# Optimal Hierarchical Power Scheduling for Cooperative Microgrids

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The decentralized generation at most renewable energy sources and the supporting technologies such as photovoltaics and micro-turbines, have driven the demand for a new distributed power grid system, the *Microgrid* (MG) [1]. Unlike traditional centralized power generation, the MG features distributed generation (DG) to support local users. DG is the basis of distributed energy resource (DER) systems, which is usually comprised of small power units, such as micro-turbines (25∼100 KW) and small photovoltaic panels (1∼10 KW). An MG can operate in the *island* mode, where the local demand is supported with the MG's own DG and power storage, or the *grid-connected* mode, where the MG can acquire energy from, and/or contribute extra power to the Macrogrid [2]. MG is regarded as an important paradigm for the next generation power grid, the Smart Grid (SG) [3]. The SG will be able to integrate the plug-and-play MGs through common coupling points [2].

Over the past decade, MGs are built, experimented and tested around the world [4]. As advances are made in single MG systems, the problem of *cooperation* among MGs as well as the Macrogrid has attracted considerable interest only recently. With such cooperation, MGs and the Macrogrid will each gain tremendous benefits, such as reduced power loss, lower operational cost, and load peak reduction [5]–[7]. The obvious advantages stem from exploiting the *temporal, spatial, and technological diversities* in a multiple MG system. For instance, an MG supporting a business area will have a very different temporal demand profile from that of an MG supporting a residential area; the DGs in geographically distributed MGs can also have different generation levels at same time of the day; and different DGs are affected by weather differently: an MG with a photovoltaic array may suffer low generation during a storm, while a neighboring micro-turbine based MG, caught in the same storm, may generate a large amount of power exceeding its own demand. As in wireless communications systems, exploiting such diversity through MG cooperation could bring about more efficient power generation and distribution.

The problem of cooperative MGs has been considered in several recent papers. In [5], the authors present a decentralized control strategy modeling the MGs as a team of cooperative agents to minimize the costs of energy storage and the power exchanged among the MGs. In [7], the authors formulate the optimal decision making problem in cooperative MG networks as a linear quadratic Gaussian problem. Although these recent works achieve the cooperation of MGs, none of them includes the power flow between the MGs and the Macrogrid. However, the power grid is currently under a transition from traditional centralized distribution to decentralized distribution. In practice, the distributed generations in MGs are usually hard to generate power stably and constantly. On the other hand, MGs can provide surplus power to the Macrogrid. Therefore, it is important to incorporate all the key factors in a holistic manner, such as the generation cost, power generation and transmission losses, load smoothing, distributed storage, and the utility of power users. A control strategy would be highly desired that considers all the key factors for both the Macrogrid and MGs.

In this work, we consider a power grid consisting of the Macrogrid and several cooperative MGs, shown in Fig. 1. The goal is to exploit the *MG diversity gain* to optimize both the MG performance and user satisfaction. With cooperation, an MG is able to share its excess power with other MGs nearby or with the Macrogrid. Due to limited storage capacity, the MG can sell its extra power to other MGs suffering power shortage. Alternatively, the MG could buy power from other MGs as well when its DG suffers low generation, such that the power loss and cost can both be reduced compared to buying power directly from the Macrogrid. On the other hand, the Macrogrid could provide more storage capacity for the MGs, while the extra power from the MGs will in turn reduce the need of traditional power generation in the Macrogrid. Grid load smoothness of the Macrogrid could be achieved if the power flows from/to the MGs are optimally managed and scheduled.

In particular, under some mild assumptions, we firstly formulate the cooperative MG problem as a convex optimization problem by capturing the key factors in a grid system shown in Fig. 1, i.e., operation cost, power generation and transmission losses, user utility, distributed storage, and grid load smoothing. We then decompose the original problem into a two-tier convex optimization problem. The first-tier control is for the Macrogrid, aiming to maximize user utility, minimize power transmission cost from/to the Macrogrid, and smooth the grid load of the Macrogrid. The second-tier control is for each MG, aiming to minimize the cost within the MGs and during transmission, while guaranteeing the power demand of MG users. It balances the power level with the Macrogrid and makes energy trading

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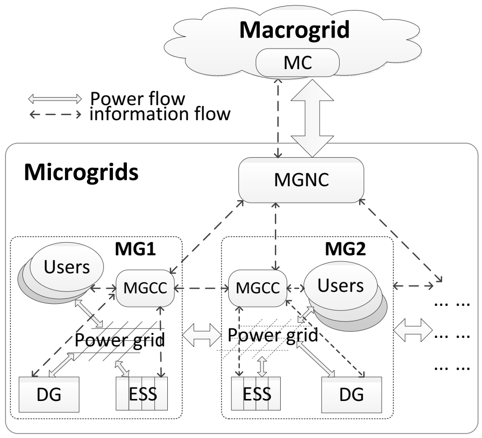


Figure 1. Illustration of the power grid network.

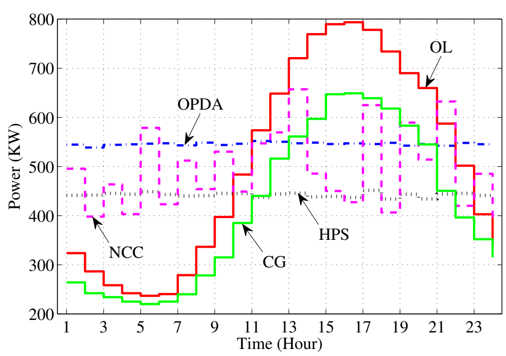


Figure 2. Macrogrid load under different power scheduling schemes.

and storage decisions within the MG network. For the first-tier problem, we develop an effective online algorithm that does not require any future information and is proven to be asymptotically optimal; for the second-tier problem, we develop a distributed algorithm for optimal solutions.

The performance of the proposed hierarchical power scheduling scheme is validated with trace-driven simulations, where fast convergence and superior performance over several comparison schemes are observed. The simulation data and parameters for the Macrogrid are based on the power usage traces in the Southern California Edison (SCE) area recorded in 2011 [8]. We consider a power system as in Fig. 1 with a Macrogrid and four Microgrids. The Macrogrid supports 400 power users, while each MG supports 100 users. The user demand is based on the SCE trace and user utility function is defined as [9].

We provide a comparison study of our hierarchical power scheduling algorithm (HPS) versus several existing schemes [6], [9]. In Fig. 2, we show the load of the Macrogrid under five different power scheduling schemes. The original load (OL) is based on the SCE trace of a one day period in September, 2011. The online power distribution algorithm (OPDA) proposed in [9] has considered many factors including user utility and grid load variance in a Macrogrid, but no MG is involved in the model and algorithm. Thus, the OPDA curve in Fig 2 is obtained by running OPDA in a Macrogrid with 800 users. A coalition game (CG) is used in [6] to minimize the power loss in an MG network, where power flows between MGs and Macrogrid are allowed. However, it does not consider smoothing the Macrogrid load. For comparison purpose, we also develop another scheme (termed as no cooperation control scheme (NCC)), which only allows power flow between each MG and the Macrogrid, while power trading among the MGs is not allowed. It can be seen that the HPS curve is the smoothest one among all the curves, and it is lower than the OPDA curve, indicating the smallest peak power and the smallest variation.

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