The automatic phase-selective photovoltaic grid-connection system used to control three-phase imbalance of low voltage power grid

Peng Yi-wen1,a, Zhu Si-tong2,b, Miao Yi-lin3,c, Wang Xinyao4,d, Wang Li-di5,e*
1,2,3,4,5College of Information and Electrical Engineering, Shenyang Agricultural University, Shenyang, Liaoning, China.
*aemail: olhabudnik@qq.com, bemail:646394276@qq.com, cemail:874087972@qq.com,
demail:13940853329@163.com
*eemail: wanglidi@syau.edu.cn

Abstract: Three-phase balance degree is an important quality index of power grid operation. Excessive three-phase imbalance will bring serious harm to power grid. To solve the problem of three-phase unbalance of low voltage power grid, this paper proposes and implements an automatic distributed photovoltaic phase-selective grid-connection system based on PLC control. The main functions include: photovoltaic automatic phase-selective grid connection, realization of three-phase unbalanced treatment of low-voltage power grid, low voltage and over voltage treatment of power grid. The main structure includes: monitoring & execution unit, logic control unit and photovoltaic power generation unit. Based on the voltage and load of each phase of the power grid, photovoltaic power generation module can realize automatic phase-selective grid-connection, so as to improve the three-phase imbalance of low-voltage power grid, solve both low voltage and over voltage problems, and realize the comprehensive control of voltage level of low-voltage power grid.

1. Introduction
In recent years, photovoltaic power generation has been rapidly developed in the world due to its clean, renewable and other kinds of advantages. Distributed photovoltaic power generation grid connection system has improved the disadvantages of traditional centralized power supply and distribution system, such as long construction cycle and large investment, which has a profound and good influence on the development of power grid, the situation of the power quality to a large extent affected the people's economy and benefit. Therefore, it is necessary to study the grid connection of photovoltaic power generation system in detail to make it play a role beneficial to the power grid as much as possible. Poor power quality will have a negative impact on the operation of the system, which may lead to a large number of industrial products scrapping or production chaos, and even endanger personal safety. To solve the problem of power quality caused by unbalanced three-phase loads in the low-voltage grid, this paper proposes a scheme for controlling unbalanced three-phase loads in the low-voltage grid with distributed photovoltaic flexible grid-connected system based on PLC control.

2. Harm of three-phase imbalance of low-voltage grid
The power supply of low voltage grid generally uses three phase four wire system connection mode, single-phase load accounts for a high proportion of the total load, moreover, due to the
unpredictability of load growth, random phase access to new users, the difference of service time of power equipment and the instability of seasonal power consumption, the three-phase imbalance phenomenon is increasing. According to the State Grid Corporation, the number of single-phase overloaded transformers in rural areas is 80% of that in urban areas. If the grid runs for a long time under the condition of three-phase unbalance, it will cause many problems, such as increasing transformer and line loss, increasing neutral line loss, three-phase voltage asymmetry, affecting the safe operation of electrical equipment, etc.\(^1\)

3. Design of automatic phase-selective photovoltaic grid connection system

The existing distributed photovoltaic power generation adopts single-phase grid-connected mode to connect to the low-voltage grid when the capacity is small\(^2\). At present, the connection between a single photovoltaic power generation unit and the power grid is fixed on a certain phase, which lacks flexibility. The traditional three-phase power balance regulator is used to transfer the unbalanced current from the phase with large current to the phase with small current. Although it can meet the requirement of power balance, the equipment has complex structure, high cost and no economy from the perspective of energy consumption. In order to solve the above technical problems, this project provides an automatic photovoltaic phase-selective grid-connection system for three-phase load imbalanced low-voltage power grid, which can realize a three-phase balanced power grid and achieve the purpose of improving power quality, reducing power consumption, saving energy and environmental protection.

![FIG. 1 Structure diagram of the automatic phase-selective grid-connected photovoltaic system](image_url)

As shown in figure 1 for the design of the automatic phase-selective grid-connected photovoltaic system structure, the voltage and current in each phase of the grid are monitored in real time. The programmable logic controller (PLC) is used to realize the power supply of photovoltaic modules automatically to the maximum load phase of the three-phase power grid, which can alleviate the influence of three-phase imbalance.

KM 1, KM 2, KM 3, KM 4, KM 5, KM 6, KM 7 are AC contactors, coils 1, 2, 3, 4, 5, 6, 7 are connected with the PLC, respectively corresponding to KM 1, KM 2, KM 3, KM 4, KM 5, KM 6, KM 7 contactor coils, the control of the IT 1, IT 2 and IT 3 are the first to third current transmitters and their serial Numbers, and the XT 1, XT 2, XT 3 are the first to the third voltage transducer, AD
represents the analog-digital converter, A, B, C and N respectively represent the three-phase and neutral lines of the three-phase four-wire grid.

PLC accepts the real-time monitoring voltage values of each phase of the power grid issued by XT 1, XT 2 and XT 3. After comparative analysis and calculation, the photovoltaic grid-connected or energy storage is determined and the corresponding control coil 7 is driven to control the on-off state of KM 7, and determine that when KM 6 operates (i.e. connected to the grid), coils 2, 3 and 4 are driven to control the switching state of KM2, KM3 and KM4, then power supply is carried out to the maximum load phase. When real-time data analysis and processing of each phase of the system is realized based on PLC, the specific logic is as follows: real-time acquisition of IT 1, IT 2 and IT 3 signals converted by AD; analysis of whether the three phases of the power grid are balanced; if it is balanced, control KM 7 action to make the photovoltaic array supply power for the energy saver; if it is imbalanced, K6, K8 and K2, K3 and K4 are controlled to supply power to the maximum phase of load power in the grid.

The main structure includes photovoltaic power generation unit, monitoring & execution unit and logic control unit.

The photovoltaic power generation unit includes photovoltaic array, single-phase grid-connected inverter, battery, energy storage control device, voltage transmitter, current transmitter. After the acquisition and processing of signals by PLC, the photovoltaic array is controlled to receive solar energy and convert it into direct current energy, which is provided to the single-phase grid-connected inverter. The single-phase grid-connected inverter can obtain the maximum power acquisition through internal adjustment, and then convert it into AC electric energy in line with the national standard of low-voltage grid, or provide it to the energy storage system for energy storage. The signals collected by voltage and current transmitters enter the analog-digital converter to control the operation of decision making.

The logical control unit, including PLC, AD converter, AC contactor. The digital output point of the PLC is connected with the input end of the control coil of each AC contactor, and the output end of the control coil of the AC contactor is connected with the neutral line of the municipal power supply. Before the photovoltaic grid connection, the central processor judges whether the three-phase load of the municipal power supply is balanced, whether there is low voltage phenomenon and whether there is over voltage problem by comparing the current and voltage of phase A, B and C. The calculation method of three-phase unbalance degree \( \varepsilon \) is as follow:

\[
\varepsilon = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}}} \tag{1}
\]

\( I_{\text{max}} \) is the current of the maximum three-phase current of the low-voltage grid; \( I_{\text{min}} \) is the current of the minimum three-phase current of the low-voltage grid; \( \varepsilon \) is the three-phase unbalance degree. The specific control logic is as follows: In the case of overvoltage, the maximum voltage is connected to the external load or connected to the energy storage device to consume power and make the voltage drop to the normal range; When the low voltage and over voltage occur simultaneously in the three phases of the power grid, the photovoltaic power generation unit gives priority to supply the lowest voltage phase to the normal range. After the photovoltaic power generation system is connected to the low-voltage grid, the voltage level of the connected nodes will also increase accordingly, and its voltage is likely to exceed the allowable range of the grid voltage. \( \varepsilon \) is the three-phase unbalance degree. For example, in the case of sufficient sunshine, the output voltage of photovoltaic panels is very high, or the circuit is light loaded after the photovoltaic grid-connected system is connected to the power grid, or when the photovoltaic power generation is connected to the end of the low-voltage grid, etc. Therefore, the operation state of the power grid needs to be considered when solving the problem of three-phase imbalance. The three-phase unbalance degree calculated by the real-time monitoring three-phase current value of the grid-connected system is taken as the criterion. When the three-phase unbalance degree meets and is less than the maximum specified by the State Grid, the switching equipment executes the PLC instruction to stop the grid-connected power supply and enters the working state of the energy storage.
system.
The monitoring & execution unit: the output current of the photovoltaic power unit and each phase current of the three phases of the municipal power supply are obtained by combining the analog-digital converter in the logic control unit with the current and voltage transmitter, and the output current value of the photovoltaic power unit and the current value of the three phases of the municipal power supply are output to the logic control unit. PLC contact control operating screen, real-time display of the voltage and current values of various parts.

4. Design of logical control unit
The logic control unit is used to judge whether the three-phase load of the municipal power supply is balanced according to the power current of phase A, B and C of the municipal power supply. If it is balanced, the logic control unit controls the photovoltaic power generation unit to enter the energy storage state. If it is unbalanced, the maximum load phase is determined, and the logic control unit controls the connection between the photovoltaic power generation unit and the maximum load phase for three-phase balance adjustment. The automatic phase selection algorithm includes: $I_A$ is the phase A power supply current, namely the detection value of the second current transmitter; $I_B$ is the phase B power supply current, namely the detection value of the third current transmitter; $I_C$ is the phase C power supply current, namely the detection value of the fourth current transmitter; $I_D$ is the output current of the AC side of the photovoltaic power generation unit, namely the detection value of the first current transmitter.

Considering the three-phase load unbalance criterion, when the three-phase unbalance degree of the power grid is greater than 15%, the algorithm before photovoltaic grid-connection. $I_X$ is the maximum of the three-phase power supply current $I_A, I_B, I_C$.

$$I_X = \text{Max}\{I_A, I_B, I_C\}$$

In this case, if $I_X = I_A$, the AC contactor corresponding to A acts to realized photovoltaic power supply system to supply power to A phase grid;
If $I_X = I_B$, the AC contactor corresponding to B acts to realize the photovoltaic power supply system to supply power to B phase grid;
If $I_X = I_C$, the AC contactor corresponding to C acts to realize the photovoltaic power supply system to supply power to C phase grid;

Considering the three-phase load unbalance criterion, when the three-phase unbalance degree of power grid is higher than 15%, the algorithm after photovoltaic grid-connection includes:
$I_U$ is set as the maximum value of the three-phase load current, i.e.

If $I_U = I_A + I_D$, the AC contactor remained in the original state, and the photovoltaic power supply system continued to supply power to A phase grid;
If $I_U = I_B$, the AC contactor acted to disconnect the A phase and connect the B phase, and the PV power supply system continued to supply power to the B phase to the grid.
If $I_U = I_C$, the AC contactor acted to disconnect the A phase and connect the C phase, and the photovoltaic power supply system continued to supply power to the C phase to the grid.

If $I_U = I_A$, the AC contactor action: disconnect B phase, connect C phase, photovoltaic power supply system supply power to C phase grid;
If $I_U = I_A$, AC contactor action: disconnect C phase, connect A phase, photovoltaic power supply system supply power to A phase grid;
If $I_U = I_B$, AC contactor action: disconnect C phase, connect B phase, photovoltaic power supply system supply power to B phase grid;
If $I_U = I_C$, AC contactor action: disconnect B phase, connect C phase, photovoltaic power supply system supply power to C phase grid.
Before the photovoltaic power supply system is connected to the grid, the output current of the inverter AC side after the grid connection is calculated according to the DC current output of the photovoltaic panel as follows:

\[ I_f = \frac{V \cdot I_E}{V_1} \tag{3} \]

\( V \) is the working voltage of photovoltaic panel (the first voltage transmitter test value), \( I_E \) is the DC side current of photovoltaic power generation unit (the fifth current transmitter test value), \( N \) is the working efficiency of grid-connected inverter, \( V_1 \) is the voltage level of municipal power supply at the pre-grid-connected side, \( I_f \) is the current value injected into the grid by the photovoltaic power supply system after calculation.

\[ I_f = \text{Max}\{I_A, I_B, I_C\} \tag{4} \]

\[ I_f = \text{Max}\{I_A, I_B, I_C\} \tag{5} \]

If \( I_f \leq (I_V - I_W) \), the photovoltaic power supply system disconnects the energy storage AC contactor and enters the grid-connected power supply mode.

After the photovoltaic power supply system is connected to the grid, the calculation formula is as follows:

\[ I_w = \text{Max}\{I_A, I_B, I_C\} \tag{6} \]

When \( I_X = I_W \) (indicating that the power grid is in an oversupply state), the photovoltaic power supply system stops being connected to the grid and enters the working state of the energy storage system. When overvoltage occurs in a certain phase of the power grid, the system will control the corresponding switch to make the energy storage device absorb power from the power grid for energy storage or fix the impedance elements to the power grid, so as to make the voltage drop to the normal range. When photovoltaic power generation efficiency is low in rainy weather or during peak power consumption in the evening, the energy storage unit in the PLC control system automatically selects the phase and connects the grid for power generation through the inverter. The grid-connected power of the battery is calculated by PLC and the output power of the inverter is controlled through RS485 communication between PLC and the inverter controller. The whole set of devices can provide the role of "peak load cutting" for the power grid.

5. Test result & Discussion

The simulation test is carried out after the development. This experiment connects two inverters based on the above automatic phase selection algorithm: the main inverter and the secondary inverter. The main inverter can be connected to the phase of maximum load, the three-phase unbalance degree is considered again after the main inverter is connected to the grid, the secondary inverter is connected into the second largest load phase of grid under the condition that it does not meet the national standard, the choice of two inverters can meet more situations of the three-phase unbalanced power grid.

![FIG. 2 Device appearance of the automatic phase-selective photovoltaic grid-connection system](image)
can operate under the three-phase equilibrium condition.

Second, by increasing the load power of Phase A and Phase C, the current of phase A and phase C is increased to 260mA and 298mA respectively, thus causing three-phase imbalance in the three-phase four-wire power grid. The specific experimental data are shown in the figure below:

In the third step, it is detected by the monitoring & execution unit that the voltage of phase A and Phase C is low, the current of phase A and phase C is high, and the three-phase imbalance degree of the power grid is higher than the normal index. The output current value of the photovoltaic power unit and the three-phase power current value of the municipal power supply are obtained through the cooperation of the analog-to-digital converter in the logic control system with the current transmitter and voltage transmitter. The PLC commands the photovoltaic power unit to implement automatic phase-selective grid connection to phase A and Phase C to inject power into the grid. Finally, the grid voltage of the node is increased and the current is decreased, so that the three-phase imbalance degree is reduced to the normal index range.

Aiming at the low-voltage power grid, this device combines distributed photovoltaic power generation into the grid to solve the problem of three-phase imbalance, and makes full use of the local clean energy represented by photovoltaic, which can not only improve the local three-phase imbalance of power grid, but also improve the utilization rate of clean energy. The automatic phase-selective grid connection strategy based on PLC control improves the existing single-phase grid connection flexibility of distributed power supply, and solves the limitation that the grid connection of distributed power supply can only be incorporated into a fixed phase.
6. Conclusions
The automatic photovoltaic phase-selective grid-connection device enables photovoltaic power generation module to realize automatic grid-connection of photovoltaic power generation unit based on the voltage and load of each phase of the grid. This system can improve three-phase unbalanced situation of low voltage power grid, and give consideration to low voltage and over voltage problems of the power grid, realize voltage level comprehensive control of low voltage grid. The device can also be installed in the original small distributed photovoltaic power station. Selective single-phase grid-connection can be carried out according to the demand of the power grid, either injected power or consumed power can be carried out according to the demand of the power grid during the three-phase unbalanced period, and three-phase grid-connected generation can still be carried out during the three-phase balanced period of the power grid, which not only meets the grid-connected power supply, but also takes into account the control of the three-phase unbalanced period. Under the background of renewable energy utilization rate is higher and higher, better take the advantages of distributed photovoltaic grid power generation, using its over the low voltage grid three-phase imbalance, in order to strengthen the use of renewable energy and realize photovoltaic power generation system flexible and economic operation, can not only improve power quality, reduce the unnecessary power consumption, also make contribution to the environment protection.

Acknowledgments
Supported by Graduate Education and Teaching Reform Research Project (2020-YJS-27) of Shenyang Agricultural University.

References
[1] Chen Zi-hui, Wu Zhi-ying, Liu He, Chen De. (2020) Effect of voltage deviation and three-phase unbalance on cable line loss [J]. Guangdong electric power,33(05):125-132.
[2] Hu Shi, Yuan Xufeng, Cao Mingjie, Zhang Tianwei, Tan Zhukui, Wang Mian. (2019) Research on balance compensation technology of low-voltage distribution grid for single-phase photovoltaic access [J]. Power big data,22(04):60-66.
[3] Wu Jun, Zhu Jun, Shen Haiping, Feng Yuan. (2019) A brief analysis of approximate calculation method for three-phase unbalance degree of distribution grid [J]. High voltage electric appliance,55(12):211-214.
[4] Pan Jingsheng, Li Mengjia, Liu Xiujie, etl. (2018) Influence of distributed photovoltaic power supply access on power quality of distribution network [J]. Shandong Electric Power Technology, 45(09):22-25.