Practicability Research on “Phase-Hopping” AC–AC Frequency Conversion Technology

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ABSTRACT The “Phase-Hopping” AC-AC frequency conversion technology proposed on the basis of traditional technology has the advantages of no circulating current, no dead zone and output frequency that can be improved to close to the power frequency. However, the research on this technology at present is still limited to the low voltage level, and problems such as low system capacity and high harmonic wave still exist, which cannot be applied in practice. To this end, a three-phase series-connected six-fold “phase-hopping” AC-AC frequency conversion main circuit is designed on the basis of traditional series-connected multiple technology, which addresses the voltage withstanding problem of thyristors, reduces harmonic content and enlarges system capacity, and the circuit is simulated by MATLAB. Furthermore, a single-phase series-connected six-fold “phase-hopping” AC-AC frequency conversion experiment platform is set up, which includes the key main circuit and the trigger circuit and improves its synchronous detection circuit. The simulation and experimental results are consistent with the theoretical analysis. In view of the technical transformation of “phase-hopping” AC-AC frequency conversion of common high-voltage and large-capacity pump station motors, the main circuit is designed, the model selection of thyristor is conducted, and the cost estimation of frequency converter is carried out. The analysis shows that the system has a high cost performance, thus it can be seen that this technology has a broad practical application prospect.

INDEX TERMS AC-AC frequency conversion, high voltage, large capacity, MATLAB.

I. INTRODUCTION

According to statistics, the total potential market space for frequency converters in China is about RMB120-180 billion [1]. Among them, constant-voltage frequency converters account for about 60% of the market share. The demand for medium- and high-voltage converters is relatively small. However, due to its high power and high price of a single converter, it also accounts for about 40% of the market share. At present, there are at least 180 million kW of installed capacity of motors with variable load and energy-saving potential in China, which provides an extremely huge market for the application of frequency converters. In recent years, the frequency converter market in China has maintained a growth rate of 12%-15%. It is expected that the market demand of frequency converter will maintain a growth rate of more than 10% in the next five years at least. If the high cost problem of high-voltage converters is solved, the demand for converters will be further stimulated.

In the frequency conversion technology, there are mainly two forms: AC-DC-AC frequency conversion and AC-AC frequency conversion. The former can achieve smooth stepless speed regulation and has a wide speed regulation range and low harmonic content, but it has complex frequency conversion system and cost high. The latter does not have the DC link, with simple main circuit, no DC circuit and filter part [2]. Compared with the general AC-DC-AC converter, AC-AC converter has the advantages of high conversion efficiency [3], especially in the case of small operation speed and very large power. However, its application is subject to limitation [4], [5] to an extent due to its low power factor, high harmonic content, low output frequency [6], [7], narrow range of variation and large number of components used.

At present, very few studies have been carried out on AC-AC frequency conversion which uses semi-controlled
devices as its core around the world, and rare literature is available. Inspired by the research results of Professor Du Qingnan from Henan Polytechnic University [8]–[10], the author creatively put forward the idea of “phase-hopping” AC-AC frequency conversion, by which the shortcomings of circulating current or dead zone of traditional AC-AC frequency converters can be addressed, and the output frequency of AC-AC frequency converter can be close to power frequency, thereby the application scope of AC-AC frequency converter can be extended. However, the research of this technology at present is still limited to the low voltage level, and problems such as small system capacity and high harmonic wave still exist, therefore it cannot be applied in practice yet.

In the previous research on the “phase-hopping” AC-AC frequency conversion technology, it was found that the series-connected triple “phase-hopping” AC-AC frequency conversion circuit, drawing on traditional series-connected multiple technology, has the advantages of higher operating voltage and less harmonic content than single circuit. If the multiplex of the circuit is further increased, it is expected to obtain a kind of high-voltage and large-capacity converter whose system harmonic content complies with national standard, which is composed of low-cost and low-voltage withstanding devices, thus allowing this technology truly being applied to practical systems.

II. PRINCIPLE SIMULATION AND ANALYSIS

The basic idea and principle of “phase-hopping” AC-AC frequency conversion have been introduced in detail in the articles published before, and will not be repeated here [11]–[13].

On the basis of the previous research on the triple “phase-hopping” AC-AC frequency conversion circuit, it is now expanded to a three-phase six-fold circuit. The research method and simulation model are basically the same as before, with the only difference that the circuit is extended to a six-fold circuit. As shown in Figure 1, two three-phase rectifier bridge structures (positive and negative respectively) are in reverse parallel to form a single “phase-hopping” AC-AC frequency conversion circuit; six single “phase-hopping” AC-AC frequency conversion circuits are connected in series to form a single-phase six-fold “phase-hopping” AC-AC frequency conversion circuit; three groups of series-connected six-fold AC-AC frequency conversion circuits are connected in series in a star or triangle shape to form a series-connected three-phase six-fold “phase-hopping” AC-AC frequency conversion circuit.

In the article studying triple “phase-hopping” AC-AC frequency conversion circuit, the output frequencies 45Hz, 42.86Hz and 37.5 Hz.

Firstly, according to Formula (1), the number of power frequency cycles needed for completing a large cycle can be obtained using the required output frequency f

$$n = \frac{50}{50 - f}$$

(1)

Then the time interval between every twice phase hopping is obtained by using Formula (2).

$$\Delta t = n \times 20/6 (ms)$$

(2)

This time interval is used to control triggering the thyristors.

In the six-fold circuit, the triggering time interval of two adjacent corresponding pulses is expressed in Formula (3). When the time interval is delayed, the pulse will be sent to the next corresponding thyristor, so the desired output frequency can be obtained at the output end of the six-fold circuit.

$$t = \frac{\Delta t}{6}$$

(3)

In order to make the output a three-phase standard voltage, the trigger pulses sent to the thyristors of the first phase need to be delayed by 1, 20° and 2, 400°, i.e. 6.67ms and 13.33ms, respectively, and then sent to the corresponding thyristors in the second and third phases. Other conditions remain unchanged.

According to the above analysis, the simulation parameters are set. The input phase voltage of the three-phase six-fold circuit is set as 505V, the resistance value of the resistive load is set as 36Ω, and the inductance value is 80.6mH. The simulation result is as shown in Figure 2.

From the simulation data in Figure 2, it can be seen that the harmonic distortion rates of the three-phase six-fold “phase-hopping” AC-AC frequency conversion output 45Hz, 42.86Hz and 37.5Hz are 4.69%, 4.51% and 4.43% respectively, which are all less than 5%, much lower than the triplex situation [15]. The greatly reduced harmonic content has reached the national standard level, so that the “phase hopping” frequency conversion technology can be directly connected to the grid and put into practical application.
III. EXPERIMENTAL VALIDATION

In order to verify the conclusions of theoretical and simulation analysis, an experimental platform is established for implementing analysis on the experimental data at a lower voltage level. Since three-phase six-fold AC-AC frequency converter circuit is composed of three groups of series-connected six-fold AC-AC frequency conversion circuit, three-phase frequency conversion circuits connected in a star or triangle shape, the three-phase situation can be roughly inferred from the results of single-phase experimental result. For the sake of simplicity, Experiments were carried out on one group of series-connected six-fold AC-AC frequency conversion circuit.

A. DESIGN OF MAIN CIRCUIT OF AC-AC FREQUENCY CONVERTER

Figure 3 is a schematic diagram of the first pair of thyristors in the single fold of the AC-AC frequency conversion main circuit of the system. The other thyristor circuits are similar as shown in Figure 3. Trigger excitation requires a certain voltage and a certain current. Since the trigger pulse of the main control board cannot directly trigger the thyristor to make it conduct, a trigger drive circuit is needed to increase the driving ability of the pulse, so it is isolated by an optocoupler MOC3022. This kind of circuit features reliable triggering and wide application range. In Figure 3, R1, R2, R13 and R14 are current limiting resistors, and the negative input end of the optocoupler is the trigger pulse provided by the main control board. P1 and N4 are BT151 type unidirectional thyristors, which are used as switching tubes on the bridge arm of the main circuit of AC-AC frequency converter. R25 and C1 together form an absorption circuit. A is the input of Phase-A power supply and O is one of the output terminals of each circuit.

B. DESIGN OF SYNCHRONOUS DETECTION CIRCUIT

According to the principle of “phase-hopping” AC-AC frequency conversion, the generation of all trigger pulses must have a strict time relationship with the phase of grid voltage. Therefore, it is a key point in hardware circuit design to detect the voltage phase of the power grid and to control and process synchronous signals accordingly with the detected result as a reference. Wrong detection may lead to short circuit of power supply or even serious accident, and detection not accurate enough may lead to a significant degradation in system performance.

First of all, in terms of the circuit principle, the principle of diode limiting is used to convert sine waves into a square waves. Secondly, the optocoupler H11L2 is used to isolate...
the high voltage and low voltage parts, and the input terminal LED of the optocoupler is used as a limiter diode. This makes the cost and volume of hardware circuits greatly declined compared with the solution of performing detection after using synchronous transformer to convert the high voltage of the power grid to a low voltage, besides the detection sensitivity is also increased. In the aspect of selection of circuit components, constant-current diodes are used instead of current limiting resistors. Since the constant-current diode exhibits a small resistance at low voltage, the sensitivity of the detection circuit can be ensured, and at high voltage, it can be known according to the characteristics of the constant-current diode that, the value of resistance at both ends is also increased. Meanwhile the current is always kept low, so the power consumed is also low [16]. Besides, the series connection of constant-current diodes can improve the overall withstand voltage of the circuit, and the withstand voltage value of the entire circuit is the sum of the withstand voltage values of all the series-connected constant current diodes. Therefore, for the 220V AC power grid, the series connection of four constant-current diodes can ensure the safety and stability of the circuit. The designed synchronous signal acquisition circuit is shown in Figure 4. Phase-A voltage is collected as phase reference. D1, D2, D4 and D5 are constant-current diodes with a constant current of 5.6mA and with the maximum forward voltage of 100V. The role of D3 is to remove the negative half-wave part of Phase-A alternating current. R1 and C1, R2 and C2 form a low-pass filter respectively, which are used to eliminate the interference of clutter in power grid through two-stage passive filtering. The Sync Signal at the optocoupler output end is a standard 5V square-wave synchronous signal with a duty cycle of about 50%. It is used as a time reference for the main control board.

C. EXPERIMENTAL PLATFORM

The structure of the experimental platform is shown in Figure 5, which is mainly composed of the main control board, synchronous detection circuit, single-phase six-fold AC-AC frequency converter main circuit, three-phase six-fold phase-shifting transformer, and fan load.

The main control board adopts the cyclone series FPGA [17], model EP3C16Q240, whose main function is to output the pulse signal needed by thyristors. Three-phase six-fold phase-shifting transformer converts 380V voltage of power grid into six groups of three-phase power supply with phase difference of 100 each other, which are supplied to the six groups of AC-AC frequency conversion circuits respectively. The load is a 2.2kW/220V fan load. The output frequency of the frequency converter can be observed intuitively through the change of the speed of the fan.

Based on the principle similar to triple circuit, the voltage needed by the system can be obtained by vector superposition method [9]. Select one of the six vectors that may be output by each single fold AC-AC frequency conversion circuits, arrange and combine the output selections of the six-fold circuits, there will be 6 × 6 × 6 × 6 × 6 × 6 = 46656 different combinations generated. Then the output voltage can be obtained through vector superposition, with the repetitive part eliminated. The actual output voltage has about 690 different results. The relationship between the output voltage and the input voltage is as shown in Formula (4):

\[ |U_{out}| = U_0 \sqrt{(\cos \theta)^2 + (\sin \theta)^2} \]  

where, \( U_{out} \) is the output voltage, \( U_0 \) is the input voltage, \( \cos \theta \) and \( \sin \theta \) are the components of the total voltage of the circuit on the horizontal and vertical axis of the coordinate system respectively. The relationship between them and the inputs is as shown in Formulas (5) and (6):

\[ \cos \theta = \cos \theta_1 + \cos \theta_2 + \cos \theta_3 + \cos \theta_4 + \cos \theta_5 + \cos \theta_6 \]  
\[ \sin \theta = \sin \theta_1 + \sin \theta_2 + \sin \theta_3 + \sin \theta_4 + \sin \theta_5 + \sin \theta_6 \]  

where \( \theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \) and \( \theta_6 \) are the vector angles of the six-fold line voltage respectively, each single-fold circuit has six different line voltages, then, it can be obtained that the output voltage is within the range of 0.026 to 5.737 times of the input voltage. It can be approximately considered that the output voltage can basically achieve continuous change and meet the needs of practical applications.

Since the rated voltage of the fan load used for the experiment is 220V, according to the aforementioned analysis, the grid voltage is reduced using a phase shifting transformer to a voltage of 220V(5.6/\sqrt{3})=22V, which is suitable for the experiment.

Figure 6 shows the picture of the experimental platform. A is the synchronous signal acquisition board, B is the FPGA main control board, C is the main circuit of the AC-AC frequency converter; At D, the six groups of three-phase power sources from the phase-shifting transformer are connected through 18 fuse tube; E is a power meter for measuring the output power; At F, the 2.2kW fan load is connected, and G is a heat dissipation fan used for heat dissipation of thyristors.
D. EXPERIMENTAL RESULT ANALYSIS

On the above six-fold experimental platform, the experimental output voltage signal of 45Hz, 42.86Hz and 37.5Hz are obtained by setting appropriate trigger control signals. The waveforms attenuated 200 times through RP1000D series high-voltage differential probes are as shown in Figure 7. Adjust cursors A and B to the appropriate positions, the output frequency of AC-AC converter can be read directly according to $1/\Delta T$. It can be seen that it is consistent with theoretical analysis and simulation results aforementioned in the foregoing sections, which proves the correctness of the theoretical and simulation analysis in the foregoing sections.

IV. DESIGN OF PRACTICAL “PHASE-HOPPING” AC-AC FREQUENCY CONVERSION CIRCUIT

Considering the situation that, in the field of drainage and irrigation stations in China, a large number of water pumps are running driven by 6kV and 800kW motors, and none of them are equipped with frequency converters, this paper uses 6kV and 800kW motors to design a practical “Phase-Hopping” AC-AC frequency converter.

As phase-shifting transformers and cabinets can directly refer to existing technologies, only the design of main circuit of “phase-hopping” frequency converter is elaborated here. Its circuit structure is shown in Figure 1. The key is to choose appropriate thyristors.

A. THYRISTOR MODEL SELECTION

Firstly, the voltage factor is analyzed. Since the objective is to use a three-phase six-fold “phase-hopping” AC-AC frequency conversion circuit to drive a 6kV motor, it means that the output line voltage is 6kV. According to Formula (7), the phase voltage is 3.46kV. The phase voltage here is the output voltage $U_{\text{out}}$ previously described.

$$U_{\text{line}} = \sqrt{3} U_{\text{phase}}$$  \hspace{1cm} (7)

According to the relation Formula (4) between output voltage and input voltage, in the ideal state, the proportional coefficient is generally 5.7, then the line voltage at both ends of the thyristor is 0.61kV, therefore, the operating voltage at both ends of the thyristor is

$$U_1 = U_N \div \sqrt{3} = 0.35kV$$  \hspace{1cm} (8)

That is, the peak voltage of the thyristor is

$$U_{\text{peak}} = \sqrt{2} U_1 = 0.496kV$$  \hspace{1cm} (9)

For the sake of safety of circuit operation, the thyristor’s rated voltage is usually 2~3 times of the operating voltage, which is used as the margin to allow the operation of overvoltage. Then the rated voltage of the thyristor is as shown in Formula (10), so thyristors of 1,600V can be selected.

$$U_{\text{rated}} = (2 \sim 3) U_{\text{peak}} = (0.99 \sim 1.48) kV$$  \hspace{1cm} (10)

Secondly, the current factor is analyzed. The value range of the power factor in the driving system such as fans and pumps is generally within the range of 0.7-0.95, we take 0.85 here, then the power of the motor is

$$P_N = 3 U_N I_N \cos \varphi = \sqrt{3} U_l I_l \cos \varphi$$  \hspace{1cm} (11)

Using Formula (11), the rated current IN of the circuit can be obtained:

$$I_l = I_N = \frac{P_N}{\sqrt{3} U_l \cos \varphi} = \frac{800}{\sqrt{3} \times 6 \times 0.85} = 90.57A$$  \hspace{1cm} (12)
Then the maximum operating current of each phase is:

\[ I_{d_{\text{max}}} = \sqrt{2} I_N = 128.07 \text{ A} \]  \hspace{1cm} (13)

Using Formulas (14) and (15), the rated current of the thyristor can be obtained:

\[ I_{VT} = \frac{I_{d_{\text{max}}}}{\sqrt{3}} \]  \hspace{1cm} (14)

\[ I_N' = \frac{(1.5 \sim 2) I_{VT}}{1.57} \]  \hspace{1cm} (15)

\[ I_N' = \frac{128.07 \times (1.5 \sim 2)}{\sqrt{3} \times 1.57} = (70.64 \sim 94.19) \text{ A} \]  \hspace{1cm} (16)

By analyzing the current, a thyristor with a current of 100A should be selected.

It can also be seen from the above analysis that using the multiple technology, thyristors with lower withstand voltage can be used in high voltage systems, thereby reducing system cost or solving the problem of no component available.

**B. PRACTICAL SYSTEM COST ANALYSIS**

The cost of “Phase-hopping” AC-AC frequency converter system includes the phase-shifting transformer, the control cabinet and the core components of the converter. From the analysis on the thyristor model in the previous sections, it is found from market research that the KP100A/1600V model thyristor produced by Wuhan Wuzhen Rectifier Co., Ltd., accommodates the requirements of the practical system design in this paper. And by consulting, we know that the market retail price \( P \) of this model of thyristor is 55 Yuan/each. Under the condition of having the same withstand voltage, the cost of a single thyristor has decreased by half or more compared with the full-control device. From the three-phase six-fold AC-AC converter main circuit, we know that the thyristor quantity \( M \) required for the system is:

\[ M = 12 \times 6 \times 3 = 216 \text{ (each)} \]  \hspace{1cm} (17)

Then the cost \( W \) of the core device of the frequency converter is:

\[ W = M \times P = 216 \times 55 = 11880 \text{ (Yuan)} \]  \hspace{1cm} (18)

It is only a small percentage of the hundreds of thousands of frequency converter systems. The market price of 6kV/800kVA phase shifting transformer is about RMB100,000, and the cost of the control cabinet is about RMB20,000, so the total system cost is below RMB140,000. At present, the price of converters of the same capacity on the market is about RMB500,000. Obviously, even if the market price of the 6kV/800kW frequency converter system designed in this paper is fixed at RMB200,000, it is only 40% of the current selling price of frequency converters on the market. Moreover, the market price of this system has a certain space for reduction, so it is highly competitive in the market.

Since the output flow of the fan and pump systems is proportional to their rotation speed and the power consumed is proportional to the cube of the rotation speed [18], [19], the “phase-hopping” AC-AC frequency converter has a great improvement effect on the energy conservation. For example, if the frequency is reduced from 50Hz to 45Hz, the motor speed is reduced to 90% of the rated value, the flow rate is reduced by about 10%, then the reduced power consumption is

\[ \Delta P = (1 - 0.9 \times 0.9 \times 0.9) P_N = 0.271 P_N \]  \hspace{1cm} (19)

That is, it can save energy by 27.1%; if the frequency is further reduced to 40Hz, the rotation speed is reduced to 80% of the rated value, then the reduced power consumption is:

\[ \Delta P' = (1 - 0.8 \times 0.8 \times 0.8) P_N = 0.488 P_N \]  \hspace{1cm} (20)

This nearly saves half of the energy. The effect is very significant, and at this point the flow rate can still maintain 80% of the rated flow. Generally speaking, the maximum flow demand is usually used in design, but the actual operation condition is not always under the maximum flow demand, so the actual flow demand of the system can generally be met by reducing the motor speed.

Taking the transformation of existing pumping stations as an example, China has built more than 500,000 large-, medium- and small-sized fixed pumping stations with a total installed capacity of more than 70 million kilowatts. Assuming a 30% of power-saving capacity, it could reach 21 million kilowatts, roughly equivalent to the installed capacity of the Three Gorges hydropower station. When the Three Gorges Project was initially designed in 1992, it was estimated that the total dynamic investment was about RMB 203.9 billion [20]. The investment in the Three Gorges Project includes the hub project and the relocation and resettlement of migrants within the scope of the Three Gorges Reservoir Region and the interest expense on the project lending and issuance. The investment for the geological disaster control in the Three Gorges Reservoir Region and the power transmission and transformation project are not included in the investment calculation. Therefore, using the solution of “phasing-hopping” AC-AC frequency conversion, the cost calculated based on 800kW/RMB200,000 is only RMB1.75 billion, less than 1% of the investment of the Three Gorges Project.

Therefore, the application of “phase-hopping” AC-AC frequency conversion has quite high cost performance in practice. If other types of pump and fan systems are considered, this technology has a larger application range.

**V. CONCLUSION**

“Phase-hopping” AC-AC frequency conversion technology plays a great role in energy conservation transformation, which especially exhibits a remarkable energy saving effect in the fan and pump driving systems. By adopting six-fold technology, the problem of withstand voltage of devices can be addressed, the operating voltage class can be increased and the system capacity can be expanded. Moreover, the “phase-hopping” AC-AC frequency converter can achieve free...
adjustment of voltage. In addition, it has another very realistic significance: the harmonic content is dropped to less than 5% which is required by national application standard, making it can be directly put into practical application. In the improvement of the synchronous detection circuit design, firstly, the use of optocoupler, replacing synchronous transformer, not only decreases the volume of the synchronous detection circuit but also reduces the cost of designing circuit. Secondly, the use of constant-current diode, replacing current limiting resistor, can overcome the disadvantages of the solution when using current-limiting resistor, that is: low detection sensitivity due to its too large resistance and excessive current and large power consumption due to its too small resistance. In terms of the existing 6kV/800kW pumping station motors which have a large quantity and are widely applied, the selection of thyristor model and the calculation of frequency converter cost are carried out, and the cost performance of the system is analyzed in this paper. The analysis result shows that the system has a high cost performance and market competitiveness. Therefore, the use of “phase-hopping” AC-AC frequency conversion technology for frequency conversion transformation, widely used in high-power fan and pump driving systems which have a limited requirement for speed control accuracy, has broad application prospects, and its large-range popularization can produce huge economic benefits and social benefits.

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