Microgrid multi-source coordination optimal control based on multi-scenarios analysis

Changchun Cai¹,², Haolin Liu¹,², Hao Zheng³, Feng Chen³, Lihua Deng¹,², Qianqian Xu¹,²

¹Jiangsu Key Laboratory of Power Transmission & Distribution Equipment Technology, Hohai University, Changzhou 213022, Jiangsu Province, People’s Republic of China
²College of The IOT Engineering, Hohai University, Changzhou 213022, Jiangsu Province, People’s Republic of China
³Anhui Electric Power Company, Hefei 230061, Anhui Province, People’s Republic of China
E-mail: caicc@hhu.edu.cn

Published in The Journal of Engineering; Received on 10th October 2017; Accepted on 1st November 2017

Abstract: The utilisation of ocean energy provides a significant support for the offshore island exploitation, and the coordination control of different energy sources can improve the reliability of electrical power supply. Island microgrid contains tide generator system, PV generation, wind generation and diesel generation, storage system is installed to keep the microgrid stability. A distribution generation coordination optimal control strategy is proposed in this paper; the model considers the characteristics of local load, the natural characteristics of different generations and the non-linear charge and discharge characteristics of the storage system. Under different microgrid operation scenarios, a comprehensive optimal model is established with the goal of microgrid economic operation. The model takes accounts of the gas fuel cost of diesel generation, environmental benefit, maintenance cost and the depreciation cost of equipment. Furthermore, the capacity of the different distribution generation, the percentage of lost Wind/PV and the reliability of electrical supply are defined as the constraint of the model. Finally, the proposed method was applied to the actual microgrid under different scenarios to prove its availability.

1 Introduction

With the progress of renewable energy power technology, more and more renewable distributed generation will connect into power system which provides an important power support for the traditional power industry [1–4]. Especially, island microgrid is a good way to improve the reliability of island power supply. On the one hand, it can realise self-sufficiency of island energy and provide enough energy for the development and exploitation of the offshore island. On the other hand, it could combine with tourism, fisheries, transportation and other related industries to maintain the sustainable development of island economic and social environment [5].

The main renewable energy that island can develop are wind energy, solar energy and ocean energy. Island microgrid is an effective carrier for solar, wind and ocean energy generation systems, using a distributed energy and diesel power generation system, energy storage system to build a controllable island microgrid system. Owing to the different energy structure, the operating characteristics of each distributed generation are different. How to coordinate the distributed generation to meet the economic and reliability requirements of the island microgrid when it operates in a different environment is an important subject to be studied and it is also the main basis of the island’s renewable energy development and utilisation.

In recent years, there are a lot of research studies for the island microgrid architecture, control and operation in the world. Microgrid achieves optimal operation of flexible control through the coordination of the distributed generation in different operating scenarios. Microgrid optimisation problem is a multi-objective, multi-constrained non-linear problem. An optimal control problem to improve dc microgrid stability while minimising its operation cost method is proposed in [6], the optimal control algorithm is designed to improve the system performance by appropriately selecting the operation modes. Based on fuzzy mathematics theory, a fuzzy multi-objective optimisation model with related constraints method is proposed in [7], the distributed generation cooperates with storage devices to obtain the optimal capacity controllable micro-sources. A smart energy management system is used to optimise the operation of the microgrid is proposed in [8], based on the power forecasting module, the photovoltaics output under different weather conditions is studied and energy storage needs to be optimised considering the influence of energy price structures. A bilevel optimal control scheme is proposed for grids characterised by renewable and traditional power production, bidirectional power flows and stochastic modelling issues in [9], and it uses available information at the local level to solve a stochastic optimisation problem. Che et al. [10] discuss the interconnected network of multi-microgrids and an approach that applies a probabilistic minimal cut-set-based iterative methodology for the optimal planning for the interconnection microgrids. Eduardo et al. [11] present a hierarchical microgrid management system using task sharing and an evolutionary game theory-based dispatch strategy, the proposed method shares the total load demand to the distributed generators efficiently.

This paper analyses the operating characteristics of distributed generation system such as PV system, tidal power generation system and diesel power generation system. The peak shifting and valley filling characteristics of energy storage system to realise the optimal operation model of island microgrid. The optimisation model takes into account the operating costs of the microgrid system, the cost of environmental translation and the operational constraints of the distributed generation. The objective function and the constraint equation are solved by the particle swarm optimisation (PSO). The feasibility and effectiveness of
the proposed method are verified by experiments that the method can guide the operation of the island microgrid for the operation characteristics of PV, tidal current and diesel generator.

2 Optimisation control model of microgrid

2.1 Distribution generation model

Microgrid is composed of micro-sources, load, energy storage device and other components. Micro-source is a distributed generation in the microgrid which is mainly composed of wind turbine (WT), photovoltaic cells (PV), fuel cell, micro-turbine and diesel generator. In this paper, a microgrid system consists of photovoltaic generation system, diesel power generation system, tidal power generation system and energy storage system. According to the literature [10], the corresponding mathematical model is established for the electrical characteristics of different distributed generation.

2.1.1 Photovoltaic generation system: The output power of the photovoltaic cell is non-linear, and is related to the sunshine intensity, environment temperature and weather conditions. Photovoltaic generation system output direct current and the power output model can be written as follows:

\[ P_{pv} = P_{STC} \cdot G_{STC} \cdot (1 + k(T_e - T_i)) \]  \hspace{1cm} (1)

where \( P_{STC} \) is the maximum output power under standard test conditions (100 W/m², 25°C), \( G_{STC} \) is the irradiation intensity (W/m²), \( G_{STC} \) is the irradiation intensity under standard test conditions, \( k \) is the power temperature coefficient, \( T_e \) is the Photovoltaic cell temperature and \( T_i \) is the reference temperature.

2.1.2 Wind generation system: Turbine blades drive wind turbine rotation to produce electricity, and the output power of WT relate with the wind speed is expressed as follows:

\[ P_W = \begin{cases} 0, & v < v_c \text{ or } v > v_f \\ \frac{1}{2} P_{R} R^2 v^3 C_p, & v_c \leq v \leq v_R \\ \frac{P_{R} R^2}{v_c}, & v_R < v < v_f \end{cases} \]  \hspace{1cm} (2)

where \( P_{R} \) is the rated power of wind turbines, \( v_c \) is the cut into the wind speed, \( v_f \) is the rated wind speed, \( v_f \) is the cut-out wind speed, \( \rho_{air} \) is the air density, \( R \) is the WT blade radius, \( v \) is the tip wind speed and \( C_p \) is the wind energy conversion efficiency.

2.1.3 Ocean energy generation system: Ocean power generation system refers to the power generation system that realises the power conversion through the generation of tidal and tidal power generators. At present, the main power generation systems which use the ocean are wave power generation and tidal power generation. Tidal power device converts kinetic energy of the tidal into the mechanical energy through the turbine, and then converts the low-speed and high-torque mechanical energy obtained by the turbine into the high-speed and low-torque mechanical energy through the growth speed of the gearbox. The gearbox output shaft drives the coupling permanent magnet synchronous generator to convert the mechanical energy into electrical energy. Under the rated wave, the output power of the tidal generation system is

\[ P(t) = \frac{0.1455 \rho g A^2 \omega \cos^2 (\omega t - \alpha)}{\Pi} \]  \hspace{1cm} (3)

where \( \rho \) is the water density, \( g \) is the gravitational acceleration, \( \lambda \) is the wavelength of the waves, \( \omega \) is the angular velocity of the waves, \( \alpha \) is the initial phase angle of the waves and \( A \) is the height of the waves.

2.1.4 Diesel generation system: The fuel cost of the diesel engine is its consumption characteristic function, and its fuel cost adopts the quadratic function expression as follows:

\[ C_{DE} = aP_{DE}^2 + bP_{DE} + c \]  \hspace{1cm} (4)

where \( C_{DE} \) is the fuel costs for diesel generators; \( P_{DE} \) is the output power diesel generator; \( a, b, c \) are the diesel fuel cost coefficients, in this paper, \( a = 8.5 \times 10^{-6}, b = 0.012, c = 6 \).

2.1.5 Battery energy storage system: An important parameter of the battery is the state of charged (SOC), SOC is the ratio of the remaining capacity of the battery to the capacity at the time of full battery charging. The relationship between the SOC and the battery’s output power is as follows:

\[ SOC_{i+1} = SOC_i + \frac{P_{bat}}{\Delta T} \]  \hspace{1cm} (5)

where \( SOC_{i+1} \) and SOC are the SOC at the time \( i + 1 \) and the time \( i \), \( P_{bat} \) is the battery’s charge and discharge power at the time \( i \) and \( \Delta T \) is the total capacity of the battery.

When the SOC is between 60 and –80% and the charge and discharge current is small, the battery is in the most efficient state, so it should try to make the battery work in this state. When the SOC is between 40 and –60%, the battery needs to charge to return to efficient working conditions. When the SOC is between 20 and –40%, the output power of the microgrid should give priority to the battery charge. When the SOC is less than 20%, the battery enters the discharge protection state. When the SOC is more than 95%, the battery no longer absorbs the excess power of the microgrid. Therefore, in the process of operation of the island smart microgrid, it should try to reduce the battery workload to protect the battery.

2.2 Multi-objective optimisation model for microgrid

2.2.1 Objective: Microgrid optimal operation problem is multi-objective and multi-constrained non-linear. In this paper, we consider the economy and environmental protection as the optimisation objective function to construct the microgrid optimisation model:

\[ \min F_{DG} = F_W + F_R + F_D \]  \hspace{1cm} (6)

\[ F_W = \sum_{i=1}^{24} \left( K_1 \cdot P_{wt,i} + K_2 \cdot P_{wt,j} + K_3 \cdot P_{wt,j} + K_4 \cdot P_{wt,j} \right) \]  \hspace{1cm} (7)

\[ F_R = \sum_{i=1}^{24} \left( C \cdot P_{bat,i} \cdot G_i \right) \]  \hspace{1cm} (8)

\[ F_D = (s/n) \cdot p \]  \hspace{1cm} (9)

where \( F_{DG} \) is the microgrid operating costs, \( F_W \) is the maintenance costs of distributed generation systems, \( F_R \) is the fuel costs, \( F_D \) is the battery replacement costs of energy storage system, \( K_1 \) is the maintenance factor of photovoltaic generation system, \( K_2 \) is the maintenance factor of wind generation system, \( K_3 \) is the maintenance factor of ocean energy generation system, \( K_4 \) is the maintenance factor of diesel generation system, \( P_{wt,j} \) is the output power of the photovoltaic generation system at the \( j \)th hour, \( P_{wt,j} \) is the output power of the wind generation system at the \( j \)th hour, \( P_{bat,j} \) is the output power of the diesel generation system at the \( j \)th hour, \( s \) is the battery purchase costs of energy storage system, \( n \) is the energy storage system battery’s charge and discharge times.
that is determined by the fitness function. In the algorithm, the solution of the optimisation problem is the position of the particle in the search space. The particle velocity determines the direction and distance of the particle speed, so that each particle is optimised with the current optimal position and its own experience in the solution space. At the time of initialisation, the position and velocity of each particle are randomly distributed in the solution space, and then dynamically adjusted their position and velocity according to the two extremes, which can be written as follows:

\[ v_i^{t+1} = wv_i + r_1 \cdot c_1 \cdot (p_{\text{best}}^i - x_i^t) + r_2 \cdot c_2 \cdot (x_{\text{best}} - x_i^t) \]  

\[ x_i^{t+1} = x_i^t + v_i^{t+1} \]  

(16)

(17)

\( v_i \) is the speed of the \( i \)th particle at the time \( t \), \( x_i^t \) is the position of the \( i \)th particle at the time \( t \), \( p_{\text{best}} \) is the individual optimal extreme value of the \( i \)th particle at the time \( t \), \( x_{\text{best}} \) is the global optimal extreme value of all particles at the time \( t \), \( r_1 \) and \( r_2 \) are random numbers between (0,1), \( c_1 \) and \( c_2 \) are the learning factor and \( w \) is the dynamic weight value of particle swarm.

Solar energy, wind energy and tidal energy are all natural energy, with intermittent, and their output power is uncontrollable, so the renewable generation output power cannot be used as an optimisation variable.

Diesel generation and energy storage system battery’s output power are controllable. Diesel generation fuel costs and energy storage system battery replacement costs are the main costs in the microgrid operation, so choose them as optimisation variables. The optimisation variables in this paper are the 24 h output power of diesel generation and energy storage system battery:

\[ P_{dg,1}, P_{dg,2}, \ldots, P_{dg,24}, P_{bat,1}, P_{bat,2}, \ldots, P_{bat,23}, P_{bat,24} \]

According to the optimisation strategy and PSO algorithm, we obtain the economically optimal steps to solve the operation of island smart microgrid by the PSO algorithm (see Fig. 1), as follows:

\textbf{Step 1:} Determine the basic parameters of PSO, particle dimension, population number, maximum number of iterations etc.

\textbf{Step 2:} Initialise the particles. The particles are randomly assigned to the initial values within the upper and lower limits of the SOC, and the initial velocity value is randomly assigned to the speed range.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{algorithm_flowchart.png}
\caption{Flowchart of the algorithm}
\end{figure}
Step 3: According to the current particles calculate the 24 h storage system battery’s output power.

Step 4: Calculate the net charge $P_{net}$ of 24 h a day based on the definition of net charge. Find the 24 hours output power of diesel generation through $P_{net}$ and $P_{bar}$.

Step 5: Judging whether the values obtained in step 4 are within the restriction range, if they are less than the lower limit of the restrictions, then make the value equal to the lower limit of the restrictions. Similarly, if they are more than the upper limit of the restrictions, make the value equal to the upper limit of the restrictions.

Step 6: The fitness value of the current particle is obtained by the objective function, and it is taken as the individual optimal value of each particle, and then the current global optimal value is obtained from them.

Step 7: According to (16) and (17) to update the particle speed and location, and to determine the updated particles in the boundless range. If not, then adjust it that if it is less than the lower limit of the restrictions make it equal to the lower limit of the value. Similarly, if they are more than the upper limit of the restrictions, then make the value equal to the upper limit of the restrictions.

Step 8: According to the updated particles to calculate the value of $P_{bat}$ and $P_{dc}$ as step 5 and step 6, and determine whether it is within the limited range, if not, then adjust.

Step 9: The fitness values of the particles are obtained according to the new $P_{bat}$, $P_{dc}$ and the objective function, and then compared with the existing individual optimal value and the global optimal value to decide whether to update individual optimal and global optimal values.

Step 10: To determine whether the maximum number of iterations has been reached, and if so, then end the algorithm. If not, then return to step 7 to continue running.

4 Simulation and analysis

4.1 Microgrid system and operating parameters

Similar to the actual island microgrid system, this microgrid consists of photovoltaic generation system, diesel generation system and energy storage system that uses batteries. The maximum capacity of the energy storage system SOCmax is 250 kW/h and the minimum capacity SOCmin is 5 kW/h. The power upper and lower limits of the energy storage system are 30 and –30 kW, respectively. The power upper and lower limits of the diesel engine are 120 and 12 kW, respectively. The power of the photovoltaic generation system in the next day is shown in Fig. 2. The power requirements within a day of island are shown in Fig. 3. The parameters of the particle swarm algorithm are set as follows: particle size $N$=20, maximum number of iterations is $inter_{max}=100$ and $c_1=c_2=2$, $w_{max}=0.9$, $w_{min}=0.4$.

4.2 Simulation results and analysis

Due to the high degree of environmental friendliness of photovoltaic generation and wind generation and in order to make full use of natural energy, it is generally working in the maximum power tracking mode without optimisation. According to the actual electrical characteristics of the photovoltaic power generation and tide power generation, simulate its output data.

Fig. 4 shows the optimised storage system battery’s 24 h charge and discharge status. When the SOC value drops, it indicates that the energy storage system is in the discharge state; otherwise, when the SOC value rises, it indicates that the storage system battery is in the charging state. From 0:00 a.m. to 8:00 a.m., the energy storage system battery’s charge state unchanged has been maintained at a maximum of 0.8. At 8:00 a.m. the energy storage system battery began to discharge, until 9:00 a.m. discharge to the lowest state of charge, and then began charging to 12:00 p.m. From 12:00 p.m. to 17:00 p.m. the state remains unchanged, this time the battery is neither charged nor discharged. At 17:00 p.m., it begins to discharge to 18:00 p.m. and then began to charge to 19:00 p.m. An optimised energy storage system battery discharges three times in 24h, charging three times, and each time it discharges to the discharge lower limit or charges to the charge upper limit.

It can be seen from Fig. 5 that as the number of iterations increases, the operating costs of the island smart microgrid also decrease. After the first iteration, the operating cost is 38,960 yuan. After the fifth iteration, the iterative effect is stable, and the running cost is no longer changed, which is 38,400 yuan. Therefore, the minimum cost of the island microgrid in this paper is 38,400 yuan.

The simulation results of the distributed power generation system are shown in Fig. 6.

Fig. 6 shows that when $P_{net}>0$, the renewable energy distributed power system output power cannot meet the needs of the load, then the diesel generation system began to work as a generator, the output power for the load power supply, so at 9:00 a.m.–11:00 a.m., 17:00 p.m.–22:00 p.m. when the diesel generation system works, there is power output. At 1:00 a.m.–4:00 a.m., the $P_{net}<0$ that means renewable energy distributed power generation systems’
that as the energy storage system considerations, this time the user can turn off some unnecessary units. It can be seen in Fig. 6, that when the photovoltaic power generation system does not work, wind power generation systems and tidal power generation systems have output power, but the wind power system at this time the output power has been able to meet the load requirements. It can be seen that the operation and maintenance factor of the tidal power generation system is larger than that of the wind generation system, so the tidal power system can be turned off at this time. The same person can infer other units of the operation or stop the state.

It can be seen from Fig. 7 that as the energy storage system battery charging and discharge more often, there is a charge which has not been charged to the state of charge. Compared to the cost of the optimisation completed in the above, the operating cost of the island smart microgrid is also increased when the energy storage system battery is charged and discharged more frequently. It can be seen in the process of operation that the island smart microgrid should try to reduce the number of battery charge and discharge, which can not only protect the battery to extend its life, but also can reduce the island smart microgrid operating costs and it is good for the island to realise the economic optimisation of the island Microgrid.

5 Conclusion

Island power supply is a guarantee for the development and utilisation of the island. In this paper, the principles of photovoltaic generation system, wind generation system, tidal generation system, diesel generation system and energy storage system have been studied, and the mathematical model has been built too. In this paper, the structure and operation of the island microgrid system has been studied, and the mathematical model of its optimal operation and the optimisation strategy has been built. PSO is used to simulate and optimise the economic optimisation. The simulation results are analysed, and the minimum cost of the island microgrid operation is obtained. Finally, the paper analyses the actual operation of the microgrid system. The results show that it can provide a reliable scheme for the economic operation of the island microgrid.

6 Acknowledgments

This paper was funded by the National Natural Science Foundation of China (51607057), Science and Technology Project of State Grid (NY71-16-024). Thank you for your cooperation in complying with these instructions.

7 References

[1] Jose L., Bernal-Agustín J.L., Dufo-López R.: ‘Simulation and optimization of stand-alone hybrid renewable energy systems’, Renew. Sustain. Energy Rev., 2009, 13, pp. 2111–2118
[2] Hatzigiargiou N., Asano H., Iravani R., et al.: ‘Microgrids’, IEEE Power Energy Mag., 2007, 5, pp. 78–94
[3] Yang H.X., Zhou W., Lou C.Z.: ‘Optimal design and techno-economic analysis of a hybrid solar wind power generation system’, Appl. Energy, 2009, 86, pp. 163–169
[4] Peng M.H., Liu L., Jiang C.W.: ‘A review on the economic dispatch and risk management of the plug-in electric vehicles (PHEVS)-penetrated power systems’, Renew. Sustain. Energy Rev., 2012, 16, pp. 1508–1515
[5] Lopes J.A. Peças, Moreira C.L., Madureira A.G.: ‘Dynamic population simulation and optimisation of interconnected microgrids’, IEEE Trans. Smart Grid, 2016, 7, pp. 2624–2632
[6] Ma W.J., Wang J.H., Lu X.N., et al.: ‘Optimal operation mode selection for a DC microgrid’, IEEE Trans. Smart Grid, 2016, 7, pp. 2624–2632
[7] Li P., Xu D., Zhou Z.Y., et al.: ‘Stochastic optimal operation of microgrid based on chaotic binary particle swarm optimization’, IEEE Trans. Smart Grid, 2016, 7, pp. 66–73
[8] Chen C., Duan S., Cai T., et al.: ‘Smart energy management system for optimal microgrid economic operation’, IET Renew. Power Gener., 2011, 5, pp. 258–267
[9] Riccardo M., Michela R.: ‘A bilevel approach for the stochastic optimal operation of interconnected microgrids’, IEEE Trans. Autom. Sci. Eng., 2017, 14, pp. 482–493
[10] Che L., Zhang X.P., Shahidehpour M.: ‘Optimal interconnection planning of community microgrids with renewable energy’, Sources. IEEE Trans. Smart Grid, 2017, 8, pp. 1054–1063
[11] Eduardo M.N., Carlos A.M., Nicanor Q.: ‘Dynamic population games for optimal dispatch on hierarchical microgrid control’, IEEE Trans. Systems, Man, and Cybern.: Syst., 2014, 44, pp. 306–317