Research on Restraining Distributed Power Unbalance through Optimizing Electrical Vehicle Charging

Xinyu Zhang1,*, Yang Wang2, Wei Du1, Dongliang Zhang3 and Dan Zhao1

1Electric Power Research Institute of State Grid Liaoning Electric Power Co.Ltd., Shenyang city, Liaoning province, 110006, China
2State Grid Liaoning Electric Power Co.Ltd., Shenyang city, Liaoning province, 110001, China
3State Grid Anshan Electric Power Supply Company, Anshan city, Liaoning Province, 114001, China
*Corresponding author’s e-mail: dk_zz@126.com

Abstract. At present, with more and more single-phase distributed power sources being connected to the distribution network, the three-phase unbalance in the power grid becomes more serious, which ultimately affects the power quality. This paper proposes a method of adjusting the three-phase load by controlling the charging price of the electrical vehicle to restrain the three-phase unbalance. This paper establishes a probability model of the electrical vehicle charging quantity with the electricity price, and sets the phase-of-use electrical vehicle charging price to guide owners to charge in the appropriate phase. Finally the three-phase distribution load will be optimized. In this paper, different scenarios of the electricity price, the number of electrical vehicle in three phases and the unbalance of the distribution networks are simulated to verify the correctness and effectiveness of the proposed method.

1. Introduction
At present, a large number of single-phase distributed power sources, e.g. photovoltaic power source, are connected to low-voltage distribution networks[1][2]. The high-permeability access of single-phase distributed power leads to two major problems: the first is that the power generation has a strong time-varying, and the second is the unbalance of the three-phase power source[3]. The unbalance of the three-phase power source will cause the three-phase unbalance, which will affect the power quality, increase the power line loss, reduce the qualified rate of the factory products, and even endanger the safety of the power facilities[4][5]. In order to ensure the stable operation of the power system and the safety of the users, it is necessary to solve the problem of unbalanced three-phase power sources.

The current literature has made some research on solving the problem of three-phase unbalance caused by distributed power. In [6], it is proposed that when the three-phase unbalance occurs in the distribution network, the operator can adjust the load by pulling the line with light load and long overhead lines, and finally eliminate the three-phase unbalance. Although such operations can correct the phenomenon of three-phase unbalance in time, the method is too strong, which will affect the normal use of electricity by some power users, and the enthusiasm of users is low. Article [7]-[10] propose that if the electric vehicle is properly configured for charging and the government increases the power generation capacity of wind power, it will reduce carbon dioxide emissions and alleviate the problem of air pollution. However, if the charging time and location of the electric vehicle are not properly
configured, the stability of the power system will be seriously affected. Article [11][12] proposes that electric vehicles can be used to generate electric energy generated by distributed generation power sources such as photovoltaics and wind power generation in electric power systems. But the article does not explain the impact of electric vehicles on the three-phase imbalance of the power system. In [13], it is proposed that PHEV can adjust the three-phase frequency of the power system during charging and discharging. However, the article does not mention a solution to the system's three-phase power imbalance caused by distributed power. Article [14][15][16] propose air compression energy storage technology and flywheel energy storage technology, and propose that energy storage technology can help the power system to improve power quality. However, considering the economic factors and technical factors, the existing battery capacity is limited, and the battery cannot store all the surplus power of the power generation, so the energy storage technology cannot meet the user's demand. The article [17][18] proposes that if the electric vehicle charging is not properly configured, the load and voltage of the power system will be severely unbalanced, and the article proposes to use the electric vehicle to charge the load at night to reduce the impact. However, the night charging method is less feasible. Article [19] proposes a method for adjusting the three-phase load by using the mechanism of electric vehicle charging pile selection line. However, since most of the charging piles that have been installed currently do not have the function of selecting a line, the method needs to modify the existing charging device, which increases the economic cost of the adjustment. Moreover, many electric vehicle owners do not use the charging pile charging method, but use the household charging line for charging, and the implementation effect of the method is greatly weakened. Article [20] proposes that if a reasonable charging price is established, the electric vehicle will have a huge adjustment capability for the power system. However, the article does not explain how to adjust the stability of the power system through electricity prices, and does not propose a specific electricity price policy. Article [21][22] proposes a method of adjusting the charging of electric vehicles by adjusting the charging price of electric vehicles and finally adjusting the load of the power system. However, the article does not propose a solution to the three-phase power imbalance caused by single-phase distributed power generation.

The number of electrical vehicles is currently increasing. If the charging time and charging position of the electrical vehicle are controlled properly, the problem of strong time-varying and three-phase unbalance of the distributed power source will be solved at the same time. This paper proposes a method of setting up a phase-of-use charging price mechanism for electrical vehicles. The price of a certain phase with more distributed power source is set lower than other two phases and the price can be displayed at the user terminals to guide the owners to charge in the optimal phase. As a result the power source and load of the distribution network will be equal and the unbalance will restrained. This paper fully considers the electrical vehicle owner's travel regularity and the randomness of vehicle charging. Simulation verifies the correctness and feasibility of the proposed method.

2. Analysis of single-phase distributed power source characteristics

Assuming that single-phase distributed power sources are composed of photovoltaic panels, the power sources have two characteristics. The first is that the power generation varies strongly with time\cite{23,24}, and the second is that the three-phase power source is prone to serious unbalance.

2.1. Strong time variation

As can be seen from figure 1, the amount of photovoltaic power generation is closely related to the irradiance of sunlight, and changes with time. Meanwhile, other factors also affect the output of photovoltaic panels, such as cloud density and atmospheric humidity.
2.2. **Three-phase unbalance**

The single-phase distributed power sources are connected to the power grid through single-phase lines[25]. When the number of distributed power source in three phases are unequal, the single-phase distributed power generation will cause the three-phase power unbalance. The development of single-phase distributed power generation has become a trend in the world[26][27]. In the future single-phase distributed power sources will continue to increase, therefore the three-phase unbalance problem will become more serious.

The output of distributed power sources from three phases in a certain region of China is shown in figure 2.

The solid line in the figure is the power of phase A; the long dashed line is the power of phase B; and the short dashed line is the power of phase C. As can be seen from the figure, the three-phase power imbalance has appeared.
3. Technology of optimizing electrical vehicle charging by using electricity price

This paper proposes a method that applies the phase-of-use charging price to the distribution networks. The charging price in a certain phase which has most distributed power sources is the lowest, so that more owners of electrical vehicles will charge in the phase which has much power generation.

3.1. Electrical vehicle model

First, the article needs to establish an electric vehicle charging power model. After statistics, electric vehicles are divided into three categories: household electric vehicles, medium and high-grade electric vehicles and off-road electric vehicles. The representative examples of each type of car in the table are as below: As for ordinary family car, e.g. BYD E1, and the slow charging power of this electrical vehicle is 4.68 kW. As for mid-to-high-end electrical vehicle, e.g. BYD Qin pro EV, and the slow charging power of this electrical vehicle is 6.15 kW. As for the electrical off-road vehicle, e.g. Beiqi EX5, and the slow charging power of this electrical vehicle is 5.98 kW. The specific values are shown in the table 1.

| Type of Electric Vehicle | Slow Charging Power/kW |
|-------------------------|------------------------|
| Household Electrical Vehicle | 4.68 |
| Intermediate and Advanced Electrical Vehicles | 6.15 |
| Electrical Off-road Vehicle | 5.98 |

According to the proportion of each type of electrical vehicle, the average charging power $P_v$ of the electrical vehicle can be finally obtained as

$$ P_v = \sum_{i=1}^{n} P_i \cdot \alpha_i $$  \hspace{1cm} (1)

where $P_i$ is the slow charging power of the i-type car, $\alpha_i$ is the ratio of the total number of electrical vehicles occupied by the i-type car and i is the number of electrical vehicles.

3.2. The phase-of-use electricity price mechanism

The amount of the phase-of-use electricity price difference will directly affect the profit of the power company and the user's participation. Therefore, if you want to adjust the choice of electrical vehicle charging line through electricity price, that is, space selection, you need to determine the electricity price from the actual situation of each line.

At the same time, considering that the power generation of single-phase distributed power sources has a peak of power generation and a low power generation, it is possible to attract electrical vehicles to increase charging at the peak of power generation and to reduce charging when power generation is low by setting an appropriate price of electricity, that is, the time adjustment of the electricity price.

The article proposes the self-electricity price influence coefficient $\rho_{ii}$ and the cross-electricity price influence coefficient $\rho_{ij}$. $\rho_{ii}$ reflects the influence of the power source of the i-phase circuit on the charging price of the i-phase line; $\rho_{ij}$ reflects the influence of the power source of the j-phase line on the charging price of the i-phase line. The electricity price coefficient is related to the actual situation of the line itself, the single-phase distributed power access, and the power characteristics of the distributed power generation. It needs to be adjusted according to the actual situation in different regions. The amount of electricity price change has the following relationship with the amount of power change:

$$ \begin{bmatrix} \Delta P_A / P_A \\ \Delta P_B / P_B \\ \Delta P_C / P_C \end{bmatrix} = \begin{bmatrix} \rho_{AA} & \rho_{AB} & \rho_{AC} \\ \rho_{BA} & \rho_{BB} & \rho_{BC} \\ \rho_{CA} & \rho_{CB} & \rho_{CC} \end{bmatrix} \begin{bmatrix} \Delta Q_A / Q_A \\ \Delta Q_B / Q_B \\ \Delta Q_C / Q_C \end{bmatrix} $$  \hspace{1cm} (2)

where $Q_i$ is the power source of the i line before the price adjustment; $\Delta Q_i$ is the power source that needs to be adjusted in the i line after the price adjustment is implemented; $\rho_{ii}$ is the self-electricity price influence coefficient of the i line, and $\rho_{ij}$ is the intersection of the line j and the line i electricity price
Electricity price impact coefficient; $P_i$ is the electricity price of the i-line before the electricity price adjustment; $\Delta P_i$ is the electricity price change of the i-line after the electricity price adjustment.

Due to the economic conditions of the owner and the accidental factors during charging, not all electrical vehicle owners will choose the line with the lowest electricity price for charging. Therefore, the probability model of the charging phase of the electrical vehicle should be established considering the actual situation.

The electrical vehicle is divided into two parts in total: one part is the constant quantity of the charging line that does not change with the change of the electricity price, and the other part is the variable quantity of the charging line that changes with the change of the electricity price. Among them, the variable quantity is related to the factors of different owners, the external conditions during charging, and the hysteresis during phase selection.

After counting the number of charging cars of different phase lines, the relationship between the number of electrical vehicles charged and the price of electricity can be expressed by a function expression as below, and the expression may be a piecewise function.

$$Y_{nc} = f(P_n)$$  \hspace{1cm} (3)

where $Y_{nc}$ is the variable number of charging on the n-phase line; $f(P_n)$ is an expression representing the relationship between the variable quantity and the electricity price obtained by fitting approximation; $P_n$ is the charging electricity price on the n-phase line; n is A, B, C.

When the statistical electricity price change is small enough, the piecewise function can be represented by a coherent function expression. By deriving the expression, the charging rate response rate $\epsilon_n$ is obtained:

$$\epsilon_n = \frac{df(P_n)}{dp_n}$$  \hspace{1cm} (4)

The article defines the response rate of the charging price to reflect the change in the number of electrical vehicles charged on each phase line. The rate reflects a change in the price of electricity that can cause a change in the number of charging cars on the line. The larger the value, the more sensitive the vehicle owner of this type is to the price change, and the owner prefers to select the line with low electricity price; the smaller the value, the more sluggish the vehicle owner of this type is, and the owner does not care about the price change, so he chooses the previous line for charging. The rate $\epsilon_n$ is determined by the willingness of each type of vehicle owner on the same phase line and the ratio of the number of vehicles of each type.

$$\epsilon_n = \sum_{i=1}^{m} \epsilon_{0i} \cdot k_i$$  \hspace{1cm} (5)

where $\epsilon_n$ is the charging power price response rate on the n-phase; $\epsilon_{0i}$ is the charging power price response rate of the i-type vehicle owner; $k_i$ is the ratio of the i-type vehicle to the total number of electrical vehicles; and $m$ is the total number of electrical vehicles.

The expression of the electrical vehicle charging quantity on each phase line can be obtained as below:

$$Y_{nt} = Y_{n0} + Y_{nc}$$  \hspace{1cm} (6)

where $Y_{nt}$ is the total number of charging cars on the n-phase; $Y_{n0}$ is the constant number of charging cars on the n-phase; $Y_{nc}$ is the variable number of charging cars on the n-phase; n is A, B, C.

3.3. Three-phase unbalance calculation formula

Unbalanced three-phase active power can result in unbalanced three-phase voltage. According to GB/T 15543-2008 "Power quality: Three-phase voltage unbalance", the unbalanced voltage can be calculated as below.

$$\varepsilon = \frac{U_2}{U_1} \times 100\%$$  \hspace{1cm} (7)

where $U_1$ is the positive-sequence root mean square value of the three-phase voltage, and $U_2$ is the negative-sequence root mean square value.
4. Simulation model establishment

In this paper, the IEEE 30 nodes model is used as an example to analyze the distribution network with electrical vehicles and distributed power sources, as shown in figure 4.

![Figure 3 IEEE 30-node test system](image)

In the figure, nodes 8, 14, 15, 18, 21, 26 are provided with single-phase distributed power access, and nodes 12, 13, 14, 15, 16, 18, 21, 23, 26, 29, 30 are provided with electrical vehicles charging. There are 176 users of solar power installations in the area, and each solar power generation unit can generate 5kW. Among them, 152 households can connect excess electricity to the grid. Among them, there are 82 households connected to Phase A, 41 households to Phase B, and 29 households to Phase C.

The article assumes that 180 electric vehicles in the area need to be recharged. The number of types of electric vehicles is shown in the following table:

| Number of household electrical vehicle | Number of middle and advanced electrical vehicles | Number of electrical off-road vehicles | Number of total amount |
|---------------------------------------|-------------------------------------------------|---------------------------------------|-----------------------|
| 96                                    | 37                                              | 47                                    | 180                   |

Due to the different conditions of various types of owners in various places, the charging rate response rate of different types of vehicle owners is set up in the article is shown in Table 3. The specific data still needs to be determined according to the specific conditions of each place.

| Charging rate response rate | 0.65 | 0.22 | 0.45 |

4.1. Scenario 1: Equal price of three phases

The number of electrical vehicles charged in each phase and the electricity price are shown in Table 4:
Table 4 The number of electrical vehicles charged in each phase and the electricity price

|                  | Phase A | Phase B | Phase C |
|------------------|---------|---------|---------|
| Number of vehicles | 63      | 56      | 61      |
| Electricity price/yuan | 0.5  | 0.5     | 0.5     |

The three-phase voltage is shown in Figure 5. The solid line denotes the phase A voltage, the long dashed line denotes the phase B voltage, and the short dashed line denotes the phase C voltage.

Figure 4 Three-phase voltage change value

The unbalanced voltage is shown in figure 5.

Figure 5 The unbalanced voltage

4.2. Scenario 2: Different price of three phases

The number of electrical vehicles charged in each phase and the electricity price are shown in Table 5:

Table 5 The number of electrical vehicles charged in each phase and the electricity price

|                  | Phase A | Phase B | Phase C |
|------------------|---------|---------|---------|
| Number of vehicles | 82      | 53      | 45      |
| Electricity price/yuan | 0.35  | 0.58    | 0.60    |

The price of phase A is reduced by 0.15 yuan, the number of electrical vehicles which is charging of phase A is increased to 82; the price of phase B is increased by 0.02 yuan, the number of electrical vehicles which is charging of phase B is reduced to 53; the price of phase C is increased by 0.04 yuan, the number of electrical vehicles which is charging of phase C is reduced to 45.

The three-phase voltage is shown in figure 7. The solid line denotes the phase A voltage, the long dashed line denotes the phase B voltage, and the short dashed line denotes the phase C voltage.
The unbalanced voltage is shown in figure 8.

By comparing figure 6 and figure 8, it can be seen that after using the phase-of-use electrical vehicle charging price, the unbalanced voltage is significantly reduced from 4.7% to 2.1% and the three-phase balance is significantly improved.

5. Conclusion
In order to solve the problem of unbalance caused by the increasing penetration of single-phase distributed power source, this paper proposes a method that the owners of electrical vehicles are encouraged to select appropriate charging phase to match the active power of distributed power sources by using phase-of-use electricity price mechanism. The conclusions can be drawn as below:

1. When a single-phase distributed power source is connected to the distribution network, the three-phase unbalance will occur.
2. When the charging price changes, some owners will select the phase with lower price to charge.
3. Through the phase-of-use charging price mechanism, the three-phase unbalance problem can be effectively tackled.

References
[1] Li Wei. (2016) Research on Distributed Energy Generation Microgrid Energy Supply System. Science and Technology Outlook, 26(18):96.
[2] Gunderson, I. , Goyette, S. , Gago-Silva, A. , Quiquerex, L. , & Lehmann, A. . (2015) Climate and land-use change impacts on potential solar photovoltaic power generation in the black sea region. Environmental Science & Policy, 46: 70-81.
[3] ZHU Wei, WEI Gang, CHEN Qiu-nan, HE Jing. (2013) Research on Control Method of Distributed Single-Phase Grid-Connected Inverter. Electric Power Science and Engineering, 29(09): 6-12.
[4] Zhang Quan, Zhu Yongqiang. (2017) Power Quality Lecture 4: Three-phase Unbalance Problem
of Power Grid Related to Distributed Power Access. Electrical Appliances and Energy Efficiency Management Technology, 24:61-64.

[5] Mizutani, R., Koizumi, H., Kamiya, E., & Hirose, K. (2012) Three-phase to Single-phase Matrix Converter for Improvement of Three-phase Voltage Unbalance in Distribution System. In: 2012 IEEE Asia Pacific Conference on Circuits and Systems. Kaohsiung. 169-172.

[6] Duan Wei, Wang Juhong. (2012) Influence and treatment of three-phase voltage imbalance in distribution network. Science and Technology Vision, 21:221-223+237.

[7] Reiner, U., Elsinger, C., & Leibfried, T. (2012) Distributed self-organising Electric Vehicle charge controller system: Peak power demand and grid load reduction with adaptive EV charging stations. In: Electric Vehicle Conference. Greenville. 69-72.

[8] Weis, A., Michalek, J. J., Jaramillo, P., & Lueken, R. (2015) Emissions and cost implications of controlled electric vehicle charging in the u.s. pjm interconnection. Environmental Science & Technology, 49(9): 5813-9.

[9] Papadopoulos, P., Skarveliskazakos, S., Grau, I., Cipcigan, L. M., & Jenkins, N. (2010) Predicting electric vehicle impacts on residential distribution networks with distributed generation. In: Vehicle Power & Propulsion Conference. Hanoi. 68-71.

[10] Galiveeti, H. R., Goswami, A. K., & Dev Choudhury, N. B. (2018) Impact of plug-in electric vehicles and distributed generation on reliability of distribution systems. Engineering Science and Technology, 26: 45-48.

[11] Shimizu, K., Masuta, T., Ota, Y., & Yokoyama, A. (2010) Load Frequency Control in power system using Vehicle-to-Grid system considering the customer convenience of Electric Vehicles. In: Power System Technology (POWERCON). In: 2010 International Conference on Power System Technology. Hangzhou. 26-28.

[12] Ahmadian, A., Sedghi, M., Aliakbar-Golkar, M., Fowler, M., & Elkamel, A. (2016) Two-layer optimization methodology for wind distributed generation planning considering plug-in electric vehicles uncertainty: a flexible active-reactive power approach. Energy Conversion and Management, 124: 231-246.

[13] Sandoval, M., & Grijalva, S. (2012) Electric Vehicle-Intelligent Energy Management System (EV-IEMS) for frequency regulation application. In: 2012 IEEE Transportation Electrification Conference and Expo (ITEC). Dearborn. 216-218.

[14] Song Jie, Hou Jiya. (2019) Voltage Regulation Control Method for DC Distribution Network Based on Compressed Air Energy Storage System. Electric Power Construction, 40(06): 49-56.

[15] Arani, A. A. K., Karami, H., Gharahpetian, G. B., & Hejazi, M. S. A. (2017) Review of flywheel energy storage systems structures and applications in power systems and microgrids. Renewable and Sustainable Energy Reviews, 69: 9-18.

[16] Padulles, J., Ault, G. W., & Mcdonald, J. R. (2000) An approach to the dynamic modelling of fuel cell characteristics for distributed generation operation. In: Power Engineering Society Winter Meeting, New York. 16-18.

[17] Hana Gerbelová, Genikomsakis, K. N., & Ioakimidis, C. S. (2013) Electric vehicles charging under a G2V and V2G approach: The case of the Portuguese power system. In: 26th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2013. Guillin. 26-29.

[18] Shahnia, F., Ghosh, A., Ledwich, G., & Zare, F. (2013) Predicting voltage unbalance impacts of plug-in electric vehicles penetration in residential low-voltage distribution networks. Electric Power Components and Systems, 41(16): 1594-1616.

[19] Su Haifeng, Zhao Kewei, Li Yan, Li Meng, Wen Helong, Wang Yong. (2018) Three-phase load balancing charging line selection device and simulation analysis for large-scale electric vehicles. Electric Power Automation Equipment, 38(06): 103-108.

[20] Liu Jian, Wang Zhongying, Zhao Yongqiang. (2017) Research on the Application Value and Charge and Discharge Price of Electric Vehicle Power System. China Price, 11:54-57+91

[21] Ge Shaojun, Wang Long, Liu Hong, Feng Liang, Huang Wei, Zhu Tao. (2013) Study on the
Optimization Model of Peak and Valley Electricity Price Period Considering Electric Vehicles Entering the Network. Power System Technology, 37(08): 2316-2321.

[22] Bhatti, Abdul & Salam, Zainal. (2018) A Rule-Based Energy Management Scheme for Uninterrupted Electric Vehicles Charging at Constant Price Using Photovoltaic-Grid System. Renewable Energy, 125:10-12.

[23] Jin Zhuoyu, Xiang Tieyuan, Chen Hongkun, Chen Ruonan, Tao Yuan. (2017) Distributed photovoltaic power generation access planning method considering power quality problems. Power System Protection and Control, 45(09): 1-8

[24] Fettinger, N., Ten, C. W., & Chigan, C. (2012). Minimizing residential distribution system operating costs by intelligently scheduling plug-in hybrid electric vehicle charging. In: IEEE Transportation Electrification Conference & Expo. California. 65-67.

[25] Tian Yongjun, Zeng Xiaobo, Ge Qing. (2018) Research on grid-side optimization control of user-side photovoltaic power generation based on time-of-use tariff policy. Instrumentation Users, 25(12): 13-16

[26] Zhou Jing, Yao Jianguo, Wang Wei, Shi Fei, Zeng Dan. (2015) Continuous Probabilistic Load Flow Analysis Method Considering Price-Type Load Response Process. Automation of Electric Power Systems, 39(17): 56-61+107.

[27] Ogura, K., Nishida, T., Hiraki, E., Nakaoka, M., & Nagai, S. (2004) Time-sharing boost chopper cascaded dual mode single-phase sinewave inverter for solar photovoltaic power generation system. In: IEEE Power Electronics Specialists Conference. Aachen. 125-126.