

Proportional type Output 3-phase Cycloconverter

Keiju MATSUI* and Yohachi WATANABE*

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This paper is concerned with the proportional type 3-phase output cycloconverter. Many practical cycloconverter systems of single phase have been reported, however, until recently, the 3-phase output cycloconverter has not been developed for the complication of the controlling circuit. In this paper we have designed a controlling circuit to simplify the system, where the period of the output current conducting through each phase is 120 degrees. The output voltage becomes variable in the amplitude, by controlling the pulses over the period of 60 degrees of input power.

It is found that the reactive power is also controlled by pulses, and that this device operates sufficiently at any load, that is, resistive load, inductive load and capacitive load. The frequency of power supply can be intermittently controlled from dc to the half of the frequency of input power.

1. Introduction

The cycloconverter systems can be divided into two types, that is, the sequential type and the proportional type in accordance with output frequency. The former is fit for use of operating the induction motor and so forth. The latter is mainly employed as mono frequency converter system. Both types possess advantages and disadvantages so that their applications are limited, which seems to be less practical. As the sequential type literally means a sequential conversion, it is convenient to control the speed of the motor like the induction motor described above which requires the variable frequency. Nevertheless, the wave distortion is indispensable as the ratio of the supply frequency with the output frequency becomes low. Therefore, it can be easily conjectured that the sequential type contains lower frequencies than the output frequency in addition to high frequencies. Besides, the gate controlling circuit becomes more and more complicated, and in 3-phase some simplification will be inevitable. And in the frequency controlling system, the various phase signals must be connected with each other by means of oscillators. On the other hand in the proportional type, the distortion is rather small even if the frequency is low. Moreover, as the phase relation between source and output frequency is well regulated, the lower frequency component than the output frequency is not included. The greatest advantage for it is the simplification of controlling circuits. However it is possible only to control the frequency intermittently and inadequate to change continuously. Besides, in contrast with sequential type, no improvement of the wave distortion can be admitted even if the ratio of frequency is larger.

*Department of Electrical Engineering

For the practical application, both types have been employed at the large ratio of frequency. For instance, the output power with small distortion can be obtained by using the high frequency generator. Therefore its applications seems to be restricted to the electric power or the source of aircraft or that of railway train. Furthermore, the cycloconverter possesses various advantages as compared with inverter. For instance, too many commutation circuits are unnecessary because it is a direct conversion from ac to ac. At the same time it is sufficiently possible to feed back the reactive power to the source even without using condensers. Although the miniature size element like SCRs may increase more or less, it is still possible to make the capacity small and they are expected to be applied to the transportation of limited space. As for the ultra low frequency, by considering its stable operation, the cycloconverter is used for relatively low frequency while the inverter is for high frequency. As far as the cycloconverter keeps stable during operation, the torque in the induction motor increases as much. Therefore its wide application including a spinning industry is quite possible. As the load of the electric power converter system described in this paper means mainly the lagging load, it is inevitable to establish the controlling system with which the reactive power should be treated. With respect to this point, it is quite possible for the cycloconverter to feed back the reactive power directly to the source.

Since the mercury commutator ages, the various studies of single phase cycloconverter have been reported by many authors. However, the actual designs about 3-phase have not been reported because each phase affects others and because the control becomes complicated, although the possibility of 3-phase has been considered. The application of the former single phase sequential type to 3-phase is considered to be inadequate because of the mutual actions of each phase. Therefore the firing angle of controlling signal should be constant, and each phase relation should be fixed. Under these condition, there is no necessity of oscillators and the like. As the firing angles of each phase are standardized, the sequential control in frequency becomes unsuited and it becomes intermittent variable. However, the various characteristics described above make up for this defect sufficiently.

The design of the 3-phase cycloconverter by the authors is considered to possess many various remarkable characteristics. Thus these conditions and characteristics are expressed concretely as follows.

- (1) Input supply3-phase, 200 V, 50 Hz / 60 Hz
- (2) Output powerfull-wave proportional type, variable from a half input frequency to dc
- (3) Firing anglevariable
- (4) Period of current flowing
.....120°
- (5) Method of treating the reactive power
.....by feeding back and by wire of terminal of SCRs
- (6) Oscillator for control...nothing

The authors tried to make the device light and small so that it is employed mainly

for the transportation as described before.

2. Circuit blockdiagram

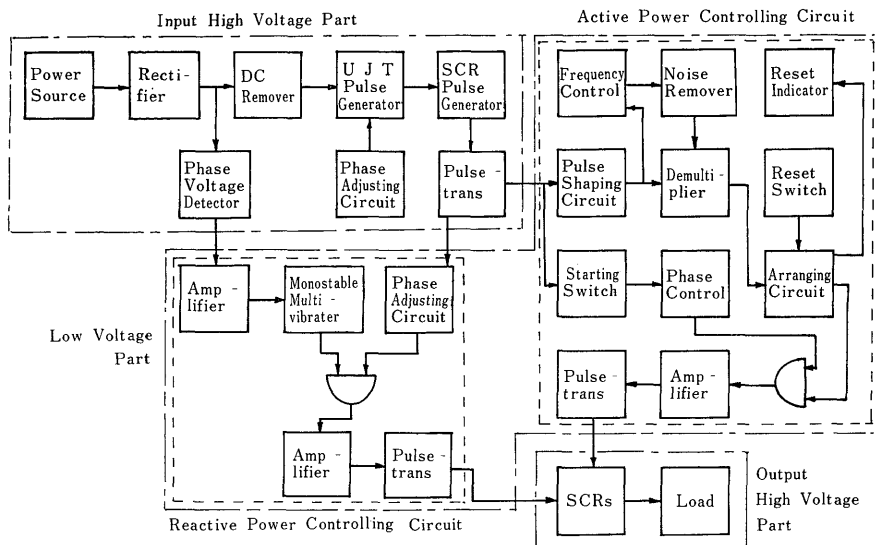


Fig. 1. Block diagram of 3 ϕ cycloconverter.

Fig. 1 is a circuit blockdiagram of the cycloconverter. First of all, a whole construction is shown roughly with chain lines and the problems of the actual manufacture will be described. The high voltage circuit and the low voltage circuit are completely insulated except a signal transferred by the pulse-transformer. Actually on the way of the manufacture, they are completely separated in order to prevent a misoperation by the electric discharge or the leakage from the high voltage side to the low voltage side. The stabilized power source supplies the voltage of ± 12 V to the low voltage circuit. The small size condenser with the sufficient large capacity is connected in order to prevent the misoperation which will be caused by the voltage variation at each bias point. In such a manner the stabilization of operation is carefully made. As a plenty of noise is expected especially at the time of the switch turn of intermittent frequency control, the voltage changes between the bias source and the elements are prevented by choke coils and condensers. However, this is not sufficient to avoid the noise. Therefore, this noise is taken away in the way of a circuit in the next section.

3. Input high voltage circuit

Since to make the device light and small is necessary by the reasons described above, the transformer is not employed for the detection of phase voltage except the transformer of bias source and the miniature pulse-transformer. Therefore, a specific circuit for the output pulse synchronized by the source was presented by the authors and employed. Fig. 2 shows a part of the circuit. First of all, the input power is rectified in full-wave and the unchanged dc component is cut off in the way of avoiding

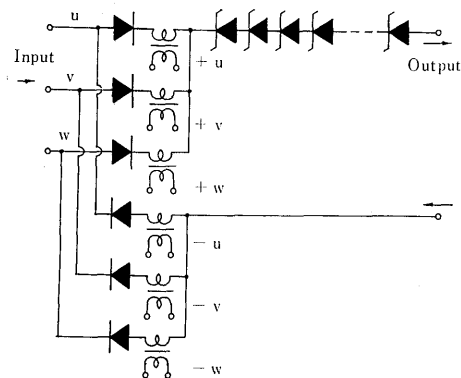


Fig. 2. A part of input high voltage part.

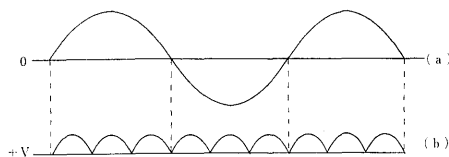


Fig. 3. (a) Waveform of source.

(b) Output waveform of Fig. 2.

flowing out to the output side. The output waveform is indicated in Fig. 3(a). The waveform is reduced by one-third than that of Fig. 3(b). The miniature transformers at the right side of the diode in Fig. 2 are pulse-transformers for phase voltage detection. These circuits will be explained later in this paper. The UJT pulse generating circuit, the SCR pulse generating circuit and the phase adjusting circuit are designed by slight transforming the usual ones. The phase adjustment is controlled by the half-fixed resistance. Once the proper adjustment is given, it is fixed and the phase control will be done at the later stage.

4. Low voltage circuit

Active power controlling circuit: The demultiplying circuit in the low voltage circuit in Fig. 1 reduces the number of pulses and is designed from flip-flop combinations. The problem is to improve the input pulse waveform especially the transient, therefore, the pulses are shaped and the transient is improved by the monostable-multivibrator of the pulse shaping circuit. The control of the number of the input pulses in the demultiplier is performed at the frequency controlling circuit. As it is a intermittent control, a push button switch (Toko, Inc.) is employed. Since it has only seven keys, the reducing ability is only one-eighth of the source frequency. Therefore, adding another switch is capable of one-sixteenth reduction. The noise of this output is prevented through the monostable-multivibrator as well as by the method of the noise prevention described above. But it is necessary to operate until the noise disappears after the switch is put on. Thus the operating resistance and the condenser are experimentally designed. The noise caused by itself unless the element is operating is unavoidable. However, such a noise does not lead a serious misoperation like a short circuit of source. Because the surplus pulse caused by misoperation has no relation to the arranging order of the arranging circuit which may lead misoperating. The output pulses from the demultiplier enter the arranging circuit. One example of the arranging circuit is shown in Fig. 4. As for the 3-phase inverter, the ring counter is generally used for this circuit. Since this device is a 120° flowing full-wave type, the output waveform of the arranging circuit must be considered. This waveform is shown in

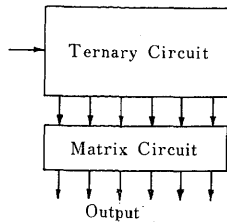


Fig. 4. A example of arranging circuit.

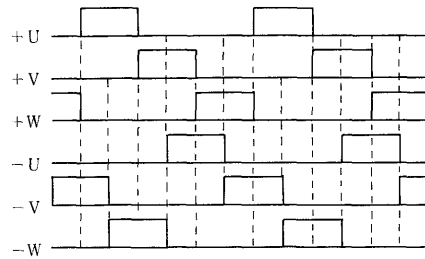


Fig. 5. Output waveform of arranging circuit.

Fig. 5. The reason of setting 120° flowing type is that on the way from a signal to the next same signal with different polar, the latter should enter after the last operating SCR by that signal completely turns off. Therefore, the interval for signal is necessary. On account of simplification of circuit, the period of signal in electric angle is set without regard for output frequency. Consequently there is no problem when the ratio in frequency is large. But when the minimum ratio in frequency is 2 to 1, the interval period must be taken into considerations. For example the period of zero voltage in Fig. 11(b) in the following becomes a problem. In this case the period of (2), that is, $\pi/12$ of the output frequency is the margin angle until the next signal. The ratio of output frequency of 2 to 1 is the minimum frequency ratio in this method. The reset switch is for use of starting the ternary circuit with better arrangement. A monitor lamp is equipped in order to recognize the reset condition, and each condition of the flip-flop is indicated. This circuit also makes it possible to start with constant better arrangement without a reset switch. The phase control of the output pulse (gate input pulse) is performed from another terminal of the pulse-transformer of the input high voltage circuit. Two monostable-multivibrator is used at the next stage. The first stage is for use of proper phase fixation. And at the second stage the operating resistance changes the firing angle from 0° to 180° (the period of a wave out of full wave is supposed to be 180°). The output of this phase controlling circuit is properly converted to pulses, and then these pulses and the output of arranging circuit as described above enter in a logic circuit as shown in Fig. 6. This output can be put on and off at any time by a starting switch. The monostable-multivibrator of the phase controlling circuit also takes part in preventing the noise. The output of the logic circuit is amplified by two stages and enters into each gate of the main circuit

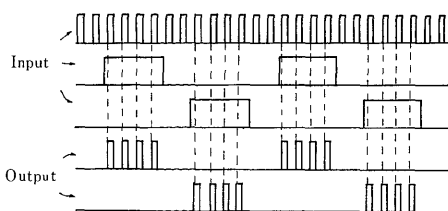


Fig. 6. A part of logic circuit operation.

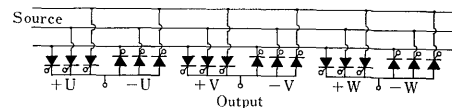


Fig. 7. Main circuit (described by active power groups).

by way of the pulse-transformer as in Fig. 7.

Reactive power controlling circuit: The pulse-transformers in Fig. 2 are transformers for phase voltage detection in the reactive power controlling circuit. As in the figure, whenever the SCR at the SCR pulse circuit of the input high voltage circuit fires, the current flows out of the source. For instance, in the case of $|E_{uv}| > |E_{vw}|$, $|E_{wu}|$ in Fig. 2, the current flows from the diodes $+u$ to $-v$ and others do not flow.

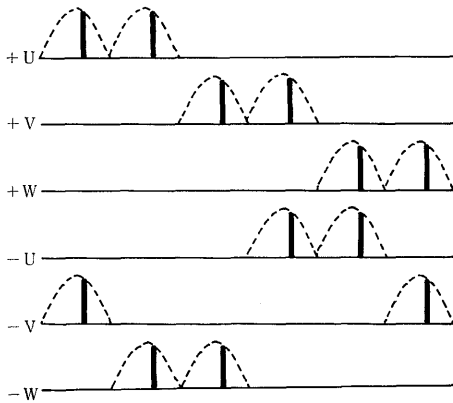


Fig. 8. Output waveform of phase detector.

The output waveforms of each pulse-transformer will be shown in Fig. 8. This output is amplified in the amplifier and the phase is properly adjusted by the monostable-multivibrator. Then it also plays a part in the noise prevention. Also, the output is gained from the logic circuit with the phase controlling circuit of monostable-multivibrator. The operating period of the monostable-multivibrator by the pulse from the phase voltage detecting transformer is taken longer so that every phase output could be controlled by the half-fixed resistance of the phase controlling circuit at the same time. Then the phase adjustment is possible during this operation period. The output of this logic circuit is still amplified by two stages and enters through each pulse-transformer to the gates of SCRs group as input. These input positions are different from those of the active power controlling pulse as mentioned in Fig. 7. These phases are also different from those. The gate group of SCRs should be put together as shown in Fig. 9 in the source side. The

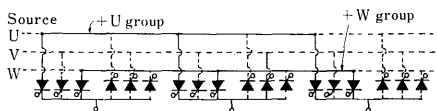


Fig. 9. Main circuit (described by reactive power groups).

Detected Signal	Input Group
+ U	→ + W
+ V	→ + U
+ W	→ + V
- U	→ - W
- V	→ - U
- W	→ - V

Fig. 10. Groups where detected phase signals enter.

output obtained by the phase voltage detecting transformer as shown in Fig. 8 must not be put into the controlling groups with the same phase as in Fig. 9, but into the controlling circuit of the phase which is indicated as the input group of the phase voltage detecting signal as shown in Fig. 10. These signals give only a slight distortion of waveform at the pure resistive load. Only at the reactive power load this signals give a satisfactory operation to SCRs.

5. Output high voltage circuit

The output high voltage circuit consists of eighteen SCRs. The actual circuit consists of the main circuit as shown in Fig. 7 or Fig. 9 and the output load terminals. The SCRs can be easily substituted and they are laid of each alminium board of two millimeters thick.

6. Output waveforms

Case of pure resistive load: In the case of pure resistive load, there is no difference whether the reactive power controlling circuit in Fig. 1 is open or put. But when the reactive power controlling signal is put, the output voltage appearing for the active power controlling signal does not result in turning on of surplus SCR or turning off of operating SCR, although it causes a slight falling phenomenon. To make it brief, the following assumption was made. (1) No falling phenomenon is caused by a reactive power controlling signal. (2) Firing angle is zero, that is, it starts just from the crossing of each voltage waveform. (3) SCRs operate as the complete switches.

Fig. 11(a) shows the relation between the signals for a half of the input supply frequency and the output waveform. The periods which are shown by hatches are 3-phase operating domains where three varied voltages operate. The rests of the domains are 2-phase operating domains where two varied voltages operate. Fig. 11(c) shows the voltage of each domain. Now, we develop the Fourier expansion for this waveform. First, the direct current term will be solved, that is, this waveform will be equilibrated over a period. The calculation is as follows:

$$b_0 = \frac{1}{T} \int_0^T y(t) dt = 0, \quad (1)$$

where T is the time of a period and $y(t)$ denotes the waveform. Although in Fig. 11(a) the upper waveform is different from the lower waveform, this waveform has no direct current term. If the position of the gate signals moves one signal to the right or the left, the waveform as shown in Fig. 11(a) is turned upside down. This generalized waveform will be stated later. The line voltage for the star connection is also identical, but the phase voltage is quite

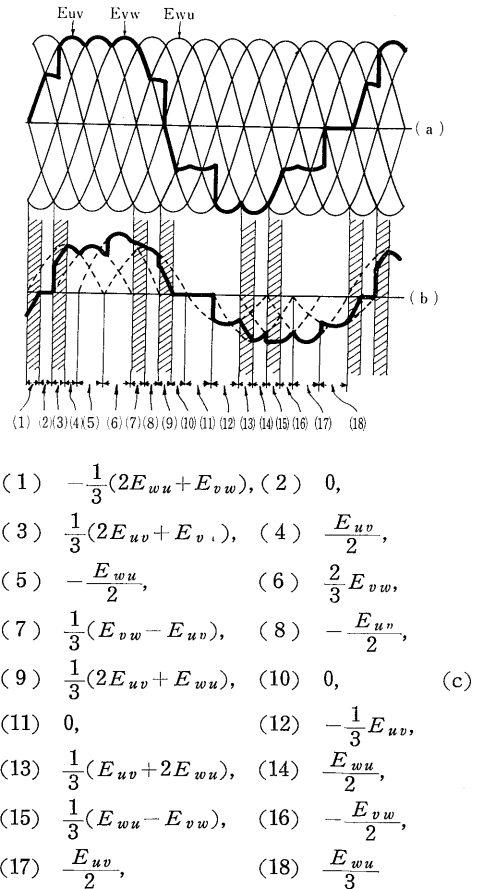


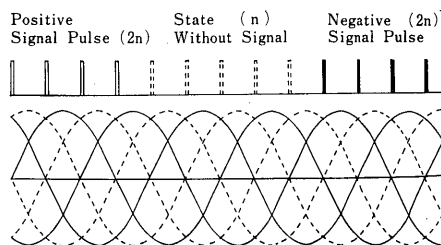
Fig. 11. (a) Output waveform of line voltage at $f_o/2$. (b) Output waveform of phase voltage. (c) Each voltage of (b).

different. In order to help the study of the reactive power control we will show this waveform in Fig. 11(b). The usage of the winding for the delta connection is better as compared with that for the star connection. But as expressed in later Eq. 2 the waveform for the delta connection has integer times harmonics of the third harmonic. It is undesirable that this harmonic has the zero-phase-sequence component and that the loop current flows. If the supply frequency is expressed as f_0 , the controlled output frequency of this device is as follows: $f_0/2, f_0/3, f_0/4, \dots, f_0/n$, where n is an integer. After this, the output frequency would be shown by this integer. In each case the waveform is developed by the Fourier expansion. The result is shown in Table 1. If

Table 1

n	Fund- mental	Harmonic (E_m/π)							
		2nd	3rd	4th	5th	6th	7th	8th	9th
2	3.07	0.41	0.00	0.34	0.36	0.00	0.25	0.15	0.00
3*	3.15	1.34	0.00	0.27	0.02	0.00	0.23	0.31	0.00
3	2.92	0.94	0.00	0.29	0.49	0.00	0.45	0.30	0.00
4	2.99	0.21	0.00	0.20	0.32	0.00	0.37	0.17	0.00
5*	3.05	1.16	0.00	0.00	0.18	0.00	0.22	0.20	0.00
5	2.90	0.89	0.00	0.17	0.28	0.00	0.22	0.13	0.00
6	2.96	0.14	0.00	0.14	0.42	0.00	0.43	0.13	0.00
7*	3.01	1.08	0.00	0.06	0.18	0.00	0.21	0.20	0.00
7	2.89	0.88	0.00	0.18	0.27	0.00	0.22	0.13	0.00
∞	3.00	0.00	0.00	0.00	0.60	0.00	0.43	0.00	0.00

the output waveform is developed by it over a period about the integer times harmonic of third harmonic, the value becomes zero. Thus the integer times terms of the third harmonic are shown to be zero in Table 1. The larger n , the nearer to a limitation the maximum value of the fundamental waveform approaches. It is shown that it approaches irregularly, for there are countless cases for the output. Now, the practical waveform can be mentioned as follows. The full-wave type as this device has been studied in order to improve the output waveform of a half wave type. But this type has a weak point. In Fig. 12 there is no signal between one signal and another signal of the

Fig. 12. State of signals at f_0/n .

different polar. If it is expressed as the number of the synchronous pulses of the supply frequency, it is n . We assume that it starts ideally just from the crossing point. This waveform as shown by full line will be called a positive voltage peak. Similarly, the waveform as shown by dotted line will be called a negative voltage peak. The signal pulses which start from the positive voltage peak, end to the negative voltage peak. If n is an even number, the state of signal which starts from the positive voltage peak, ends to the negative voltage peak. The next signal pulses start from the positive voltage peak, and the output waveform is upside down. That is, in the reverse polar

respect, they start from the negative voltage peak and end to the positive voltage peak. But in this case, the another phase signal is fired, so this operating voltage grows to the maximum voltage and the negative voltage peak also appears. After all, the appeared pulses of the opposite side increase by one, so the upper waveform is different from the lower waveform. When n is an odd number, the number of the state without signal as shown in Fig. 12 is also an odd number. One signal pulse ends, that is, the waveform ends to the negative voltage peak as shown by dotted line. Another signal pulse of the opposite polar side starts from the positive voltage peak

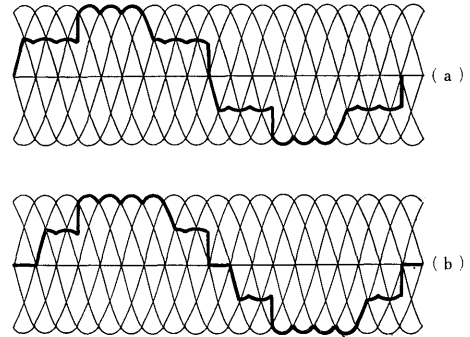


Fig. 13 Comparison of waveform at signal aberration.

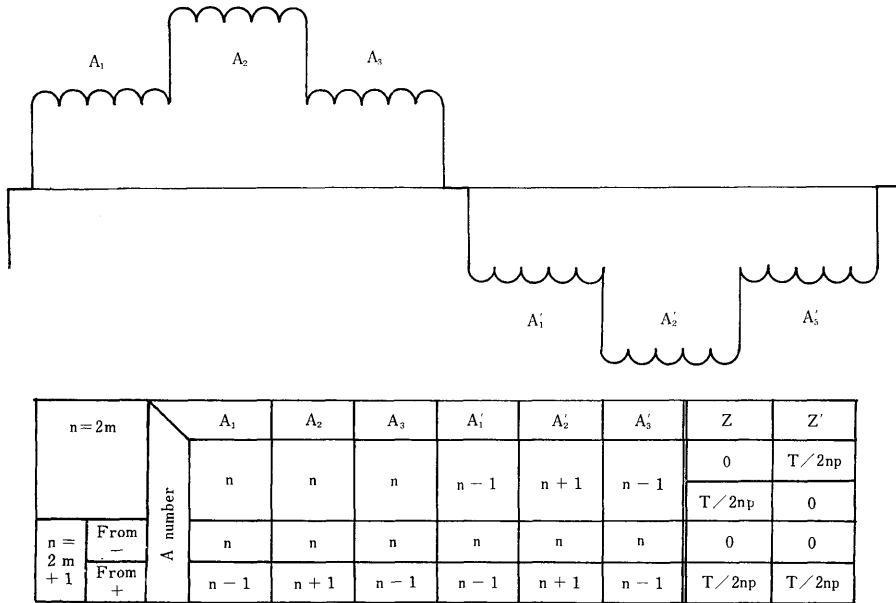


Fig. 14. Model of output waveform for pure resistance.

as shown by full line. When this signal pulse starts from the negative voltage peak as shown by dotted line, the appeared number of the upper and lower signal pulses increase. This waveform is shown in Fig. 13. The usage of winding for (a) is worse as compared with for (b), but the maximum value of the fundamental waveform is larger as shown in Table 1. Each waveform approaches to a limitation as the frequency ratio

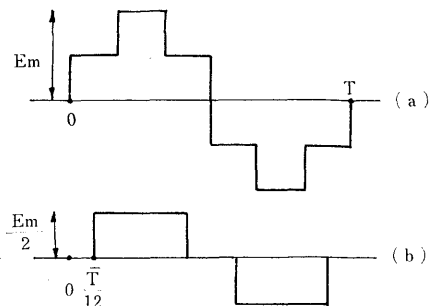


Fig. 15. Output waveform for infinite signal.

becomes larger. This generalized waveform is shown in Fig. 14. At the periods Z and Z' the voltages are zero. The waveform for the infinite limitation is shown in Fig. 15(a). In Table 1. this harmonic is shown in the section that n is infinite. The phase voltage for the star connection is shown in Fig. 15(b). The waveform is given as follows,

$$f(t) = 2\frac{\sqrt{3}}{\pi} E_m \left(\sin \omega t - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\omega t + \frac{1}{11} \sin 11\omega t \dots \right). \quad (2)$$

If Eq. 2 and the section that n is infinite shown in Table 1 are referred, it becomes clear that the line voltage and the phase voltage have no zero-phase-sequence component. But when we control the voltage as the firing signal is delayed, the waveform has some zero-phase-sequence component. After all, in the case of the delta connection we must consider the zero-phase-sequence-component, so the star connection is desirable. In the case of the delta connection, this three zero-phase-sequence components are added, and the loop current of three times flows. But the sum of the positive-phase-sequence component and the sum of the negative-phase-sequence component are zero. But even in the star connection, the neutral ground is improper, for the zero-phase-sequence current flows into or out of this point. We should consider not only the magnitude but

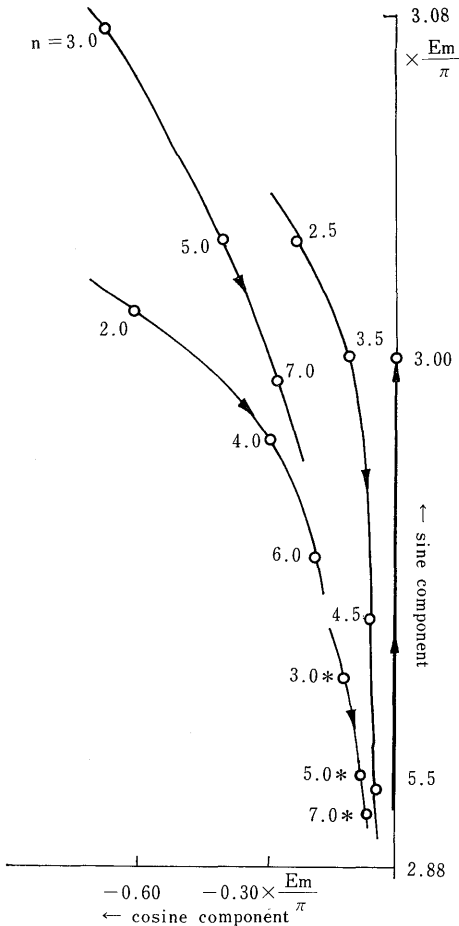
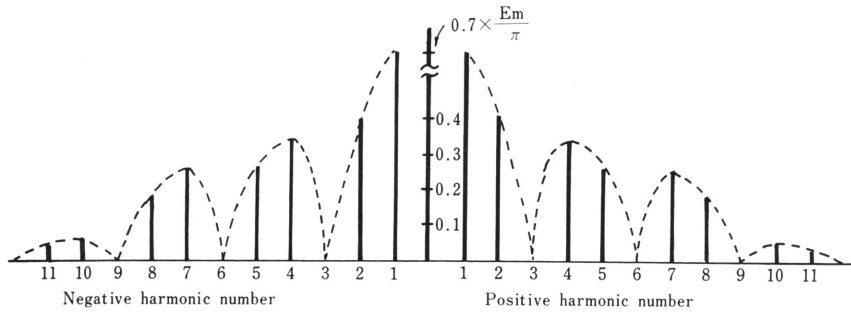
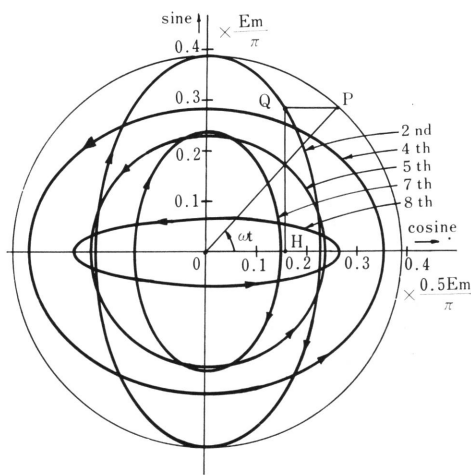


Fig. 16. Fundamental wave analysis.

also the phase. By this reason we divide the value of the spectrum into the sine component and the cosine component. The arrow shown in Fig. 16 is the direction as the value of n becomes larger. The output waveform has countless modes, for example the sequential cycloconverter which is simply obtained by the application of this device has countless modes. In Fig. 16 the proportional type and a part of the sequential type are also shown on the complex plane. When we develop the Fourier expansion, it will be clear that cosine component has not only the positive component but also the negative component. But the absolute value of the negative component is identical with the positive component, so we remove the negative component. If n becomes larger and larger, the dotted point approaches to a limitation over the countless lines. After this dotted point passes a minimum value, it goes up to the limitation 3.0 along the vertical line (sine axis). It is undesirable that the waveform has the cosine component, for the phase of the fundamental output waveform is affected by it. For this reason

Fig. 17. Spectrum of harmonic at $n=2$.Fig. 18. Wave indication by vector type at $n=2$.

(sine component) and plot both values as the time variation. It is preferable that the harmonic is indicated by this vector type. The arrow direction, the counter clockwise, is the time direction which is the same direction with the fundamental waveform. The clockwise is the reverse direction with the fundamental waveform. If the elliptic motion is long up and down, the waveform includes larger sine component. If the elliptic motion is long right and left, the waveform includes larger cosine component. Also, it is evident how much the decline rate for the higher harmonic is. Each value at the arbitrary time is solved by the method as shown, where we draw a circle, a line OP

it is desirable that the dotted point as shown is near by the vertical axis. The frequency spectrum of the output waveform harmonic component shown in Fig. 17 is a scalar type. It is no evident how much it has the cosine component and the sine component. For example, in Fig. 18 we draw a horizontal line (cosine component) and a vertical line

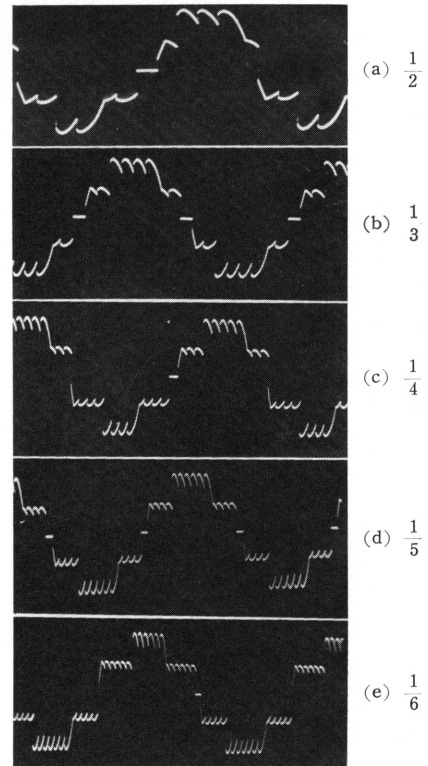


Fig. 19. Waveforms from one-half to one-sixth the input power frequency.

and a horizontal line PQ from this point P. The line QH is the sine component and the line OH is the cosine component.

7. Conclusion and Discussion

The practical waveform from $n=2$ to 6 are shown in Fig. 19. All of them are the cases that the signals start from the negative voltage peak. If we push on a switch, the power supply with its frequency feeds to the load at stable state. So, the frequency controlled machine also operates at stable state. If it is an induction motor or like that, not only its speed, but also its starting torque are controlled. Therefore this device will be applied as the starter of the synchronous machine, etc.

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