End-Users Electricity Analysis of a DC-Coupled Hybrid Microgrid by Real-Time Simulation

Yu-Jen Liu,[1,*], Gary W. Chang[1], Yi-Feng Pai[1], Yung-Ruei Chang[2], and Yih-Der Lee[2]

[1] Department of Electrical Engineering, National Chung Cheng University, Chiayi, Taiwan (R.O.C.)
[2] Nuclear instrument division, Institute of Nuclear Energy Research, Taoyuan, Taiwan (R.O.C.)

***Abstract* — Microgrid has been used to improve the reliability and resilience of existing electric grid, to manage the integration of various renewable energy sources, and to provide the electricity saving benefit by demand side management. It is now emerging from test benches and demonstration sites into commercial applications, which is driven by technological growth. In this paper, a DC-coupled hybrid microgrid is studied and the end-users electricity analysis is discussed. A simulation-based analysis platform is implemented using MATLAB/Simulink and OPAL-RT real-time simulation technology. The investigations involve modelling, and simulation mechanism. The used control strategies are presented, and two different electricity price rates are introduced to calculate the electricity bill for the studied microgrid system operating in different scenarios. Findings demonstrate the benefit of electricity saving provided by the operation of the microgrid system.**

***Index Terms* — microgrid, electricity analysis, MATLAB/Simulink, real-time simulation.**

I. Introduction

Microgrid (MG) is proposed as an application for designing and operating the electric grid in order to achieve a more sustainable and cost-effective energy system while generally providing alternative-energy sources-driven power supply to meet the load demands of grid end-users. Electricity end-users have higher expectancies to seek reliable and lower costs electricity. Thus, the increase in the use of localized energies with the MG solutions is considered to reach this goal. Electricity in a MG system can be collected by different sides, including utility side, end-user side, and MG system side. In the past, some of electricity analysis efforts have been proposed by using time-series simulation tools with simplified (or phasor-type) models [1], [2]. Furthermore, various means such as energy-saving lights and inverter-based electric appliances have also been introduced for electricity saving. To understand the manner of electricity supply and consumption in the MG system, this paper aims to create a simulation-based electricity analysis platform by integrating MATLAB/Simulink and OPAL-RT simulation packages. A power balance electricity management strategy is used for MG electricity control. To observe the performance of purposed simulation platform and to investigate the electricity response of end-users in MG, two simulation scenarios, end-users with and without using load peak shaving mechanism, are implemented. In addition, two different electricity price rates are introduced to calculate the end-users electricity bill.

Overall, the proposed methodologies may be helpful for user demand management and system operation control in MG applications. The rest of this paper is organized as follows. Section 2 describes the configuration of studied MG system and major model characteristics. Section 3 illustrates the various used control strategies and proposed real-time simulation mechanism. Section 4 presents the simulation results obtained using different case scenarios in this work, and conclusions are given in Section 5.

II. Modelling of a DC-coupled hybrid microgrid

Microgrid can be considered as a hybrid electricity system with AC and DC elements. Generally, it refers to an MG system that includes both AC and DC energy sources and loads and depends on how the energy sources and loads are connected to the MG system and how the AC and DC buses are set up. Hybrid AC/DC MG can often be classified into three types: AC-coupled, DC-coupled and AC-DC-coupled [3]. The focus of this research is a DC-coupled one since it is commonly used for low-voltage residential MG application. The investigated DC-coupled hybrid MG (DCHMG) system and its modelling methodologies are presented as follows:

[*] Corresponding author.
E-mail: azenliu@ccu.edu.tw

http://dx.doi.org/10.25729/esr.2018.03.0001
Received November 14, 2018. Revised December 12, 2018.
Accepted December 13, 2018. Available online Jan. 25, 2019.

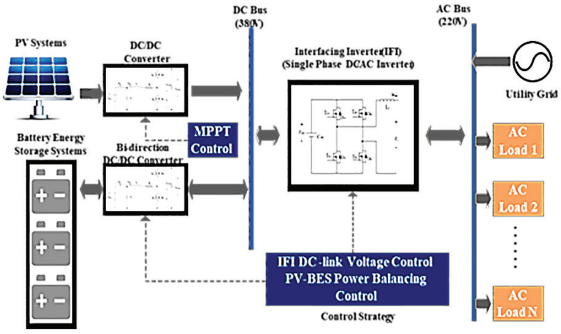


Fig. 1. Configuration of the DCHMG.

A. System Configuration

Figure 1 shows a studied DCHMG system where photovoltaic (PV) generations, including a boost-type DC/DC converter, and battery energy storage (BES) systems, with a bi-direction DC/DC converter, are the main alternative energy sources connected to a common. 380V DC bus. A single-phase interfacing DC/AC inverter (IFI) that provides a bi-directional power flow capability is used to link the DC bus and 220 V AC bus. Furthermore, when multi-IFIs are suited, according to the requirement of power exchange between DC and AC buses, parallel construction of IFIs may be used in order to increase the system rating and reliability. General residential AC loads or variable frequency AC loads can be connected to AC and DC bus, respectively. This structure can be used when DC power sources are major power generations beside utility in the DCHMG, and it is worth noting that if any other alternative energy sources are on AC bus, it is considered to be a different type of MG in the study.

B. Modelling

MATLAB/Simulink is used for modelling and simulation tasks in this study. Completed DCHMG system model is developed in Fig. 2; meanwhile, detailed model for each main electrical component is used in simulations to effectively present the dynamic properties of electricity consumption by the DCHMG end-users. Major models are as follows:

- PV power generations are built by single-diode equivalent circuits that describe the v-i characteristic of the PV arrays and the boost-type DC/DC converters are used to raise the output voltages from PV arrays. Maximum power point tracking (MPPT) control adopts the perturb and observe method [4].
- Lead-acid type generic battery model built-in MATLAB/Simulink is used as the BES [5]. Model parameters like nominal voltage, rated capacity and initial state of charge (SOC) etc. are required for the model inputs. The voltage of lead-acid BES nonlinearly decreases with SOC rate as the battery is in a discharging state; furthermore, lead-acid BES can easily be recharged if the discharge current gives reverse flows in battery model. Temperature effects are ignored in the lebattery model, and it is assumed that the SOC rate of the battery varies with changes in voltage and charging/discharging currents. A non-isolated bi-direction DC/DC converter model is built to achieve a bi-directional power transformation between the DC bus and the battery [6].
- Main end-users in DCHMG system are general single-phase low-voltage residential users. Single-phase full-bridge DC/AC voltage source inverter is modelled to provide AC power supply to each AC end-user [7].

III. Control Strategy and Simulation Mechanism

To carry out the electricity analysis of end-users in MG, the following control strategies and simulation mechanism were used:

A. Power Conversion Control Methods

For the DCHMG operates in either grid-connected or stand-alone modes, the major control and power management objectives are DC-link voltage control, power balancing management between power generations and load demands, and the voltage and frequency controls in AC bus; but, this study focuses only on the DCHMG system operating in a grid-connected mode with the un-dispatched power output. For this operation scenario, let IFI work in DC-link voltage control mode. Then, the DC-link voltage is adjusted to desired values [8]; the PV system should work in a MPPT control state; a constant current control on bi-direction DC/DC converter is required for charging and discharging BESs [9]; and power balancing between all power generations and loads is carried out by [10], [11].

B. Microgrid Electricity Management Strategy

In this study, the purpose of used electricity management strategy is to carry out the power balancing between power generations from each energy source and power consumptions of end-users. It means DCHMG may operate to provide as much electricity as possible to the end-users when alternative energy sources, i.e. PV power and BESs stored power, are sufficient, and then to decrease the power supply from the utility grid (P_{Grid}). To reach the goal, the flowchart in Fig. 4 is implemented to coordinate management of power from *PV* and BES in DCHMG and from utility grid. In Fig. 4, required data of solar irradiance, used to calculate *PV* power (P_{PV}), and end-users' electricity load demand (P_{Load}) are input to simulated DCHMG system for operations. Let us assume the values of P_{PV} and P_{Load}. If $P_{\text{PV}} > P_{Load}$ is false, there are two scenarios that can be met. For $P_{\text{PV}} = 0$, DCHMG end-users' electricity P_{Load} is only supplied by the P_{Grid}. For P_{PV} not equal to 0 and higher than P_{Load}, BES stored power will further be checked. If BESs state of charge (SOC) is less than its low limit of 40 %, then P_{Load} is supplied by the P_{pv} and P_{Grid}, and BESs enter into low-voltage protection stage; if BES SOC is higher than its low limit, P_{Load} is supplied by the limited

P_{PV}, *PBES, and* P_{Grid}. In addition, if $P_{PV} > P_{\text{Load}}$ is true, then BESs over-voltage protection will be checked. For

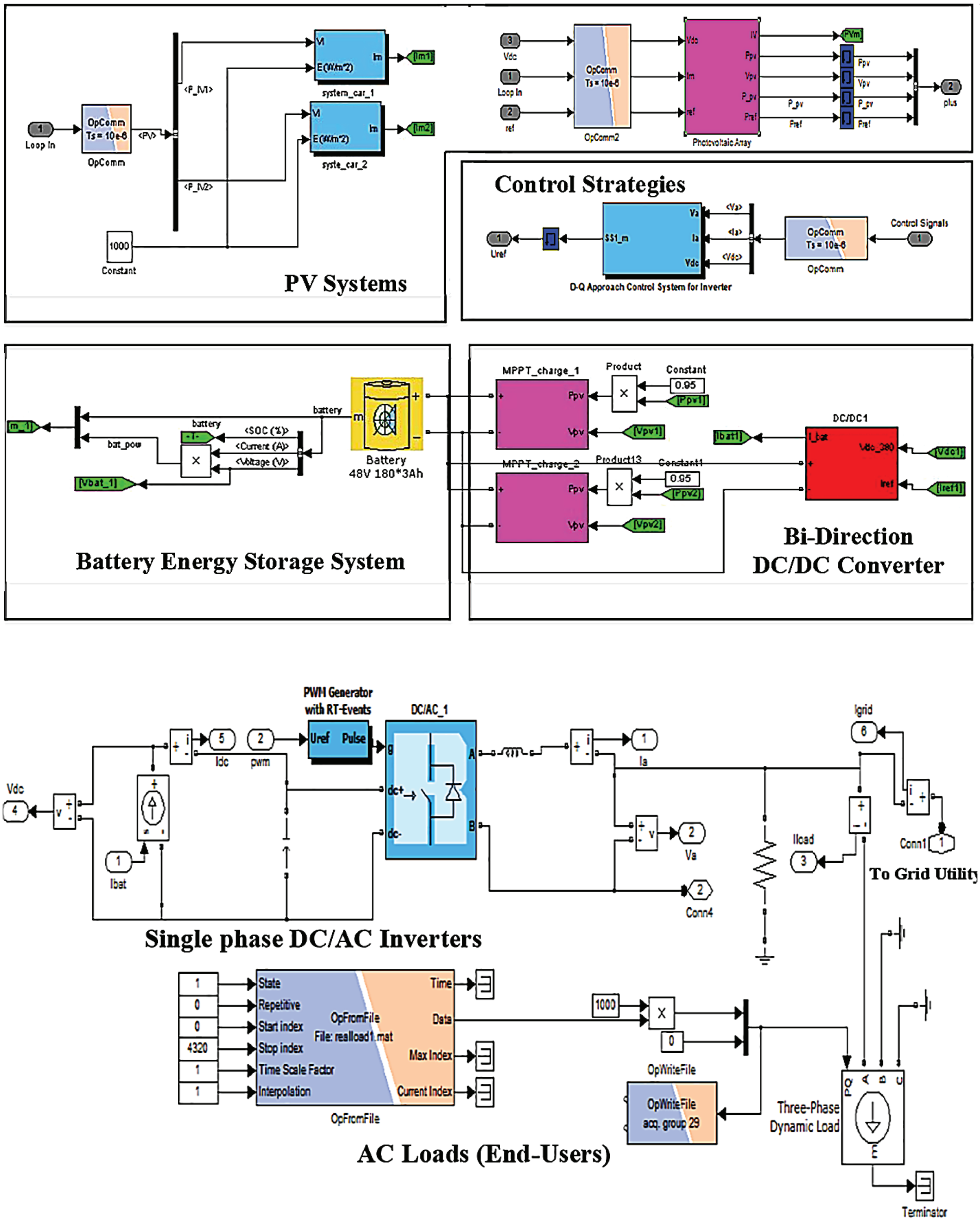


Fig. 2. Modelling of DCHMG

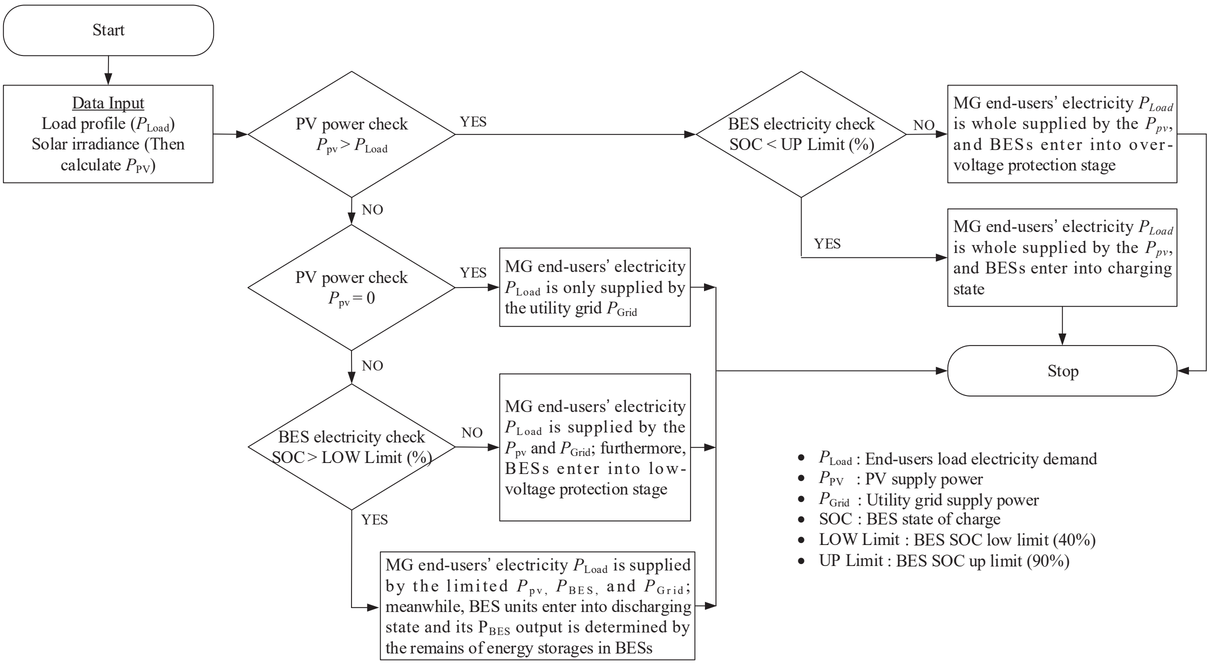


Fig. 3. Microgrid power balance electricity management strategy.

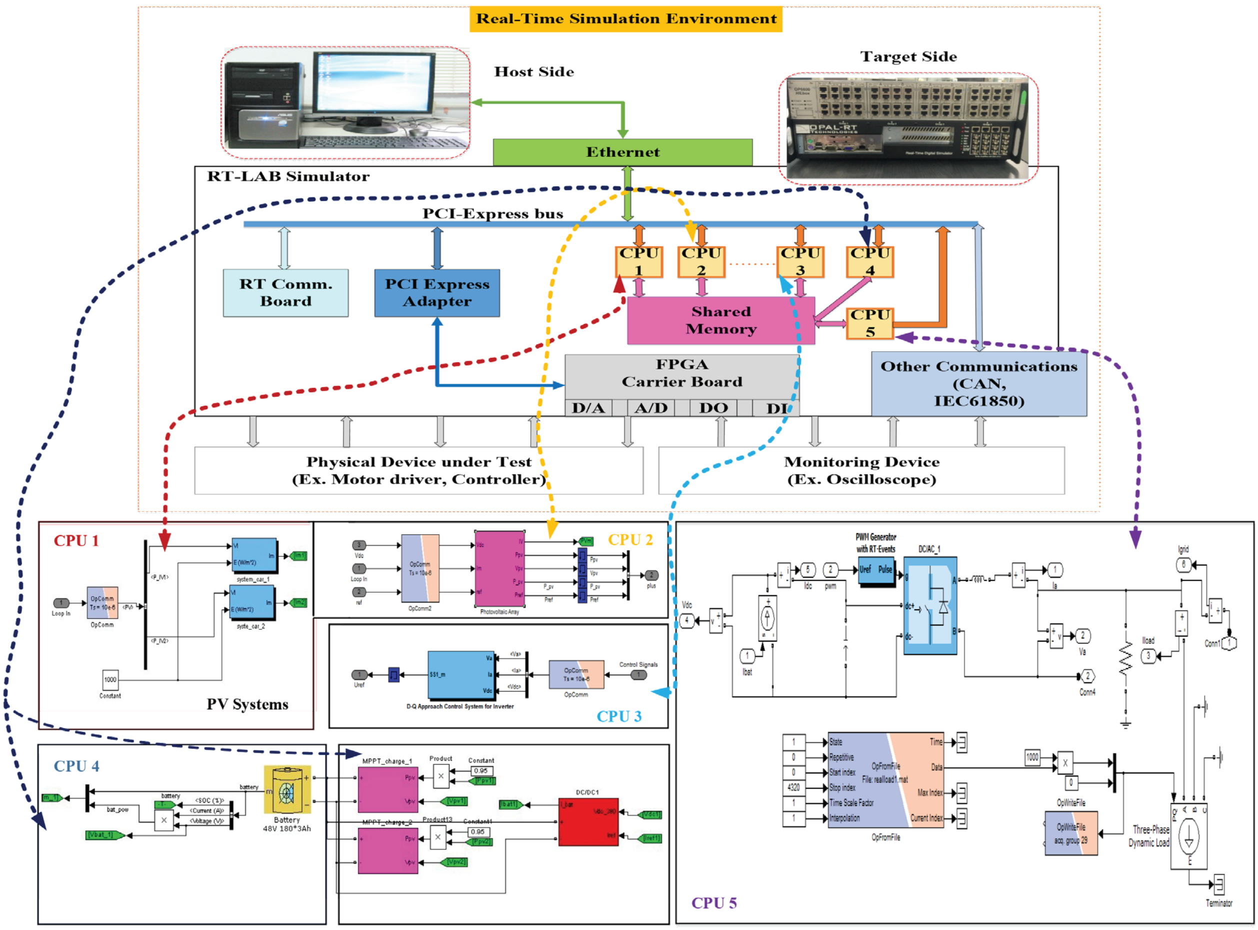
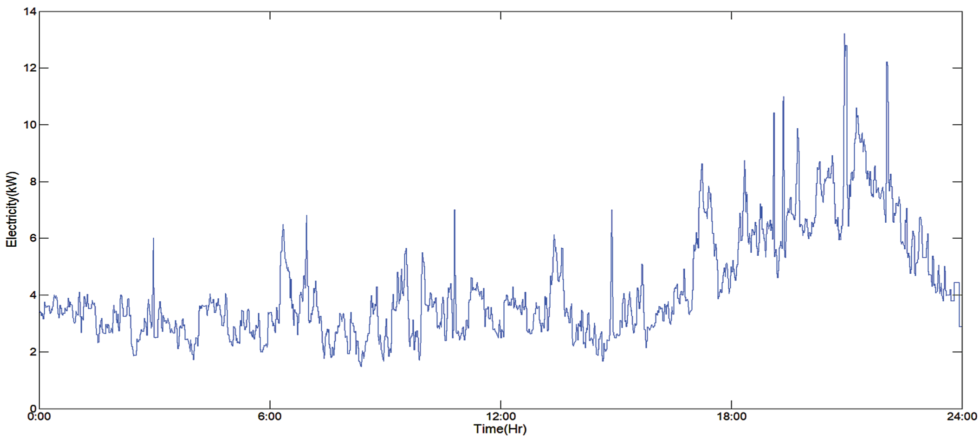


Fig. 4. Configuration of a DCHMG in real-time simulation environment.

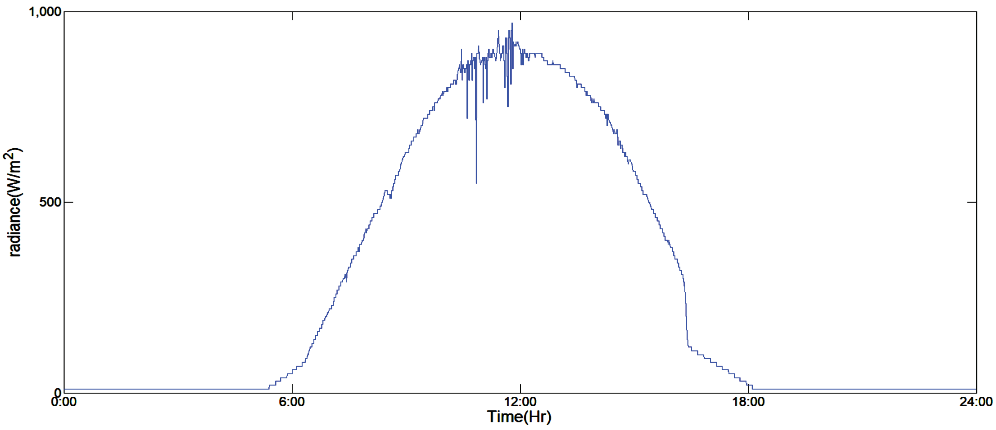
SOC higher than its upper limit of 90%, P_{Load} can be supplied by the P_{PV}, and BESs enter into charging state. For SOC less than upper limit, P_{Load} can be supplied by the P_{PV}, and BESs enter into over-voltage protection stage.C. Simulation Mechanism

OPAL-RT real-time simulation (RTS) technology is adopted in this study for electricity analysis simulations, as shown in Fig. 4 [12]. In RTS environment, the Host side and Target side are two major parts. In the former, a commercial Intel four cores 3.30 GHz CPUs and 8.0 GB RAM personal computer (PC) is used; and in the latter, the OP5600 HIL box with two Intel Xeon six cores 3.46 GHz CPUs and 4.0 GB RAM are used; furthermore, five cluster nodes (CPU cores) are used as well for parallel simulations. Completed DCHMG model in Fig. 2 that relates to the configuration in Fig.1 is divided into five subsystem models and compiled via Real-Time Workshop (RTW) for computations with these models on assigned CPU units. Data exchange between different CPUs is done through the shared memory technique used in PC motherboard that has ultra-low latency property and thus allows the parallel simulation of electric power systems at a small time-step size. The Ethernet protocol with a hundred-Mbps data rate is established to carry out the communication and data conversion between the Host and the Target sides. The operation systems for Host and Target sides are Windows 7.0 and Redhat, respectively. An interfacing software RT-LAB, which builds parallel tasks from the original MATLAB models and runs them on each CPU of the OP5600 HIL box is also required. Overall, the procedures of MG electricity analysis in the study are as follows:

- *Step 1:* to prepare required input data, including assumed system parameters, daily solar irradiance, and initial battery setting as model inputs.
- *Step 2:* to determine the required solar power generation and required battery capacity based on real operation experiences or assumed data and proposed control strategy.
- *Step 3:* to collect load profiles from actual metering infrastructures or assumed data then as end-users load model.
- *Step 4:* to run general simulations in RTS environment and then results of electricity analysis can be produced.



a) Load profile



b) Solar irradiance

Fig. 5 Input data in simulations

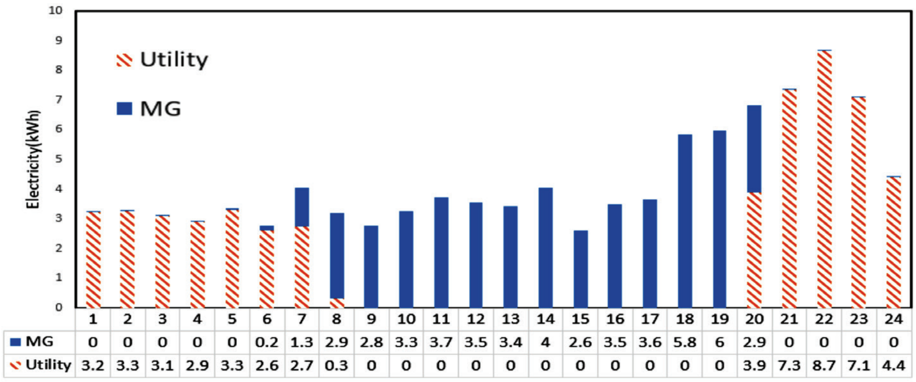


Fig. 6. Simulation results - without peak shaving.

- *Step 5:* to repeat the procedures from Step 2 to Step 4 and set various data/parameters for estimating the performances of the MG system on different test scenarios.

IV. Case study

The following two simulation scenarios are implemented on the DCHMG configuration in Fig. 1:

- DCHMG operation without peak shaving - to observe the electricity status for DCHMG operating on the original load demand profile;
- DCHMG operation with 50 % peak shaving - to observe the electricity status for DCHMG operating on the load demand with 50 % peak shaving.
- Two different electricity price rates are meanwhile substituted into the simulation results for the calculation of electricity bill of end users, and are then compared.

In simulations, the capacities of PV and BESs of about 15 kW and 1.96 kWh are used separately. We used load profile in Fig. 5(a), collected from eight single-phase 110V/60Hz AC residential end-users in DCHMG. Their total consumption of electricity is about 103 kWh in summer days, and used solar irradiance as shown in Fig. 5(b).

A. Without Peak Shaving

Figure 6 shows the simulation results for the eight end- users with a general DCHMG operation, i.e. no peak shaving is implemented. All eight end-users can only receive electricity from the DCHMG during the significant solar irradiance and battery storages durations, i.e. from 7:00 to 20:00. In this simulation scenario, about 49.9 kWh of electricity is supplied by the DCHMG and the remainder of about 53.1 kWh of electricity is provided by the utility grid.

B. With 50 % Peak Shaving

A manual peak shaving is performed to understand the differences between energy-saving solutions for the end-user to get a better effect from electricity saving. Fig. 5(a) demonstrates a peak hour time of the end-users from 18:00 to 23:00. Therefore, the consumed 50 % electricity collected from 19:00 to 22:00 is shaved and transferred to high solar irradiance durations, from 12:00 to 14:00, in this case. Then, the obtained results of electricity analysis are shown in Fig. 7. It is found that the required electricity supply from utility grid can be slightly reduced from 53.1 kWh in Case 1 to 42.0 kWh in this case.

C. Electricity Bill Comparisons of Simulation Results

Two electricity price rules, general electricity price (GEP) and time-of-use electricity price (TOUEP), are used to calculate the total electricity bill for the end-users in previous two cases, separately. Table I shows the prices for GEP, different prices are given for different kilowatt hour segments. TOUEP is given in Table II, this is a two time-segment mechanism, i.e. peak time and off-peak time, and the prices are different for weekdays and weekend days. For weekdays, 4.44 $NTD/kWh and 1.80 $NTD/kWh are used for peak time and off-peak time, respectively; for weekend days, a single price rate of 1.80 $NTD/kWh is used for the whole day electricity; and a price of 0.96 $NTD/kWh is required for the part of the day. The total used electricity exceeds 2000 kWh. Finally, a basis cost of 75 $NTD per month must be included in an electricity bill. Calculations of the total electricity bills of above-mentioned simulation results are summarized in Table III. It is found that without energy-saving measures, the

Table 1. General electricity price for summer season.

Used electricty (kwh)	Price ($NTD/kWh)
<120	1.63
121~330	2.38
331~500	3.52
501~700	4.80
701~1000	5.66
>1001	6.41

1. Supposes there are no losses in load demands and daily used electricity of these 2 months is all the same here. Thus, let 2 months (62 days) electricity be one bill.
2. Calculation of electricity bill: Total bill = {[(120) × 1.63] + [(330 - 120) × 2.38] + [(500 -330) × 3.52] + [(700 - 500) × 4.80] + [(1000 - 700) × 5.66] + [(total used electricity(per bill) - 1000) × 6.41]} × 2

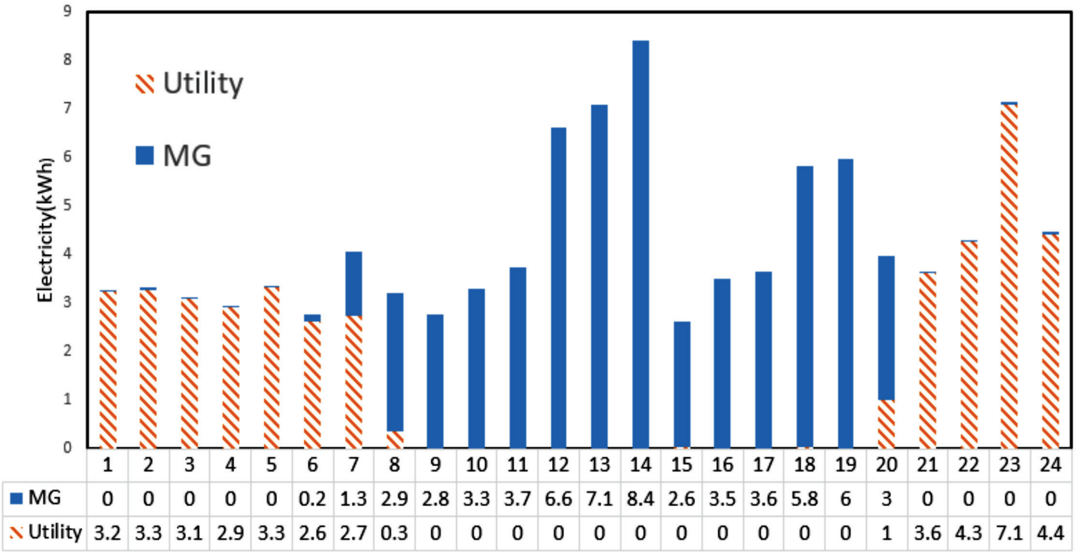


Fig. 7. Simulation results with 50% peak shaving.

Table 2. Two-segment time-of-use electricity price for summer season.

Monday to Friday (Weekdays)		Sat. to Sun. (Weekend days)
Peak time ($NTD/kWh)	Off-peak time ($NTD/kWh)	All day ($NTD/kWh)
4.44	1.80	1.80

1. Suppose there are no losses in load demands, one bill includes 2 months; meanwhile, it supposes there are 46 weekdays and 16 weekend days of electricity consumptions. Also, suppose daily used electricity in these 2 months is all the same here.
2. A base cost of 75 $NTD per month is required.
3. Calculation of electricity bill: Total bill = {75 + [(total peak time electricity per day (weekdays) × 4.44) + (total off-peak electricity per day (weekdays) × 1.80)] × (weekdays) + [weekend days × total electricity per day (weekend days) × 1.80] + (total used electricity per bill - 2000) × 0.96} × 2

Table 3. calculation of total electricity price from simulation results.

Items	Electricity Price ($ NTD)	
	General Price (Summer Season)	Time-of-Use Price (Summer Season)
Without peak shaving	15819	7762
With 50% peak shaving	11514	5588

eight end-users in the MG should pay a higher electricity price, 15,819 $NTD for GEP and 7,762 $NTD for TOUEP. Fortunately, it is apparent that the saving on the electricity bill can be met when peak shaving is implemented.

V. Conclusions

Applications of microgrid systems bring various remarkable benefits to help the operations of conventional electric grid infrastructures. Meanwhile, issues for the load demand management and electricity saving are focused on in this study. An effective simulation-based environment by implementing MATLAB/Simulink and OPAL-RT for the electricity analysis in a DC-coupled hybrid microgrid system is thus investigated. Including modelling methodology, real-time simulation mechanism, and power balance control strategy used in this paper are completely discussed. Designed scenarios that consider the options with or without peak shaving are adopted to verify the performance of the proposed electricity analysis simulation system. Finally, the saving benefit on the electricity bill for the end-users in microgird is clearly presented. Proposed microgrid simulation system can be flexibly extended to comply with various microgrid system topologies for other advanced studies. Furthermore, once the “safety” issue is paid more attention in microgrid operation, various microgrid protection means can also be investigated and tested in proposed simulation system by appropriate modelling techniques. These are MG grounding method, protection coordination for switching devices, power conversion-based tripping/disconnecting functionality, etc., which are planned as possible future studies in the context of this paper.

Acknowledgement

This work was supported by the Ministry of Science and Technology of Taiwan, Republic of China, under Grant number MOST 107-3113-E-042A-001-CC2.

References

[1] C. Sandels, “Modeling and simulation of electricity consumption profiles in the northern European building stock,” *Ph.D. dissertation, Electric Power and Energy Systems*, KTH Royal Institute of Technology, Stockholm, Sweden, 2015.

[2] J. Bajada, M. Fox, and D. Long, "Load modelling and simulation of household electricity consumption for the evaluation of demand-side management strategies," in *Proc. IEEE ISGT.* Europe, Lyngby, Denmark, 2013.

[3] E. Unamuno and J. A. Barrena, "Hybrid ac/dc microgrids-Part I: review and classification of topologies," *Renewable and Sustainable Energy Reviews*, vol. 52, pp.1251-1259, Dec. 2015.

[4] M. G. Villalva, J. R. Gazoli, and R. Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. on Power Electronics*, vol. 24, no. 5, pp. 1198-1208, May 2009.

[5] K. K. Sibi, P. Prasanth, R. Sunitha, "Generic Battery model covering self-discharge and internal resistance variation," in *Proc. IEEE ICPS*. New Delhi, India, 2016.

[6] H. Hu, X. Cheng, J. Wang, and X. Zou, "Control and simulation of bi-directional DC/DC converter for 5KW distributed wind/solar hybrid system," *in Proc. CCDC*. Chongqing, China, 2017.

[7] W. Xiao, "Power conditioning," in *Photovoltaic power system: modeling, design, and control,* 1st ed. New Jersey, USA, John Wiley & Sons Ltd, pp. 147-151, 2017.

[8] D.Chen and L. Xu, "Autonomous DC voltage control of a DC microgrid with multiple slack terminals," *IEEE Trans. on Power Systems,* vol. 27, no. 4, pp. 1897-1905, Nov. 2012.

[9] WECC Renewable Energy Modeling Task Force, "WECC battery storage dynamic modeling guideline," *Western Electricity Coordinating Council*, Salt Lake City, Utah, USA, Nov. 2016.

[10] X. Liu, P. Wang, and P. C. Loh, "A Hybrid AC/DC microgrid and its coordination control," *IEEE Trans. on Smart Grid*, vol. 2, no. 2, pp. 278–286, Jul. 2011.

[11] Y. J. Liu, S. I Chen, Y. R. Chang, and Y. D. Lee, "Development of a modelling and simulation method for residential electricity consumption analysis in a community microgrid system," *Applied Sciences*, vol. 7, no. 733, pp. 1–19, July 2017.

[12] S. Mikkili, A. K. Panda, and J. Prattipati, "Review of real-time simulator and steps involved for implementation of a model from MATLAB SIMULINK to real-time," *Journal of the Institution of Engineers (India): Series B*, vol. 96, no. 2, pp. 179-196, June 2015.

Yu-Jen Liu received his Ph.D. degree from the National Chung Cheng University in 2009. In 2010 to 2014, he has been a project manager at Taiwan Electric Research and Testing Center and leading a number of projects on renewable energy and smart grid technologies. Since 2014, he has been an Assistant Professor in the National Chung Cheng University, Taiwan. His research interests include power system real-time simulation, power quality, and microgrid.

Gary W. Chang received his Ph.D. degree from the University of Texas at Austin in 1994. He is a Professor of the Department of Electrical Engineering at National Chung Cheng University, Taiwan. Dr. Chang is a registered professional engineer in the state of Minnesota. He is the past Chair of IEEE PES Task Force on Harmonics Modeling & Simulation. At present, Dr. Chang serves as the Chair of IEEE PES Power Quality Subcommittee (2016-2017) and Vice Chair of IEEE PES T&D Committee (2017-2018). His research interests include power system optimization, power quality, and smart grid.

Yi-Feng Pai received his BSEE from National Chung Cheng University, Chia-Yi, Taiwan, in 2017. He is currently working toward his MSEE at the same institute. His research interests include modelling and simulation for renewable energy and microgrid systems.

Yung-Ruei Chang received his PhD degree in electrical engineering from National Taiwan University in 2004. He is currently the Deputy Director of Nuclear Instrumentation Division of the Institute of Nuclear Energy Research (INER), Atomic Energy Council, Taiwan, where he has been working since 1996. Since 2005, he has been responsible for power conditioning systems of the renewable energy project and led the distributed generation research group of INER. In 2007, he was a Visiting Scholar at Future Energy Electronics Center of Virginia Polytechnic and State University, USA, where he joined to develop a high-efficiency DC-DC converter for solid oxide fuel cell. Now he is in charge of microgrid project of INER. His research interests include microgrid technology, power electronic system, system reliability analysis, fault-tolerant system and dependable computing. He has published more than 40 journal and conference papers.

Yih-Der Lee received his Ph.D. degree in electrical engineering from National Sun Yat-Sen University (NSYSU) in 2009. From 1998 to 2010, he was an Associate Technical Specialist at the Southern District Waste Management Plant, Environment Protection Bureau, Kaohsiung City Government, Taiwan. Since 2010, he joined the Institute of Nuclear Energy Research (INER), Atomic Energy Council, and currently is an Associate Researcher, which is responsible for developing smart grid technology. His research interests include renewable energy, microgrid, power electronics, power system control and stability. He is a member of the IEEE.