$$

Therefore, the power loss is experienced at the receiving micro-grid, and not at the "seller" side. The maximum power that $micro\text{-}grid_i$ could buy is $|W_i(t)|$. In this case, $S_i(t) = 0$, to minimize total power loss. Based on the value of $W_i(t)$, $S_i(t)$ and $PLS_i(t)$ could be updated, and the power that $micro\text{-}grid_i$ wants to exchange with the macro-station $\delta_i(t)$ could be calculated as per following three cases.

Case 1: If $W_i(t) < 0$, then $micro\text{-}grid_i$ needs power and $S_i(t)$=0. Therefore, $micro\text{-}grid_i$ needs to buy power $\delta_i(t) = W_i(t)$ from the macro-station.

Case 2: If $W_i(t) \geq (1 - \beta_i)S_i(t) > 0$, power will be charged and transmitted to the macro-station. Assume that $\mu_i = W_i(t) - (1 - \beta_i)S_i(t)$ and $\lambda_i = S_{max} - S_i(t)$. Therefore, $S_i(t) = \min\{((1 - \beta_i)\mu_i + S_i(t)), S_{max}\}$. In addition, $PLS_i(t) = PLS_i(t) + \beta_i\mu_i$ and $\delta_i(t) = 0$ if $S_i(t) \neq S_{max}$, otherwise $PLS_i(t) = PLS_i(t) + \lambda_i\beta_i/(1-\beta_i)$ and $\delta_i = \mu_i - \lambda_i/(1 - \beta_i)$.

Case 3: If $(1 - \beta_i)S_i(t) > W_i(t) > 0$ then power will be discharged and transmitted to other micro-grids to meet their demands. Assume that $\gamma_i = S_i(t) - W_i(t)/(1 - \beta_i)$. Hence, $S_i(t) = W_i(t)/(1 - \beta_i)$, $PLS_i(t) = PLS_i(t) + \beta_i\gamma_i$, and $\delta_i(t) = 0$.

In these expressions of, $S_i(t)$ on the right side is the remaining storage after attenuating storage from the power surplus is charged. This storage is augmented after the outcome in the current time period, to provide input storage for the next time period.

If $\delta_i(t) \neq 0$, $micro\text{-}grid_i$ will exchange power with the macro-station. Three kinds of power losses (PLT, PLG, and PLC) are considered. Based on [23], $PLT_{0i}(t) = B_{0i}(t)^2 R_{0i}/U_0^2$ and $PLC_{0i}(t) = \alpha B_{0i}(t)$. Similar with [23], transmission voltages U_0 and U_1 are fixed constants ($U_0 \neq U_1$). Therefore, the power loss between $micro\text{-}grid_i$ and the macro-station, when $B_{0i}(t)$ has been exchanged, is

$$PL_{0i}(t) = \frac{B_{0i}(t)^2 R_{0i}}{U_0^2} + (\alpha + \theta_0)B_{0i}(t), \quad (12)$$

where $B_{0i}(t) = \delta_i(t)$ if $\delta_i(t) \geq 0$, otherwise $B_{0i}(t) = R_{0i}B_{0i}^2(t)/U_0^2 + (\alpha + \theta_0)B_{0i}(t) - \delta_i(t)$. α and θ_0 are power loss ratios of conversion and generation of the macro-station.

The operation time duration t is not discussed in this paper. Its impact is expected to be marginal because of relative stability in power demands in short time.

IV. Coalition Formulation Strategy for Micro-grids with Power Storage Devices

We now describe coalition formation strategy by the macro-station, which makes decision on behalf of all micro-grids. We first introduce a definition from [22] and two rules: *merge* and *split* [24].

Definition IV.1. *Consider two collections of disjoint coalitions $\mathcal{A} = \{A_1, ..., A_i\}$ and $\mathcal{B} = \{B_1, ..., B_j\}$ formed out of the same players. Their corresponding payoffs are given by eq. (7). The payoff of $micro\text{-}grid_i$ in a coalition is assumed to be $-PLA_i(t)$, which we denote $\eta_i(A) = -PLA_i(t)$ and $\eta_i(B) = -PLA_i(t)$, respectively ($PLA_i(t)$ depends on the coalition created). Collection $\mathcal{A}$ is preferred over $\mathcal{B}$ by* Pareto order*, i.e. $\mathcal{A} \triangleright \mathcal{B}$, if and only if $\mathcal{A} \triangleright \mathcal{B} \Leftrightarrow \{\eta_i(\mathcal{A}) \geq \eta_i(\mathcal{B}), \forall i \in \mathcal{A}, \mathcal{B}\}$,with at least one strict inequality ($>$) for a player* i.

The Pareto order means that a group of micro-grids (players) prefers to join a collection $\mathcal{A}$ rather than $\mathcal{B}$, if at least one player is able to improve its payoff when the structure has been changed from $\mathcal{B}$ to $\mathcal{A}$ without cutting down the payoffs of any others.

Definition IV.2. ***Merge:*** *Merge any set of coalitions $\{C_1, ..., C_l\}$ when $\{\cup_{i=1}^{l} C_i\} \triangleright \{C_1, ..., C_l\}$, hence, $\{C_1, ..., C_l\} \rightarrow \{\cup_{i=1}^{l} C_i\}$.*

Definition IV.3. ***Split:*** *Split any coalition $\{\cup_{i=1}^{l} C_i\}$ where $\{\{C_1, ..., C_l\} \triangleright \cup_{i=1}^{l} C_i\}$, hence, $\{\cup_{i=1}^{l} C_i\} \rightarrow \{C_1, ..., C_l\}$.*

The above definitions will help the micro-grids, as players of a cooperative game, to maximize their payoffs, and find the proper micro-grids to form coalitions. We propose coalition formation algorithm for micro-grids and macro-station by exploiting the merge and split operations as shown in Alg. 1.

For $micro\text{-}grid_i$, $W_i(t)$, $S_i(t)$, $PLG_i(t)$ and $PLS_i(t)$ are calculated depending on $G_i(t)$, $S0_i(t)$, and $D_i(t)$. The information I_i ($W_i(t)$, $S_i(t)$, $PLG_i(t)$ and $PLS_i(t)$) is sent to the macro-station. Then $micro\text{-}grid_i$ waits for the response of the macro-station. The macro-station returns ACK message to corresponding micro-grids. If $micro\text{-}grid_i$ does not receive ACK message and if time-out occurs, it will resend its demand to the macro-station. Based on the received information, and the parameters of potential power exchanges among micro-grids, the macro-station generates a set of micro-grid pairs known as Potential Exchange Pair Set of micro-grids (PEPS) $\{(i,j)\}$. Each pair is able to reduce total power loss by exchanging power.

Power exchange among different micro-grids pairs from PEPS causes different power losses. Hence, we need a function to help the macro-station to find the proper micro-grid pairs to exchange power, so as to minimize the total power loss. The "Reducing power loss per Unit 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,

$$RUP(B_{ij}(t)) = \frac{PL_{0i}(t) + PL_{0j}(t) - PL_{ij}(t)}{B_{ij}(t)}. \qquad (13)$$

This function represents potential extra payoffs (reducing power loss) per unit exchange power for the coalition, if $micro\text{-}grid_i$ joins the coalition. $PL_{0i}(t)$ and $PL_{0j}(t)$ represent power loses if the same power $B(i,j)$ was exchanged with the 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 more power per unit power. Therefore, based on eq. (13), the micro-grids can make the best decisions to merge their coalitions. For instance, assume that there are two coalitions (1 and 2); micro-grid a chooses one of them to join so as to reduce power loss. Also assume that the micro-grid a could exchange power with micro-grid b which belongs to the coalition 1, and micro-grid c which belongs to the coalition 2. The demands of the micro-grids are W_a=10, W_b=-11, and W_c=-13. Therefore, exchange powers are B_{ab}=B_{ac}=10, and corresponding power losses are $PL_{ab}(B_{ab})$=2, $PL_{ac}(B_{ac})$=1.5, $PL_{0a}(B_{ab})$=3, $PL_{0b}(B_{ab})$=4, and $PL_{0c}(B_{ac})$=3. Hence, $RUP(B_{ab})$=0.5, $RUP(B_{ac})$=0.45. Based on RUPs, micro-grid a will join the coalition 1, so as to minimize the total power loss.

The macro-station calculates RUP (eq. 13) of PEPS and sorts PEPS in descending order according to RUP, and considers the first element (i,j) from PEPS if PEPS is not empty. It generates exchange power pair (i,j) and exchange power $B_{ij}(t)$. Coalitions containing $micro\text{-}grid_i$ and $micro\text{-}grid_j$ will be merged. If $|B_{ij}(t)| = |W_i(t)|$ then the macro-station deletes the pairs in PEPS that i belongs to, because its demand becomes 0. $W_i(t)$ and $W_j(t)$ will be updated based on $B_{ij}(t)$. This action will continue until PEPS is empty. At this stage, the micro-grids that still need power $((W)_i(t) < 0)$ will receive it from the macro-station. The micro-grids with excessive power $((W)_i(t) > 0)$ will store them in own storage devices.

For instance, assume that there are 4 micro-grids (MG1 to MG4) and a macro-station (MS). In Fig. 2 the negative sign means the MGs need power to meet the demands of the users, zero means supply is equal with demand, positive means the MGs need to sell power to others. Assume that S_1=0, S_2=0, S_3=1, and S_4=3. First, the MGs send their information to the MS, and receive ACK message from the MS. Next, when the MS receives the information, the unordered set PEPS $\{$(1,4), (2,4)$\}$ is generated. Then the MS calculates the RUP of PEPS, and sorts PEPS in descending order according to RUP. Assume that RUP(1,4) = 5 and RUP(2,4) = 3. Hence, PEPS is $\{$(1,4), (2,4)$\}$. Thus MG1 and MG4 could calculate exchange power before MG2 and MG4. Next, the MS gets pair (1,4) from PEPS to generate exchange power pair $(1,4)$ and exchange power B_{14} = 3.8. When MG1 and MG4 exchange power, demand of MG1 will be met. Hence, MG4 will discharge and transmit power to meet W_1, and this process will cause PLT and PLS. After power exchanging, W_1=0, PL_{14}=0.2, and W_4 = 0.97. Because demand of MG1 is met, the MS deletes MG1 from PEPS. Then pair $(2,4)$ is taken from PEPS with $B_{24} = 0.96$ (considering PLS of MG4). After that W_4 = 0 and W_2 = -1.14. Then delete MG4 from PEPS. It causes PEPS to be empty. When PEPS is empty, the MS generates storage power for micro-grids (S_i = 0). After that the MS generates exchange power pair between macro-station and

Algorithm 1 Power Exchange and Minimize Power Loss Algorithm. (Input: $D_i(t)$, $G_i(t)$, Output: exchange power pairs (i,j), $B_{ij}(t)$, $S_i(t)$, $B_{0i}(t)$, and $PLA_i(t)$)

BEGIN
For $micro\text{-}grid_i$
  Calculate $PLG_i(t)$, $S_i(t)$, $W_i(t)$ and $PLS_i(t)$ based on eqs. (2), (3), and (4), respectively.
  Send $W_i(t)$, $PLG_i(t)$, $S_i(t)$, and $PLS_i(t)$ to the macro-station
For the macro-station
 Loop
  Receive $W_i(t)$, $PLG_i(t)$, $S_i(t)$, and $PLS_i(t)$ from $micro\text{-}grid_i$.
  Return ACK message.
  Generate PEPS, calculate RUP of PEPS, and sort PEPS order in descending according to RUP.
  While (PEPS is not empty)
   Get first element $(i,\ j)$ from PEPS, generate exchange power pair $(i,\ j)$ in PEPS, and calculate power loss $PL_{ij}(t)$ and exchange power $B_{ij}(t)$, based on eqs. (8) and (9), respectively.
   If $(|W_i(t)| = |B_{ij}(t)|)$
    Delete potential exchange pair that i belongs to.
   Else
    Delete potential exchange pair that j belongs to.
   Endif
   Update $W_i(t)$, based on eqs. (10) and (11).
   Send $(i,\ j)$, $B_{ij}(t)$ to $micro\text{-}grids$ i and j.
  Endwhile
  Based on exchange power pair(s), set coalitions of the micro-grids by using $Merge$ and $Split$ operations.
  Update $S_i(t)$ and $PLS_i(t)$, and generate $\delta_i(t)$, based on cases 1 to 3.
  Based on eq. (12), calculate $B_{0i}(t)$ and $PL_{0i}(t)$.
  Calculate $PLA_i(t)$, based on eq. (5).
  Send $S_i(t)$ and $B_{0i}(t)$ to $micro\text{-}grid_i$.
 Endloop
For $micro\text{-}grid_i$
  Exchange power $B_{ij}(t)$ with $micro\text{-}grid_j$, store power $S_i(t)$ and exchange power $B_{0i}(t)$ with the macro-station.
END

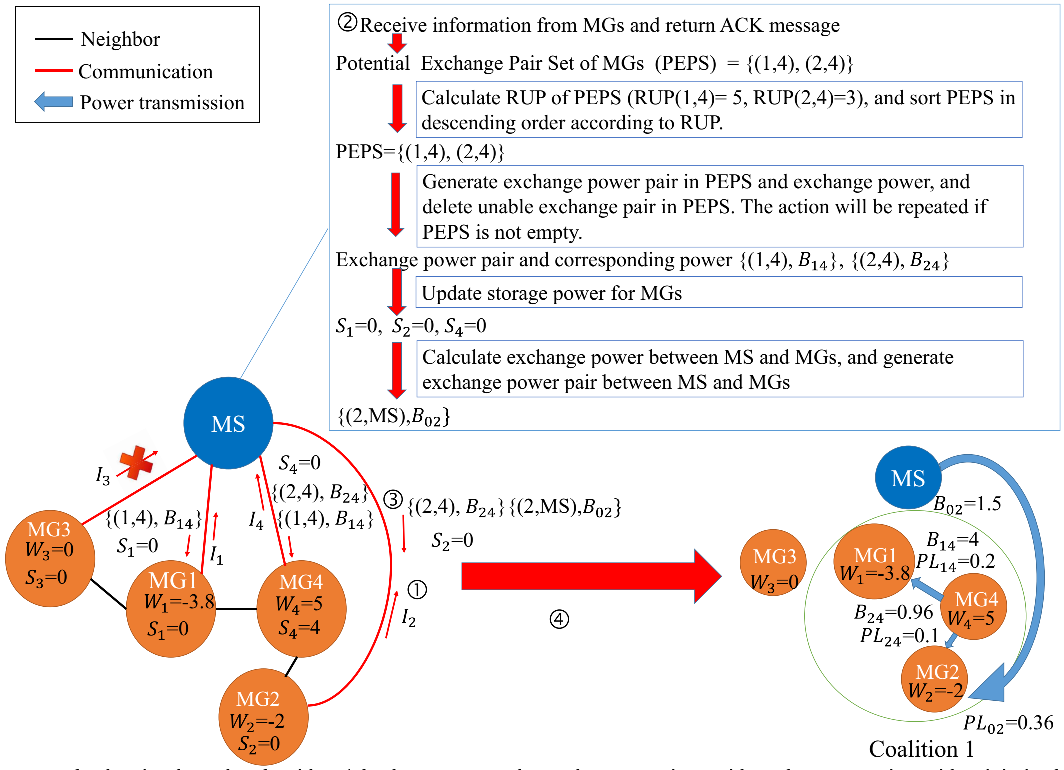


Fig. 2. A simple example showing how the algorithm 1 lead to power exchange between micro-grids and macro-station with minimized power loss.

micro-grids ({(MS,2)}), and calculates the exchange power between the MS and the micro-grids (B_{02}=1.5). The MS will then send exchange pair and exchange power to corresponding MGs. MG1 receives {(1,4), B_{14}} and $S_1 = 0$. MG2 receives {(2,4), B_{24}}, {(2,MS), B_{02}} and $S_2 = 0$. MG4 receives {(1,4), B_{14}}, {(2,4), B_{24}} and $S_4 = 0$. Based on these pairs and demands, the MGs form coalition (MG2, MG1, and MG4), and exchange power with others or/and the MS.

After the merge and split operations in Alg. 1, the network becomes a partition composed of disjoint coalitions, and no coalition may have any incentive to perform further merge or split operation (the partition is *merge-and-split proof*). The micro-grids will find the coalition where they obtain most profits and join it. The algorithm can be re-applied when demand loads in the micro-grids change, to guarantee that the micro-grids may maximize their respective profits. We now show that our proposed algorithm is stable and convergent.

Definition IV.4. *A coalition C:* $= \{C_1, ..., C_k\}$ *is* $\mathbb{D}_{hp}$*-stable if the following two conditions are satisfied [25].*

(a) for each $i \in \{1, ..., k\}$ *and for each partition* $\{P_1, ..., P_l\}$ *of the coalition* C_i*:* $v(C_i) \geq \sum_{j=1}^{l} v(P_j)$.

(b) for each set $T \subseteq \{1, ..., k\}$*:* $\sum_{i \in T} v(C_i) \geq v(\cup_{i \in T} C_i)$.

Lemma IV.1. *The coalition formed by the proposed algorithm is* $\mathbb{D}_{hp}$*-stable [4].*

Lemma IV.2. *In the studied* ($\mathcal{N}$,v) *micro-grids coalition game, the proposed scheme converges to the Pareto optimal* $\mathbb{D}_{hp}$*-stable partition, if such a partition exists. Otherwise, the final partition is merge-and-split proof [4].*

Our solution is Pareto optimal. Hence, the merge and split operations will help the micro-grids to maximize their utilities (minimize the total power loss), until the $\mathbb{D}_{hp}$-stable situation occurs. In this situation, no micro-grid can decrease its total power losses without increasing other micro-grids' total power losses.

By using our algorithm, the micro-grids could exchange power among themselves instead of with the macro-station so as to alleviate power loss. After exchanging power, some generated power could be stored in the micro-grids.

V. Experimental Results

In this section, we present some experimental results to verify the effectiveness of our algorithm. The performance of our proposed scheme is compared with that of the non-cooperative scheme used in [26]. In the non-cooperative scheme, the micro-grids only exchange power with the macro-station and they cannot exchange power with the other micro-grids. Our considered simulation scenario comprises a power distribution grid topology, and the area is 10×10 km^2. The macro-station is placed at the center of the grid, and the micro-grids are deployed randomly in the topology. The resistance between the micro-grids is the same as that between the macro-station and any micro-grid, and its value is set to $R = 0.2$ Ω per km. The fraction of power transmission α is set to 0.02 according to the assumptions made in [28]. For simplicity, θ_i and β_i are regarded as constant in our simulation. Similar to the assumption made by [23], the power demand D_i of $micro\text{-}grid_i$ is derived from a Gaussian distribution between 10 MW and 316 MW. The power generation G_i is obtained from a Gaussian distribution between 10 MW and 316 MW. Assume that the capacity of power storage device is 200 MW, and the minimum storage power is 10 MW. 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

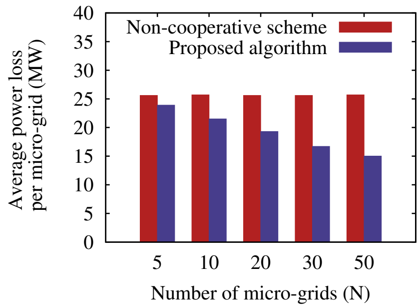


Fig. 3. Comparison of the average power loss in the non-cooperative scheme and our proposal.

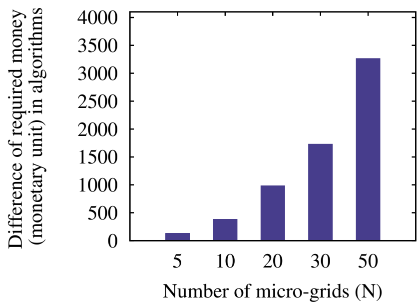


Fig. 4. A mount of saved money in our proposal is employed.

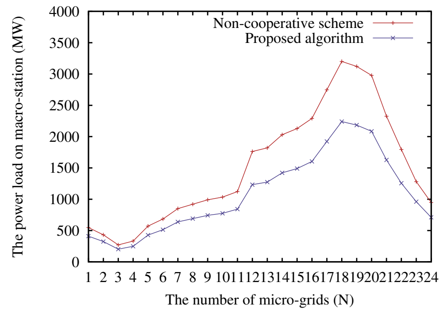


Fig. 5. The power load on the macro-station in the non-cooperative case and our proposal.

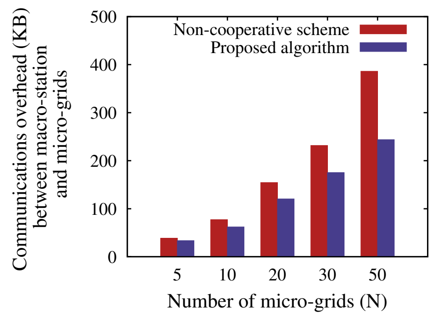


Fig. 6. The communications overhead between the micro-grids and the macro-station in the non-cooperative case and our proposal.

networks [28]. The prices of a unit power loss are set as $w_1 = 1$ and $w_2 = 3$ [4]. In our proposal, the users send the information to the corresponding micro-grids, and the micro-grids also exchange the information to other micro-grids or the macro-station if necessary. Assume the micro-grids can communicate with the macro-station though an optical backbone network, capacity of which is 100Mbps. For simplicity, each micro-grid is assigned to meet the demands of 100 users. The length of packets from the users to the micro-grid is set to 102 bytes [27], and the length of packets exchanged among the micro-grids is set to 112 bytes. The simulation results are presented in the remainder of this section.

Fig. 3 demonstrates the average power loss per micro-grid for varying number of the micro-grids from 5 to 50 in case of the non-cooperative scheme and our proposal when $\theta_i = 0.05$ and $\beta_i = 0.01$, respectively. From the results depicted in the figure, in the non-cooperative scheme, the power loss per micro-grid does not improve (in fact does not change) because the micro-grids only obtain power from the macro-station. On the other hand, in our proposal, the average power loss is improved substantially with the increasing number of the micro-grids. The reason behind this performance improvement in case of our proposal can be credited to the coalitions formed by the micro-grids with the objective of optimally alleviating the power loss. When the micro-grids could successfully form coalitions, they could exchange power with other micro-grids instead of the macro-station leading to the reduction of the average power loss.

Fig. 4 demonstrates the difference of the money required for purchasing power in case of the non-cooperative scheme and that in our proposal. As demonstrated by the figure, when the number of micro-grids increases, the difference of the required money (i.e., saved money by using our proposal) becomes larger. This is because in the non-cooperative case, surplus power in off-peak time is sold to the macro-station. In addition, during peak time (when the supply power is less than the demands of users), the micro-grids buy power from the macro-station. These lead to PLT and PLC. However, in our proposal, the micro-grids can form coalitions and they could exchange power with other micro-grids. Additionally, the power loss among the micro-grids is lower than that between the micro-grids and the macro-station. Hence, the amount of total power losses in our proposal is lower than that in the other case. Furthermore, the micro-grids in our proposal can buy power in lower unit power price through the micro-grids coalitions. Thus, this presents an incentive to the users in terms of a chance to save money by using our micro-grids coalitions based proposal.

Fig. 5 depicts that the micro-grids want to buy the power from the macro-station for N=20 micro-grids in both the considered schemes. Assume that the peak period in a day is from 12 PM to 9 PM. Furthermore, the situations of the micro-grids are considered to remain fixed since their initial random deployment in the simulated grid. Although in both schemes, the micro-grids have the power storage devices that they could charge in off-peak time and discharge in peak time, note that compared with the non-cooperative case, the result achieved by our proposal (i.e., the burden in terms of the power load inflicted upon the macro-station) is lower. It is because the micro-grids in our proposal can buy power from neighboring micro-grids instead of the macro-station while the micro-grids in the non-cooperative case the micro-grids can only exchange power with the macro-station. The results presented so far demonstrate that both the users and the macro-station can obtain benefits from forming coalitions through our proposed scheme.

Fig. 6 plots the communications overhead for varying num-

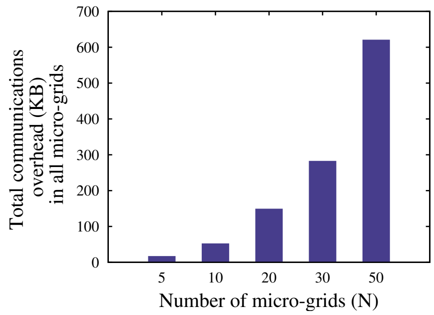
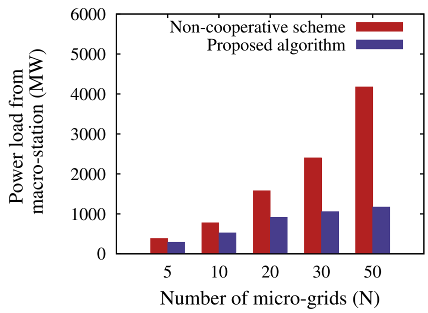
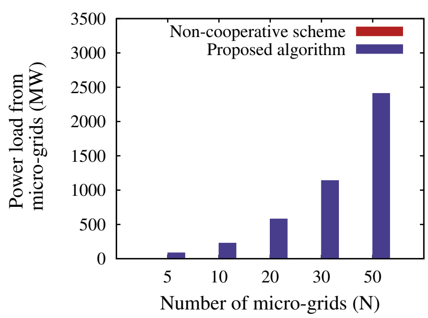


Fig. 7. The total communications overhead experienced by all the micro-grids for varying numbers of micro-grids in our proposal.

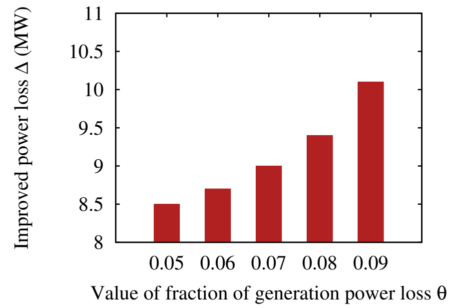


(a) Average power load from macro-Station

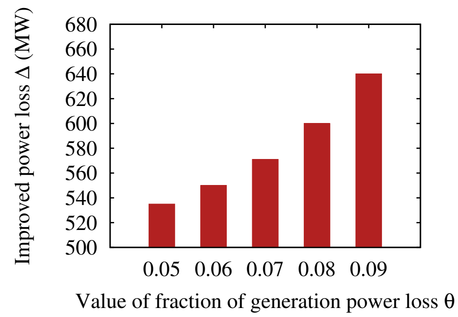


(b) Average power load from micro-grids

Fig. 8. Average power load from macro-station and micro-grids

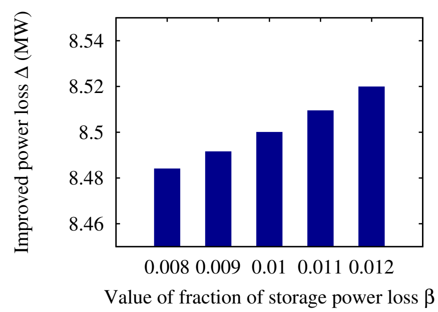


(a) Number of micro-grids = 5

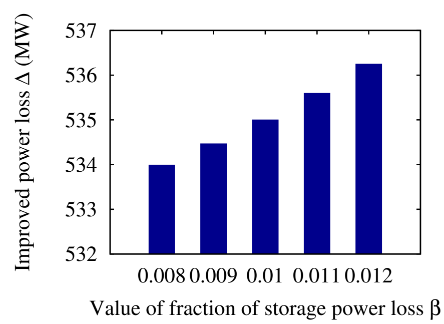


(b) Number of micro-grids = 50

Fig. 9. Improved power loss in different parameter θ environment



(a) Number of micro-grids = 5



(b) Number of micro-grids = 50

Fig. 10. Improved power loss in different parameter β environment

bers of micro-grids. When the micro-grids exchange power with the macro-station, they need to send packets (i.e., power demand, current situation, and so forth) to the macro-station. From the figure, it should be noted that with increasing number of the micro-grids, more bandwidth is consumed. However, the communications overhead of both the schemes are not much when compared with the available bandwidth of the communication infrastructure of the considered power grid. Moreover, compared to the non-cooperative case, the micro-grids in our proposal can form coalitions and exchange the power with other micro-grids instead of the macro-station resulting in less messages exchange with the macro-station.

To evaluate the communications overhead due to the negotiations amongst the micro-grids to form coalitions, Fig. 7 plots total communication overheads in all the micro-grids for varying numbers of micro-grids. It is worth noting that the non-cooperative scheme does not consider such negotiations amongst micro-grids. The micro-grids sent offer to their neighbors so as to form coalitions, based on the power exchange pair $(i,\ j)$. Then by using our proposed scheme, the micro-grids form coalitions so as to maximize their payoffs. When the coalitions are formed, the micro-grids belonging to the same coalition communicate with other micro-grids and exchange power with them. With increasing number of the micro-grids, the total communication overhead becomes larger as shown in Fig. 7. However, even for a significantly high number of micro-grids (e.g., 50), the total communications overhead experienced in all the micro-grids is approximately 600 KB, which does not affect much the available bandwidth on the considered system.

Fig. 8 demonstrates that the macro-station in the non-cooperative 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 non-cooperative case, micro-grids only obtain power from the macro-station (it is the reason why the values of the non-cooperative case in Fig. 8(b) are zero) and it causes high power loss while by using our algorithm micro-grids could exchange power with others instead of macro-station so as to reduce power loss. Therefore, the proposed algorithm helps the macro-station to decrease the peak of power generation and improve efficiency of power.

Figs. 9 and 10 show the improved power loss, Δ, which is the power loss difference between our proposal and the non-cooperative case when the fraction of power generation parameter θ and the fraction of power storage parameter β are changed, respectively. In Fig. 9, θ is varied and β is fixed, and in Fig. 10, β is varied and θ is fixed. From these figures, we can find that the results are positive. It means that our proposed algorithm save more power than that in the non-cooperative case. The reason is that the non-cooperative case did not consider how to minimize the total power loss of the whole smart grid network, whilst our algorithm considers how to reduce the total power loss. Hence, our results are better than the non-cooperative case results in the same simulation environment.

VI. Conclusion

In this paper, a novel coalition formulation algorithm for micro-grids having power storage devices was proposed. Our proposed algorithm allows the micro-grids to make decisions on whether to charge or discharge their power storage devices, and to find other micro-grids (i.e., appropriate neighbors) to form coalitions so as to efficiently minimize the total power losses. We proved that our proposal offers a stable and convergent solution. Furthermore, our solution is simple to follow and implement. Finally, through computer-based simulations, we demonstrated the effectiveness of our proposal in contrast with the traditional non-cooperative scheme.

Our greedy algorithm is not always optimal. Assume that there are two "sellers' A (demand W_A=205 MW) and B (W_B=205 MW), and two (more demanding) "buyers" C (W_C=-200 WM) and D (W_D=-200 WM). PL_{AD}=5, PL_{BC}=2, PL_{AC}=3, and PL_{BD}=3. RUP_{AD}=0.06, RUP_{BC}=0.02, RUP_{AC}=0.03, and RUP_{BD}=0.04. Coalitions in our greedy algorithm is decided by the optimal among four RUPs, say between A and D. Two coalitions A, D and B, C would be created, because RUP_{AD} is the largest and W_A=W_D=0 after power exchanging. The total power loss for them is 7.1. However, if coalitions are A, C and B, D, the total power loss is 6.12, which is better than that of greedy algorithm.

It remains a challenge to design an optimal algorithm. We observe that, after power exchange between two micro-grids, one of them does not exchange further power with any other micro-grid (or macro-station), because either its demands are met, or all the remaining power delivered. This hints toward a multi-matching problem formulation. It is different from classical matching algorithm, because it allows single node to be matched with several other nodes. However, it does not allow "marriages" where both partners are allowed to have other partners.

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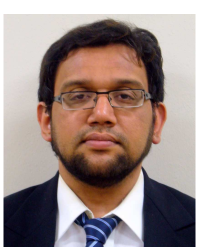

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