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A Control Architecture for Optimal Power Sharing among Interconnected Microgrids

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***Abstract*—Energy management system of a microgrid (MG) is responsible for determining its optimal generation schedule which fulfills the load demand while satisfying several constraints related to the equipment and system operation. When many MGs are interconnected, it is sometimes preferable to exchange power among MGs in such a manner so as to minimize their operating cost while reducing dependency on the main grid. This paper proposes a cost based power sharing scheme combined with a more realistic EMS scheme. These two schemes are implemented in two control layers which communicate with each other to optimize MG operation. Simulation results demonstrate the benefits of the proposed approach.**

***Index Terms*—Microgrids, power sharing, energy management system, unit commitment, optimal power flow, model predictive control.**

I. Introduction

Microgrids (MGs) are small-scale electrical grids comprising several distributed energy resources and energy storage systems (ESSs). The ability to integrate a high share of renewable energy sources (RES) motivates research towards the implementation of MGs. ESS is mainly used to shave load peaks and absorb possible power fluctuations due to the intermittent nature of RES [1]. Energy management system (EMS) facilitates the economic operation of MGs through the efficient utilization of RES and ESS to reduce operating costs of fuel-based dispatchable sources such as diesel generators. In general, MGs are expected to be self-dependent in terms of energy requirement. However, depending on the application, MGs can be operated either in grid-connected or standalone modes. Specifically, neighboring MGs can be interconnected to share power among themselves as necessary so as to optimize operational benefits. Decentralized EMS schemes are more attractive for grid connected or interconnected multiple MG applications [1]. This paper proposes a multi-period decentralized two-layer control scheme to optimize resource utilization among interconnected MGs based on nodal pricing.

The energy management (EM) problem includes operational characteristics of power sources, power flow equations and system security constraints in its formulation. Thus, a complete EM problem formulation would combine unit commitment (UC) and optimal power flow (OPF) problems [2]. In general, it turns out to be a mixed-integer nonlinear (nonconvex) problem which is NP-hard. Model Predictive Control (MPC) framework has recently gained popularity in the context of developing EM formulations for MGs [1]. There are several efficient solving techniques used to address the EM problem including Lagrangian relaxation [3], mixed-integer quadratic program (MIQP) [2], dynamic programming [4] etc. Several researchers have proposed different formulations to reduce the model complexity [4], [5], [6].

Distributed computations hold a lot of promise in the context of reducing computational time. In [5] and [6], centralized cooperative schemes are proposed for standalone MGs. The UC problem is formulated based on the power nodes framework and is solved in conjuntion with the OPF problem so as to adjust generator set-points to satisfy power flow equations. In [5], the approach is extended to large-scale networks by creating sub-problems which are solved in a distributed fashion. In [3], a method is developed to coordinate storage and intermittent resources in multiple control areas based on optimality condition decomposition. Reference [4] demonstrates a constraint management strategy to maximize main grid energy imports while reducing the cash outflow by dispatching ESS. In [7], the power sharing problem among interconnected MGs is addressed using a centralized controller. An MPC based algorithm is used to compute the power sharing and energy storage scheduling considering forecasted energy prices of the main grid and other MGs. The authors do not consider dispatchable sources such as diesel generators (DGs) which are common in remote MGs. Moreover, the problem becomes more complex to formulate with the presence of dispatchable sources and system constraints. Also, power losses are sometimes significant in the context of MGs which may render the power dispatch impractical.

In this work, we focus on a detailed problem formulation which includes DGs, ESS, wind and solar PV power plants, and power exchange with the main grid and neighboring MGs. A two-stage decentralized EMS architecture is implemented to decide the optimal generator schedule and power dispatch. A novel, cost based power sharing scheme is developed as a tertiary layer which couples with the EMS to realize the requirements/preferences of each MG in terms of power exchange.

II. System Model

The system in this study consists of several MGs interconnected with each other and the main grid. A particular

MG may contain several DGs, wind power plants, solar PV power plants and ESS as power generation sources. DGs are controllable sources with a quadratic fuel cost function of real power dispatch. Power output of the i^{th} DG at the time instant t (P_i^t), is constrained by real and reactive power output bounds, ramp rate constraints, minimum uptime and downtime constraints (see [2] for the formulations). The cost function for DGs is expressed as follows:

$$C_{DG,i}^t = SU_i^t d_i + U_i^t a_i + b_i P_i^t + c_i (P_i^t)^2 \tag{1}$$

where DG is the set of DGs; $\forall i \in DG$; a_i, b_i and c_i are the cost coefficients of the i^{th} DG; U_i^t is a binary variable which is 1 if unit i is committed during hour t and SU_i^t is a binary variable which is 1 if unit i is started up during hour t (both are 0 otherwise) and d_i is the start-up cost for unit i.

An ESS is considered to mitigate demand fluctuations and facilitate peak clipping (or valley filling) in a cost-effective manner. Moreover, we consider a realistic ESS model which includes intertemporal constraints for the state-of-charge (SOC), operational limts, and a battery degradation cost to reflect the cost of purchase based on its utilization (charging and discharging) [8]. The battery cost and constraint modelling are presented below.

$$C_{ES,i}^t = \frac{I_i}{2B_{cap,i}N_i}\left[\frac{P_{bc,i}^t}{T_{bc,i}} + \frac{P_{bd,i}^t}{T_{bd,i}}\right] \tag{2}$$

$$SOC_i^t = SOC_i^{t-1} + \left(\eta_{c,i}P_{bc,i}^t - P_{bd,i}^t/\eta_{d,i}\right)/P_{1E,i} \tag{3}$$

$$SOC_i^{min} \leq SOC_i^t \leq SOC_i^{max} \tag{4}$$

$$0 \leq P_{bc,i}^t \leq P_{bc,i}^{max} \tag{5}$$

$$0 \leq P_{bd,i}^t \leq P_{bd,i}^{max} \tag{6}$$

Here, ES is the set of ESSs; $\forall i \in ES$; $P_{bc,i}^t$ and $P_{bd,i}^t$ are the charging and discharging powers respectively at hour t; $P_{1E,i}$ is the power required by the ESS to charge 100% in 1 hour i.e. $1E$ rate, $(.)^{min}$ and $(.)^{max}$ represent the minimum and maximum bounds of the corresponding parameters respectively; N_i is the expected number of cycles before the ESS reaches its end of life; $T_{bc,i}$ and $T_{bd,i}$ are the average number of hours the battery charges and discharges in a day respectively; $\eta_{c,i}$ and $\eta_{d,i}$ are the charging and discharging efficiencies respectively; I_i is the cost of purchasing the ESS and $B_{cap,i}$ is the capacity of the i^{th} ESS in kWh [8].

The thermal units and ESS are modelled using HYSDEL [9]. HYSDEL is based on the Mixed Logical Dynamical (MLD) modelling framework, described in [10]. Considering the hybrid nature of the scheduling problem, MLD provides a convenient framework to implement all relevant features of the microgrid [11]. More details can be found in [11] and [12].

III. Microgrid Hierarchical Control System

In a hierarchical control structure, multiple control layers are assigned to fulfill various operations and control tasks sufficiently in the MGs. The hierarchical control system aims at optimizing resource utilization to satisfy the load demand. In this scenario, facilitating power transfer among interconnected MGs will provide an opportunity to share cheaper energy sources across MG boundaries. The primary level in this structure is responsible for frequency control or power sharing within the MG according to droop settings. The secondary layer is called the energy management system (EMS). It schedules generation (implements commitment and sends dispatch commands) for optimal MG operation while considering load and RES generation forecasts, SOC of ESS, operational status of DGs etc. The tertiary layer examines the status of neighboring MGs and the main grid to coordinate power sharing among them. The focus of this paper is on the secondary and tertiary layers so as to develop a cost based controlling scheme to share power among MGs to optimize the operating cost of the whole system of MGs.

A. Energy Management System Architecture

The EMS controller of each MG is operated separately to optimize its own operating cost. The proposed EMS architecture decomposes the complete EM problem into two stages. The first stage is a UC problem to determine the optimal generation schedule. The second stage is an OPF problem which considers power flow and security constraints of the system for that schedule to examine its practicality. The EMS is implemented under the following assumptions:

1) Power sharing among MGs and between the main grid and individual MGs is assumed to be deregulated i.e. it depends on market prices. The buyer MG (which demands power) does not have the flexibility to decide the price. It should buy the required power at the price offered by the seller MG (which supplies power) i.e. the nodal price at the seller MG.

2) The day-ahead buying and selling prices of the main grid at each point-of-common coupling (PCC) are available. All MGs are assumed to be price takers in trading with main grid i.e. MGs should buy/sell energy from/to the main grid at pre-specified prices.

3) The day-ahead load demand profile and RES output forecasts are known with sufficient accuracy.

The two-stage EMS implementation is explained below.

1) UC-based Cost Minimization: The objective of the first stage is generation scheduling to satisfy active power demand for the given time frame in an optimal manner. Factors considered in the optimization include characteristics of DGs, characteristics of ESS, day-ahead wind and solar power generation forecasts, nodal prices, power surplus or deficit information from neighboring MGs, selling and buying prices of the main grid, day-ahead load forecast and power losses. The optimization problem is developed in the MPC framework [11]. The overall objective function (7) and load balance constraint (8) are as mentioned below. This UC problem is an MIQP problem which can be efficiently solved in polynomial time. In addition to (8), the problem is constrained by (3)-(6) and constraints related to DGs as mentioned in the first paragraph of Section II. For i^{th} and j^{th} MGs - Let $P_{MGp,i,j}^t$ and $P_{MGs,i,j}^t$ be power values that the i^{th} MG would like to purchase from and supply to the j^{th} MG respectively. However, the model ensures that $P^t_{MGp,i,j}P^t_{MGs,i,j} = 0$ to avoid bidirectional power flow in between two MGs at the same time instant.

Minimize the total operating cost (TOC) of k^{th} MG:

$$\begin{aligned}\text{Min } \ TOC_k = &\sum_t \sum_{i\in DG} C^t_{DG,i} + \sum_t \sum_{i\in ES} C^t_{ES,i} \\ &+ \sum_t \sum_{\substack{i\in MG \\ i\neq k}} \left(\lambda^t_{MG,i}P^t_{MGp,k,i} - \lambda^t_{MG,k}P^t_{MGs,k,i}\right) \\ &+ \sum_t \left(c^t_{gp}P^t_{gp} - c^t_{gs}P^t_{gs}\right)\end{aligned} \tag{7}$$

Real power balance:

$$\begin{aligned}&\sum_{i\in DG} P^t_i + \sum_{i\in ES}\left(P^t_{bd,i} - P^t_{bc,i}\right) + P^t_{gp} - P^t_{gs} \\ &+ \sum_t \sum_{\substack{i\in MG \\ i\neq k}} \left(P^t_{MGp,k,i} - P^t_{MGs,k,i}\right) \\ &+ \sum_{i\in WG} P^t_{w,i} + \sum_{i\in PV} P^t_{pv,i} = PD^t + P^t_{loss}\end{aligned} \tag{8}$$

where WG and PV are sets of wind and solar PV generators respectively; c^t_{gp} and c^t_{gs} are the purchasing and selling prices of the main grid; P^t_{gp} and P^t_{gs} are power purchased from and sold to the main grid respectively during time period t which are complementary to each other; PD^t is the total power demand, and P^t_{loss} is the power loss during time period t, which is obtained by solving the OPF problem in Section III-A2.

2) OPF-based Loss Minimization: The problem in the second stage comprises AC non-linear power flow equations and security constraints of the system (refer [2] and references therein for constraint formulation). Therefore, it is a study of the practicality of the generation schedule obtained from the first stage. Controllable power sources are given a limited degree of freedom (a reduced domain) about their original dispatch values. The ramp constraints and minimum and maximum generation limits are also considered in computing the reduced domain. The task for the OPF problem is to evaluate the objective function (7) to refine the optimal power dispatch so as to minimize the cost of power losses in the system while satisfying the power flow and system security requirements. This also gives optimal reactive power outputs and voltage profile for the MG. Most importantly, for each bus, locational marginal price (LMP) which reflects the cost of the next MWh unit can be computed from Lagrangian multipliers. LMPs of PCCs are used as bases to trade power with other MGs.

In this approach, the complete EM problem is decomposed into convex (UC problem) and nonconvex (OPF problem) optimization subproblems which are solved alternately in each iteration. This is computationally efficient compared to solving the two problems combined together [2], [5]. These two subproblems are solved alternately at each iteration by passing power dispatch values from stage 1 to stage 2 and power losses from stage 2 to stage 1 until convergence. The proof of convergence for this approach is given in [2]. Fig. 1 illustrates the computations happening in the EMS layer.

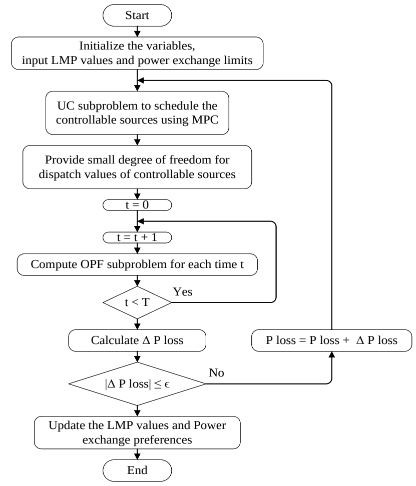

Fig. 1. Flowchart for EMS layer computations.

B. Global Coordination Control for Power Sharing among Microgrids

There are physical limitations on the power transfer capacity between two MGs and also between individual MGs and the main grid. At first, the EMS of each MG schedules generation expecting maximum support from neighboring MGs and the main grid. The EMS will compute LMP values at PCCs with neighboring MGs and the power supply (surplus) or demand (deficit) information of each MG for each hour over the time frame $t \in \{1, 2, ..., T\}$ (see Fig. 1). Some MGs may wish to supply power (seller MGs) and others may wish to demand power (buyer MGs) at time interval t. Subsequently, these results are passed to the tertiary layer which is the power sharing coordination controller (PSCC). It globally compares the power exchange preferences/requirements of each MG. Power sharing can only be facilitated if the demand and supply of two interconnected MGs suit each other at the same time interval. PSCC processes the requirements of each MG and decides possible combinations where power sharing can be facilitated. The amount of power to be shared and the cost of power sharing will be computed in the following manner for each possible combination.

Case 1: If $P^t_{MGp,i,j} \geq 0$ and $P^t_{MGs,j,i} \geq 0$ - power exchange can be facilitated at the price offered by the j^{th} MG $\left(\lambda^t_{MG,j}\right)$. The power transferred from the j^{th} MG to the i^{th} MG is calculated as follows:

$$P^t_{MG,j,i} = \min\left\{P^t_{MGp,i,j}, P^t_{MGs,j,i}\right\} \tag{9}$$

Case 2: If $P^t_{MGs,i,j} \geq 0$ and $P^t_{MGp,j,i} \geq 0$ - power exchange can be facilitated at the price offered by the i^{th} MG $\left(\lambda^t_{MG,i}\right)$. The power transferred from the i^{th} MG to the j^{th} MG is calculated as follows:

$$P^t_{MG,i,j} = \min\left\{P^t_{MGs,i,j}, P^t_{MGp,j,i}\right\} \tag{10}$$

Case 3: If $P^t_{MGs,i,j} \geq 0$ and $P^t_{MGs,j,i} \geq 0$ or $P^t_{MGp,i,j} \geq 0$ and $P^t_{MGp,j,i} \geq 0$ - both MGs wish to act either as sellers or buyers respectively. In this scenario, power exchange cannot be facilitated between the two MGs.

$$P^t_{MG,i,j} = P^t_{MG,j,i} = 0 \tag{11}$$

The cost of power sharing is calculated as follows:

$$C^t_{PS,i,j} = \lambda^t_{MG,i} P^t_{MG,i,j} + \lambda^t_{MG,j} P^t_{MG,j,i} \tag{12}$$

Algorithm 1 describes computations which happen in the tertiary control layer to coordinate power exchange.

Algorithm 1 Power Sharing Coordination

```
Compute EM problem for all the MGs as in Fig. 1.
Extract LMP values and power exchange preferences.
  /requirements of each MG over the time frame.
Select two MGs for comparison.
for t = 1 : T do
    Compare the power exchange preferences at time t.
    if Two MGs is a buyer-seller combination at time t;
  (i.e. case 1 or 2) then
        Update the power sharing limit as the minimum
  requirement of the two MGs as in (9) and (10).
        Use (12) to calculate the cost of power sharing.
    else (i.e. case 3)
        Set the power sharing limit and cost to zero (11).
    end
end
```

The PSCC updates power sharing limits. The results are fed back to the EMS to compute the new generation schedule, power exchange preferences and LMP values. The simulation continues till the maximum relative difference of power sharing cost in two consecutive iterations is lower than the specified tolerance.

IV. Case Study

A. Test System and Data

In the simulations, two grid connected MGs (MG 1 and MG 2) were considered. Both MGs were also assumed to be interconnected and to have DGs, an ESS, a solar PV and a wind power plant as power sources. The characteristics of DGs used in the simulation are shown in [2] (see Table I therein). MG 1 contains all DGs and MG 2 contains DG 1 and DG 2 only. Both MGs were assumed to have identical ESSs. For ESSs, B_{cap} was $1,020$ kWh; N was taken as 6000 h; $P_{1E,i}$ is 1020 kW and the cost of ESS was taken as \$400 per kWh [8]; P^{max}_{bc} and P^{max}_{bd} were taken as 300 kW each, and SOC^{min} and SOC^{max} were considered as 0.3 p.u. and 0.9 p.u respectively. The initial SOC value of ESS in each MG was set at 0.6 p.u. T_{bc} and T_{bd} were both found to be around 3 h for each MG in simulation studies. η_c and η_d were both taken as 0.95. Forecasted solar PV and wind power plant power generation profiles were taken from [2]. Power purchasing and selling prices for the main grid were taken from [13] for 01st of Jan 2016. The maximum power transfer limits from individual MGs to the main grid and to the other MG were taken as 500 kW and 1000 kW respectively.

MG 1 and MG 2 systems were assumed to be standard IEEE 30-bus and 14-bus test systems respectively [14]. For both MGs, base power value was taken as 8000 kVA and line resistance values were increased to 5 times that of the p.u. values provided in [14]. However, the p.u. values of line reactances were kept unchanged. In MG 1, DGs 1, 2 and 3 were connected to buses 27, 2 and 3 respectively. Both the wind power plant and ESS were connected to bus 22 and the Solar PV plant was connected to bus 13. Buses 1 and 23 were PCCs with the main grid and MG 2 respectively. In MG 2, DGs 1 and 2 were connected to buses 3 and 8 respectively. Both the wind power plant and ESS were connected to bus 6 and the Solar PV plant is connected to bus 2. Buses 1 and 14 were PCCs with the main grid and MG 1 respectively.

B. Simulation Results and Discussion

The algorithm was implemented in MATLAB. The optimal scheduling problem was formulated using YALMIP [15] and solved using CPLEX. The matrices generated from the MLD model using HYSDEL were used to formulate constraints for the scheduling problem. The OPF simulations were performed using the MATPOWER OPF solver package [14].

In simulation studies, the optimal generation schedule for each MG was first computed without power sharing among MGs. Then, power sharing was enabled to observe changes in the generation schedule for MGs. In both cases, MGs are kept connected with the main grid. Figs. 2 (a) and (c) depict the dispatch of DGs along with their load profiles for MG 1 and MG 2 respectively. It can be seen that all DGs are operated during peak demand hours for both MGs. Figs. 2 (b) and (d) show power exchanges with main grid and charge/discharge power of ESS respectively. In MG 1, ESS discharges during peak demand hours. However, ESS of MG 2 discharges during two time intervals and charges to its maximum SOC during load valley periods. Notably, MG 1 demands power from the main grid for 15 hours including peak demand hours and supplies power for 8 hours during off-peak hours. Altogether, MG 1 demands $2,916.8$ kWh from the main grid. Contrarily, MG 2 acts mostly as a supplier to the main grid. It demands power only for 3 distinct hours and supplies power during remaining hours including peak demand hours. The total power supplied is 8,168.6 kWh. TOC is \$ 14,968 for MG 1 and \$ 5,112 for MG 2.

Figs. 3 (a), (b), (c) and (d) show the power generation of two MGs when power sharing is enabled. Clearly, all DGs are operational during peak demand hours for both MGs. The behavior of ESSs of both MGs are more or less similar to the earlier case when power sharing was disabled. In addition to the parameters mentioned in the previous paragraph, power exchange between both MGs are depicted in Figs. 3 (b) and (d). It is observed that power transfer happens only from MG 1 to MG 2. This is determined by LMPs for each hour at the PCC between both MGs. The total energy transferred in 9 hours is 4,372 kWh. The power loss of MG 1 is higher during

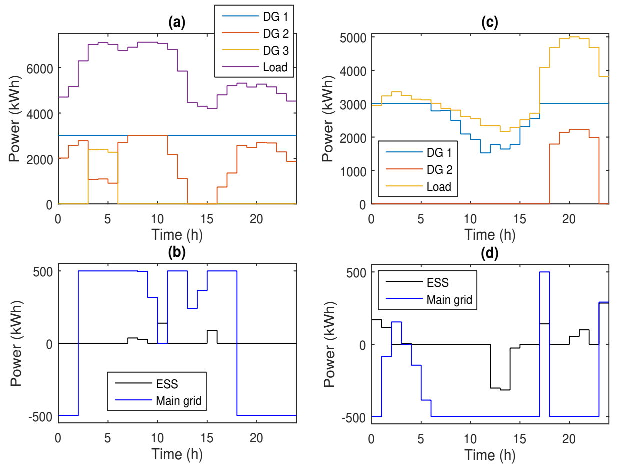

Fig. 2. Power genertion schedule of MG 1 and 2 without power sharing.

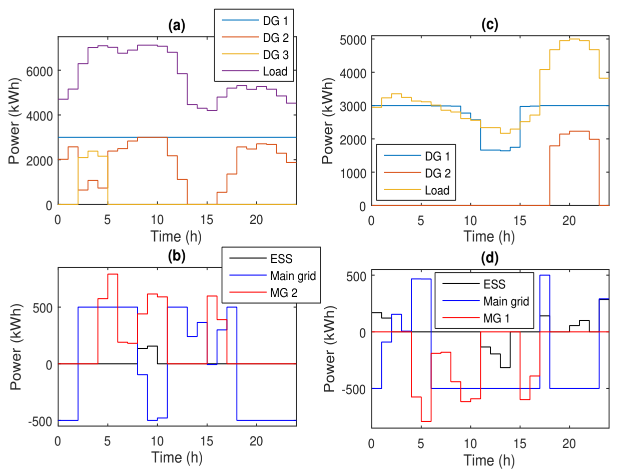

Fig. 3. Power genertion schedule of MG 1 and 2 with power sharing.

hours 9-11 (peak demand hours). Notably, MG 1 purchases energy (1,647 kWh in total) from MG 2 and supplies energy (1,074.5 kWh in total) to the main grid for this 3-hour time interval. This is because the EMS tries to control power flow so as to reduce the cost due to power losses. A similar scenario is observed in MG 2 for hours 5-6. MG 2 supplies 1,366.4 kWh in total to MG 1 and purchases 933.6 kWh in total from the main grid. Furthermore, MG 1 is less dependent on the main grid due to power sharing. It only demands a total of 323 kWh from the main grid. Also, MG 2 supplies less energy to the main grid (6,704.8 kWh). However, the combination of MG 1 and MG 2 supplies 1,130 kWh more energy to the main grid compared to the case when power sharing was disabled. TOC is $ 14,830 (reduction of $ 138) for MG 1 and $ 5,108 (reduction of $ 4) for MG 2. In this simulation, DG 1 and DG 2 of both MGs have identical operating characteristics. Moreover, MG 1 has a higher load factor (80.8%) compared to MG 2 (66.2%). These may be the reasons why power transfer happens only from MG 2 to MG 1.

V. Conclusions and Future Works

A multi-layered control architecture is presented in this paper to coordinate power sharing efficiently among interconnected MGs. The proposed approach optimizes the operational cost of each MG separately while also sharing power with neighboring MGs whenever possible. The secondary layer optimizes generation schedule while the tertiary layer facilitates power sharing. Two distinct MGs are used for simulation studies. The results show that with the proposed approach, the combination (MG 1 and MG 2) has a lower TOC, lower grid dependency and supplies more power to the main grid. Future studies will involve a greater number of MGs with different load profiles. The problem formulation may be extended to explore how power sharing can be optimized to reduce load shedding and maintain reserve requirements under uncertain RES generation and load forecasts.

References

[1] D. E. Olivares, J. D. Lara, C. A. Caizares, and M. Kazerani, "Stochastic-predictive energy management system for isolated microgrids," *IEEE Transactions on Smart Grid*, vol. 6, pp. 2681–2693, Nov 2015.

[2] S. X. Chen and H. B. Gooi, "Jump and shift method for multi-objective optimization," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 4538–4548, Oct 2011.

[3] K. Baker, G. Hug, and X. Li, "Optimal integration of intermittent energy sources using distributed multi-step optimization," in *2012 IEEE Power and Energy Society General Meeting*, pp. 1–8, July 2012.

[4] L. N. An and T. Quoc-Tuan, "Optimal energy management for grid connected microgrid by using dynamic programming method," in *2015 IEEE Power Energy Society General Meeting*, pp. 1–5, July 2015.

[5] P. Fortenbacher, A. Ulbig, S. Koch, and G. Andersson, "Grid-constrained optimal predictive power dispatch in large multi-level power systems with renewable energy sources, and storage devices," in *IEEE PES Innovative Smart Grid Technologies, Europe*, pp. 1–6, Oct 2014.

[6] M. Kahl, C. Freye, and T. Leibfried, "A cooperative multi-area optimization with renewable generation and storage devices," *IEEE Transactions on Power Systems*, vol. 30, pp. 2386–2395, Sept 2015.

[7] A. Ouammi, H. Dagdougui, L. Dessaint, and R. Sacile, "Coordinated model predictive-based power flows control in a cooperative network of smart microgrids," *IEEE Transactions on Smart Grid*, vol. 6, pp. 2233–2244, Sept 2015.

[8] K. Chaudhuri, A. Ukil, S. K. Kollimala, and U. Manandhar, "Energy storage management for public ev charging stations: Comparison of uncoordinated and statistical charging loads," in *42nd IEEE Annual Conf. on Industrial Electronics - IECON*, Oct 2016.

[9] F. D. Torrisi and A. Bemporad, "Hysdel-a tool for generating computational hybrid models for analysis and synthesis problems," *IEEE Transactions on Control Systems Technology*, vol. 12, pp. 235–249, March 2004.

[10] A. Bemporad and M. Morari, "Control of systems integrating logic, dynamics, and constraints," *Automatica*, vol. 35, no. 3, pp. 407 – 427, 1999.

[11] A. Krishnan, B. V. Patil, H. B. Gooi, and K. V. Ling, "Predictive control based framework for optimal scheduling of combined cycle gas turbines," in *2016 American Control Conference (ACC)*, pp. 6066–6072, July 2016.

[12] A. Parisio, E. Rikos, and L. Glielmo, "A model predictive control approach to microgrid operation optimization," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 1813–1827, Sept 2014.

[13] Energy Market Company, *Price Information*. https://www.emcsg.com/marketdata/priceinformation, Oct. 2016.

[14] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Transactions on Power Systems*, vol. 26, pp. 12–19, Feb 2011.

[15] J. Lofberg, "Yalmip : a toolbox for modeling and optimization in matlab," in *Computer Aided Control Systems Design, 2004 IEEE International Symposium on*, pp. 284–289, Sept 2004.