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# Real-time energy exchange strategy of optimally cooperative microgrids for scale-flexible distribution system

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ABSTRACT

This paper presents an optimal coalition formation mechanism of microgrids in a smart distribution system and analyzes the characteristics from the *coalitional game* theoretical perspective. Microgrids coalitions can (1) minimize the energy burden and dependency on the utility grid, (2) minimize the overall grid network power loss, and (3) maximize intra-coalition energy transfer. In order to form cooperative microgrids, a Hierarchical priority based Coalition Scheme (*HRCoalition*) is proposed. Given an intra-coalition distance threshold, the proposed *HRCoalition* mechanism can provide the *optimal coalition* that achieves the aforementioned objectives. The optimality is realized by reaching a state of cooperative equilibrium for all microgrids and coalitions. The optimality of the formed coalitions is proved by *Coalitional Game Theory*. A Greedy based strategy is designed to perform network constrained energy exchange *(GreedEnEx)* within a formed coalition. Thus, *HRCoalition* provides a higher level optimization while, *GreedEnEx* yields system level optimization using output of *HRCoalition*. The proposed *HRCoalition* scheme is computationally very efficient and can scale up to a huge number of microgrids and thus makes it suitable for near real-time operation. An equivalent pricing mechanism is designed to provide a form of economic incentive to the microgrids participating coalition formation. The performance of the proposed method is reported to scale up to 500 microgrids with a loss reduction ranging from 26% to 80%. The provided numerical simulation results back the claim of optimality as well as prove the effectiveness of the proposed coalition formation method.

## 1. Introduction

The power system operation and control took a significant turn after the introduction of deregulation in power market and consequent boom of smart grid technology related research and development. These changes impose challenges (exciting, interesting and more importantly necessary ones) into both research and structural development levels. The activities of developing and deploying smart grid infrastructure further fueled by the continuous depletion of natural energy resources and inevitably growing concerns on greenhouse effect. Moreover, soaring cost of the natural energy resources due to increasing demand for energy with a rise of world population and rapid economic growth of developing countries also fasten the drives towards a smarter grid architecture. With these motivations on mind, the electricity distribution system needs to be renovated by grouping several distributed energy resources (DERs), storages and loads into one interactive and automated entity given a particular network settings and geographical area. Such an entity formation idea incepted the concept of microgrid system (Katiraei, Iravani, Hatziargyriou, & Dimeas, 2008). The DERs contain renewable energy sources in conjunction to energy storages and/or small scale generators. Traditionally, a microgrid operates in grid-connected mode where the energy requirement is fulfilled by purchasing/selling energy between that microgrid and the utility grid. This transfer, however causes power loss due to the transmission/distribution line and transformers. Although, cost minimization (Hernandez-Aramburo, Green, & Mugniot, 2005) in microgrid or smart-grid (Chakraborty, Ito, Senjyu, & Saber, 2013) in the form on unit commitment has been extensively studied, the research related to loss-reduction phenomena in the whole distribution grid as well as attainment of a “net-zero-energy” society are still premature and demand considerable attention. A remedy of aforementioned loss reduction while moving towards a “net-zero-energy” society is envisioned as formation of microgrids coalitions. Microgrids inside a coalition perform necessary energy transfer within the coalition and finally interact with utility grid as the last resort to minimize losses. With the realization of

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Digital-grid (Abe, Taoka, & McQuilkin, 2011) architecture, the interactions among microgrids in power/energy level are readily viable in distribution network. Therefore, microgrid coalition formation is practical and can be thought of an important addition to future smart distribution energy management system.

In recent years, streams of outstanding works are presented in the area of real-time and optimal energy management system for microgrid while focusing on e.g. variable grid price (Velik & Nicolay, 2014), day-ahead market (Marzband, Sumper, Ruiz-lvarez, Domnguez-Garca, & Tomoiag, 2013), inclusion of distributed generators (Liao, 2012), etc. However, most of these reported works concentrate on the energy management and control inside microgrid considering either islanded or grid-connected mode. That being said, the contributions are focused on the primary and secondary control level. The aggregation or grouping schemes of microgrids for optimal energy exchange in the tertiary level are being ignored. However, the aggregation (dynamic) of multiple microgrids in distribution level is of critically important while designing future smart distribution based services for new independent power producers, stake-holders that rise due to the presence of deregulation in energy market.

The usage of game theory (Shoham & Leyton-Brown, 2008) in smart grid application domain (especially in the area of energy) is getting considerable attention in recent years, e.g. (Saad, Han, Poor, & Basar, 2012) (Microgrid coalition), (Ramchurn, Vytelingum, Rogers, & Jennings, 2012; Chakraborty, Ito, & Senjyu, 2014) (Incentive based demand response), etc. The cooperative game theory has been effectively applied in areas like smart grid, microgrid, forming virtual power plant, energy sector etc. (e.g. (Alam, Ramchurn, & Rogers, 2013)). For example, (Alam et al., 2013) provides a cooperative energy exchange scheme in order to reduce the battery usage as well as improving the efficiency of houses locating in remote communities. In cooperative game theory point of view, a coalition should be formed such a way that each participated microgrid will gain benefit (or at least not lose) by participating in a coalition. Intuitively, a *grand coalition* (i.e. a single coalition of players) always produces the maximized benefit for players (Alam et al., 2013). However, to form a grand coalition of microgrids is practically infeasible because *grand coalition* does not consider inter-microgrid distance. A slightly similar approach to form microgrid cooperation was reported in Saad et al., 2012 (and (Wei, Fadlullah, Kato, & Takeuchi, 2013); apparently applied same basic mechanism) who used merge/split operation. Although, the merge/split operation (Apt & Witzel, 2009) to form coalition can provide stable partition, it was not clear how the model described in (Saad et al., 2012) reacts with the scalability of the problem space (the number of microgrids, in this context). Because, merge/split operation in coalition formation is an *NP-hard* problem (Rey et al., 2010) which yields an exponential computational complexity in the worst case.

We propose a hierarchical priority based strategy to form optimal microgrid coalitions and analyze the characteristics through the eyes of *Coalitional Game Theory* framework (Shoham & Leyton-Brown, 2008). The proposed method can form optimal coalition by reaching an equilibrium state and can scale very high in terms of number of microgrids due to the inherent quadratic computational complexity. We present the hourly interactions among microgrids given their hourly energy status and extend the method up to multiple hours (e.g. 24-h) considering the dynamic energy status (loads/supply) of microgrids.

The proposed method can effectively locate itself within the smart distributed energy management system in order to perform energy exchange operation among microgrids by forming the optimal coalition. The optimality, as we will show, is defined by minimizing the power loss by effectively avoiding the interactions with utility grid. The designed scheme can also be used as one of the analytical tools for setting up new microgrid substations and communication and electric infrastructure. At the miniature level, such method has a potential to dynamic formation virtual aggregator for smart homes. A pricing mechanism is designed to complement the formed coalition which somewhat provides the base line of mechanism design for coalition formation. The proposed method is computationally very efficient and highly scalable in compare with other optimal coalition formation techniques. Therefore, the designed method can be applicable in (near) real-time energy management system.

The rest of the paper is organized as follows. The system model with energy exchange scenario is described in Section 2. Section 2 further briefs the Coalitional Game Theory and how it can be applied in proposed model. Some game theoretic observation, analysis and proofs are provided in Section 3. The optimality of *HRCoalition* scheme is proved in this section as well as the computational and communication complexity are analyzed. Section 4 presents the numerical simulations with associated discussions and analysis. The simulations are carried by initially providing the hourly-interactions among microgrids and formed coalitions. Later the whole scenario is extended up to 24-h in order to incorporate the dynamic energy status of microgrids.

## 2. System model and coalition formation scheme

A microgrid requires to purchase/sell energy from/to *utility grid (UG) owned by utility company* depending on its internal energy status. Every microgrid requires energy for serving the loads within it. We denote the total demand of a microgrid $i$ (where $i \in N$; $N$ is the set of microgrids) by $D_i$. At the same time, internal DERs (which include renewables and storages) of $i$ are responsible of energy supply within $i$. We assume, $i$'s EMS (Energy Management System) already optimizes the usage of internal DERs. Let assume, the total supply for $i$ is $S_i$. Therefore, the energy difference for $i$ is $E_i$ $(= S_i - D_i)$. A positive value of $E_i$ denotes, $i$ can sell $E_i$ amount of energy while a negative value denotes, it requires $E_i$ amount of energy to purchase from outside (from the *UG*, in particular). In conventional architecture of microgrid, such energy transfer is conducted between the microgrid and *UG*. Therefore, the transfer has to be conducted through the substation connected with that microgrid which leads to power losses due to the presence of voltage transformer(s). In addition to that, power loss can be more severe due to the $I^2R$ effect if the *UG* is located far way. At the same time, energy transfer of this sort increases the burden to the *UG*. One of the remedies of such situation can be achieved by forming microgrid coalitions. The microgrids within a particular group (or coalition) will share the energy among each other. After conducting the intra-coalition energy management, the surplus or deficit of energy will be compensated with *UG*.

The proposed architecture of the distributed network is shown in Fig. 1. Every microgrid in the distribution system is expected to connect with the utility grid through medium voltage line. A microgrid can be connected with another microgrid with low voltage line. During the time of operation, every microgrid will send their energy status (via microgrid's energy controller unit; ECU) to an Aggregator (can be a service provider or distribution system controller). The Aggregator intelligence system contains Microgrid Cooperation Module (MCM), which is responsible for decide optimal coalition. An energy transfer matrix, resulted from MCM, will be sent to the participated microgrids via wireless communication system. The functionalities of these units will be detailed in the later part of the manuscript. The microgrids will communicate pairwise to initiate the energy transfer and realize the transfer via low-voltage line. We, therefore, assume the microgrids, utility company and the Aggregator are connected via wifi communication infrastructure. Additionally, a database of distributed network profile is also a part