Researching on Multiple “Phase Hopping” AC-AC Frequency Conversion Circuit

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ABSTRACT Frequency converter is a kind of important energy-saving device. As a kind of improved cycloconverter, the “phase hopping” AC-AC frequency converter can increase the output frequency to close to the line frequency and has the advantages of no circulation current and no dead zone. By combining multiple-stage AC-AC frequency conversion technology, the “phase hopping” AC-AC frequency conversion can regulate the output voltage and the output frequency at the same time. Relative to current frequency converters, it has the advantages of large capacity, high voltage level, and low cost. Taking a six-fold circuit as an example, all the voltage results are analyzed according to the voltage vector superposition method. Three groups of parameters are chosen as instances and performed a simulation with MATLAB in the condition of constant voltage to frequency ratio. Then an experimental platform is set up and the experimental analysis has been carried on. The experimental results are in good agreement with theory and simulation studies.

INDEX TERMS Frequency conversion, multiple-stage, MATLAB, vector superposition.

I. INTRODUCTION

As an important part of clean energy, electric energy plays an irreplaceable role in various fields. However, with the widespread application of electric energy, the degree of energy utilization has also attracted the attention of researchers. In actual production, the use of frequency conversion technology can improve the energy-saving performance of fans and pumps. However, the output frequency of the traditional AC-AC frequency converter is less than 1/2 of the grid frequency. In some applications, the system requires a larger output frequency range of the inverter, which leads to fewer applications of the inverter. For high-voltage inverters, in the high-voltage and large-capacity occasions, the IGBT devices are very expensive, which limits the application occasions. Therefore, the solution to the above problems can better promote the development of frequency converters.

AC-AC frequency conversion circuit, compared with AC-DC-AC circuit, there is no DC circuit [1], [2], and AC-AC conversion circuit have a high conversion efficiency [3], but the AC-AC frequency conversion circuit needs a lot of circuit components, low power factor, high harmonic content, and low output frequency [4], [5], limiting the development of converters [6], [7]. However, Professor Du Qingnan of Henan University of Technology has been committed to the technical research of AC/AC frequency conversion circuits based on thyristors. A double-variable control method is proposed and successfully applied to some actual speed control systems. His research results have a certain enlightening significance of the generation of the “phase hopping” AC-AC frequency conversion [8], [9], and [10]. Some scholars have put forward the idea of multiple AC/AC frequency conversion circuits [11], [12], but they can only change the output frequency of the circuit singly, which limits the use of frequency converters.

The “phase hopping” AC-AC frequency conversion uses the thyristors to connect the output terminals to the input terminals of different phases to achieve frequency conversion. Therefore, it calls “phase hopping” frequency conversion. The “phase hopping” frequency conversion can output far higher frequency than that of traditional AC-AC frequency conversion methods, the output frequency can be close to the power frequency, and there is no circulation current and no dead zone in the frequency conversion process. However, the output frequency of the single-phase “phase hopping” AC-AC frequency conversion circuit can be changed as needed; the output voltage is difficult to be changed. Combined with traditional multiple technologies output voltage is
difficult to be changed. Combined with traditional multiple technologies, the output voltage can be changed as needed. A vector superposition is carried out for each output voltage [12]. Different output voltages are got by using different angles between different vectors. This technology has a good application prospect of high voltage, high capacity, and high output frequency.

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Equation (1) is the phase that decreases with the number of jumps $M$ in a cycle of the output voltage.

$$ \Delta \varphi = M \times \frac{\pi}{3} \quad (1) $$

Equation (2) is the total phase of the output voltage increasing at a 50Hz power frequency of a complete period.

$$ \varphi = \Delta \varphi + 2\pi \quad (2) $$

Equation (3) is the period of the output voltage.

$$ T = \frac{\varphi}{2\pi} \times 20 (ms) = \frac{10}{3}M + 20 (ms) \quad (3) $$

Equation (4) is the frequency of the output voltage.

$$ f = \frac{1}{T} = \frac{300}{M + 6} (Hz) \quad (4) $$

The traditional AC-AC frequency conversion topology is used in the main circuit so that the thyristor changes simultaneously at different times. The output voltage changes from AC, BC, BA, CA, CB, and AB. The working process of a negative group is like that of a positive group. Each time the circuit jumps, the output voltage will jump from one input line voltage to the next input line voltage. The phase delay in the output voltage is $\pi/3$, and six jumps will introduce a total phase delay of $2\pi$. The actual number of cycles after completing a large cycle (six jumps) is one less than that of the 50 Hz frequency cycle. That is, the output voltage achieves $N$ cycles in the $N + 1$ line frequency period. Equation (5) is the total length of the whole of a large cycle interval.

$$ T_{all} = (N + 1) \times 20 (ms) \quad (5) $$

Equation (6) is the period of each output cycle.

$$ T = \frac{20 (N + 1)}{N} (ms) \quad (6) $$

Equation (7) is the corresponding output frequency.

$$ f = \frac{1}{T} = \frac{50N}{N + 1} \quad (7) $$

We can change the output frequency by changing $N$. When $N = 6$, the output frequency is about 42.86 Hz, and the output waveform is shown in Fig. 2.

In Fig 2, the output frequency is close to power frequency 50 Hz, every time interval between two jumps is 23.33ms, in this period the output voltage is always an input line voltage, two terminals of the frequency conversion circuit are connected to two input phases. In the first piece of the smooth curve in Fig. 2, the output voltage is the input line voltage BC, when using the “jump” frequency conversion method, within the 23.33ms interval, four thyristors, P3, P2, N6, N5, are always triggered while all other thyristors are not triggered by any pulse, because P-B connection and O-C connection are maintained all the time, any conduction case of the four thyristors will not result in short circuit, there will be no circulation current. Moreover, the pulses are always sent to the positive and negative group thyristors, and the current can change direction freely in the positive and negative groups with no dead zone time. Characteristics of no circulation current and no dead zones have overcome the serious defects of the traditional AC-AC frequency conversion method, and the output frequency can be close to the line frequency.
B. Multiple "Phase Hopping" Frequency Conversion Circuit and Output Voltage Regulation Principle

According to the method, using a single AC-AC frequency conversion circuit can achieve AC-AC frequency conversion, however, because the single circuit output voltage is an input line voltage. The value of the output voltage is difficult to be controlled as needed. To solve the problem of voltage changing, the traditional multiple technologies were combined with the "phase hopping" frequency conversion technology, getting the actual application of multiple “phase hopping” frequency conversion circuit, as shown in Fig. 3, it is a six-fold “phase hopping” AC-AC frequency conversion circuit.

In Fig. 3, D1, D2, D3, D4, D5, D6 are basically AC-AC frequency conversion circuits made up of two bridge rectifiers. It is fed by six independent sets of three-phase power supplies through a phase-shifting transformer, the phase of A1, A2, A3, A4, A5, A6 differs to the adjacent one of 10° respectively, the phase of B1, B2, B3, B4, B5, B6 differs 10° respectively, the phase of C1, C2, C3, C4, C5, C6 differs 10° respectively.

Because the six groups of three-phase power are independent of each other, the basic AC-AC frequency conversion circuits will work independently, each one circuit outputs an input line voltage of its power group that results in the output voltage of the whole six-fold circuit is the sum of the output voltages of six basic circuits. For each sine wave line voltage, the total output voltage of the circuit is obtained by vector superposition.

For the convenience of analysis, the letter “U” representing “voltage” is omitted here, each of the six voltages can be represented by BC, BA, CA, CB, AB, and AC, for example, the voltage from B to C is represented by BC. Numbers 1–6 are used to show the voltage belongs to which one basic circuit, such as BC1, BC2, BC3, BC4, BC5, and BC6. All voltages are represented by vectors with BC1 as the horizontal axis drawing the vector diagram as showed in Fig. 4.

Each of these vectors is assumed to be 1, and we can represent each voltage in coordinates, they are BC1(cos 0°, sin 0°), BA1(cos 60°, sin 60°), CA1(cos 120°, sin 120°), CB1(cos 180°, sin 180°), AB1(cos 240°, sin 240°), AC1(cos 300°, sin 300°), BC2(cos 10°, sin 10°), BA2(cos 70°, sin 70°), CA2(cos 130°, sin 130°), CB2(cos 190°, sin 190°), AB2(cos 250°, sin 250°), AC2(cos 220°, sin 220°), BC3(cos 20°, sin 20°), BA3(cos 80°, sin 80°), CA3 (cos 140°, sin 140°), CB3(cos 200°, sin 200°), AB3(cos 260°, sin 260°), AC3(cos 320°, sin 320°), BC4(cos 30°, sin 30°), BA4(cos 90°, sin 90°), CA4 (cos 150°, sin 150°), CB4(cos 210°, sin 210°), AB4(cos 270°, sin 270°), AC4 (cos 330°, sin 330°), BC5(cos 40°, sin 40°), BA5 (cos 100°, sin 100°), CA5 (cos 160°, sin 160°), CB5 (cos 220°, sin 220°), AB5 (cos 280°, sin 280°), AC5 (cos 340°, sin 340°), BC6 (cos 50°, sin 50°), BA6 (cos 110°, sin 110°), CA6 (cos 170°, sin 170°), CB6 (cos 230°, sin 230°), AB6 (cos 290°, sin 290°), AC6 (cos 350°, sin 350°).

Equation (8) is the value of the output voltage.

\[ |U_{out}| = U_0 \sqrt{(\cos \theta)^2 + (\sin \theta)^2} \] (8)

where \( U_0 \) is the input line voltage amplitude, according to the above assumption, the value is 1, \( \cos \theta \) and \( \sin \theta \) are the components of the total output voltage of the circuit on the horizontal and vertical axes of the coordinate system, respectively. Equation (9) and equation (10) are the relationships between the input quantity.

\[
\cos \theta = \cos \theta_1 + \cos \theta_2 + \cos \theta_3 + \cos \theta_4 + \cos \theta_5 + \cos \theta_6 \quad (9) \\
\sin \theta = \sin \theta_1 + \sin \theta_2 + \sin \theta_3 + \sin \theta_4 + \sin \theta_5 + \sin \theta_6 \quad (10)
\]

Here, \( \theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6 \) are the vector angles of six output voltages. Because there are six different line voltage voltages. Every angle has six values of the equation, so there are a total of \( 6 \times 6 \times 6 \times 6 \times 6 = 46656 \) different situations. By computer programming calculation, we found that in all the situations there are 690 different values of the overall voltage, distributed in the range of 0.026~5.736. It can be considered that the voltage can be changed continuously.

III. SIMULATION

As mentioned before, the frequency conversion is realized by changing the connection between one line voltage to another, which results in gaps between the available output

![FIGURE 4. The voltage vector diagrams of the six-fold circuit.](image)
frequencies, that means cannot adjust the output frequency continuously. And the voltage regulation adopts the vector superposition method. The output voltage cannot be changed continuously. So, the controlling precision of the output frequency and voltage cannot reach the level of frequency converters based on IGBTs.

Therefore, this method is difficult to be applied to high-demand occasions. However, some dragging systems, such as fans and pumps, have the characteristics of large capacity, and they do not need a high demand for speed control. The “phase hopping” AC-AC frequency conversion can be well applied to these systems.

The simple constant voltage-frequency ratio method is often used to control fans and pumps, so the constant voltage-frequency ratio method is adopted here to simulate the effect of frequency conversion. In the simulation, three sets of data were selected from the above 690 kinds of output voltages.

A. SIMULATION MODEL

As shown in Fig. 5, it is a block diagram of the six-fold “phase hopping” frequency conversion which mainly includes: six series-connected frequency conversion circuits and fan load. The main circuit structure of subsystem 1-6 is composed of Figure 3, subsystems 1~6 are composed of three-phase voltages with the same amplitude and frequency. The phase angles are (−120°, 0°, 120°), (−130°, −10°, 110°), (−140°, −20°, 100°), (−150°, −30°, 90°), (−160°, −40°, 80°), (−170°, −50°, 70°). As shown in Fig. 6, it is the internal structure of the subsystem which includes a trigger generation circuit and a basic frequency conversion circuit marked by convt1. As shown in Fig. 7, it is the simulation model within convt1.

The simulation parameters are set according to the principle of the constant voltage-frequency ratio. If the output voltage is 2500V when the output frequency is 50Hz, then the proportion $U/f = 50V/Hz$. According to the analysis before, the maximum output phase voltage is 5.7368 times of the input line voltage, so we set the maximum output line voltage is 2500V, the input phase voltage of the three-phase power supply is roughly $2500/(5.7368 \times \sqrt{3}) = 358V$. The load parameter is set as the resistance of 5Ω and inductance of 30mH according to the parameter of a normal fan.

1) OUTPUT 45Hz
According to the proportion of $U/f = 50V/Hz$, the output phase voltage is 2250V when the output frequency is 45Hz.

In (11), the following six-line voltages are selected from 690 cases mentioned before.

$$
BC1(sin 0°, cos 0°) + BA2(sin 70°, cos 70°) + BC3(sin 20°, cos 20°) + BA4(sin 90°, cos 90°) + BC5(sin 40°, cos 40°) + BC6(sin 50°, cos 50°) \tag{11}
$$
Using the simulation model mentioned before and the setting parameters, the simulation waveform results are got as shown in Fig. 8.

As can be seen from Fig. 8, the output frequency is 45 Hz, and the output voltage fluctuates near 2220V, the result meets the expectation.
2) OUTPUT 42.86Hz
Similar to the case of output 45Hz, the output voltage should be 2143V when the output frequency is 42.86Hz according to the proportion of $\frac{U}{f} = 50\text{V/Hz}$. In (12), the following six-line voltages are selected from 690 cases.

$$AC1(\sin 300^\circ, \cos 300^\circ) + BC2(\sin 10^\circ, \cos 10^\circ) + BC3(\sin 20^\circ, \cos 20^\circ) + BC4(\sin 30^\circ, \cos 30^\circ) + BC5(\sin 40^\circ, \cos 40^\circ) + BC6(\sin 50^\circ, \cos 50^\circ)$$ (12)

The resulting simulation waveform is shown in Fig. 9.

As can be seen from Fig. 9, the output frequency is 42.86Hz, and the output voltage fluctuates near 2122V, which meets the expectation.

3) OUTPUT 37.5Hz
Similarly, the output voltage should be 1875V when the output frequency is 37.5 Hz. In (13), the following six-line voltages are selected.

$$BC1(\sin 0^\circ, \cos 0^\circ) + BA2(\sin 70^\circ, \cos 70^\circ) + BC3(\sin 20^\circ, \cos 20^\circ) + AC4(\sin 330^\circ, \cos 330^\circ) + BA5(\sin 110^\circ, \cos 110^\circ) + BC6(\sin 50^\circ, \cos 50^\circ)$$ (13)

The resulting simulation waveform is shown in Fig. 10.

As can be seen from Fig. 10, the output frequency is 37.53Hz, and the output voltage fluctuates near 1823V, which meets the expectation.

From Fig. 8 to Fig. 10, we can see the simulation results show that the output voltage and frequency can be controlled according to the “phase hopping” frequency conversion theoretical analysis. The waveform distortion caused by the jumps is slight. That illustrates its harmonic content is at a low level. The total harmonic distortion rates of the three cases that can be got through the simulation analysis are 5.97%, 6.86%, and 6.51% respectively, which means this method can be used directly or together with a small capacity harmonic treatment device in fan and pump driving systems.

IV. EXPERIMENTAL VERIFICATION
To verify the principle of the “phase hopping” frequency conversion, an experimental platform is built, and some comparative experiments were carried out under a low voltage level, and some valuable experimental data were obtained.

A. EXPERIMENT PLATFORM
As shown in Fig. 11, it is a block diagram of the experimental platform which mainly includes: master control board, driver board, AC-AC frequency converter, phase-shifting transformer, and fan load. The master control board uses an ALTERA’s MAX II series CPLD, which model is EPM1270T144C5. It uses to generate the trigger pulses for the thyristors. The driver board provides power amplification for the trigger pulses. The driver board also has some auxiliary parts such as a synchronous detection circuit, current detection circuit, and resistance-capacitance absorption circuit. The load of the frequency converter circuit is a 2.2 kW/220 V fan, and the output frequency of the circuit can be conveniently observed by the fan speed.

The phase-shifting transformer has two functions: a phase shift and voltage transformation. For the limitation of laboratory conditions, the phase-shifting transformer can only output three groups of three-phase power of phase difference
to each other of 20°. So, a triple circuit rather than a six-fold circuit is built-in the experimental platform. Similar to the analysis of the six fold circuit, the line voltage is set to 220V/(2.88 × √88) = 44V to fit the experiment.

B. ANALYSIS OF EXPERIMENTAL RESULTS
Experiments are made based on the triple circuit platform. The master control board generates the trigger pulses according to the “phase hopping” theory and refers to the synchronous signal. The experimental output waveforms of 37.5 Hz, 42.86 Hz, and 45 Hz frequencies are obtained respectively, as shown in Fig. 12. The blue waveforms are the output voltage waveforms. The yellow ones are the output of the current waveform. The frequency converter can reduce the harmonic content generated when the power electronic device is switched so that the voltage and current waveforms at the load end is smoother. The output frequency can be read directly from 1/ΔT in Fig. 12. Though the circuit is a triple one rather than a six-fold one, according to the change of the number of “phase hopping”, the output frequency can be changed, and the output voltage can be adjusted by combining the multiple circuits, the output current without circulation, and without the dead zone, it can be seen that the experimental results are in good agreements with the above theoretical analysis and simulation, that verifies the correctness of the above theoretical analysis and simulation analysis.

V. CONCLUSION
The multiple phases hopping AC-AC frequency conversion circuit has a remarkable energy-saving effect on the driving system of fan and pump. And in the case of a thyristor with a low withstand voltage, it can output a very high voltage, and reduce the harmonic content of the system while adjusting the output voltage. The frequency conversion method of “phase hopping” is used to increase the trigger time interval. This method can increase the output frequency close to the line frequency. By triggering thyristors of positive and negative groups at the same time and maintaining the output terminal connected to the same input terminals, the circuit can overcome the shortcomings of circulation current and dead zone of the traditional AC-AC frequency conversion.

The multiple phases hopping AC-AC frequency conversion circuits can be used in the driving system of fans and pumps. It can also be used in some high-pressure, large-capacity, and low-speed drive systems with low accuracy. With a broad application prospect. This idea can be supported by the harmonic analysis results, which will be explained in detail in an article coming soon.

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