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The Rotational Speed measurement of three-phase Induction Motor by use of delivering unbalanced input from PWM Inverter

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Abstract

We often use induction motor in the hard environment including vibration and high ambient temperature, or in maintenance free operation, because induction motor has durable and simple structure. However, when we use it as servo actuator or accurate speed control motor, we have to equip sensor such as encoder and tachogenerator with the motor control system. And generally those sensor's abilities against bad environment are less than the induction motor itself. So if we can remove these sensors from the system, it'll have more environmental resistance, and the cost will also be reduced. Actually this removal has been achieved in limited field. However, that needs complex calculations and a certain elapse time for data processing. In our study, we intended to estimate the rotational speed from the motor current instead of speed sensor, easily and rapidly in comparison to former methods.

1 Introduction

In the operation of induction motor, estimation of the states such as speed or generating torque from the current or input voltage has realized as sensorless vector control for special purpose. [1][2] And also, using current of induction motor, we can see the acceleration of motor. [3] Like this, the current or voltage of motor are measured for several purposes. In our study, we use the special current to estimate the rotational speed of induction motor easily and rapidly without extra speed sensor. To generate this special current, we added sinusoidal voltage to only one terminal of three-phase motor, while delivering normal balanced three-phase voltage to all of three terminals. Then, the phase difference of the current through another two terminals excited by this added input gives us rotational speed of motor. In the following chapter, we describe the fundamental principle and some experimental results. Further, most induction motors are driven by PWM inverter for variable speed operation. So, we explain the PWM inverter and how to add the measuring signal to normal three-phase waves. And in order to make our measurement well, the choice of frequency of added signal will be discussed.

2 Fundamental principle

When single-phase sinusoidal voltage is applied to only one terminal of three-phase induction motor, it makes two current through the other two terminals. They have different phase and amplitude. And these differences are due to mechanical rotational speed of motor. Then we can estimate the rotational speed from these differences. The qualitative theory is as follows.

A sinusoidal voltage applied to one phase, can be decomposed into three components by the method of symmetrical coordinates and superposition theory.[4]

That transfer equation is

$$\begin{bmatrix} V_0 \\ V_p \\ V_n \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

where $\alpha = e^{j\frac{2}{3}}$

in this case $V_b = V_c = 0$

V_a, V_b, V_c three - phase voltage

V_0 zero phase voltage

V_p positive phase voltage

V_n negative phase voltage

This decomposition can make understanding about the difference in phase of two current easier. Using this, we can specify the current excited by unbalanced three-phase voltage from the standpoint of two balanced inputs.

Concretely, when the rotational speed is zero, both current of positive and negative have the same phase and the same amplitude. But at the time that the motor rotates to the positive direction, each component (a, b, c) of positive phase rotates forward, and its amplitude decreases, and the negative phase is opposite to it. Fig.1 illustrates these appearances.

And the changes of each phase(p, n) is explained well by use of the circle diagram of induction motor like Fig.2.

When the rotational speed is zero (stop), both primary currents, which are sums of exciting current and secondary current, are the same vector. As the rotation speed increases, the phase of positive current shifts counterclockwise on the circle, and the phase of negative current shifts clockwise. In other words, the positive phase works as motor, and the negative phase works as break. This is classical method but still very useful. [5]

Next, we have to consider the quantitative relation of rotational speed and this phase difference. If we know motor's constants transfered into primary circuit and excitation current, the phase difference may be calculated.

However, the constants and excitation current are only derived from practical test of motor, locked rotor test and no-load test. Therefore, we can say that, it is exact and accurate method to get characteristics curve of phase shift beforehand. And, in PWM operation, the rotational speed might be estimated on the base of this curve, for betters.

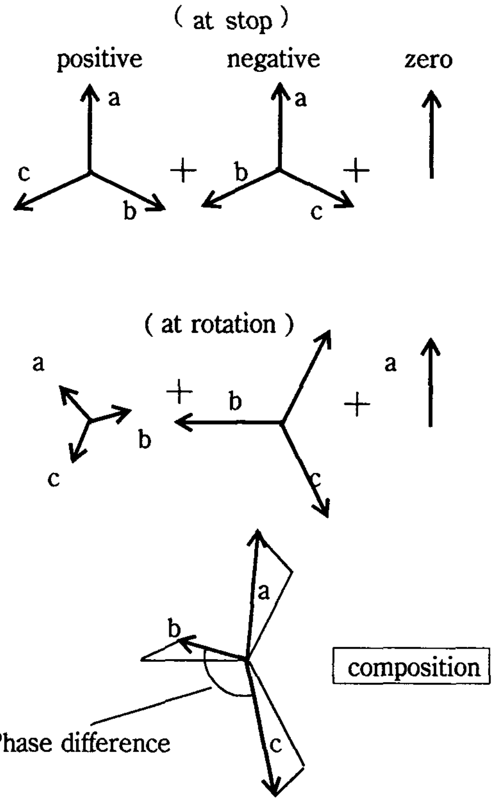

Fig.1 Phase symmetrical coordination of current

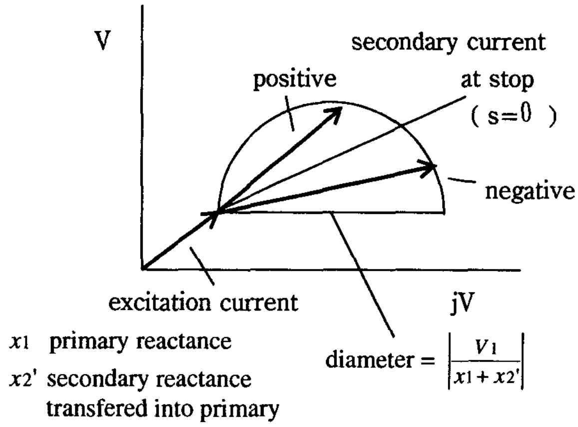

Fig.2 Induction motor circle diagram

Fig.3 shows experimental results of the phase difference of two currents with rotational speed. These curves have been obtained by set-up like Fig.9. However, in this experiment PWM inverter wasn't used, but analogue sinusoidal voltage was applied between one terminal and the others. The parameters of four curves are the frequency, 25, 50, 75, 100Hz, and the speed ranges of each curve are from zero to its synchronous speed. (The used motor has four poles.) These curves are consistent with above explanation. As the frequency varies, the final phase differences also varies. The phase of excitation current lags and the phase of negative current changes too because of increase of reactance.

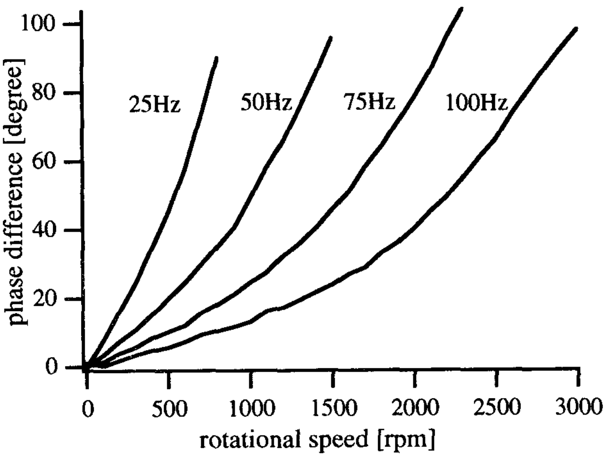

Fig.3 Experimental phase difference

3 Addition of the measuring signal by PWM inverter

A Addition of the measuring signal

In chapter2, we have described that the phase difference of the currents through two terminals excited by single-phase voltage, gives us the rotational speed. Next, we will consider how to apply this voltage to one of three terminals, while applying normal three-phase voltage. If we use an switching inverter as the power supply, it is easy to do. Because we can do it by only software.

By the way, inverters are classified into several types, including voltage-fed or current-fed inverter and PAM (pulse amplitude modulation) or PWM (pulse width modulation) and so on. Now, after this point, we suppose a voltage-fed six-phase inverter driven by the PWM signal by the triangular wave comparison method. It is utilized widely for VVVF(variable voltage variable frequency) operation. Its main circuit and PWM signal generation are illustrated in Fig.4,5. Fig.5 explains the principle of this modulation. The comparison between carrier wave (triangle wave) and modulated wave (requiring wave) makes PWM signals. And, when we want to add the signal for measurement, all we need to do is to add the measuring wave to the original modulation wave. Of course, we have to pay attention so that the modulation factor would not be in excess of 1.

Fig.6 is an extreme example, sinusoidal wave with twice frequency number of basic wave is added to phase **a** signal. The ratio of amplitude is 1:1.

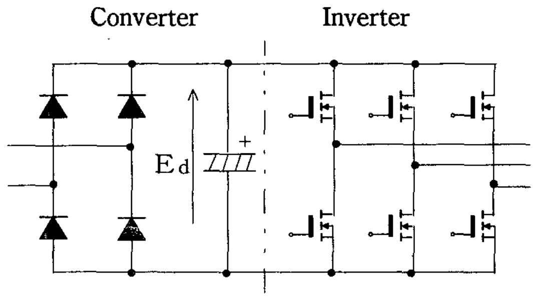

Fig.4 Constitution of inverter

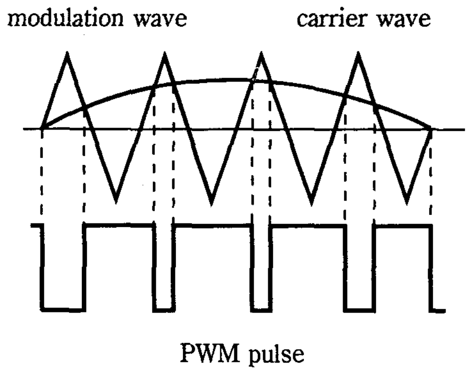

Fig.5 PWM by comparison with triangular wave

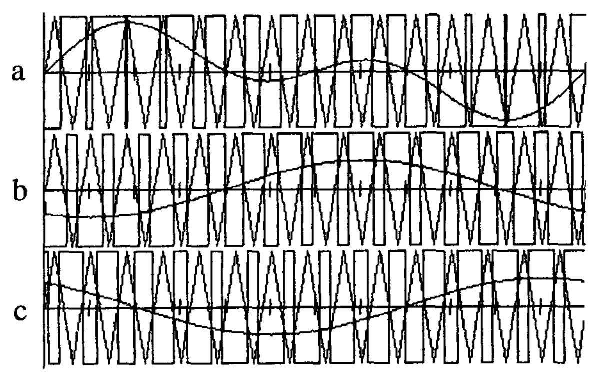

Fig.6 Example of addition of measuring signal

B Selection of frequency in the aspect of PWM harmonic

Frequency components of the inverter output should be considered carefully. The PWM signal consists of a lot of frequency components. And the calculation analysis of that components is very complex.

If any frequency components coincide with measuring signal's frequency, the angle difference of two current won't show accurate rotational speed. This frequency distribution has been already researched. Many researcher had written about this frequency components. [6][7]

Based on it, the components are,

ω_s and $n\omega_c \pm k\omega_s$

$$\begin{cases} n = 1,3,5,\cdots \\ k = 3(2m-1) \pm 1, \quad m = 1,2,\cdots \end{cases}$$

$$\begin{cases} n = 2,4,6,\cdots \\ k = \begin{matrix} 6m+1, & m = 0,1,\cdots \\ 6m-1, & m = 1,2,\cdots \end{matrix} \end{cases}$$

amplitude of ω_s is

$$\frac{\sqrt{3}}{2} mEd$$

amplitude $n\omega_c \pm k\omega_s$ is

$$\frac{\sqrt{3}}{2}\frac{4Ed}{n\pi} Jk\left(\frac{mn\pi}{2}\right)$$

ω_s modulation wave angular frequency
ω_c carrier wave angular frequency
m modulation factor defined as ceiling of modulator / carrier
Ed converter DC voltage
Jk kth order Bessel function

This constitution is related to the modulation scheme, including phase number, and modulation or carrier waveform. Above case is three-phase sinusoidal modulation wave, and triangular carrier. The practical example is shown in Fig.7, under condition that ω s is 60Hz and ω c is 5kHz . Though each components have line-spectrum in the theory, there are considerable width in actual spectrum. This is because it is impossible to make ideal rectangular pulse practically.

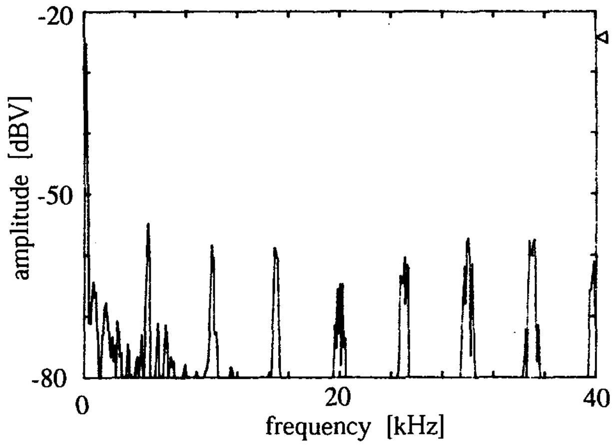

Fig.7 Actual PWM frequency distribution

In using our method to measure the rotation speed, the frequency of added signal for measurement should be chosen to avoid these frequency components. All PWM harmonics are balanced three-phase voltage which have angle difference of 120 degree each other constantly. Then they would affect to our measurement. The larger its ratio to added signal is, the affection is also greater. Fig. 8 shows the case of the coincidence. This is experimental results, which shows the relationship between rotational speed and angle difference with three ratio of basic signal to measurement signal. In the figure, top curve is the basis (by analogue sinusoidal wave). Another two curves are sum of the measuring signal and PWM harmonic. The amplitude ratio of middle curve is 13, and that of bottom one is 24, when the motor is at stop. With increasing the rotation speed, the effect decreases gradually and approaches to minimum at 1500rpm (synchronous speed). This is because of the balanced three-phase current decreases to exciting current(minimum value) with rotational speed, but signal for measurement, exactly negative phase signal doesn't decrease. So, the adverse effect becomes smaller relatively, as the rotation speed increases. This effect might be used to improve accuracy by calculation. However, that method makes measurement complex, which reduces one of advantages of our method. So we prefer to avoid these frequency.

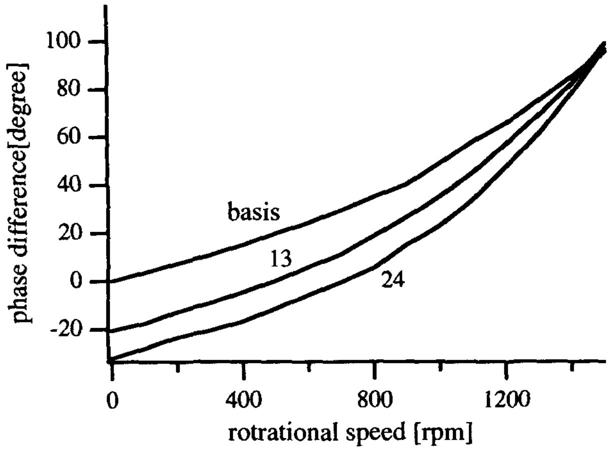

Fig.8 Affect of PWM harmonics

C Selection of frequency in the aspect of other demanding

In this section, we consider the other points on selecting the frequency for measurement. The choice of higher frequency permits this measurement to be rapid. Because the required time to sample data for Fourier Transfer will be shorter. This is one of advantages of our method. Further, the measurable speed range becomes wide by higher frequency, as shown in Fig.3.

As we described in chapter 1, single-phase input to measure generate some torque. But the torque is small essentially, since this input current make both motor and break at the same time. It is just like single-phase motor. And if we make its frequency higher, the torque will become still smaller. This is the same as setting its amplitude at the lower value. Here, as additional information, in the common 200V operation we can say that the torque generated by measuring input will be less than 1 percent of original torque. In our experiment, normal rated current of used motor is 0.25A, and measuring current is 0.01A at a stop.

Thus the high frequency seems better for our method in the theory. However, in practice, sensitivity of current sensor, sampling period of AD converter, and SN ratio don't permit extreme high frequency, since it is difficult to excite large current and its phase shift to measure is small. Also, making high frequency wave by PWM needs high frequency carrier, it increases switching loss of inverter.

4 Experimental equipment

Experiment have been performed using the set-up like Fig.9. The motor on the right side in this figure, is for speed control. It works as either induction motor or break, was driven by inverter power supply. The motor for measurement is left side one. It is connected to speed control motor, with rotary encoder (60P/R) which gives true rotational speed. Both motors are three-phase induction motor with squirrel cage rotor, and its rated output is 200V 25W. PWM inverter has six-phase structure which is assembled of FET, and voltage-fed type and driven by the signal made by means of comparison with triangular wave. The PWM signal is supplied from personal computer. The used current sensors are Hall effect device.

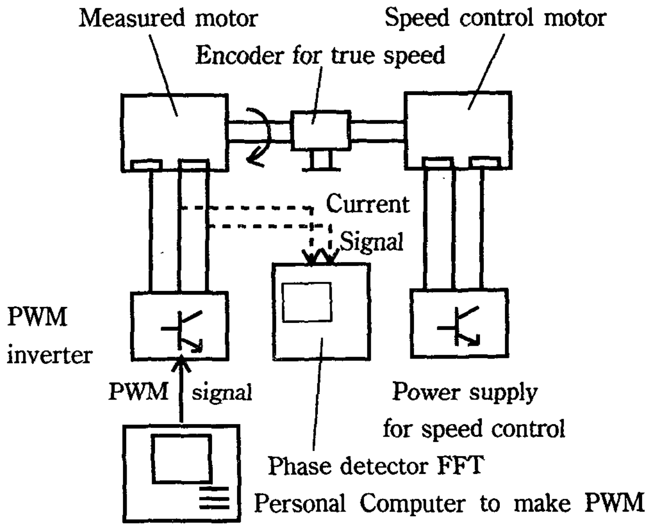

Fig.9 Experimental set up

5 Experimental result

Using the set-up of Fig.9, we have performed experiment for real motor operation with PWM inverter.

The added sinusoidal frequency for measurement was 50Hz and the balanced three-phase input was 100Hz. The component of 50Hz was abstracted from the current through two terminals. The phase difference between these two components with rotational speed is shown in Fig.10. The base curve is obtained by an accurate analogue sinusoidal input. From this figure, we can see the two curves are coincident well. This result reveal that our method is applicable to practical operation with PWM inverter.

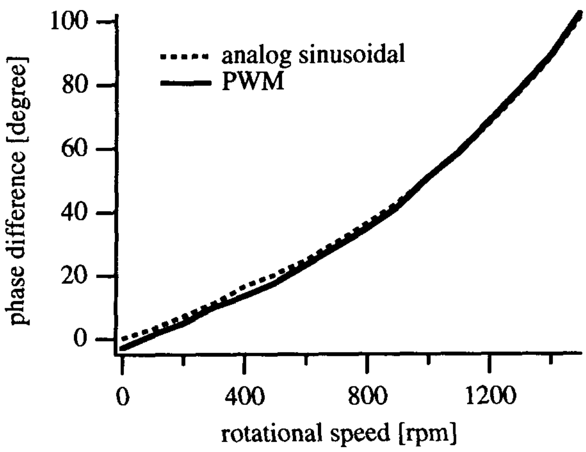

Fig.10 Experimental result

6 Conclusion

As is stated above, we have shown the possibility to measure the rotational speed of induction motor by use of unbalanced input. In addition, the applicability to real motor operation driven by PWM inverter has been shown too. As you know, the measurement by use of normal balanced three-phase current is also possible. And that fundamental principle is the same.

We summarize the advantages of our method again here. The first point is the simpleness and easy to understand. The method of sensorless vector control is difficult to make calculation for its axis transformation. V/f (voltage/frequency is constant) control is used as a conventional speed control. The speed estimation used in sensorless vector control, isn't suitable for the control like this , in which high precision is not required.

The second point is relative accuracy. If we want to avoid complex calculation, we can estimate the speed from normal current , that are phase shift between input voltage and current, or variation of amplitude. However, this method is not very precise, since these variation with speed is small.

The last point is rapidness. In digital signal processing, it takes a certain time to specify the phase shift of periodic wave. And if the frequency is higher, the needed time is shorter. Since our method is able to choose the frequency, we have some advantage in this point.

As coming study about this measurement, we would like to research resolution and appropriate frequency in the practical operation. And in the final step, we'd like to compare our method with encoder and tachogenerator in accuracy and needed time for measurement, on the V/f speed control system with feed back.

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