# VV-VF 制御에 의한 3相誘導電動機의 高効率化 運轉에 관한 硏究

論 文
30~7~3

# The Optimal Efficiency Drives of 3-Phase Induction Motor by VV-VF Control

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**Abstract**

The aim of study in this paper is that in a system drive of the converter-inverter fed induction motor, the minimum input power can be maintained by control the voltage and frequency of the motor.

In theoretical and experiment results describtion motor efficiency is improved by properly varying the ratio v/f. At lightly load condition, for example its efficiency was improved from 44% to 66% as the ratio of v/f varied from 1 to 0.57.

## I. Introduction

A great quantity of electric power has been consumed as energy resources by electrical or mechanical facilities. But 60% of their total consumption is for operation of electrical rotary machines. In other words it can be said that to drive electric motors with high efficiency is to save electric power.[1]

Especially an induction motor among different types of electrical machines has a lot of inherent advantages for industrial applications. Therefore, about 80% of the motors, by virtue of its merits, is induction motors. However, induction motors have generally been viewed as essentially constant speed machines. But developments in static power controllers have made reliable and flexiable frequency supplies available. So this has been enabling us to adopt a robust induction motor in variable speed drives with high performances.

Usually in closed-loope speed control of induction motor, where the speed of the motor is controlled by varying its frequency through inverter, it is essential to operate the motor under all speed and load conditions at the nominal flux defined by the machine name-plate voltage and frequency. Operating the motor at the constant nominal air gap flux value results in the same pullout torque at all supply freqencies and hence permits constant full-load torque capability of the motor at all frequencies.

In general, induction motors are designed to have a high efficiency in the region of 75% to 100% variation of a full load. So it will be desirable to operate the motor under these circumstances.[2] Because the same machine shows different colors in performance, as the load factor become lower that eventually lead to considerable degradation of the motor efficiency of a lightly loaded induction motor can be very substantially improved by controlling the voltages applied to it and also adjusting the freqency through inverter.

The aim of study in this paper is that in a system drive of the converter-inverter fed induction motor, the minimum input power can be maintained although the voltage and frequency of the

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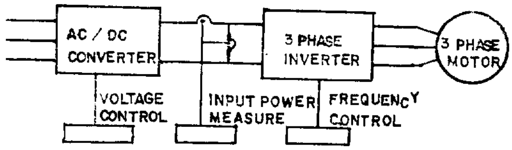


**Fig. 1.** Basic Block Diagram of v/f Control

motor is adjusted as shown in Figure 1 in order to build up accurate speed control and and as well get the optimal efficiency operating characteristics.

## II. Improvement in Efficiciency of Induction Motor

### A. The Contorl Scheme

As shown in Figure 1, depending on the difference between the desired and actual speed, the speed control algorithm adjusts the inverter frequency and also modulates the width of pulses of a dc chopper simulataneously so as to maintain the constant ratio of voltage/frequency. Thus the motor speed is controlled to the desired speed over a wide speed range.

At the motor shaft speed $f_M$(equivalent frequency of speed) adjusted like this way(fixed load,), as can be seen in Figure 2, the inverter frequency is increased by a bit to satisfy the equation $v_1/f_1=v_2/f$, and at the same time the voltage is decreased to a voltage v for the broken line to go through the point P. At last completion of changes of above two variables will lead to the inequality $v_1/f_1>v/f$, and reduction of the air gap flux at the constant speed $f_M$ But the algolithm described may eventually generate a great number of torque-speed curves on which the point P in

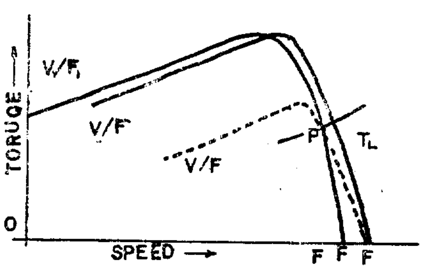


**Fig. 2.** Developed Torque-Speed Curve by v/f Control for Constant Drive Speed

figure 2 always exists, and one curve will show a different efficiency from the others at the point P.

### B. Theoretical Technics

Disregarding the higher harmonics of the inverter supplied stator, the approximately equivalent circuit of an induction motor is shown in figure 3 as well known in adjustuable motor speed drives by means of the stator frequency $f$. By the way the operating characteristics at low load factor can be precisely obtained with this approximately equivalent circuit.[2]

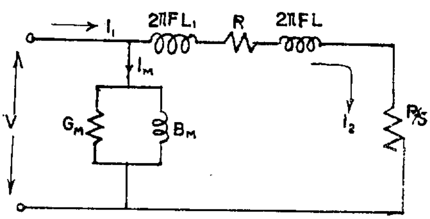


**Fig. 3.** Approximately equivalent circuit

(1) In systems, the stator frequency $f$ is controlled slightly over the frequency $f_M$ so that $f \doteqdot f_M$. (2) There is no need of considering saturation effects because v/f is usually less then motor rated voltage/frequency. (3) $G_M$ and $B_M$ are evaluated when the frequency is equal to $f_M$.

In this circuit, stator current is

$$\mathbf{I}_1=\mathbf{V}\left\{G_M-jB_M+\frac{1}{(R_1+R_2/s)+jf(2\pi L_1+2\pi L_2)}\right\} \quad (1)$$

slip $s$, the ratio between rotor slip frequency($f-f_M$) and stator frequency $f$, is

$$S=\frac{2\pi f-2\pi f_M}{2\pi f}=\frac{f-f_M}{f} \quad (2)$$

The magnitude of current in equation (1) can be expressed in terms of frequency $f$ instead of slip $s$. That is,

$$\begin{aligned}\mathbf{I}_1=&\frac{\mathrm{v}}{f}\left[fG_M+\frac{R_1/f+R_2/(f-f_M)}{\{R_1/f+R_2/(f-f_M)\}^2+\{2\pi(L_1+L_2)\}^2}\right]+\\ &j\frac{\mathrm{v}}{f}\left[fB_M+\frac{2\pi(L_1+L_2)}{\{R_1/f+R_2/(f-f_M)\}^2+\{2\pi(L_1+L_2)\}^2}\right]\end{aligned} \quad (3)$$

From equation (3), the active current of the stator current is

$$I_1\cos\theta_1=\frac{v}{f}\left\{fG_M+\frac{R_1/f+R_2/(f-f_M)}{Z^2}\right\} \quad (4)$$

where

$$Z=\sqrt{\{R_1/f+R_2/(f-f_M)\}^2+\{2\pi(L_1+L_2)\}^2}$$

from figure 3, the rotor current $I_2$ is

$$I_2=\frac{v}{fZ} \quad (5)$$

And the torque equation is as following.

$$T=\frac{m}{4\pi f/P}I_2^2R_2\Big/\left(\frac{f-f_M}{f}\right)$$
$$=\frac{3P}{4\pi}\left(\frac{v}{f}\right)^2\left[\frac{R_2/(f-f_M)}{\{R_1/f+R_2/(f-f_M)\}^2+\{2\pi(L_1+L_2)\}^2}\right] \quad (6)$$

Where $P$ is no. of pole, $m$ is no. of phase.

When induction motor drived at the stator frequency $f$, the frequency, at which the pull-out torque is generated, can be evaluated by differentiating equation (6) with respect to $(f-f_M)$ and then let the derivative be equal to zero. That is,

$$(f-f_M)_{T_m}=\frac{R_2}{(R_1/f)^2+(2\pi L_1+2\pi L_2)^2} \quad (7)$$

Where $T_m$ is maximum torque.

Now, from equation (4), the input power is,

$$P_{in}=3vI_1\cos\theta_1$$
$$=\frac{3v^2}{f}\left\{fG_M+\frac{R_1/f+R_2/(f-f_M)}{Z^2}\right\} \quad (8)$$

and from equation (2) and equation (5), the output power is

$$P_{out}=T\cdot\frac{4\pi f}{P}\left(1-\frac{f-f_M}{f}\right)$$
$$=\frac{3v^2}{f}\cdot\frac{R_2\{1/(f-f_M)-1/f\}}{Z^2} \quad (9)$$

And the motor efficiency is well written as the following equation from equation (8), equation (9)

$$\eta=\frac{P_{out}}{P_{in}}=\frac{R_2\{1/(f-f_M)-1/f\}}{[\{(R_1/f+R_2/(f-f_M))^2+(2\pi L_1+2\pi L_2)^2\}fG_M+R_1/f+R_2/(f-f_M)]} \quad (10)$$

At the **steady state, the efficiency** slip frequency with the **maximum efficiency** can be easily obtained from the $d\eta/d(f-f_M)=0$

$$(f-f_M)_{\eta_m}=\frac{R_2}{\frac{R_2}{f}+\sqrt{\frac{(R_1+R_2)^2}{f^2}+\frac{R_1+R_2}{f^2G_M}+(2\pi L_1+2\pi L_2)^2}} \quad (11)$$

Where $\eta_m$ is maxmum efficiency.

Comparing equation (7) with equation (11), we can realize the following; $(f-f_M)_{T_m}>(f-f_M)\eta_m$, and the slip frequency, at which the maximum torque occurs, is in the stable region represented in figure 2, and also the maximum efficiency curve at the point P can be selected just according to the control algorithms. Thus, this assumption refers to a motor having a maximum efficiency slip frequency within 8 cycles. And it will prove that there exists no significant errors even if $G_M$ and $B_M$ are utilized as the exciting parameters in changing the voltage and frequency in the equivalent circuit represented in figure 3.

figure 4 represents the efficiency curves as a function of v/f for the induction motor described above that has a following specifications; 25KW, 60Hz, 3$\phi$, 220V and 8 poles. In Figure 4 the ratio v/f (=1 per unit) is referred to as $220/\sqrt{3}/60$, and $f_M$ equals 58 Hz (870 rpm) at the constant speed and constant load. From the above facts, it is seen that when v/$f$=1, the lower the

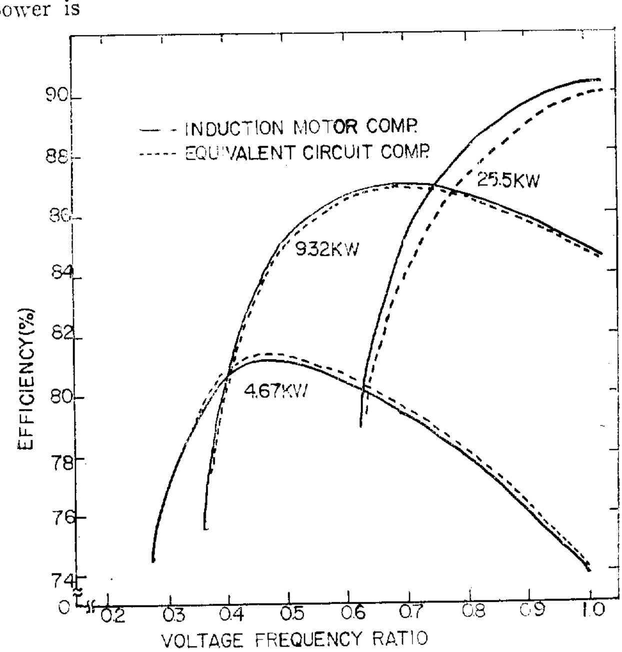


**Fig. 4.** Effect of Voltage/Frequency Varation on the Motor Efficiency

load factor, the more inefficient becomes the induction motor. So there has to be a proper value of v/f (<p.u) with which an optimal efficiency drive can take place. Moreover, the efficiency may be more considerably improved at particularily low load factors than at high ones.

## III. Test Set-Up & Results

### A. Set-Up

The results reported are obtained using a 3$\phi$ induction motor with the full-load ratings of 230V, 400W and 1730rpm. The motor was mechanically loaded by means of a dc generator whose effecicency was carefully evaluated at various power outputs.

In figure 5 microprocessor inputs are the motor shaft speed and input power. In large power systems, a current-detecting input can be added for the sake of system stability.[3] The input power can be measured from voltage-current multiplying, and low pass filterring. Microprocessor outputs are the dc chopper voltage and inverter frequency information.

First, the microprocessor control the speed of a induction motor with the constant voltage/frequency ratio. When the motor speed is set and speed errors are in the tolerance range, the microprocessor will decrease the chopper voltage and increase the inverter frequency a little respectively and then motor speed may be changed slightly. In this case the microprocessor adjusts the inverter frequency only for speed seting. And if the speed is set again, then the microprocessor will read the input power information and begin to memorize. And again the microprocessor decreases the voltage and increase the frequency (air gap flux decrease), and for accurate speed, adjusts the frequency only, and reads input power again. Next, the microprocessor compares this input power with the memorized last input power. If this input power is less than or equal to the last input power, then the microprocessor will continue to increase the frequency and decrease the voltage by a fit respectively. Otherwise, the microprocessor will increase the voltage and decrease the frequency (air gap flux increase) and adjust the frequency only, read input power to compare again one another. According to the rapid load torque changes, whenever the speed exceed the given tolerance range, the microproceesor will control the speed of the induction motor with the rated voltage/frequency ratio. After setting the speed, the microprocessor may control the voltage and the frequency separately according to the input power.

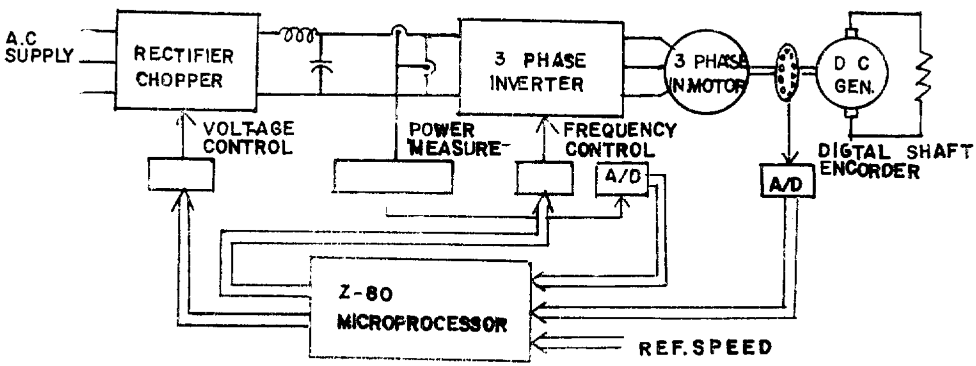


**Fig. 5.** System Block Diagram of Induction Motor Drive for Speed Control & Energy Saving

### B. Test Results

The data obtained in the procedures of the previous section A are shown in figure 6, where the induction motor specifications are; rating 400W, fixed speed 1700 rpm. The diverse curves refer to

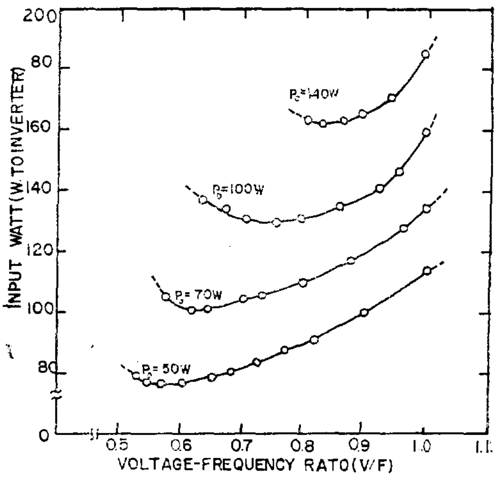


**Fig. 6.** Input Power $P_{in}$ Variations by Voltage/Frequency Control at constant Output $P_{out}$

kinds of input power with respect to v/f for motor output such as 35%, 27.5%, 22.5% and 12.5% of the rated output. Obviously can we know that each curve has a minimum input on itself. According to figure 6, table 1 can be readily made and is representing what a remarkable improvement in effieciency there exists. Now the results can be summarized as the following.

**Table 1.** Reduction in Power Consumed to v/f Control

| induction motor output (%) | efficiency at $V/f=1$ (%) | improve efficency (%) | $V/f$ ratio | $V/f=1$ effi.-impr. effi. (%) |
|---|---|---|---|---|
| 35 | 75.7 | 86.3 | 0.83 | 10.7 |
| 25 | 62.5 | 78.1 | 0.75 | 15.6 |
| 17.5 | 51.9 | 70.0 | 0.65 | 18.1 |
| 12.5 | 43.9 | 65.7 | 0.57 | 21.8 |

(1) Efficiency is improved by properly varying the ratio v/f as can be seen in figure 7 and especially at low load it will be apparent. For example, at 12.5% load the efficiency was improved from 44% to 66% as the ratio of v/f varied from 1 to 0.57.

(2) Speed of an induction motor can be maintained constant at the reference speed even though the load or v/f is varied. If was shown in figure 8 at top curve.

(3) The induction motor drive must be performed just utilizing a microprocessor (in this experiment Z-80 was utilized) for the results to conform with energy saving as shown in figure 8.

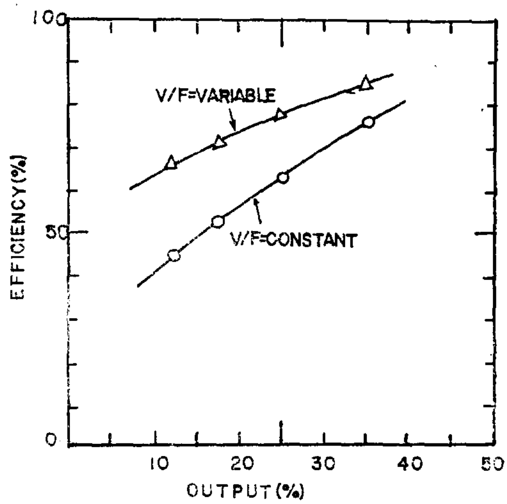


**Fig. 7.** Compareing Improved Efficiency with the Conventional

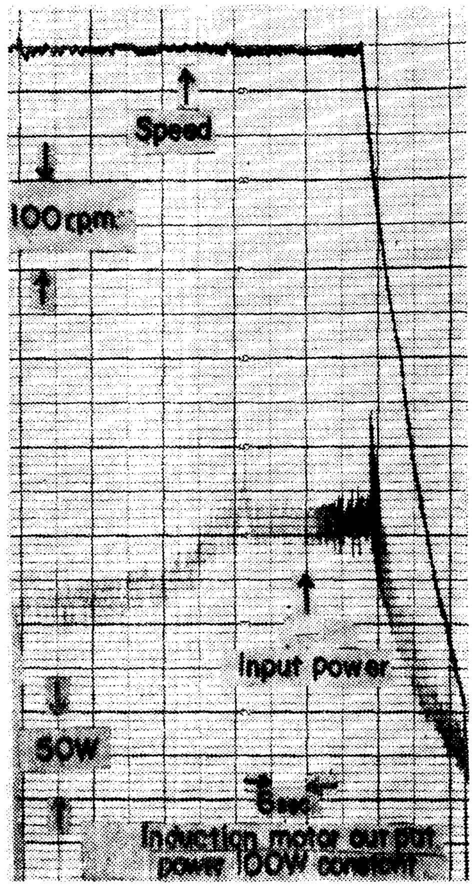


**Fig. 8.** Experimet Results, the Curves Shown in Constant Speed & Saving Energy

(4) It is proposed to investigate the disturbance in load and stability of this system as an extension of our present work.

## IV. Conclusions

This paper shows that in lightly loaded induction motor its efficiency are improved by voltage/frequency control at optimal values. In both of theory and experiments under constant speed drive of induction motor with inverter and microprocessor the resultants are already described above section and we are arrived such a conclusion as very substantial energy savings are possible.

So further work is be done application in many cases of industrial fields that using induction motor under the low load conditions.

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