Generation and Demand Scheduling for a Grid-Connected Hybrid Microgrid Considering Price-based Incentives

Hernández, Adriana Carolina Luna; Aldana, Nelson Leonardo Diaz; Savaghebi, Mehdi; Wei, Feng ; Sun, Kai; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.

Published in:
Proceedings of 43rd Annual Conference of the IEEE Industrial Electronics Society, IECON 2017

DOI (link to publication from Publisher):
10.1109/IECON.2017.8216420

Publication date:
2017

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Hernández, A. C. L., Aldana, N. L. D., Savaghebi, M., Wei, F., Sun, K., Quintero, J. C. V., & Guerrero, J. M. (2017). Generation and Demand Scheduling for a Grid-Connected Hybrid Microgrid Considering Price-based Incentives. In *Proceedings of 43rd Annual Conference of the IEEE Industrial Electronics Society, IECON 2017* (pp. 2498-2503). IEEE Press. https://doi.org/10.1109/IECON.2017.8216420

Generation and Demand Scheduling for a Grid-Connected Hybrid Microgrid Considering Price-based Incentives

Adriana C. Luna*, Nelson L. Diaz†, Mehdi Savaghebi*, Wei Feng ‡, Kai Sun ‡, Juan C. Vasquez*, and Josep M. Guerrero*

*Dept. Energy Technology, Aalborg University, Aalborg, Denmark,
Email: acl@et.aau.dk, mes@et.aau.dk, juq@et.aau.dk, joz@et.aau.dk
http://www.microgrids.et.aau.dk

†Dept. Electronic Engineering, Universidad Distrital F.J.C., Bogota, Colombia,
Email: nldiaza@udistrital.edu.co

‡ Dept. Electrical Engineering, Tsinghua University, Beijing 100084, China
Email: fwqqrse@163.com, sun-kai@mail.tsinghua.edu.cn

Abstract—**Microgrids rely on energy management levels to optimally schedule their components. Conventionally, the research in this field has been focused on the optimal formulation of the generation or the demand side management separately without considering real case scenarios and validated only by simulation. This paper presents the power scheduling of a real site microgrid under a price-based demand response program defined in Shanghai, China managing generation and demand simultaneously. The proposed optimization problem aims to minimize operating cost by managing renewable energy sources as well as shiftable loads considering the preferred time of use. The proposal has been tested experimentally in a laboratory prototype.**

I. Introduction

Microgrids require coordinating their distributed power generation to supply the local demand [1]. In this way, microgrids contain energy management levels that define the operating conditions of the distributed units. In operation level, the management is in charge of optimally assigning references for the Distributed Energy Resources (DER). In the case of grid-connected microgrids, the energy surplus can be harnessed either by selling it or by including Energy Storage Systems (ESS) for energy arbitrage [2].

On the other hand, demand response (DR) programs have been recently defined in smart grid in order to provide flexibility in the management of loads [3]. In the specific case of microgrids, demand side management can be performed, while price-based programs are used as exogenous information. One kind of price-based DR is the Time of Use (ToU) program that persuades users to change their consumption behavior by means of establishing variable tariffs along the day. In this case, the electricity tariffs are usually released in advance and kept unchanged for a long time period [3].

Optimal management of microgrids is an active research field, mainly focused on the formulation of the optimization problem [4], [5], [6], [7]. These formulations have been defined as linear and nonlinear models [5], but the nonlinear models do not ensure global optimal solutions [8]. Moreover, many papers have focused their contribution on developing generation side or demand side management separately, such as [3], [9], [10]. Besides, some other studies have already considered energy and demand, simultaneously. For instance, [11] uses Demand Side Management (DSM) approach that does not consider the duration and preferences of the users. However, most of these works are validated only by simulations and do not consider physical limitations as the case of [12] that presents a proposal of the management of loads and controllable generation but does not address the likely fact of having a surplus of RES energy.

This paper presents the modeling and experimental validation of an optimization problem that aims to minimize operating costs and maximize revenues in a DR scheme settled in Shanghai, including the management of controllable loads. The grid-connected microgrid is composed of 6 strings of photovoltaic (PV), 2 Wind Turbines (WT), one battery bank, a variable non-sheddable load and a resistive sheddable load. In this work, the optimization problem has been modeled as a Mixed Integer Linear Programming (MILP) considering the operation mode of DERs, as well as, a real case of ToU demand response scheme and the obtainable revenue due to subsidies for PV generation. The proposed optimization problem aims to minimize the cost of buying energy from the main grid and maximize the profits from the subsidies given to the PV energy generation while preserving the lifetime of the ESS based on batteries by avoiding overcharge and deep discharge cycles. Also, it is including the fact that the WT generation only can be used locally. Accordingly, the sheddable load is shifted to the most convenient time, fulfilling the requirements of duration and time preferences. The proposal has been tested experimentally in a laboratory prototype of the real hybrid microgrid site located in Shanghai, China.

II. MICROGRID DESCRIPTION

The system is a 200 kW PV-wind-battery microgrid connected to the main grid that supplies two kinds of loads, one variable non-shedding load (0-4 kW) and one shedding resistive load (8 kW). The DERs inverters operate in current-controlled mode as grid-following units, while the main grid regulates the voltage and frequency conditions at the point of common coupling [13]. The microgrid is composed of six PV strings that follow a local Maximum Power Point Tracking (MPPT) algorithm. Also, it includes two wind generators that can receive power references provided by the Energy Management System (EMS) to curtail part of the available energy [1]. The WT generation is not traded since this is not subsided. Additionally, the microgrid has a battery bank of 50 kWh. For charging and discharging, a two-stage procedure is implemented [14]. In the first stage (limited power charge), the ESS is charged following the power reference defined by the EMS, taking into account power ratings of the ESS. The second stage (constant voltage charge) is activated once the battery voltage reaches a threshold value when the ESS is considered full-charged. In this stage, the controller keeps constant the battery voltage [1], [14], [15].

The microgrid is installed in Shanghai, China. In this region, the local government has formulated additional policies in order to encourage PV implementation, which is deployed by means of subsidies for the PV generation [16]. Therefore, the price of PV generation is composed of the basic tariff plus subsidies from the State and also from each local region. In this way, the PV generation in Shanghai is paid around 1.147 (Yuan/kWh).

Moreover, cities in China have different retail electricity rate structures [16]. In Shanghai, the electricity price is established based on a ToU scheme defined in three stages depending on the amount of energy consumption [17]. In this paper, only stage 1 is used since it is settled for consumption between 0 to 3120 kWh, which contains the total load of the case study. The tariffs of Stage 1 are set to 0.617 (Yuan/kWh) during the day (from 6:00 to 18:00) and 0.307 (Yuan/kWh) during the night.

In this context, the generation provided by WT can only be used for local demand while most of the PV generation should be injected into the grid. Accordingly, the battery and the shedding loads are scheduled to be used at the most beneficial hours of the day to maximize the revenue for the owner of the microgrid.

III. OPTIMIZATION PROBLEM

The proposed mathematical model aims to minimize operating costs and maximize revenues of the microgrid by managing the ESS power, the curtailment of the WT, and shifting a load that should operate during preferred hours established by the user.

Table I summarizes some relevant parameters used in the model. The values are presented in per unit (p.u.) using a base of 136.08 kW, which is the power rating of the PV generation.

A. Mathematical Formulation

The problem has been formulated as a MILP, represented in discrete time t with intervals of $\Delta t = 1$ h and with $T = 24$ h as the time horizon [18]. The software GAMS has been used to solve the optimization problem by setting the solver CPLEX. The model uses real and binary variables, x and z respectively, considering average values at each time interval, as,

$$x(t) = \begin{bmatrix} p_{buy}(t) \\ p_{sell}(t) \\ p_{wt_{(j)}}(t) \\ p_{bat}(t) \\ soc(t) \end{bmatrix}, \quad z(t) = \begin{bmatrix} z_{grid}(t) \\ z_{load}(t) \\ z_{load_{ON}}(t) \\ z_{load_{OFF}}(t) \end{bmatrix} \tag{1}$$

where $p_{buy}(t)$ and $p_{sell}(t)$ are the power absorbed and injected from/to the main grid, respectively; $p_{wt_{(j)}}(t)$ is the power reference for controlling the WT generation; $p_{bat}(t)$ is the power reference for the usage of the battery; $soc(t)$ is the State of Charge (SoC) of the battery; $z_{grid}(t)$ is the status of the grid, i.e. injecting or absorbing power; $z_{load}(t)$ is the binary variable that establishes if the shiftable load is connected; and $z_{load_{ON}}(t)$ and $z_{load_{OFF}}(t)$ are auxiliary binary variables to include the additional constraints related to the load. The variables used in the mathematical formulation are presented in lower-case in order to recognize them easily. It is worth to point out that the controllable renewable resources are the wind turbines, while the PV generators are always working by following an MPPT.

The optimization problem minimizes the cost of buying energy from the utility grid and maximizes the revenue obtained by selling energy generated from the PVs while avoiding deep discharges of the battery [19]. This last condition also makes the surplus renewable energy to be stored rather than curtailed. Accordingly, the objective function has been defined as,

$$\sum_{t=1}^{T} \left\{ p_{buy}(t) * \Delta t \right\} * C_{buy}(t) - \sum_{t=1}^{T} \left\{ p_{sell}(t) * \Delta t \right\} * C_{sell}(t) + \sum_{t=1}^{T} \left[\frac{SoC_{max} - soc(t)}{100\%} \right] * \chi \tag{2}$$

where $C_{buy}(t)$ is the energy tariff of buying electricity with different prices during the day and the night as mentioned before; $C_{sell}(t)$ is the elementary cost of selling energy to the utility according to the tariffs settled in [17]; SoC_{max} is the maximum SoC of the battery; and χ is a penalty cost to the battery and has been set as ten

Table I: Parameters of the model

Name	Description	Value
T	Number of time slots	24 (h)
Δt	Duration of interval	1 (h)
n_i	Number of PV arrays	1
n_j	Number of WT	1
$C_{sell}(t)$	Cost of selling energy	1.147 (Yuan/kWh)
$C_{buy}(t)$	Cost of buying energy (night)	0.307 (Yuan/kWh)
	Cost of buying energy (day)	0.617 (Yuan/kWh)
$P_{PV_{max}}(i,t)$	Max power for PV arrays	1 (p.u.)
$P_{WT_{max}}(j,t)$	Max WT power $\forall j$	0.073 (p.u.)
$P_L(t)$	Power required by the load	0.157 (p.u.)
$P_{bat_{max}}$	Maximum power of battery	0.3 (p.u.)
$P_{bat_{min}}$	Minimum power of battery	-0.3 (p.u.)
$P_{grid_{max}}$	Max. power absorbed from utility	1 (p.u.)
SoC_{max}	Maximum SoC	100 (%)
SoC_{min}	Minimum SoC	50 (%)
$SoC(0)$	Initial Condition of SoC	100 (%)
Cap_{bat}	Capacity of the battery	0.372 p.u.h.
χ	Penalty cost to the battery	$C_{buy}(t) * 0.1$(Yuan/kWh)
$duration$	Duration of the controllable load	3 (h.)
t_{start}	Preferred start time for using controllable load	6 (h.)
t_{stop}	Preferred stop time for using controllable load	20 (h.)

times smaller than $C_{buy}(t)$ in order to assign less weight to this constraint as in [20], [19].

In this way, the first two terms in (2) fulfill the requirements of the optimization problem for the considered time horizon while the third term is included to store the surplus energy in the ESS [19].

On the other hand, the problem is constrained in order to get feasible solutions. First of all, the optimization problem has to consider the energy balance, that can be written as,

$$\begin{aligned} &\left\{p_{buy}(t) * \Delta t - p_{sell}(t) * \Delta t\right\} + p_{bat}(t) * \Delta t + \\ &\sum_{i=1}^{n_i} P_{PV_{max_{(i)}}}(t) * \Delta t + \sum_{j=1}^{n_j} p_{wt_{(j)}}(t) * \Delta t + \\ &= P_L(t) * \Delta t + P_L^{nint} * \Delta t * z_{load}(t), \quad \forall t \end{aligned} \tag{3}$$

where $P_{PV_{max_{(i)}}}(t)$ is the expected profile of the power generated by the n_i PV arrays, $P_L(t)$ is the power profile of the non-shedding load and P_L^{nint} is the power of the shedding load.

The boundaries related to the power of WTs and the utility can be defined as,

$$0 < p_{wt_{(j)}}(t) < P_{WT_{max_{(j)}}}(t), \forall t, j \tag{4}$$

$$0 \leq p_{buy}(t) \leq P_{grid_{max}} * z_{grid}(t), \forall t \tag{5}$$

$$0 \leq p_{sell}(t) \leq \sum_{i=1}^{n_i} P_{PV_{max_{(i)}}}(t) * \left(1 - z_{grid}(t)\right), \forall t \tag{6}$$

where $P_{WT_{max_{(j)}}}(t)$ is the expected power profile of the WTs and $P_{grid_{max}}$ is the maximum power that can be absorbed from the grid. By means of (6), the power sold by the microgrid is limited to be lower than the power produced by the PV arrays at every time t. It is worth emphasizing that only the power generated by PVs can be traded whereas WT power and ESS should be used locally.

Related to the battery, the following constraints have been defined,

$$soc(t) = soc(t-1) - \frac{p_{bat}(t) * \Delta T}{Cap}, \quad \forall t \tag{7}$$

$$P_{bat_{min}} < p_{bat}(t) < P_{bat_{max}}, \quad \forall t \tag{8}$$

$$SoC_{min} < soc(t) < SoC_{max}, \quad \forall t \tag{9}$$

where Cap is the nominal capacity defined in kWh, $P_{bat_{min}}$ and $P_{bat_{max}}$ are the limits of charging and discharging power given by the battery manufacturer, and SoC_{min} is the minimum SoC of the battery, defined to avoid fast degradation [14].

Related to the shiftable load, the binary variable $z_{load}(t)$ is defined to schedule its status. As a requirement, the load should work for the $duration = 3$ h, between $[t_{start} = 8:00, t_{stop} = 20:00]$.

In order to include these constraints in the formulation, the auxiliary binary variables $z_{load_{ON}}(t)$ and $z_{load_{OFF}}(t)$ are also defined. These variables establish when the shiftable load is started and stopped, respectively, as shown in Fig. 1.

Accordingly, $z_{load_{ON}}(t)$ is equal to zero until the load is used and, after that, the value is set to one. Likewise, $z_{load_{OFF}}(t)$ is zero until the load is off, when its value changed to one. Mathematically, it can be written as,

$$z_{load_{ON}}(t+1) \geq z_{load_{ON}}(t), \quad \forall t \tag{10}$$

$$z_{load_{OFF}}(t+1) \geq z_{load_{OFF}}(t), \quad \forall t \tag{11}$$

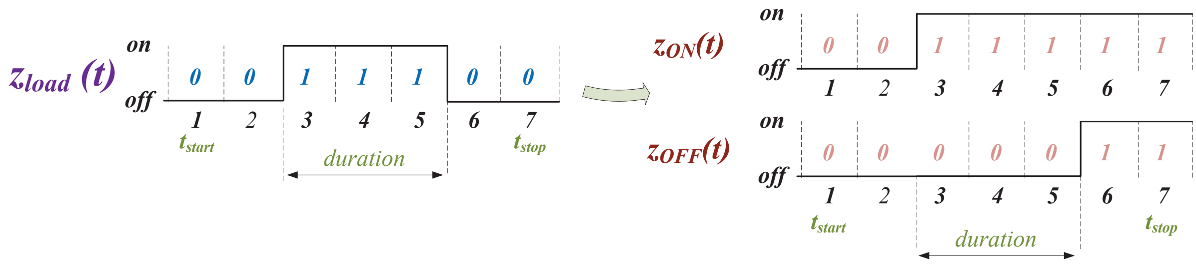

Figure 1: Binary variables associated with the controllable load.

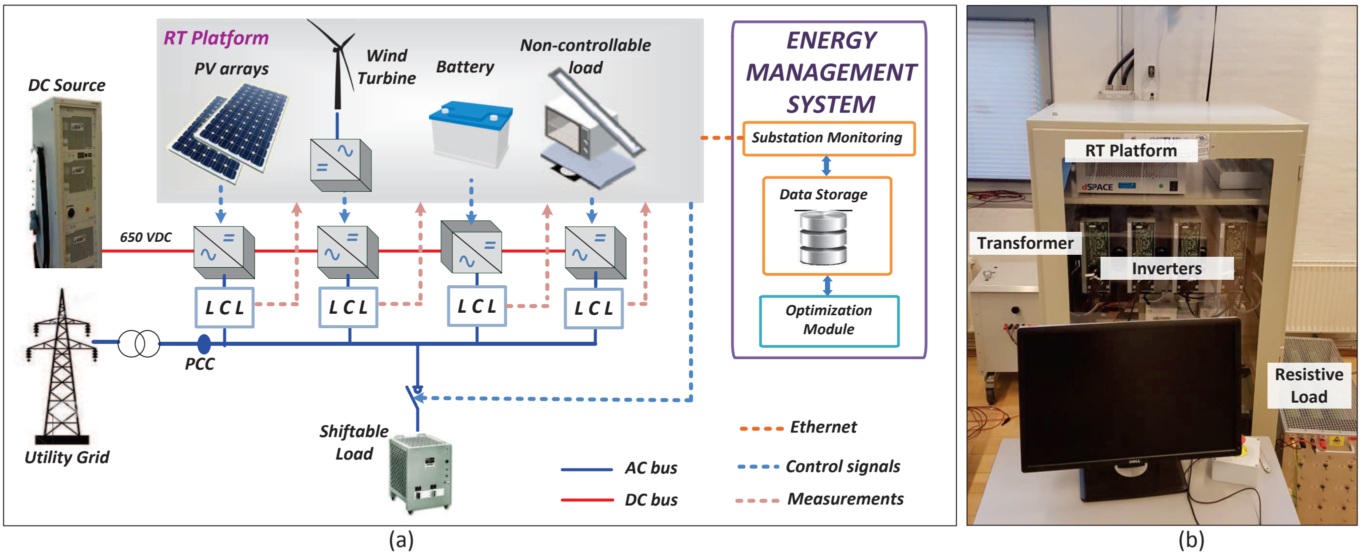

Figure 2: Schematic and experimental setup implementation of the laboratory-scale microgrid.

In this way, $z_{load}(t)$ can be defined as the difference between $z_{load_{ON}}(t)$ and $z_{load_{OFF}}(t)$, namely,

$$z_{load}(t) = z_{load_{ON}}(t) - z_{load_{OFF}}(t), \quad \forall t \tag{12}$$

As mentioned before, the shiftable load should be used uninterruptedly during the specific time *duration*. This constraint can be written as,

$$\sum_{t=1}^{T} z_{load}(t) * \Delta t = duration \tag{13}$$

Additionally, the use of shiftable load should be used in the interval $[t_{start}, t_{stop}]$, which defined the preferences of the user. In this way, the auxiliary variables of the load must also fulfil the constraints,

$$\sum_{t=1}^{T} \left(1 - z_{load_{ON}}(t)\right) * \Delta t \geq t_{start} \tag{14}$$

$$\sum_{t=1}^{T} \left(1 - z_{load_{OFF}}(t)\right) * \Delta t \geq t_{stop} \tag{15}$$

IV. RESULTS

In order to verify experimentally the performance of the proposed optimization problem, a laboratory-scaled microgrid is experimentally implemented based on the microgrid described in section II in the Microgrid Laboratory of Aalborg University [21], as shown in Fig. 2. The microgrid has a physical connection of the inverters with the main grid and a resistive load, which is the sheddable load. A Real-Time (RT) platform is used to include the controllers of the inverters, the aggregated PV and WT generation profiles, the non-sheddable load profile and a dynamic battery model. The local controllers developed in [22] have been used in this test.

A. Scheduling Results

Preliminary results are obtained by using expected generation and consumption profiles of a particular day presented in Fig. 3(a), and setting the initial condition of the SoC of the battery to $SoC(0) = 100\%$. The results are presented in per unit (p.u.).

The outputs of the scheduling sent to the controllers of the microgrid are the profiles of the controllable load (Fig. 3(b)), WT power (dash line labelled as *WT reference* in Fig. 3(c)), and battery power (Fig. 3(e)). Consequently, the microgrid is planned to exchange energy with the main grid as shown in Fig. 3(d) (dash line), where

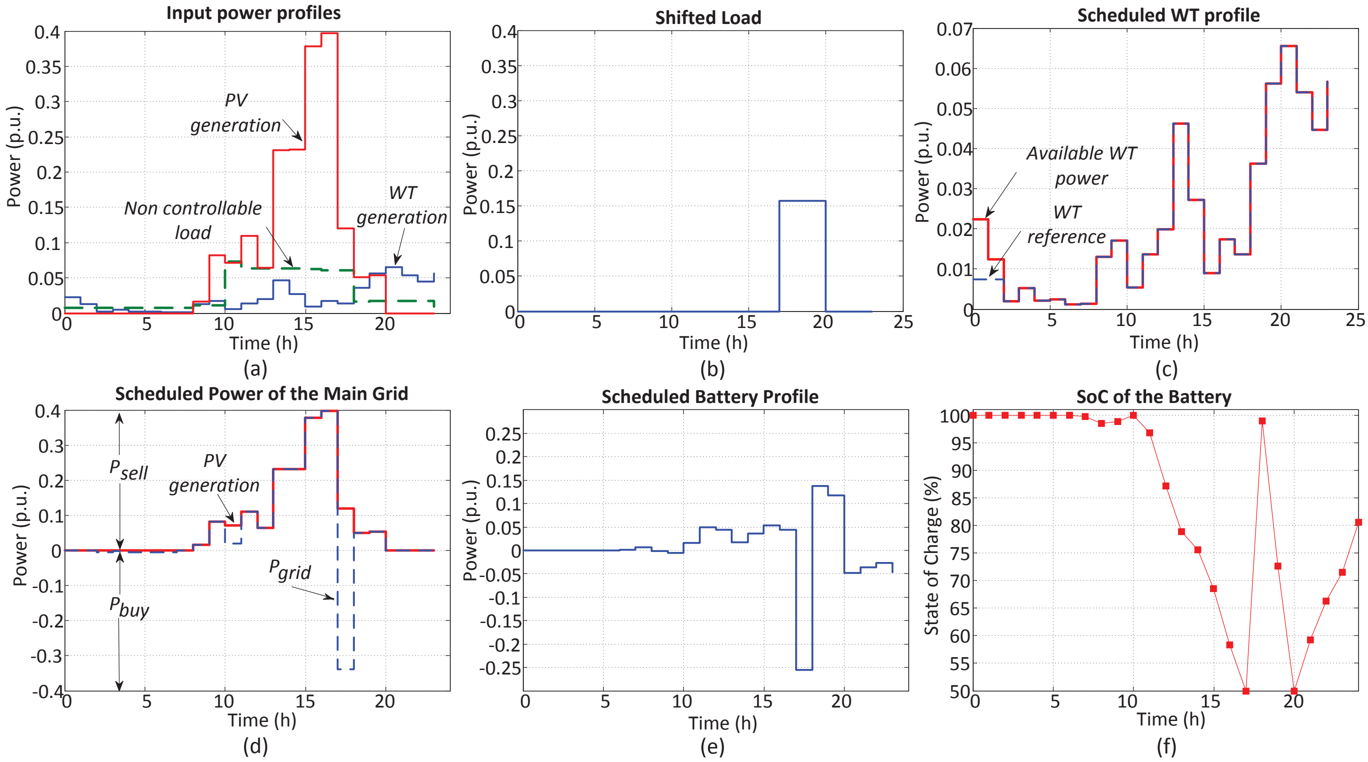

Figure 3: Scheduling results for the selected day: (a) Input generation and demand power profiles, (b) Scheduled shifting of controllable load, (c) Available and scheduled reference of WT power, (d) Available PV power and scheduled power of the grid, (e) scheduled battery power profile, and (f) scheduled SoC of the battery.

positive values represent power injection to the main grid. As can be seen from Fig. 3(d), the microgrid just absorbed energy from the utility at the beginning of the day (1:00 to 8:00) and from 17:00 to 18:00. In the first lapse, the demand and the cost of absorbing energy from the grid (due to the ToU tariff) are low. Meanwhile, in the second case, the SoC of the battery is very low ($SoC = SoC_{min} = 50\%$ in Fig. 3(f)) and the RES generation is not enough to supply the load, thus the battery power is scheduled to be charged from the grid to balance the load and RES generation during the next two hours. On the other hand, from Fig. 3(d), is possible to see that most of the energy obtained from PVs is sent to the utility, maximizing the revenue. Additionally, the WT energy surplus at the end of the day (after 20:00) is used by storing it in the battery.

B. Experimental Results

The experiments are conducted by using the outputs of the scheduling process along with the generation and demand profiles in the real-time platform of the experimental setup of the microgrid. Namely, in Fig. 4(a) are presented the power profile of the non-controllable load, as well as the scheduled WT power. The PV power profiles are presented in Fig. 4(c) and the scheduled battery profiles are shown in Fig. 4(b). The controllable load is used as the scheduled in the previous section. The values are presented in kW as used in the laboratory, with a base of 2.2 kW.

As a result, the power of the grid and the SoC of the battery are obtained and presented in Fig. 4(c) and Fig. 4(d), respectively. Comparing the results of scheduling process (Fig. 3) with the experimental (Fig. 4), it is possible to infer that the energy exchanged between the microgrid and the utility can be managed by scheduling DER/loads in order to maximize the profit for the user. In turn, the behavior of the SoC battery can be estimated even by using a linear optimization model that does not consider the fast dynamics of the batteries and the lower controllers of the microgrid.

V. Conclusion

An optimization model for a real grid-connected hybrid microgrid under a price-based demand program used in Shanghai and its performance has been defined and experimentally verified in a laboratory scale microgrid. The proposed formulation is a complete mathematical model that includes generation and demand side management in a real price-based DR. The optimization problem minimizes the cost of buying energy from the utility grid, maximizes the revenue obtained by selling energy generated by the PVs and optimally shifts the controllable loads. This model can be easily modified for different amounts of DERs and different time use

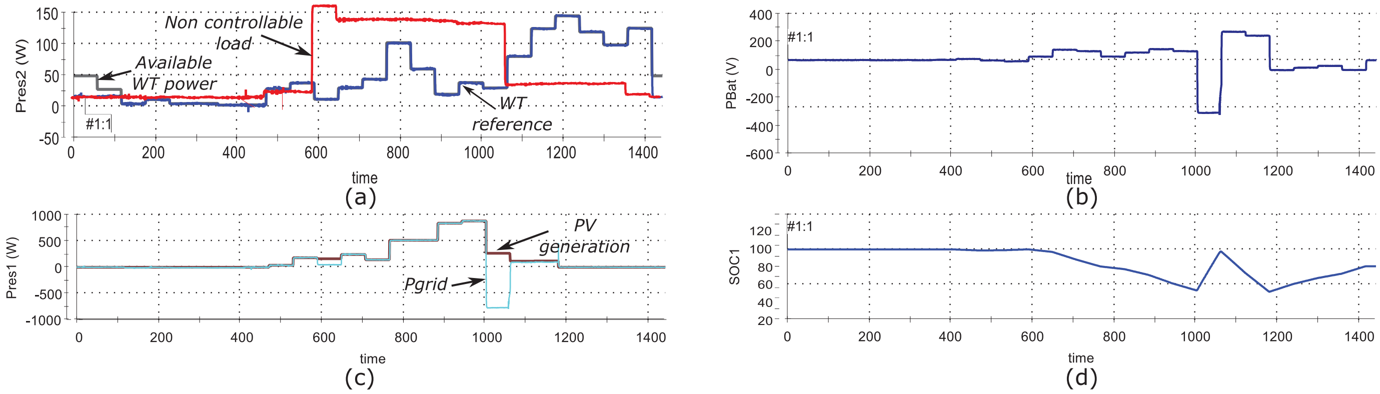

Figure 4: Experimental Results. (a) Available WT power, scheduled WT profile, non-controllable load profile, (b) scheduled battery power, (c) PV generation profile, power of the grid and (d) SoC of the battery.

preferences of the controllable loads. The optimization model is suitable for scheduling the power references and predicting accurately the behavior of the SoC in the battery as well as estimating the energy absorbed from the main grid. As future work, it is relevant to consider the impact of managing the operation of the microgrid over the distribution network in order to assess the feasibility of spreading out their implementation.

Acknowledgment

This work has been supported by the Danish Energy Technology Development and Demonstration Program (EUDP) through the Sino-Danish Project Microgrid Technology Research and Demonstration (meter.et.aau.dk) and also by the International Science & Technology Cooperation Program of China, project Number 2014DFG62610.

References

[1] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," *Power and Energy Magazine, IEEE*, vol. 6, no. 3, pp. 54–65, May 2008.

[2] M. Pereira, D. Limon, D. M. de la Pea, L. Valverde, and T. Alamo, "Periodic economic control of a nonisolated microgrid," *IEEE Trans. Ind. Electron.*, vol. 62, no. 8, pp. 5247–5255, Aug 2015.

[3] R. Deng, Z. Yang, M. Y. Chow, and J. Chen, "A survey on demand response in smart grids: Mathematical models and approaches," *IEEE Trans. Ind. Informatics*, vol. 11, no. 3, pp. 570–582, June 2015.

[4] M. Iqbal, M. Azam, M. Naeem, A. Khwaja, and A. Anpalagan, "Optimization classification, algorithms and tools for renewable energy: A review," *Renewable and Sustainable Energy Reviews*, vol. 39, no. 0, pp. 640 – 654, 2014.

[5] A. H. Fathima and K. Palanisamy, "Optimization in microgrids with hybrid energy systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 431 – 446, 2015.

[6] L. Meng, E. R. Sanseverino, A. Luna, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Microgrid supervisory controllers and energy management systems: A literature review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1263 – 1273, 2016.

[7] K. Shimomachi, R. Hara, H. Kita, M. Noritake, H. Hoshi, and K. Hirose, "Development of energy management system for dc microgrid for office building: Day ahead operation scheduling considering weather scenarios," in *Power Systems Computation Conference (PSCC), 2014*, Aug 2014.

[8] Z. Zhao, "Optimal energy management for microgrids," Ph.D. dissertation, Clemson University, 2012.

[9] M. Elsied, A. Oukaour, H. Gualous, and R. Hassan, "Energy management and optimization in microgrid system based ongreen energy," *Energy*, vol. 84, pp. 139 – 151, 2015.

[10] G. B. Shrestha and S. Qiao, "Price-based scheduling for gencos," in *Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling*, J. P. S. Catalao, Ed. CRC Press, 2015, ch. 6.

[11] R. Palma-Behnke, C. Benavides, F. Lanas, B. Severino, L. Reyes, J. Llanos, and D. Saez, "A microgrid energy management system based on the rolling horizon strategy," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 996–1006, June 2013.

[12] R. Wang, P. Wang, G. Xiao, and S. Gong, "Power demand and supply management in microgrids with uncertainties of renewable energies," *International Journal of Electrical Power & Energy Systems*, vol. 63, pp. 260 – 269, 2014.

[13] D. Wu, F. Tang, T. Dragicevic, J. Vasquez, and J. Guerrero, "Autonomous active power control for islanded ac microgrids with photovoltaic generation and energy storage system," *IEEE Trans. Energy Conversion*, vol. 29, no. 4, pp. 882–892, Dec 2014.

[14] I. S. C. C. 21, "Guide for optimizing the performance and life of lead-acid batteries in remote hybrid power systems," *IEEE Std 1561-2007*, pp. C1–25, 2008.

[15] N. L. Diaz, J. G. Guarnizo, M. Mellado, J. C. Vasquez, and J. M. Guerrero, "A robot-soccer-coordination inspired control architecture applied to islanded microgrids," *IEEE Transactions on Power Electronics*, vol. PP, no. 99, pp. 1–1, 2016.

[16] F. Zhang, H. Deng, R. Margolis, and J. Su, "Analysis of distributed-generation photovoltaic deployment, installation time and cost, market barriers, and policies in china," *Energy Policy*, vol. 81, pp. 43 – 55, 2015.

[17] S. C. C. by letter Date: 2012-12-21. Shanghai region tariff table. [Online]. Available: http://www.sheitc.gov.cn/dfjf/637315.htm

[18] W. Shi, X. Xie, C.-C. Chu, and R. Gadh, "Distributed optimal energy management in microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1137–1146, May 2015.

[19] A. Luna, N. Diaz, M. Savaghebi, J. C. Vasquez, J. M. Guerrero, K. Sun, G. Chen, and L. Sun, "Optimal power scheduling for a grid-connected hybrid pv-wind-battery microgrid system," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2016, pp. 1227–1234.

[20] N. L. Diaz, A. C. Luna, J. C. Vasquez, and J. M. Guerrero, "Centralized control architecture for coordination of distributed renewable generation and energy storage in islanded ac microgrids," *IEEE Transactions on Power Electronics*, vol. PP, no. 99, pp. 1–1, 2016.

[21] Intelligent microgrid laboratory. Aalborg University. [Online]. Available: http://www.et.aau.dk/department/laboratory-facilities/intelligent-microgrid-lab/

[22] A. C. Luna, N. L. D. Aldana, M. Graells, J. C. Vasquez, and J. M. Guerrero, "Mixed-integer-linear-programming based energy management system for hybrid pv-wind-battery microgrids: Modeling, design and experimental verification," *IEEE Transactions on Power Electronics*, vol. PP, no. 99, pp. 1–1, 2016.