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Research on the Economic Allocation Method of High-Penetrated Distributed Generations for Smoothing the Power Fluctuation of Active Distribution Network

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Abstract. With the increasing penetration of DG and electric vehicles in distribution network, ADN gradually takes the place of traditional distribution network, which also brings higher requirements to the configuration of distributed ESS; In this paper, we mainly discuss the problem of how to optimize the capacity of wind/photovoltaic/energy storage in ADN with high penetration of DG when the total power connected to the grid of DG is fixed, in order to realize the harmonization of the economic and stable operation in power grid. Firstly, the hybrid system is analysed, which demonstrated the feasibility and rationality of proposed scheme. Secondly, being in distributed network investors' shoes and considering the constraints of distributed network, DG and ESS, the wind/photovoltaic/energy storage capacity configuration bi-level optimization model is established with the objective function of maximum annual income and minimum fluctuation of DG output power. Then the genetic algorithm is used to solve this model. Finally, the experimental results of 33-bus system verify the effectiveness of the proposed method, and the influence of different penetration scenarios on the annual income of distributed network is also analysed to provide a new idea for the economic operation of ADN.

1. Introduction

With the access of distributed power supply, the distribution network is developing from the traditional form to the active distribution network. Active distribution network(ADN) means the distribution network with capacity of active control and operation, which has high penetration of distributed generation(DG). By the coordination of local energy Management, ADN ultimately realizes the effective integration of DG, energy storage systems(ESSs) and large-scale centralized power generation. However, wind power(WG), photovoltaic power(PV) have great volatility, which is bound to impact the stability and security of the power grid [1-3].

ESS is the key for ADN to realize flexible adjustment and network optimization operation [4-5]. Combined with WG and PV systems, ESSs can effectively improve the overall characteristics of output of active power. But the devices of EES are expensive and short-lived, and it is difficult to configurate widely [6]. Therefore, the rational distribution of the DGs with a high permeability in ADNs will affect the operation and management level of the ADNs and the economy of operation.

In recent years, many scholars have been carrying out many studies for the configuration of DGs. In the literature [7], the percentages of power complete compensation time and energy compensation



are determined by combining the sliding average control and the slope limit control, and the average energy storage capacity is determined by these two indicators of power smoothing. In [8], a capacity optimization algorithm for the Fourier-Legendre series expansion of the state of charge(SOC) of the ESS is proposed. In the literature [9-10], the discrete Fourier transform is used to perform the spectral analysis on the output power to obtain the minimum storage capacity. Literature [11] studies the optimal allocation of energy storage in distribution network with high-PV permeability. However, the above literature does not take the economic problems of energy storage configuration into account. At present, some scholars have made useful attempts in terms of economic efficiency of energy storage planning: [12] establishes the hybrid optimization model based on the maximum benefit of the life cycle of ESSs, but it does not involve the configuration of DGs. Literature [13] considers the typical day as the analysis unit, and try to minimize the investment and operating costs of distribution energy storages. In [14], by considering the economy and reliability of distribution networks, the multi-objective optimal configuration model of EES with battery is established, and the improved Pareto algorithm is used to solve the Pareto frontier of the model. But most of the current economic researches consider the configuration of DGs as a known condition of the grid. So, they ignore the future ADN's requirements on the flexible control and switching of DGs.

This paper stands the point of view of the investment manager of distribution network, and defines the distributed generations and energy storage system as the main access form. The objective function is the maximum annual net profit after optimal allocation. By considering the safe operation of grid, DG outputs, SOC of storages and so on as the constraints, this paper establishes a two-tier optimization model to structure storage operation mode. Besides, the inner layer optimization model is based on the spectrum analysis results of DG power output. The frequency test method is applied to determine the required capacity of the ESSs and optimize the strategy of operation. To find the optimal economic ratio with the stable permeability of DG, the outer optimization model is used to calculate the mixing ratio of distributed generations and energy storage system by using genetic algorithm. Finally, an example based on IEEE33 node distribution network is given, and the change of annual income of system under different DG permeabilities is discussed in this paper.

2. Analysis of wind/photovoltaic/energy storage hybrid system

2.1. The analysis of output fluctuation in the distributed generation

With the increasing penetration of DGs, the impact of power fluctuations on the safe operation of the distribution network is growing. It is urgent for relevant aspects to make the standards.

The analysis of fluctuations is based on typical sample data from each DG, which are obtained from historical observations or typical daily sampling. The fluctuation degree of DG output is determined by observing DG maximum power fluctuation value ΔP_{\max} in a given time period [15]:

$$\Delta P_{\max} = \max(p_1, p_2, \dots, p_n) - \min(p_1, p_2, \dots, p_n) \quad (1)$$

Where, p_j ($j=1,2, \dots, n$) represents the output power value at time j for the given period. On this basis, this paper defines the rate of DG output power fluctuations during a given period of time is:

$$\xi = \frac{\Delta P_{\max}}{P_{\text{avg}}} \times 100\% \quad (2)$$

Where, P_{avg} is the average of DG output power.

2.2. Feasibility analysis of wind/photovoltaic/energy storage hybrid system's configuration

The devices of ESS generally have two kinds of configuration: the centralized and the distributed [16]. The centralized means that ESSs are installed intensively in the specific location, while the distributed means that each DG is configured with corresponding ESS which can only be used by its parallel DG.

This paper chooses the distributed configuration as the main research goal. The advantage of it is that the storage capacity is less than the centralized configuration, and its economy is higher and can

be installed flexibly, which can effectively increase the use rate of DG power in the power network. As the battery technology matures, the future of electric vehicles can also manage charge and discharge reasonably to assume the distributed energy storage tasks [17]. If ESSs are applied by the distributed configuration, they can better solve the planning and operation problems of the different distributed power generation units, and can take the large-scale electric vehicle management into account. So, the distributed configuration has greater feasibility, and its prospect is more long-term.

3. Optimal allocation model of wind/photovoltaic/energy storage hybrid system

3.1. Objective function

3.1.1. The outer layer optimization. In this paper, the outer layer optimization mainly focuses on the distribution network's management. Taking profit and cost into account, the outer layer optimization analyses the economic benefits of wind/photovoltaic/energy storage system's capacity allocation after being used in the multi-node of the distribution network. The objective function is shown below. Since the initial investment is large, all costs are converted to one year from the long term.

$$\max F_{total} = f_{pur} + f_{save} + f_{loss} + f_{DR} - f_{cons} - f_{main} \quad (3)$$

Where, f_{pur} is the total saved cost of electricity after DGs connected; f_{save} is the saved cost of the grid expansion due to the ESS; f_{loss} is the reduced expense of net loss; f_{DR} is the arbitrage income by reserving less and using more energy; f_{cons} is the total cost of constructing the distributed power supplies and support equipment; f_{main} is the corresponding costs of operation and maintenance [18-20].

3.1.2. The inner layer optimization. In this paper, the main function of installing energy storages is to smooth DGs' output power. T is defined as the number of sampling data in the charge/discharge cycle, and the adjacent M data consist as a time window [21]. The main goal of the inner layer optimization is to find the minimum fluctuation variance of the output power of DG smoothed by the energy storage device in each time window. The objective function is as follows:

$$\min F_{flu} = \sum_{i=1}^{T-M+1} \sum_{t=i}^{i+M-1} (P_{DG}(t) + P_{ESS}(t) - P_{av}(i))^2 \quad (4)$$

Where, $P_{DG}(t)$ represents the value of DG's output power at time t of a time window. $P_{ESS}(t)$ represents the optimal output of the ESS at time t . $P_{av}(i)$ is the average of equivalent output over the time window. The equivalent output of the i -th time window is expressed as:

$$P_{av}(i) = \frac{1}{M} \sum_{t=i}^{i+M-1} (P_{DG}(t) + P_{ESS}(t)) \quad (5)$$

The maximum absolute value of the actual charge/discharge curves $P_{ESS}(t)$ in the ESS is the maximum charge/discharge power required by ESS, and that is the rated power value P_{ESSN} of the ESS. Based on the actual output power value of the ESS, the storage energy fluctuation $W(t)$ of the energy storage system can be obtained by accumulating the charge and discharge electricity only at each sampling time. Finally, taking SOC into account, coupled with the energy fluctuations of ESS in the period of corresponding time, the minimum capacity of ESS can be found, and that is rated capacity value of the energy storage system W_{ESSN} . The expression is as follows [9-11]:

$$\left\{ \begin{array}{l} P_{ESSN} = \max \left\{ \frac{P_{ESSd}(t)}{\eta_d}, |P_{ESSc}(t)| \eta_c \right\} \\ W(t) = \sum_{t=1}^T (P_{ESS}(t) \cdot \Delta t) \\ W_{ESSN} = \frac{W_d(x) + |W_c(x)|}{SOC_{\max} - SOC_{\min}} \end{array} \right. \quad (6)$$

Where, $P_{ESSd}(t)$ is the discharge power in the energy cycle. η_d is the discharge efficiency. $P_{ESSc}(t)$ is the charging power. η_c is the charging efficiency. Δt is the interval of adjacent data points. $W_d(t)$ is the maximum fluctuation value of the forward energy in the calculation period. $W_c(t)$ is the maximum fluctuation value of negative energy. SOC_{\max} and SOC_{\min} are the upper and lower bounds of SOC.

3.2. Constraints

The constraints are mainly considered from the grid side, DG and energy storage.

3.2.1. Grid side constraints.

(1) node power balance constraint

For the distribution network system, the active power and reactive power of each node of the distribution network including DG and energy storage system must meet the equilibrium constraint condition of the equation.

(2) node voltage constraints

DG and energy storage access to change the distribution network system within the trend, which will inevitably lead to voltage deviation. Node voltages, as an important measure of power quality indicators, need to be considered as a constraint.

3.2.2. DG constraints.

(1) DG output constraints

Subject to the natural environment, operating conditions of equipment and so on, the maximum DG output is certain. The constraint for DG output can be expressed as follows:

$$\begin{cases} 0 \leq P_{DG} \leq P_{DG\max} \\ Q_{DG} \rightarrow 0 \end{cases} \quad (7)$$

Where, $P_{DG\max}$ is the maximum output of DG after being connected to the grid. It is assumed that there is no reactive power exchange operation between DG and the grid, so Q_{DG} take 0.

(2) DGs output fluctuation constraint

Fluctuations of DGs output power should be guaranteed within a certain range, so as to ensure that DGs will not have a great impact on the safe operation of the grid, when they are connected to the grid.

$$\xi_i \leq \xi_N \quad (8)$$

Where, ξ_i is the output fluctuation rate of the i -th DG, and ξ_N is the maximum output fluctuation rate allowed by the system.

3.2.3. Energy storage constraints.

(1) SOC equation constraint:

In the ESS, the state of charge represents the ratio of the remaining capacity of the energy storage device to the fully charged state capacity. The SOC of ESS at $t + 1$ is determined by the supply and demand at t and the charge / discharge state of ESS. The model is as follows:

$$SOC(t+1) = SOC(t) - (\alpha_{c,t} \frac{P_{ESS}(t)\eta_c}{W_m} + \alpha_{d,t} \frac{P_{ESS}(t)}{W_m\eta_d})\Delta t \quad (9)$$

Where, $SOC(t)$ is the state of ESS at time t ; $\alpha_{c,t}$, $\alpha_{d,t}$ is the variable of charging/discharging energy in the standardized display. At the time of charging, $\alpha_{c,t} = 1$, $\alpha_{d,t} = 0$. At the time of discharge, $\alpha_{c,t} = 0$, $\alpha_{d,t} = 1$. W_m is the rated capacity of ESS, and Δt is the time interval between charge and discharge.

(2) charge state amplitude constraint:

$$SOC_{\min} \leq SOC_t \leq SOC_{\max} \quad (10)$$

Where, SOC_{\min} and SOC_{\max} are the lower and upper limits of the SOC of ESS respectively.

(3) continuous operation constraints:

$$\Delta E = \sum_{t=1}^N \frac{P_{\text{ESS}}(t)}{3600} \Delta t = 0 \quad (11)$$

In its one cycle of operation (i.e., the time scale of the sample data), the charge and discharge energy of ESS should be substantially equal [22-23].

4. Solution of the model

4.1. Algorithm

4.1.1. The test frequency method. The sample output data of DG output power is subjected to do the discrete Fourier transform, and the width of the frequency band is gradually increased from high frequencies to low frequencies to determine the high-frequency part which should be filtered by the given power fluctuation constraint, and make the frequency band as small as possible. The filtered high-frequency power components are absorbed by the ESSs, and the remaining low-frequency power component is the smooth output of the DGs and the ESSs.

4.1.2. Genetic algorithm. Genetic algorithm has the characteristics of parallelism, adaptive optimization and so on. It is suitable for the request of using multiple distributed power supply.

In this paper, every individual generated by the genetic algorithm is encoded with a fixed number of binary numbers, and then the fitness function (objective function) is taken into the set scenario. According to genetic operation, increase the probability of individuals with high adaptability to enter the next generation. Through the cross, mutation and other operations to imitate the biological community to produce new individuals, the early precocious phenomenon, that entire population get into the local optimal, can be prevented. The next generation of the population is repeated according to the above steps until the termination condition is met.

4.2. Solution

In this paper, genetic algorithm is used to optimize the model of wind/photovoltaic/energy storage hybrid system built in Section 3. The inner layer optimization uses the test frequency method to reduce the fluctuation of the output power of the distributed power supply, and determines the storage capacity and its operation strategy according to the requirements of distributed power fluctuation. Then, the result of inner layer optimization is substituted into the outer objective function. According to the objective function, continue to screen and compare. Finally, the optimal configuration scheme is obtained under the condition of DG permeability determined.

5. Case study

5.1. Model and parameter settings

Select the IEEE33 node distribution network as the test system. The network has a total of 32 branches. The topology of the network structure shown in Figure 1. Set the Nom.19 and Nom.31 nodes of network accessed by WG, and Nom.20 and Nom.32 nodes accessed by PV.

The output data of a typical intraday WG and PV are selected as the research object, and the sampling period is 15min. Both the rated powers of WG and PV are 100 kW. The average output of the WG is 52.79kW and the maximum fluctuation rate of any 60min is 36.97%. The average output of PV in the typical daylight is 26.01kW and the maximum fluctuation rate of any 60min is 75.23%.

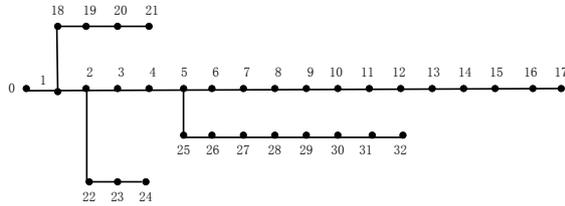


Figure 1. IEEE 33-bus system

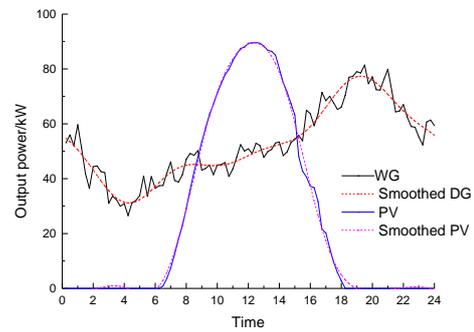


Figure 2. Curves of wind power, photovoltaic output and smooth result in typical day

In this case, the maximum fluctuation rate of the smoothed output of WG is 10% and the maximum fluctuation rate of PV output is 70% when calculating the capacity of ESS required to reduce the DG fluctuation. The capacity-type lithium-ion batteries are used as energy storage devices. Assume that both the charge and discharge efficiency are equal to 92.74%. The upper limit of SOC is 1 and the lower limit is 0.6. The characteristic curves of WG and PV output power in all the days are shown in Figure 2 respectively.

5.2. Results and analysis

5.2.1. Optimal configuration of wind-photovoltaic-storage mixed systems. Set the total capacity of the DGs connected to the grid to be 2MW, and that is about 40% of power generation. In the ADN with high permeability distributed power supply, the genetic algorithm evolves to 14 generations before convergence through the optimization method proposed in this paper. The optimal configuration scheme of the wind/photovoltaic/energy storage hybrid system is shown in Table 1.

Table 1. The optimal configuration scheme

Node	19	20	31	32
The rated power of DG /(kW)	292.68	351.22	600	756.10
Power of energy storage /(kW)	27.23	26.42	55.82	56.86
Capacity of energy storage /(kW·h)	46.52	37.92	95.32	81.63

In this scheme, the optimal matching coefficient of the WG systems and PV systems is about 0.81 through the flexible-switching technology of ADN, in which the wind power accounts for 44.63% of the total capacity of the grid-connected DGs, and the PV accounts for 55.37%. And the largest annual income of the distribution network is about 763,600 yuan.

After optimized, the fluctuation rate of WG power is reduced to 9.43% in the same time window, the fluctuation rate of PV power is reduced to 68.84% in the same time window, which satisfies the requirements of DG fluctuation in the inner layer optimization. After smoothed, the curves of the rated WG output and the rated photovoltaic output are shown in Figure 2, while the curve of energy storage device output is shown in Figure 3.

The fluctuation curve of SOC is shown in Figure 4. The WG-ESS represents the curve of the energy storage device used to smooth wind power output, and the PV-ESS represents the curve of the energy storage device used to smooth photovoltaic output. It is clear that they are normally operating within the energy storage constraints.

5.2.2. Study on changes of DG permeability. This section examines the relationship between the annual revenue of the distribution network and the change in the permeability of DGs on the grid.

When the permeability is too low, the scenery storage configuration of the power grid has little effect. Therefore, this paper mainly analyses the cases that DG's Permeability to the distribution network is from 30% to 50%, as shown in Figure 5.

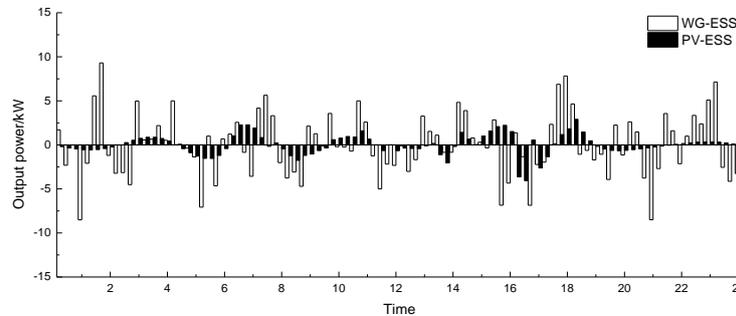


Figure 3. Curves of ESS output power.

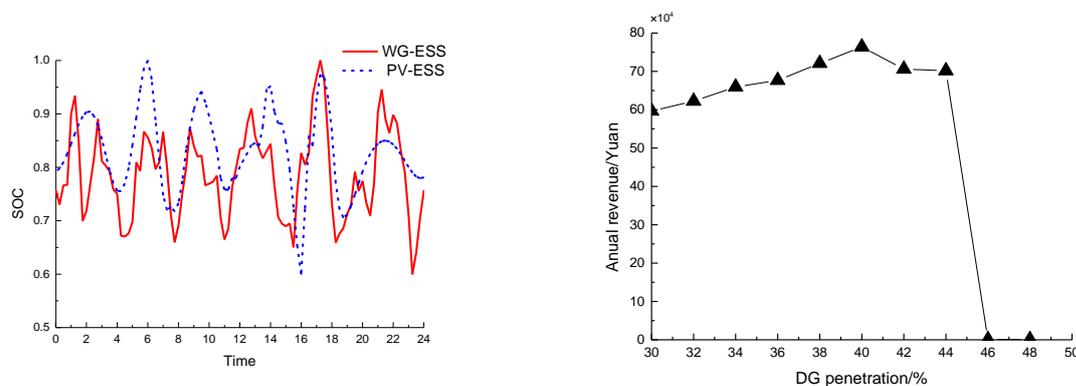


Figure 4. The change state of SOC.

Figure 5. The curve of annual income varies with penetration.

It can be found that the annual income of distribution network is gradually improved with the increase of DG's permeability. However, when the DG's permeability increased to 40%, the annual income began to decrease. Because with the DG access capacity becomes larger, the amplitude of node voltage and other constraints hinder the ratio of wind/photovoltaic/energy storage to obtain the maximum benefit. When the DG's permeability is greater than 44%, regardless of the ratio, the annual income is a minimum. Because the optimal configuration results do not meet the constraints, and the penalty is penalized by the algorithm penalty factor.

It can also be seen from the above analysis that the maximum permeability of the distributed power supply in this example is about 44%. When the permeability exceeds this value, the system node voltage amplitude will exceed the upper limit. At this point the grid will not be safe to run, and it is meaningless to discuss the economy.

6. Conclusion

The background of this paper is the ADN with high permeability of DGs. The object of this paper is to optimize the capacity of the wind/photovoltaic/energy storage hybrid system, considering the suppression of DGs' output volatility.

A double-layer optimization model is established to find the optimal economic configuration of the hybrid system's capacity. The optimization model of capacity is solved by genetic algorithm with good searching ability and convergence. The results of examples show that the model and method of

DGs and ESSs' configuration can get the reasonable scheme considering the economy and grid safety under the condition of DG's permeability determined. At the same time, the influence of different permeabilities of DG on the objective function is studied. At a later stage, the specific impacts and optimization strategy of the distributed energy storage network with the characteristics of electric vehicles will be further studied to match the development of flexible-switching technology of ADN.

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Science and Technology Project of State Grid Corporation of China: Research and Application of Plug-and-Play Key Technology for Random Power.

References

- [1] El-Khattam W, Salama M M A 2004 Distributed generation technologies, definitions and benefits *Electric Power Systems Research* **71** 119-28.
- [2] Liu Y, Wu Z and TU Y 2008 A Survey on Distributed Generation and Its Networking Technology *Power System Technology* **32** 71-76.
- [3] Dugan R C and McDermott T E 2002 Distributed generation *IEEE Industry Applications Magazine* **8** 19-25.
- [4] You Y, Liu D and Yu W 2012 Technology and Its Trends of Active Distribution Network *Automation of Electric Power Systems* **36** 10-6.
- [5] Jim M 2008 Adaptive intelligent power systems: Active distribution networks *Energy Policy* **36** 4346-51.
- [6] Xiao H, Pei W and Yang Y 2015 Energy Storage Capacity Optimization for Microgrid Considering Battery Life and Economic Operation *High Voltage Engineering* **41** 3256-65.
- [7] Han W, Liu J and Liu Y 2017 Storage Capacity Optimization in Active Distribution Network Based on Fourier-Legendre Series Expansion *Power System Technology* **41** 1123-33.
- [8] Wang C, Yu Bo and Xiao Jun 2012 Sizing of Energy Storage Systems for Output Smoothing of Renewable Energy Systems *Proceedings of the CSEE* **32** 1-8.
- [9] Sang B, Wang D and Yang B 2014 Optimal Allocation of Energy Storage System for Smoothing the Output Fluctuations of New Energy *Proceedings of the CSEE* **2014** 3700-06.
- [10] Xu X, Martin Bishop and Donna G 2016 Application and Modeling of Battery Energy Storage in Power Systems *CSEE JOURNAL OF POWER AND ENERGY SYSTEMS* **2** 82-90.
- [11] Tao Q, Sang B and Ye J 2016 Optimal Configuration Method of Distributed Energy Storage Systems in Distribution Network with High Penetration of Photovoltaic *High Voltage Engineering* **2016** 2158-65.
- [12] Xiang Y, Wei Z and Sun G 2015 Life Cycle Cost Based Optimal Configuration of Battery Energy Storage System in Distribution Network *Power System Technology* **2015** 264-70.
- [13] Tang W, Liang W and Cui R 2015 Optimal Allocation Method of Distributed Energy Storage System in Distribution Network *Electric Power Construction* **36** 38-45.
- [14] Liu F, Li B and Zhang F 2015 Battery Energy Storage System Optimal Allocation Considering Economy and Reliability of Distribution Network *Electric Power Construction* **2015** 76-83.
- [15] You Y, Liu D and Zhong Q 2014 Multi-objective Optimal Placement of Energy Storage Systems in an Active Distribution Network *Automation of Electric Power Systems* 2014 46-52.
- [16] Shen X, Shahidehpour M and Han Y 2016 Expansion Planning of Active Distribution Networks With Centralized and Distributed Energy Storage Systems *IEEE Transactions on Sustainable Energy* **8** 126-34.
- [17] Li Z, Zhao S and Liu Y 2016 Control Strategy and Application of Distributed Electric Vehicle Energy Storage *Power System Technology* **40** 442-50.
- [18] Yan Z, Wang C and Zheng Jian 2013 Value assessment model of battery energy storage system in distribution network *Electric Power Automation Equipment* **2013** 57-61.
- [19] Ted K A B, Alex Y and Annette J 2011 Optimal energy storage sizing and control for wind power applications *IEEE Transactions on Sustainable Energy* **2** 69-77.

- [20] Chen H, Thang N and Yang W 2009 Progress in electrical energy storage system: A critical review *Progress in Natural Science* **19** 291-312.
- [21] Yu D, Song S and Zhang B 2011 Impacts of Electric Vehicle on Power System as Well as the Associ-ated Dispatching and Control Problem *Electric Power Automation Equipment* **2011** 24-9.
- [22] Nick M, Cherkaoui R and Paolone M 2017 Optimal Planning of Distributed Energy Storage Systems in Active Distribution Networks Embedding Grid Reconfiguration *IEEE Transactions on Power Systems* **99** 1.
- [23] Wang Y, Tan K T and Peng X Y 2016 Coordinated Control of Distributed Energy-Storage Systems for Voltage Regulation in Distribution Networks *IEEE Transactions on Power Delivery* **31** 1132-41.