The Journal of Engineering

The 7th International Conference on Renewable Power Generation (RPG 2018)

Coordinated control and power management of diesel-PV-battery in hybrid stand-alone microgrid system

eISSN 2051-3305
Received on 29th October 2018
Accepted on 10th January 2019
E-First on 4th June 2019
doi: 10.1049/joe.2018.9290
www.ietdl.org

Xiao-Peng Ji[1] ✉, Qian-Jie Liu[2], Zhao Liu[1], Yun-Yun Xie[1], Jiang-Tao Zhai[3]
[1]*School of Automation, Nanjing University of Science and Technology, Nanjing, People's Republic of China*
[2]*Beijing Sifang Automation Co. Ltd., Beijing, People's Republic of China*
[3]*School of Electrical and Computer Engineering, Jiangsu University of Science and Technology, Zhenjiang, People's Republic of China*
✉ *E-mail: jixiaopeng_nj@163.com*

Abstract: Coordinated control and power management of distributed energy resources, such as diesel generators (DGs), photovoltaics (PVs) and battery energy storage systems (BESSs), is vital for secure, reliable and economical operation of a stand-alone microgrid system. This paper proposes a coordinated control and power management approach for a hybrid stand-alone microgrid system containing DGs and PVs and also BESSs, which commonly servers as a power supply solution for remote areas such as islands. The proposed approach takes into account the maximum utilisation of PV power, economical operation condition of diesel generators, status of battery energy storage system and their operation constraints to share the load among them. Efficacy of the proposed approach is validated through a RTDS-based simulation test and an actual project practice.

1 Introduction

Environmental concerns and reduction of fossil fuel reserves are causing energy systems to shift toward sustainability [1]. But for some far-separated islands or other remote areas, electricity supply consists primarily of diesel generation around the globe due to a variety of reasons including economic factors and reliability issues. High cost of fuel and transportation, and significant airborne pollutant emissions has constrained the economic development and improvement of living conditions. Alternatively, there is usually great potential of renewable energy sources (RESs) in these areas. The idea of merging these RESs with DGs, energy storage systems (ESSs) and controllable loads to establish a stand-alone microgrid is a promising solution to achieve viable and sustainable power supply to these areas [2–4]. Usually, diesel generators based on synchronous generator are used to form the nominal frequency and voltage in a stand-alone microgrid. However, its performance of operational control and economy will deteriorate when there exists high penetration of intermittent renewable energy sources, and novel control strategies are needed to tackle these issues.

In recent years, many related technologies have been presented to address the problems of stable and economical operation [5–9]. The main objectives of coordinated control and power management strategy are to balance the power in the stand-alone microgrid to ensure stable operation, share the loads among different generators and make proper start/stop decision of units for long-term operation under varying loads while considering the power rating and operation constraints of different generators and the safe operating limits of battery energy storage system. As described in [10], these objectives can be achieved by centralised, decentralised or distributed coordinated control and power management, categorised from the communication perspective. In centralised management, digital communication links (DCLs) are necessary and exist among the distributed generators and centralised aggregator for centralised aggregator to collect information from distributed generations and issue power management command back to them after processing. In decentralised management, there are no DCLs, and power line carrier (PLC) communication is utilised at most. In distributed management, DCLs exist but only between neighbouring distributed generators, and data processing and control strategy is executed distributedly.

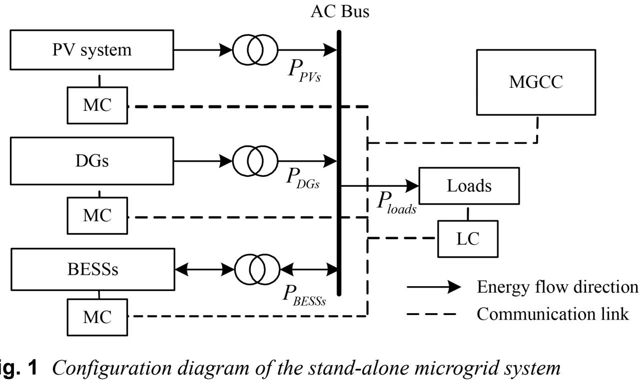

Fig. 1 *Configuration diagram of the stand-alone microgrid system*

This paper proposes a hierarchical coordinated control and power management approach for a hybrid stand-alone microgrid system containing DGs and PVs and also BESSs, as illustrated in Fig. 1, which commonly servers as a power supply solution for remote areas such as islands. Specifically, anti-reverse power flow of DGs and emergency control of frequency are the two of the most important problems, and unit commitment and optimal power dispatching is a plus on the basis of solving the aforementioned two problems for economical operation with the operation constraints of each DER.

2 Diesel-PV-battery stand-alone microgrid

2.1 System configuration

An appropriate combination of distributed energy resources is of great importance for reliable and economical operation of a stand-alone microgrid. Literature [11] studied the multi-objective optimisation of a stand-alone PV-wind-diesel-battery system, aiming to minimise the levelised cost of energy (LCOE) and the equivalent carbon dioxide (CO_2) life cycle emissions (LCE) with the strength pareto evolutionary algorithm, and the results indicate that diesel generator must be included in a stand-alone microgrid to reduce costs and emissions when life cycle emissions from PVs, wind turbines and batteries are taken into account, and PVs are also added in almost all hybrid microgrid systems.

The stand-alone microgrid system selected as a study case in this paper is composed of diesel generators, PVs, battery energy storage systems and loads. They are under supervisory control of a microgrid central controller (MGCC), several micro-source controllers (MC) and a load controller (LC) with digital communication links among them as shown in Fig. 1. Diesel generation system is composed of several DGs with medium-or small-scale in capacity instead of large-scale for secure, reliable and economical operation in the scene with large load fluctuation.

In Fig. 1, P_{PVs} is the output power of the aggregated PVs, which is determined by volatile solar irradiance and other factors on site. $P_{\rm DGs}$ is the output power of the aggregated DGs, which is determined by the renewable generations loads. $P_{\rm BESSs}$ is the charging or discharging power of the aggregated bidirectional PCS (power conversion system) for BESSs, which is controlled according to certain control strategies, and $P_{\rm loads}$ is the power consumed by the aggregated loads. The relation of these variables can be expressed as

$$P_{\rm PVs} + P_{\rm DGs} + P_{\rm BESSs} - P_{\rm loads} = 0 \quad (1)$$

Arrows in Fig. 1 give the reference directions of electrical energy flow. When the DER outputs power to AC bus, the value of the output power is positive, while negative when it absorbs power from AC bus if it exists. For loads, the value of $P_{\rm loads}$ is positive when it absorbs power from AC bus.

2.2 Analysis of operation requirements

Different from conventional power system operation, the operation of microgrid integrated with high penetration of renewable energy sources such as PV faces the variabilities from both sides of generation and consumption simultaneously. Additionally, abnormal failure of units also has a significant impact on the system operation. Therefore, operating reserve is required to ensure uninterruptable supply in most operation conditions, and two kinds of reserve capacities (normal and abnormal), should be considered.

Normal reserve capacity can be determined with consideration of the operating loads, peak loads within a time horizon of one year, and the active power of intermittent resources. Emergency reserve capacity is determined with consideration of the system operation requirements for reliability and economy. According to project experience, emergency reserve capacity is commonly not less than ten percent of the maximum loads and the rating power of each generation unit.

In this study case, the DGs are selected as the grid-forming units and responsible for ensuring the power balance between generation and consumption at any instant, i.e. in VCM (voltage control mode). The PVs work in CCM (current control mode), typically MPPT (maximum power point tracking) mode for maximum harvesting of renewable resources. The BESSs will be charged or discharged based on the operation conditions of the microgrid. Under such functional arrangement, operation constraints such as overcharge and deep discharge of BESSs, and reverse power flow of DGs, should be considered seriously in designing control strategies.

3 Operation of distributed energy resources

3.1 Operation of diesel generators

Diesel generators are responsible for forming the voltage and (amplitude and frequency) of AC bus, and ensuring the power balance in the stand-alone microgrid system. The control scheme for DG system is composed of GOV (governor), AVR (automatic voltage regulator), prime mover and the generator. AVR is used to adjust the output voltage amplitude of the DG, and GOV to maintain constant rotating speed which is related to the frequency. MC is utilised for direct control of DGs such as start/stop operation, synchronisation, load dispatch among DGs, *et al.* Isochronous control is adopted in GOV module for DGs as master units in stand-alone microgrid, which is different from the droop control commonly used by gensets in bulk power system. Frequency deviations between the actual angular frequency at the common AC bus and the nominal frequency caused by a sudden drastic change of generations or loads will vanish after a short-tern regulation.

Additionally, overload and reverse power flow are the two extreme cases often encountered by grid-forming DGs. Actually, different from other power electronics-interfaced distributed generations, DG usually has a good capability of overload for a short period of time, typically 1 h at 1.1 pu and 2 min at 1.5 pu, which is good for providing short-term reserve to compensate power unbalance between generation and consumption. However, reverse power flow for DGs is the case we should try our best to avoid because reverse power protection is commonly equipped which would stop the operation of DGs and as a result the microgrid collapses.

3.2 Operation of PVs

PVs are often working in CCM, normally operating under MPPT to obtain the maximum amount of available energy. The control scheme for PV system is composed of a PV array, a DC/AC inverter and an output filter. Dual-loop control with outer power loop and inner current loop is employed to implement MPPT and grid-connected control simultaneously. MC is utilised for direct control of PVs such as start/stop operation and reactive power setting if necessary.

Different from conventional generators, PVs cannot be dispatched flexibly due to the intermittence and volatility of solar irradiation intensity, and consequently shows its inherent stochastic nature. This is one of the main challenges in stand-alone microgrids for system operators.

3.3 Operation of BESSs

BESS is an effective means of coordinating the volatile loads and intermittent renewable resources for improved utilisation of RESs. The PCS for BESS can work in both VCM and CCM, and only CCM is considered in this paper to be compatible with DGs in VCM. The control scheme for BESS which is composed of battery stack, bidirectional DC/AC converter and output filter. Compared with the control scheme for PV system, the PCS for BESS can work in four-quadrant which means that it is able to generate and absorb both active and reactive power simultaneously while the inverter for PV is not able to absorb active power, and the reference of active power is set by MC instead of MPPT algorithm.

In order to avoid overcharge or deep discharge of BESS, special attention should be taken to regulate the state of charge (SOC) within proper operation ranges which are defined by several threshold values as shown in Fig. 2. The whole range of SOC from 0 to 1 is divided into five sub-ranges by four threshold values. $\rm SOC_{max}$ is the maximum operation limit of SOC which is usually set a bit smaller than the permitted maximum SOC of BESS to avoid overcharge, and $\rm SOC_{min}$ is the minimum operation limit of SOC usually set a bit larger than the permitted minimum SOC of BESS to avoid deep discharge. SOCs of BESSs are regulated within range A under normal conditions, and within range B and C under emergency conditions. $\rm SOC_{ref}$ is the target SOC in stable and economical operation. Range D and E are forbidden in any occasions to prevent BESSs from overcharge and deep discharge respectively. When SOC is in range B, fast charge is only permitted until SOC reaches $\rm SOC_{max}$ when there is large amount of surplus power, and discharge is preferred to regulate SOC into range A. When SOC is in range C, fast discharge is only permitted until SOC reaches $\rm SOC_{min}$ when there is large amount of vacancy power, and charge is preferred to regulate SOC into range A.

4 Coordinated control and power management

The MGCC is responsible for secure, reliable and economical operation of the stand-alone microgrid system by coordinating control and power management of DGs, PVs, BESSs and loads. Specifically, anti-reverse power flow of DGs and emergency control of frequency are the two of the most important problems, and unit commitment and optimal power dispatching is a plus on the basis of solving the aforementioned two problems for

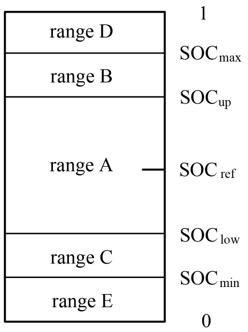

Fig. 2 *Schematic diagram of BESS operation ranges*

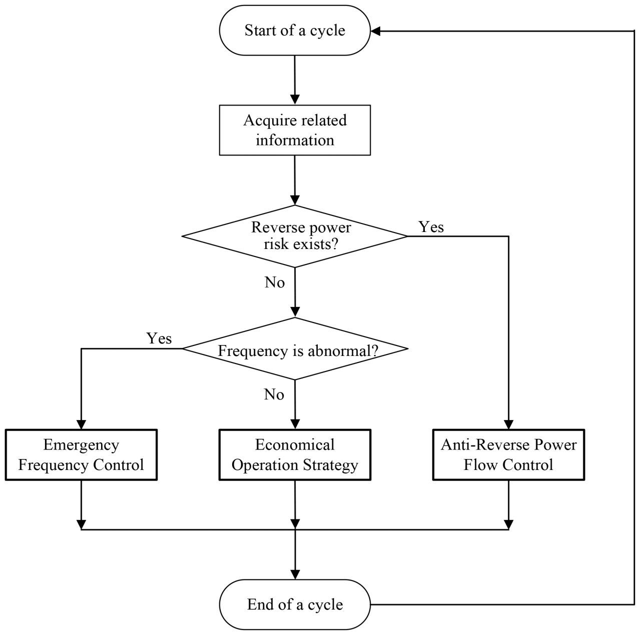

Fig. 3 *Proposed Overall scheme of coordinated control and power management*

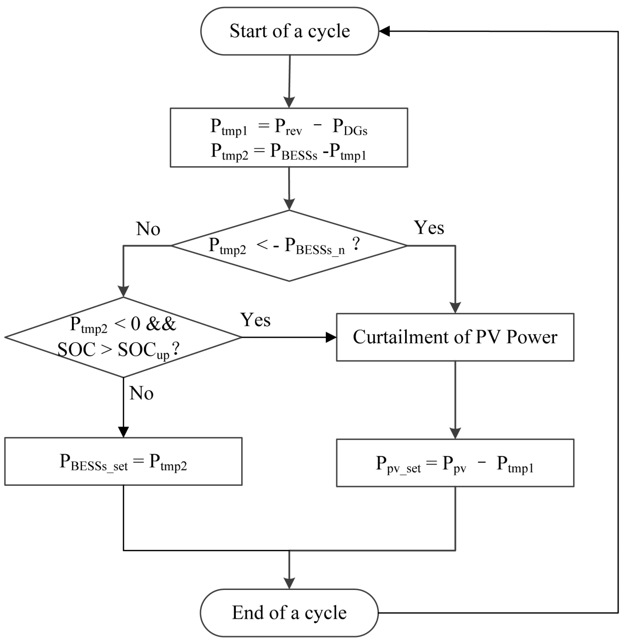

Fig. 4 *Anti-reverse power flow control*

economical operation with the operation constraints of each DER. Consequently, an overall scheme of coordinated control and power management with consideration of above issues is designed as shown in Fig. 3 which contains three main functions: anti-reverse power flow control for diesel generators, emergency control of frequency, and economical operation under normal conditions.

4.1 Anti-reverse power flow control for DGs

Reverse power flow for grid-forming DGs occurs when the generation from other DERs is larger than the load demand which is caused by load decrease or output power increase of the other DERs. We define the risk evaluation criterion of reverse power flow as $P_{\mathrm{DGs}} < P_{\mathrm{rev}}$ where P_{DGs} is the total output power of all DGs, and P_{rev} is a setpoint calculated by an off-line or on-line method. Some actions must be taken to prevent the reverse power in advance when the criterion is satisfied. Decrease the output power of PVs and BESSs are both effective means to cope with the problem, and the coordination between them is shown in Fig. 4. With the aim for maximum utilisation of renewable resources, the control of BESSs is prior to that of PVs, and power from PVs is curtailed when the operation constraints of PCSs and batteries (power of PCS and SOC of battery) are violated.

4.2 Emergency frequency control

Due to intermittence of renewable resources and loss of loads or DERs, large amount of unbalanced active power will lead to frequency fluctuation in stand-alone microgrid systems. To mitigate the negative effects of fluctuations of frequency caused by the volatility of loads and RESs, emergency frequency control is needed to enhance the stability of the system. Primary control with conventional $\omega - P$ droop control loops is usually employed to compensate the unbalanced power, which makes an effective coordination and power sharing without any communication among MCs for BESSs and other DERs. The output active power of BESS is expressed by the following equation:

$$P = P^* - K_\omega \cdot (\omega - \omega^*) \quad (2)$$

Where P^* is the reference power at the reference angular frequency ω^*, K_ω is the droop coefficient, and P is the output active power at each BESS when the angular frequency at the common AC bus is ω.

To avoid frequent transition between charging and discharging of BESS, a dead zone around the nominal angular frequency is added to the droop control above, in which frequency fluctuation is allowed and BESSs do not react. The improved droop control is descripted by the following equation.

$$P = f(\omega) = \begin{cases} P^* - K_\omega \cdot (\omega - \omega_{low}) & \omega_{\min} \le \omega < \omega_{low} \\ P^* & \omega_{\mathrm{low}} \le \omega \le \omega_{up} \\ P^* - K_\omega \cdot (\omega - \omega_{up}) & \omega_{\mathrm{up}} < \omega \le \omega_{\max} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where ω_{low} and ω_{up} are the lower and upper limits of operation dead zone which is also used as the normal frequency operation range, and $\omega_{\min}$ and $\omega_{\max}$ are the allowable minimum and maximum operation angular frequency in stand-alone microgrids respectively.

As shown in Fig. 5, BESSs is utilised to stabilise the frequency fluctuation with high priority. If SOC is not in the suitable ranges for charging or discharging power, PVs are regulated accordingly.

4.3 Economical operation

The main idea of economical operation is to maximise utilisation of renewable resources and reduce the running cost of DGs on precondition of ensuring stable and reliable operation. Generation efficiency of DG is related to its loading rate. The efficiency is the highest when working at rating power $P_{\mathrm{DG\_n}}$, and it decreases with the decrease of loading rate. Hence, the base operation power of DG, $P_{\mathrm{DG\_base}}$, is often to operate near its rating power point from the perspective of economical operation in many situations. But it is not a good idea for DGs as master units in a stand-alone

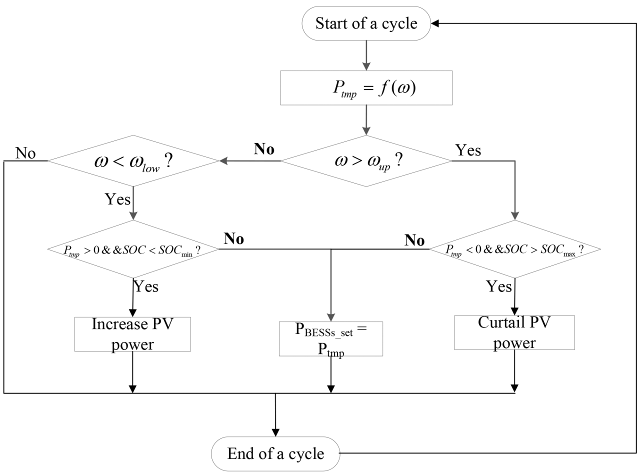

Fig. 5 *Emergency frequency control scheme*

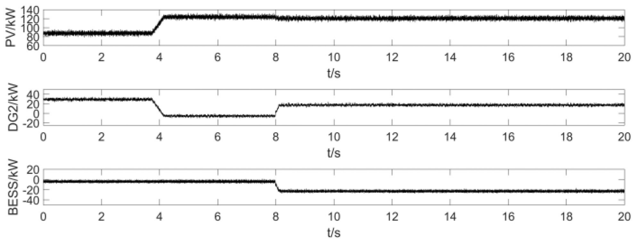

Fig. 6 *Waveforms in simulation of anti-reverse power flow control*

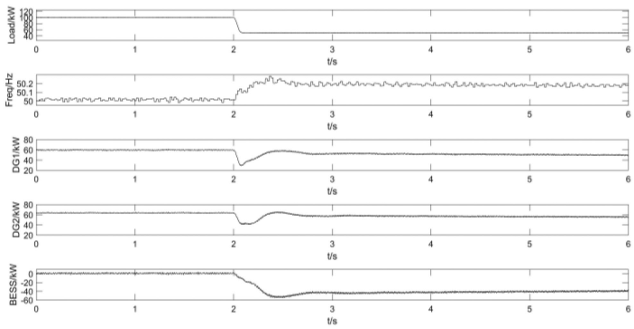

Fig. 7 *Waveforms in simulation of emergency frequency control*

microgrid for lack of sufficient operating reserve. To balance the contradiction between economical operation and sufficient operating reserve, loading rate 0.75 is often chosen, i.e. $P_{DG\_\text{base}} = 0.75P_{\text{DG\_n}}$. Additionally, the minimum operation power $P_{\text{DG\_min}}$ is usually required to be above $0.3P_{\text{DG\_n}}$, or the oil consumption per unit power will increase significantly and the lifetime of DG will be shorten dramatically.

5 Simulations and on-site operation

To verify the proposed method, we test the anti-reverse power flow of DGs and emergency control of frequency/voltage on a RTDS-based platform and the economical operation is verified by on-site operation.

5.1 RTDS-based simulation setup

The RTDS-based case study stand-alone microgrid is composed of two diesel generators (DG1 is 150 kW and DG2 is 104 kW), one PV system (300kWp), one BESS (200 kW) and loads (2595kWh/day on average and peak 180 kW).

The experimental setup can be divided into three parts as follows where MGCC and control boards of PVs and BESS are communicated with the Modbus protocol:

1) MGCC: It is implemented with an embedded device with RTOS (real-time operating system) and PLC (programmable logic control) function.
2) Control boards of PVs and BESSs:
3) RTDS platform: Two diesel generators, power converters for PV and BESS, loads and the main circuits are modelled in the RTDS platform. The platform is interfaced with MGCC and control boards of PVs and BESS with I/O cards, such as GTDI, GTDO, GTAO, *et al.*

5.2 Simulation of anti-reverse power flow control

Initial states: DG1 is shut down; DG2 is runnig in grid-forming mode around 30 kW; BESS is running in PQ mode, its output power is about −5 kW and the SOC is 0.80 which is lower than the SOC_{up} 0.85; PV's output power is about 70 kW and the controllable load is about 100 kW.

Experimental operation: Increase PV's output power from 70 kW to 120 kW to trigger reverse power of DG2.

Results and analysis: As shown in Fig. 6, with the increase of PV's output power, DG2 reduces generation and reverse power flow occurs at about fourth second. MGCC issues command to BESS after the reverse power flow of DG2 is detected. Then the BESS increases its absorbing power, and the reverse power flow is eliminated at about eighth second. With the constraints of experiment conditions, polling driven Modbus protocol is adopted in the RTDS-based simulations, which induces additional delay in the whole regulation process and degrades the control performance. However, the proposed control scheme can still be validated by this simulation.

5.3 Simulation of emergency frequency control

Initial states: DG1 and DG2 are runnig in grid-forming mode; BESS is running in droop mode and its output power is about 0 kW; the controllable load is about 100 kW.

Experimental operation: Decrease the controllable load from 100 kW to 50 kW abruptly to trigger emergency frequency control.

Results and analysis: As shown in Fig. 7, with the decrease of the controllable load, the system frequency increases significantly, and then DG1 and DG2 reduce generation at about the second second. Meanwhile, the BESS takes action to resist frequency rise and help to restore system frequency. The BESS can response to the frequency change almost without delay because the emergency frequency control does not depend on the communication from the MGCC and hence precludes the Modbus communication delay.

5.4 On-site economical operation

An actual microgrid project consists of three diesel generators (DG1 is 120 kW, DG2 is 50 kW, and DG3 is 160 kW), four PVs (30 kW of each unit and a total of 120kWp), one BESS (100 kW/ 42kWh), and loads (peak 90 kW and valley 35 kW).

We test our economical operation approach in the actual microgrid project within a time horizon of one day. As shown in Fig. 8, during the night from 18:00 to 06:00, there is almost no output power from PVs, DG1 or DG3 provides the total load demand necessary and manages the microgrid stability. From time 06:00, with the sunrise, the PVs start to pick up power generation. In response to the additional increasing PV power injection, DG1 ramps down to maintain the frequency stability until reachs its a certain (economical or technical) operation point, then DG2 is started to take over the generation of DG1, and supports the microgrid with PVs to to provide all the necessary power to the loads in the period from about 10:20 to 16:00. From 16:00, with the sunset, the PVs start to reduce power generation. In response to the reduction of PV power, DG2 ramps up to maintain the frequency stability until reachs its a certain operation point, then a new DG with larger capacity is started to take over the genenration of DG2.

In the actural project, DG3 is originally alloacated as a backup when DG1 breaks down. However, it is often difficult to start a DG after a long time outage. Hence, DG1 and DG3 are used alternately

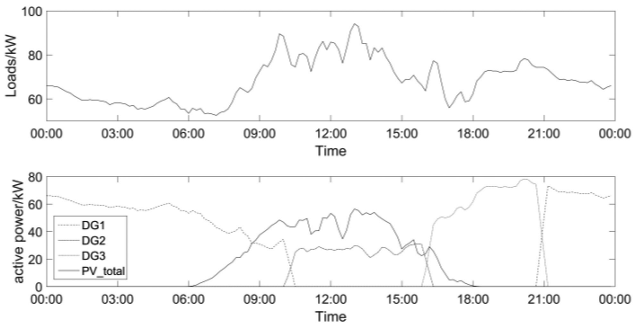

Fig. 8 *Waveforms of on-site operation within a time horizon of one day*

within a day. With the consideration of the minimum running time, switch frequency and operating efficiency, DG3 is started to take over the generation of DG2, and switched to DG1 after the minimum running time of DG3.

6 Conclusions

This paper proposes a coordinated control and power management approach for a hybrid stand-alone microgrid system containing DGs and PVs and also BESSs. Three main functions of stand-alone microgrid control system, (1) anti-reverse power flow control for diesel generators, (2) emergency control of frequency and (3) economical operation under normal conditions, are analysed and designed in detail. Efficacy of the proposed approach is validated through a RTDS-based simulation test and an actual project practice.

7 Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grants nos. 61472188, 61602247, 61702235, and U1636117), Natural Science Foundation of Jiangsu Province (Grants nos. BK20150472 and BK20160840), National Key Technology Research and Development Program of the Ministry of Science and Technology of China (Grant no. 2014BAH41B01), CCF-VENUSTECH Foundation (Grant no. 2016011), and Fundamental Research Funds for the Central Universities (30920140121006 and 30915012208).

8 References

[1] Guerrero, J.M., Chandorkar, M., Lee, T.L., *et al.*: 'Advanced control architectures for intelligent microgrids-part I: decentralized and hierarchical control', *IEEE Trans. Indust. Electron.*, 2013, **60**, pp. 1254–1262

[2] Zhao, B., Zhang, X.S., Chen, J., *et al.*: 'Operation optimization of standalone microgrids considering lifetime characteristics of battery energy storage system', *IEEE Trans. Sustainable Energy*, 2013, **4**, pp. 934–943

[3] Zhao, B., Zhang, X.S., Li, P., *et al.*: 'Optimal sizing, operating strategy and operational experialce of a stand-alone microgrid on dongfushan island', *Appl. Energy*, 2014, **113**, pp. 1656–1666

[4] Zhao, Z.L., Yang, P., Guerrero, J.M., *et al.*: 'Multiple-time-scales hierarchical frequency stability control strategy of medium-voltage isolated microgrid', *IEEE Trans Power Electron.*, 2016, **31**, pp. 5974–5991

[5] Lopes, J.A.P., Moreira, C.L., Madureira, A.G.: 'Defining control strategies for microgrids islanded operation', *IEEE Trans. Power Syst.*, 2006, **21**, pp. 916–924

[6] Kim, Y.S., Kim, E.S., Moon, S.I.: 'Frequency and voltage control strategy of standalone microgrids with high penetration of intermittent renewable generation systems', *IEEE Trans. Power Syst.*, 2016, **31**, pp. 718–728

[7] Andoni, U., Ernesto, L.B., Pablo, S., *et al.*: 'Frequency– based energy-management strategy for stand-alone systems with distributed battery storage', *IEEE Trans. Power Electron.*, 2015, **30**, pp. 4794–4808

[8] Usaola, J., Ledesma, P.: 'Dynamic incidence of wind turbines in networks with high wind penetration'. Proc. 2001 IEEE Power Engineering Society summer meeting, 2, Vancouver, Canada, 15–19 July 2001, pp. 755–760, 2001.

[9] Vittal, V., Mccalley, J. D., Ajjarapu, V., *et al.* 'Impact of increased DFIG wind penetration on power systems and markets', Final Project Report, PSERC 09-10, Power Systems Engineering Research Center, Arizona State University, Tempe, AZ, USA, 2010.

[10] Dragicevic, T., Lu, X., Vasquez, J.C., *et al.*: 'DC microgrids—part I: A review of control strategies and stabilization techniques', *IEEE Trans. Power Electron.*, 2016, **31**, pp. 4876–4891

[11] Rodolfo, D.L., JoséL, B.A., JoséM, Y.L., *et al.*: 'Multi-objective optimization minimizing cost and life cycle emissions of stand-alone PV–wind–diesel systems with batteries storage', *Appl. Energy*, 2011, **88**, pp. 4033–4041