

1-1-2019

Thyristor-based "phase hopping" frequency conversion technique

ZHENWANG XU

JARUI ZHANG

YUCHUN YI

CHENG CHEN

JIAQI YU

See next page for additional authors

Follow this and additional works at: <https://journals.tubitak.gov.tr/elektrik>



Part of the [Computer Engineering Commons](#), [Computer Sciences Commons](#), and the [Electrical and Computer Engineering Commons](#)

Recommended Citation

XU, ZHENWANG; ZHANG, JARUI; YI, YUCHUN; CHEN, CHENG; YU, JIAQI; MEI, WEI; and FENG, DAIWEI (2019) "Thyristor-based "phase hopping" frequency conversion technique," *Turkish Journal of Electrical Engineering and Computer Sciences*: Vol. 27: No. 1, Article 18. <https://doi.org/10.3906/elk-1711-162>
Available at: <https://journals.tubitak.gov.tr/elektrik/vol27/iss1/18>

This Article is brought to you for free and open access by TÜBİTAK Academic Journals. It has been accepted for inclusion in Turkish Journal of Electrical Engineering and Computer Sciences by an authorized editor of TÜBİTAK Academic Journals. For more information, please contact academic.publications@tubitak.gov.tr.

Thyristor-based "phase hopping" frequency conversion technique

Authors

ZHENWANG XU, JIARUI ZHANG, YUCHUN YI, CHENG CHEN, JIAQI YU, WEI MEI, and DAIWEI FENG

Thyristor-based “phase hopping” frequency conversion technique

Zhengwang XU^{1,2,3} , Jiarui ZHANG^{1,2,3,*} , Yuchun YI^{1,2,3} , Cheng CHEN^{1,2,3} ,
Jiaqi YU^{1,2,3} , Wei MEI^{1,2,3} , Daiwei FENG^{1,2,3} 

¹Hubei Collaborative Innovation Center for High-efficiency Utilization of Solar Energy,
Hubei University of Technology, Wuhan, China

²Hubei Key Laboratory for High-efficiency Utilization of Solar Energy and Operation Control
of Energy Storage System, Hubei University of Technology, Wuhan, China

³Hubei Power Grid Intelligent Control and Equipment Engineering Technology Research Center,
Hubei University of Technology, Wuhan, China

Received: 30.01.2018

Accepted/Published Online: 12.06.2018

Final Version: 22.01.2019

Abstract: This study proposes a new AC/AC “phase hopping” frequency conversion method based on the analyses of the disadvantages of the conventional cosine wave-crossing method. The advantages of this new method include no circulating current, no dead time, and an output frequency close to the power frequency. This study also introduces the basic principles of the “phase hopping” method and analyzes these principles combined with the voltage phase-changing comparison to that of the cosine wave-crossing method. The “phase hopping” principles are used to analyze the generation of thyristor trigger pulses, including the generation time and duration. A simulation is conducted in MATLAB, and the simulation output waveform and harmonic analysis results are then obtained. The proposed approach is verified on an experimental platform. Consequently, the results are in good agreement with those of the theoretical and simulation analyses.

Key words: AC/AC frequency conversion, cosine wave-crossing method, “phase hopping”, MATLAB

1. Introduction

Electric energy is widely considered a type of clean energy in various fields. However, a large amount of electric energy is wasted because of inefficiencies in motor loads. For example, statistics published in China showed that the amount of electric energy consumed by motors accounts for 60%–70% of the national total. Moreover, AC motors account for approximately 90% of the total electric energy consumption, while motors with pump or fan loads account for 30% of the total Chinese power consumption. The motors supplying these loads typically operate at a constant speed. Even so, the liquid or gas flows supplied by these motors change in volume from time to time. Factories adjust the flows using baffles or valves, which decreases the overall system efficiency, to ensure that the volumes match. The efficiency of fan loads is approximately 40%, whereas that of pump loads is approximately 28%, thereby showing the potential to save a significant amount of energy if the efficiency of these loads can be increased.

The preferred solution for achieving industrial energy savings is the frequency conversion technology because this approach allows the working characteristics of motors to be fully utilized. An insulated-gate bipolar transistor (IGBT) is the representative of full-control devices in the frequency conversion field. IGBT

*Correspondence: jrzhang1994@sina.com

frequency conversion products, such as AC/DC/AC or matrix converters [1], have advantages of high power factors and low harmonics, but also have disadvantages of high prices and fragility [1]. Comparing the two most common methods of AC/DC/AC and AC/AC frequency conversion, the latter has no intermediate DC link and high conversion efficiency [2]. However, the output frequency is low because of the output voltage consisting of fragments of input voltages. This method is widely used in fields requiring high power and low speed.

Nowadays most of the related works in the literature focus on frequency conversion technologies based on fully controlled devices, only very few works discuss converters based on semiconducted devices. Most of this kind of works use thyristors based on the conventional cosine wave-crossing method, and make some improvements on the control method to reduce the harmonics [3] or improve the efficiency [4]. The conventional AC/AC frequency conversion circuit that uses thyristors as the main devices is composed of either an antiparallel three-phase zero rectifier circuit or a three-phase bridge rectifier circuit [5]. Only a small number of pulse waves in each power cycle exist in this circuit's output waveform (i.e. 20 ms in duration for 50 Hz power frequency). The output frequency of the circuit is limited to a maximum of approximately 20 Hz to ensure that the harmonic content in the output waveform is acceptable. With these limitations, the conventional AC/AC frequency conversion method finds it difficult to adapt to the large frequency ranges required by some applications. The "phase hopping" frequency conversion method proposed in this paper can overcome the disadvantages of the existing technologies. Not only can the output frequency be higher, close to the power frequency, but also the reliability can be obviously improved and the cost can be significantly reduced. It is suitable for fan and pump applications.

2. Traditional AC/AC frequency conversion and its disadvantages

Since the 1970s, in frequency conversion technology development, the cosine wave-crossing method has been mainly applied in the core control theory of AC/AC frequency converter, in which the thyristors are used as switch devices using cosine wave-crossing method to obtain the trigger point [6]. The desired output voltage is generated with the required output voltage, frequency, and phase by comparing the desired sine wave and the synchronous voltage wave to determine the generation time of the trigger pulses applied to trigger the thyristors. However, because thyristors are unidirectional conduction devices [7], the positive and negative half waves of the sinusoidal output current are output by the thyristors in the positive and negative groups, respectively. A risk for short circuit exists because a thyristor in the positive group is turned on before all the thyristors in the negative group are turned off or vice versa.

The circulating current accident can be prevented in three ways [8]: the no circulating current mode, the circulating current mode, and the small circulating current mode.

"Dead time" affects the system performance in the no circulating current mode. The minimum "dead zone" that can currently be achieved is approximately 1.1 ms. The current crosses the zero point twice in each cycle. Hence, the total "dead time" is greater than 2.2 ms. Each cycle is only approximately 20 ms in duration when the output frequency is relatively high (e.g., close to 50 Hz). In other words, the system spends more than 10% of time in each cycle without any output. Therefore, the quality of the output waveform is poor. Furthermore, the harmonic content is too high to be used in an actual system.

The circulating current mode requires several large capacity reactors with high cost and large circuit volume. Moreover, the addition of reactors to the main circuit will decrease the total power factor of the system.

The small circulating current mode uses small capacity reactors and has advantages in terms of cost, volume, and power factor impact. Furthermore, no “dead time” exists in the system. However, the circulating current will be large if the reactor capacity is too small. In contrast, this mode will suffer from disadvantages similar to those of the circulating current mode if the reactor capacity is too large. The system will work in two different statuses: circulating current mode and no circulating current mode. Consequently, the working conditions will be inconsistent, thereby causing a certain amount of waveform distortion. The design and control of the entire system will also become more complex. Therefore, the three types of control methods used in the traditional AC/AC frequency conversion method all have insurmountable defects. In addition, the output frequency of each of the three methods must be lower than 20 Hz, so the application scope is limited.

3. “Phase hopping” frequency conversion theory

This study proposes a new AC/AC frequency conversion method referred to herein as the “phase hopping” method to address the disadvantages of the existing technologies. This is a new type of frequency conversion idea, which is further innovated on the basis of the cosine wave-crossing method and has not been described in any previous literature of AC/AC frequency conversion. The method allows the maximum output frequency to be close to the power frequency under the condition that the harmonic content is limited to a low level in the output waveform.

3.1. Basic principle of the “phase hopping” frequency conversion

The three-phase bridge rectifier circuit shown in Figure 1 illustrates the “phase hopping” frequency conversion method [9]. The circuit structure is identical to that used in the conventional no circulating current AC/AC frequency conversion circuit [10]. The bridge rectifier circuit comprises six thyristors (i.e. P1, P2, P3, P4, P5, and P6) in the positive group and six thyristors (i.e. N1, N2, N3, N4, N5, and N6) in the negative group. The two groups of bridge rectifier circuits are connected in an antiparallel mode. A three-phase power is applied to points C, B, and A. The single-phase sine wave is output from points E and O.

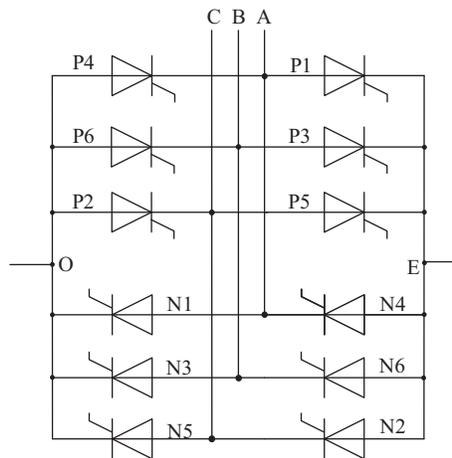


Figure 1. “Phase hopping” frequency conversion circuit.

The current in the positive group flows out from point E to the load and returns from point O. Assuming that P1 and P2 are turned on at a certain instant in time, point E is connected to point A; point O is connected

to point C; and the cycloconverter voltage is output from points A and C. The output voltage is U_{AC} , which is simplified as AC here and below for simplicity.

As an example, we let P3 turn on and P1 cut off after 33.33 ms from the instant mentioned before. Then, the cycloconverter output voltage is BC. P4 turns on after another 33.33 ms, P2 cuts off at the same time, and the cycloconverter output voltage is changed to BA. The conduction of the thyristors changes once every 33.33 ms, which causes the output voltage circulation to change sequentially through CA, CB, AB, AC, BC, and BA. The negative group operates similarly.

Because a large cycle contains six changes, each change introduces a $\pi/3$ phase delay to the output voltage, and six times can introduce a total phase delay of 2π (one cycle). Therefore, after the completion of a large cycle, the actual cycle number reduces one relative to the 50 Hz power cycle number. Assuming that a large cycle is completed within 10 power frequency cycles, which is 200 ms. That is, the total number of output voltage cycles is $10 - 1 = 9$. Thus, the final output voltage frequency is $9/(200/1000) = 45$ Hz. In other words, the use of these three-phase bridge rectifier circuits can convert a 50 Hz power to a 45 Hz one. In the process, each pair of thyristors' continuous conduction time is $200/6 = 33.33$ ms. Output frequencies other than 45 Hz can be obtained by using similar control strategies.

The AC/AC frequency conversion method proposed herein connects the cycloconverter output terminal to the different phases of the input power using a "hopping" method. Therefore, this method is referred to as the "phase hopping" frequency conversion method.

3.2. Phase-changing and frequency analysis of the cosine wave-crossing method

The output frequency variation of the cycloconverter controlled by the cosine wave-crossing method was first analyzed to explain the output frequency variation of the "phase hopping" frequency conversion method. Figure 2 shows the relationship among the input line voltage, output voltage, and the desired sine wave of the cosine wave-crossing method.

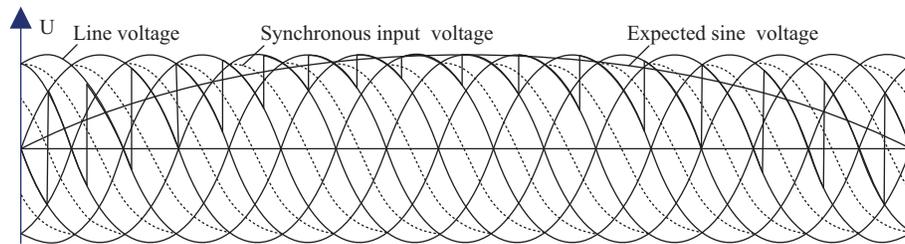


Figure 2. Cosine wave-crossing method output voltage.

As shown in Figure 2, the cycloconverter output voltage waveform under the control of the cosine wave-crossing method consists of many segments of the sine waves. If we take the input power frequency of 50 Hz as an example, its phase grows with the speed of the 50 Hz frequency when the output voltage follows a certain line voltage. The phase is reduced by $\pi/3$ when the output voltage jumps from a line voltage to the next line voltage. Clearly, the more times of the voltage jumps during an output voltage cycle, the longer the period and the lower the corresponding output frequency will be.

The phase reduced by the jumps in each cycle is expressed as follows, assuming that the number of jumps in a cycle of the output voltage is M:

$$\Delta\varphi = M \times \frac{\pi}{3}. \tag{1}$$

The phase increases by 2π by the time the voltage goes through a complete cycle. The total phase over an output voltage cycle increases at the speed of 50 Hz power frequency and is given by

$$\varphi = \Delta\varphi + 2\pi = M \times \frac{\pi}{3} + 2\pi. \quad (2)$$

The period of the output voltage is presented as follows:

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

The output voltage frequency is

$$f = \frac{1}{T} = \frac{1000}{\left(\frac{10M}{3} + 20\right)} (\text{Hz}). \quad (4)$$

Clearly, larger M values result in lower frequencies. In this method, M can be a positive integer or a positive real number. In Figure 2, M is approximately 30, and the output frequency is approximately 8.3 Hz. The output frequency is generally less than 20 Hz, and the value of M is generally greater than 9 when using the cosine wave-crossing method because of the symmetry of the positive and negative half waves of the waveform, harmonics, and other restrictions.

3.3. Analysis of the phase changes and frequency of the “phase hopping” frequency conversion method

The “phase hopping” frequency conversion method determines the trigger times of the thyristors based on the conventional cosine wave-crossing method. The cycloconverter output terminal also connects with a certain phase of the input and switches this connection relationship from time to time. The “phase hopping” frequency conversion and the cosine wave-crossing methods use the same circuit. Hence, the phase reduces by $\pi/3$, each time the triggering thyristor causes the output voltage to jump to the next line voltage. The relationship between the output voltage cycle and the number of jumps M in the cycle is given by Eq. (3), while that between the frequency and M is given by Eq. (4). The value of M is relatively small in the “phase hopping” frequency conversion method. For example, the output frequency is approximately 42.86 Hz when M is equal to 1, and the output frequency is 37.5 Hz when M is equal to 2.

As the example used before, the output frequency is approximately 45 Hz when $M = 0.667$. The time interval between two consecutive jumps is 33.33 ms, which is greater than one cycle for either 50 Hz or 45 Hz. Hence, the current will certainly switch between positive and negative during this period. The trigger pulses are sent to the thyristors both in the positive and negative groups at the same time to ensure the current positive and negative switching moment with no “dead zone”. The triggered thyristors are connected to the same input line, which ensures no circulating current between different input lines. For example, the trigger pulses are only sent to four thyristors (i.e. P1, P2, N4, and N5) when P1 and P2 needed to be turned on, and not to the others. The positive current loop consists of P1 and P2 when the current is positive, and P1 and P2 are naturally cut off when the positive current is gradually reduced to zero. N4 and N5 can be immediately turned on and will then constitute the negative current loop when the current needs to be reversed because they have been triggered. In this way, no “dead zone” will exist during the positive and negative current switch, which completely overcomes the biggest disadvantage of the no circulating current frequency conversion method. Point E is always connected to point A, and point O is always connected to point C regardless of P1 and P2 or N4

and N5 being turned on in this method. The current will automatically decide to flow through either P or N group of thyristors depending on the circuit requirements. The current must pass through the load to form a loop, such that the current will not directly flow between two phases. In this way, the biggest disadvantage of the circulating current frequency conversion method can be overcome. Figure 3a illustrates the control method of the 45 Hz output voltage, and a similar method can be used when a different output frequency is needed. The figure also depicts that the time interval between two jumps in the “phase hopping” frequency conversion method is greater than that between two jumps in the cosine wave-crossing method.

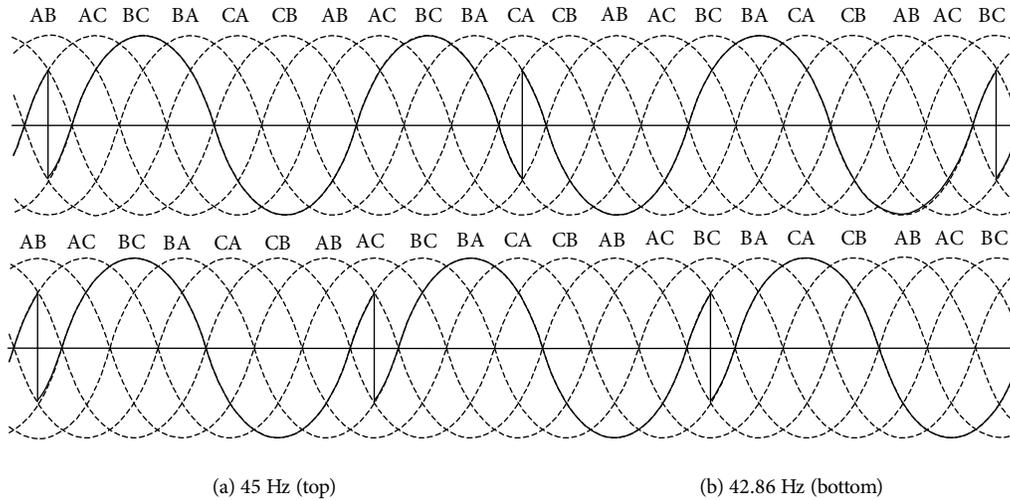


Figure 3. Illustration of the “phase hopping” frequency conversion output voltage.

3.4. Analysis of different frequency output waveforms

Figure 3 shows the line voltage cycles through AB, AC, BC, BA, CA, and CB. The output voltage at each “phase hopping” jumps from a line voltage to the next line voltage and causes a $\pi/3$ phase delay. The total phase delay after six times of “phase hopping” is 2π . In other words, a cycle is reduced. Every six times of “phase hopping” completes a big circulation. The output frequency changes if the interval between two “phase hopping” changes. As shown in Figure 3a, the interval between each of the two phase hops is 10 line voltage pulse waves or 33.33 ms, and the output frequency is 45 Hz. Meanwhile, Figure 3b illustrates that the interval between each of the two phase hops is 7 line voltage pulse waves or 23.3 ms, and the output frequency is 42.86 Hz.

4. Control method

An output voltage frequency of 42.86 Hz is used as an example to analyze the turn-on rule of thyristors. The line voltage sequence is AB, AC, BC, BA, CA, CB with a delay time of 3.3 ms between two adjacent line voltages. The output voltage changes from one line voltage to another (i.e. “phase hopping” happens) for every 7 line voltage pulse waves or 23.3 ms. Table presents the thyristor turn-on rule in the case of 42.86 Hz.

The second line in Table represents the input line voltages. Each occupies a duty of 3.3 ms. The third line shows the line voltage to which the output voltage is equal.

The fourth line shows which thyristor should be triggered to realize the output voltage changing from an input line voltage to another.

Table. Trigger rule of the thyristors for 42.86 Hz.

Parameters	1st fragment			2nd fragment			3rd fragment								
	AB	AC	BC	BA	CA	CB	AB	AC	BC	BA	CA	CB	AB	AC	BC
Line voltage	BC			BA			AC			BC			AB		
Output voltage	BC			BA			BA			CA			CA		
New trigger thyristor	N6			N1			N1			N2			N2		
Trigger thyristors	N6 + P3			N1 + P4			N1 + P4			N2 + P5			N2 + P5		
Complement thyristors	N5 + P2			N6 + P3			N6 + P3			N1 + P4			N1 + P4		
Trigger moment	1.67 ms			25 ms			25 ms			48.33 ms			48.33 ms		
Pulse duration	23.3 ms			23.3 ms			23.3 ms			23.3 ms			23.3 ms		

Table. Continued.

Parameters	4th fragment			5th fragment			6th fragment								
	CB	AB	AC	CB	AB	AC	CB	AB	AC	CB	AB	AC	CB	AB	AC
Line voltage	CB			AB			AB			AC			AB		
Output voltage	CB			AB			AB			AC			AC		
New trigger thyristor	N3			N4			N4			N5			N5		
Trigger thyristors	N3 + P6			N4 + P1			N4 + P1			N5 + P2			N5 + P2		
Complement thyristors	N2 + P5			N3 + P6			N3 + P6			N4 + P1			N4 + P1		
Trigger moment	71.67 ms			95 ms			95 ms			118.33 ms			118.33 ms		
Pulse duration	23.3 ms			23.3 ms			23.3 ms			23.3 ms			23.3 ms		

Note: “+” means “and”.

First, assume that U_{AB} is at the peak (Figure 3b). However, letter U is omitted, and U_{AB} is simplified as AB here and below for simplicity. The voltages mentioned below are simplified similarly. At this moment, the fundamental wave content of the output voltage passes the zero point in the upward direction, and the output voltage switches from AC to BC. The latter letter C remains the same as the output voltage switches from AC to BC, which means that the conducting thyristor N5 is unchanged according to Figure 1. The former letter changes from A to B when the output voltage switches from AC to BC, which indicates that the conducting thyristor switched from N4 to N6. AB is the highest voltage, and A is higher than B. Hence, N6 is positively biased when N4 is conducting state. N6 will turn on and complete the switching from A to B when N6 receives a pulse. The output voltage will then remain as BC until the next jump. The time duration between two jumps covers 7 line voltage pulse waves or 23.33 ms.

Second, the output voltage fundamental wave passes the zero point in the upward direction, and the output voltage switches from BC to BA when AC is the highest. The former letter B remains unchanged. Hence, the conducting thyristor N6 remains unchanged. The latter letter changes from C to A. Therefore, the conducting thyristor switches from N5 to N1. Accordingly, N1 is positively biased when N5 is conducting state because AC is the highest, and A is higher than C. N1 is then turned on and completes the switching from C to A when a pulse is received. The output remains as BC until the next jump.

Thereafter, the subsequent steps proceed in a similar fashion and successively trigger N2, N3, N4, and N5.

The fifth line of Table is explained as follows: when a thyristor is triggered, a pulse will be simultaneously sent to the thyristor connected in antiparallel with the new triggered thyristor. Thus, the current can freely switch between positive and negative because the thyristors in both the positive and negative groups are triggered at the same time. Therefore, no dead zone exists around the zero current. In addition, no circulating current is present even though the two triggered thyristors are simultaneously conducting because they are connected to the same line.

The sixth line of Table shows that the thyristors (e.g., N5 and P2) are triggered at the same time when the new triggered thyristors (e.g., N6 and P3) are triggered to ensure that the current loop is complete.

The seventh line of Table is explained as follows: the delay time of the trigger pulse can be calculated from the synchronization point of the moment when AC is moving upwards and crossing the zero point is considered to be a synchronization point. For example, the moment of the first jump when AB is at the peak is 1.67 ms after the AC upwards crosses the zero point.

The eighth line of Table is explained as follows: the duration of the four trigger pulses, which start from the moment determined by the seventh line.

5. Simulation and experimental analysis

5.1. Simulation model

Figure 4 shows the simulation model. The thyristor module is denoted as “ConvT” and comprises two groups of thyristors connected in an antiparallel bridge formation. The “Pulse” block generates the thyristor pulses that trigger thyristors in block “ConvT” and is shown as a single block because of the large number of devices and the complexity of the connections. “A, B, C” represent the three-phase power. Its peak voltage is equal to 180 V. The element “Z” represents a resistance–inductance load (simulate a fan load), its inductance is 0.03 H, and its resistance is 5 Ω .

The main circuit consists of six pairs of thyristors in reverse parallel connection. Therefore, only six

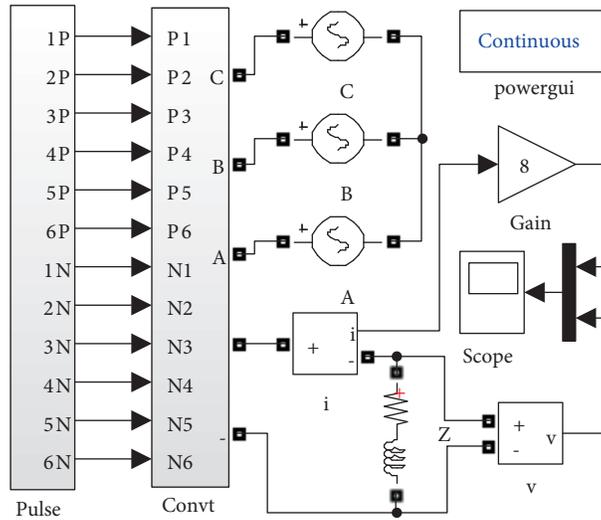


Figure 4. Simulation model.

different trigger pulses are needed to implement the control. The internal structure of the pulse module is shown in Figure 5, a pulse controls a pair of thyristors. Take 42.86 Hz as an example in Table, the period of P1 to P6 are 0.14 s and the pulse width of P1 to P6 are 33.33%. The phase delay time of P1 is 0.095 s, P2 is 0.11833 s, P3 is 0.00167 s, P4 is 0.025 s, P5 is 0.04833 s, and P6 is 0.7167s.

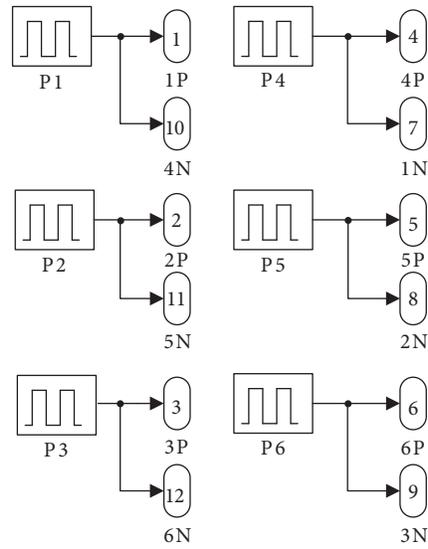


Figure 5. Pulse module.

5.2. Experimental platform

The main parts of the experimental platform include an FPGA master control board, a drive board, a “phase hopping” frequency conversion main circuit, an autotransformer, and a fan load (Figure 6).

The FPGA main control board marked with “L” in Figure 6 uses an ALTERA Cyclone Series FPGA model EP3C16Q240C8 (Altera Corp., San Jose, CA, USA) as the control kernel. The main control board is

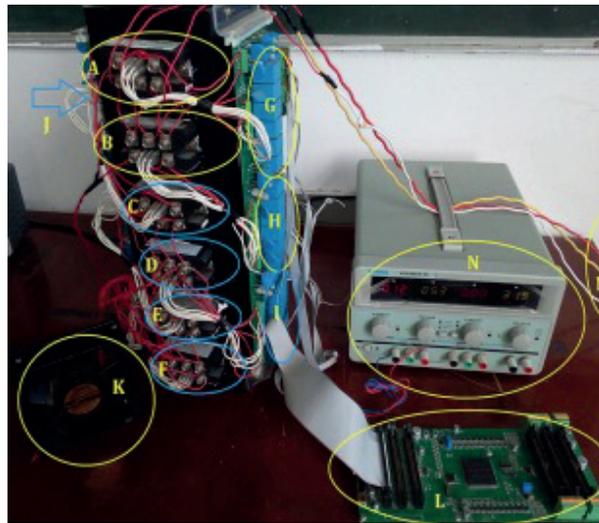


Figure 6. Experimental platform.

used to output the pulse signals required by the thyristors. A drive circuit is required because the trigger signal generated by the main control board is weak and cannot trigger the thyristors in the main circuit. The driver board marked with “G”, “H”, and “I” performs the required power amplification of the pulses to trigger the thyristors. The driver board also performs any required auxiliary functions, such as synchronous detection, current detection, resistance capacitance absorption, etc. The autotransformer connected to the wires marked with “M” and is not in the figure, is used to adjust the grid voltage to the appropriate experimental voltage. The fan marked with “K” is the load for the frequency conversion circuit. Furthermore, the output frequency of the cycloconverter can be directly observed by monitoring the changes in the fan speed. The regulated power supply marked with “N” is used to power the control circuits.

The “phase hopping” frequency conversion main circuit comprises two three-phase bridge rectifier modules marked with “A” and “B” and mounted on an aluminum radiator. The trigger pulses of the inside thyristors are driven by the part of the driver board marked with “G” and “H” and mounted on the side of the aluminum radiator. The part of the driver board marked with “I”; the other four three-phase bridge rectifier modules marked with “C”, “D”, “E”, and “F”; and another driver board mounted on the other side of the radiator pointed by the arrow marked with “J” are used for the experiments with multiple technology and can be omitted here.

5.3. Simulation waveforms and experimental results analysis

The trigger moment and the duration of each trigger signal when the output frequency is 45 Hz depend on similar trigger relationship as that outlined in Table. Figure 7a shows the simulation voltage and current waveforms of load. The trigger moment and the duration of each trigger signal when the output frequency is 42.86 Hz are determined based on the trigger relationship also outlined in Table. Figure 7b presents the simulation output voltage and current waveforms. In order to analyze the influence of harmonic on the system and the ability of frequency conversion in the intermediate frequency area, the third harmonic with 10% of the fundamental wave is injected into the input of three-phase power, and a 20° phase offset is set relative to the fundamental wave. Based on that condition, a simulation of 37.5 Hz is made, and the voltage and current waveforms are shown in Figure 7c. To make it clear, the current waveforms are expanded eight times.

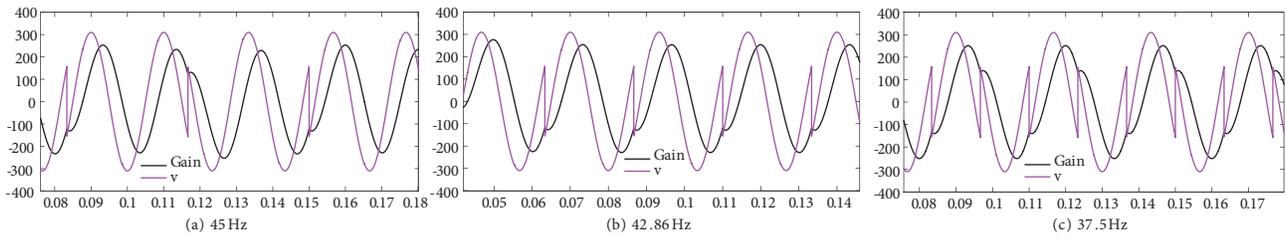


Figure 7. Simulation output voltage (red) and current (black) waveforms.

In the experiments, the cycloconverter uses the “phase hopping” method. The output terminal is connected with a single-phase fan. Figure 8a shows the experimental output voltage and current waveforms of the 45 Hz frequency. Figure 8b presents the experimental output voltage and current waveforms of 42.86 Hz. The output frequency can be read out by $1/\Delta T$ shown in the figure. The pictures show that the theoretical analysis is consistent with the simulation results described in the previous section.

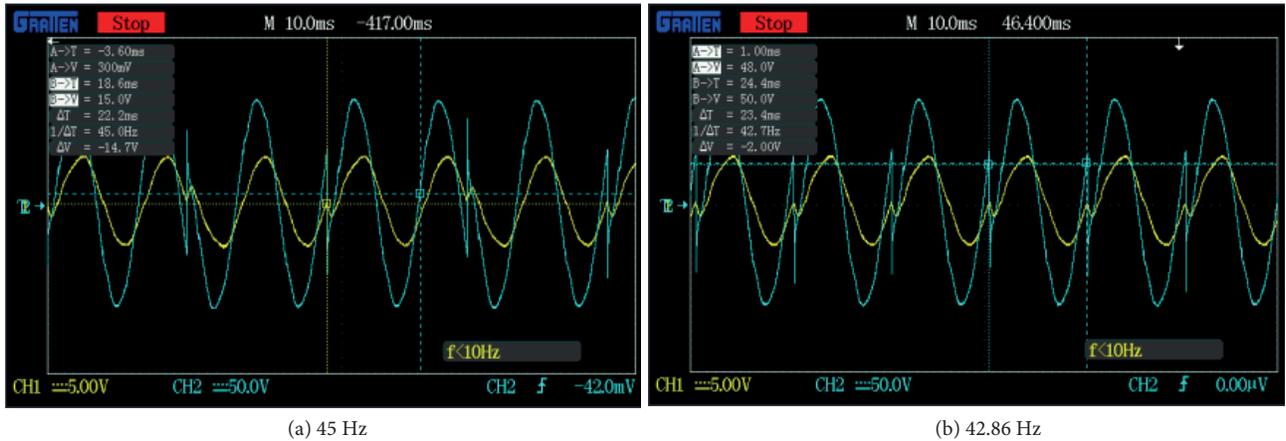


Figure 8. Experimental output voltage (blue) and current (yellow) waveforms.

A comparison of Figure 8a with Figure 7a shows a “phase hopping” happening for approximately every 1.5 cycles of the power voltage. The analysis in Section 3.4 implies that the interval between each of the two “phase hops” is 10 line voltage pulse waves. The time of 1.5 cycles of the power voltage is $1.5 \times 20 = 30$ ms, while that of the 10 line voltage pulse waves is $10 \times 3.3 = 33$ ms. Therefore, the results of the theoretical analysis, simulation, and experiments are in good agreement with each other. We can obtain the same conclusion by comparing Figure 8b with Figure 7b. An interval of approximately 1 cycle of the power voltage or 20 ms or 7 line voltage pulse waves can be observed between two “phase hops”.

Figure 9 presents the harmonic simulation analysis results with a 45 Hz output current and voltage based on the “phase hopping” frequency conversion circuit. Figure 9 shows that the total output harmonic distortion rate of the “phase hopping” frequency conversion circuit is 16.94% for current and 31.64% for voltage under the condition that the output is a higher frequency (i.e., 45 Hz) close to the power frequency (i.e., 50 Hz). The value allows it to be used in less demanding situations. The multiple techniques used in the conventional frequency conversion can be combined with the “phase hopping” frequency conversion technique proposed herein if the actual application needs to further reduce the total harmonic distortion of the output. In this way, the total harmonic distortion can be reduced significantly. For example, according to the similar simulation analysis,

the total voltage harmonic distortion can be reduced to 9.87% if the triple technology, where three groups of “phase hopping” frequency conversion circuits are connected in series or in parallel, is used. These specific circumstances will be detailed in another paper.

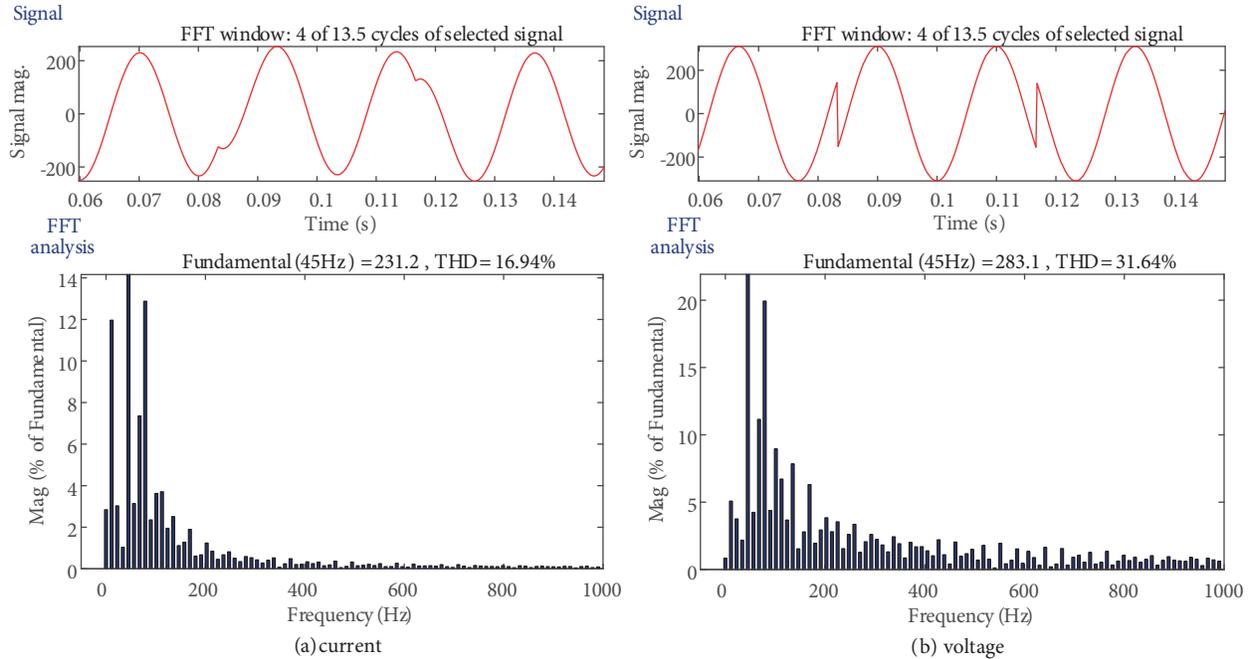


Figure 9. 45 Hz output current and voltage harmonic simulation results.

6. Conclusion

The “phase hopping” frequency conversion method is realized based on the traditional cosine wave-crossing method by properly arranging the trigger pulses of the thyristors, connecting the cycloconverter output terminal with a certain phase of the input, and changing the connection between the input lines from time to time. The cycloconverter uses a “phase hopping” frequency conversion method to overcome the disadvantages of traditional cycloconverters. Moreover, the output frequency can be a higher frequency close to the power frequency. Hence, the technique can be applied in a wider field. We verified the feasibility of the proposed “phase hopping” frequency conversion method by a simulation and an experimental analysis. The output of the cycloconverter based on the “phase hopping” frequency conversion method will have a relatively low harmonic content and can be directly used in applications where the harmonic content requirement is not very high. The addition of multiple technologies can further reduce the harmonic content, thereby expanding the range of applications.

We point out that the present study is based on the simplest design, it has the ability of changing frequency but cannot change the output voltage; thus, it temporarily cannot be put into application in practical production. However, if the “phase hopping” method is used together with the multiple technology, according to the method of voltage vector superposition, the overall output voltage is the vector combination of all output voltages of all circuit stages, so the output voltage can be changed as desired when the frequency is changed. The pertinent theory, specific experimental procedures, and phenomena will be detailed in another article.

Acknowledgments

This work was supported by Nansha District Science and Technology Plan Project of Guangzhou, China (Grant NO. 2016CX011).

References

- [1] Idris Z, Hamzah MK, Saidon MF. Implementation of single-phase matrix converter as a direct AC-AC converter with commutation strategies. In: IEEE 2006 Power Electronics Specialists Conference; 18–22 June 2006; Jeju, South Korea. New York, NY, USA: IEEE. pp. 1-7.
- [2] Nair HS, Ramchand DR. A new switching algorithm for an AC-AC converter with high frequency link. In: IEEE 2015 Conference of the IEEE Industrial Electronics Society; 9–12 November 2015; Yokohama, Japan. New York, NY, USA: IEEE. pp. 4615-4620 .
- [3] Cho Y, Cokkinides GJ, Meliopoulos AP. Advanced time domain method for remote wind farms with LFAC transmission systems: power transfer and harmonics. In: IEEE 2012 International Conference on Harmonics and Quality of Power; 17–20 June 2012; Hong Kong, China. Washington, DC, USA: IEEE. pp. 1-6.
- [4] Chen X, Du QN. Research on modified pulse triggering control strategy of AC-AC converter. *Colliery Mech Elect* 2014; 3: 34-37.
- [5] Azam, MA. Three to single phase buck-boost regulated high power quality cycloconverter. In: IEEE 2012 Innovative Smart Grid Technologies-Asia; 21–24 May 2012; Tianjin, China. Washington, DC, USA: IEEE. pp. 1-6.
- [6] Symonds A, Laylabadi M. Large cycloconverter drives in mining applications. In: IEEE 2013 Industry Applications Society Annual Meeting; 6–11 October 2013; Lake Buena Vista, FL, USA. New York, NY, USA: IEEE. pp. 1-12.
- [7] Bhowmik PK , Yellapragada S, Manjrekar M. Dynamic analysis and controller design for a center-point-clamped AC-AC converter. In: IEEE 2015 Applied Power Electronics Conference and Exposition; 15–19 March 2015; Charlotte, NC, USA. New York, NY, USA: IEEE. pp. 535-542.
- [8] Basirifar M, Shoulaie A. A comparative study of circulating current free and circulating current cycloconverters. In: IEEE 2010 Power Quality Conference; 14–15 September 2010; Tehran, Iran. Washington, DC, USA: IEEE. pp. 1-4.
- [9] Imam MHT, Azam A, Azad AN, Kabir MA. Three to single phase buck and boost cycloconverters with good input power quality. In: IEEE 2012 Innovative Smart Grid Technologies-Asia; 21–24 May 2012; Tianjin, China. Washington, DC, USA: IEEE. pp. 1-6.
- [10] Khodabandeh M, Zolghadri MR, Shahbazi M, Noroozi N. T-type direct AC/AC converter structure. *IET Power Electron* 2016; 9: 1426-1436.