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Low Speed Control Enhancement for 3-phase AC Induction Machine by Using Voltage/ Frequency Technique

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Abstract: The torque competence is a big challenge in Alternative Current (AC) induction machines at a low speed. An enhanced method of Voltage/ Frequency (V/Hz) is presented in this paper to control the induction machine speed when torque is applied. Furthermore, transient analysis is implemented for machine speed to demonstrate the capability of the machine with and without load. Practically, voltage drop can be neglected in the stator resistance and leakage inductance at high speed and/ or small load torque. However, the issue is appeared at the low speeds where this assumption is not valid, and compensation of voltage drop is necessary to prevent machine lack. A Simulation tool has been used based on Matlab/Simulink functions to test the new enhanced model. In addition, an open-loop constant V/Hz method for induction motor has been used to show the performance of the machine at the low speeds. The simulation results shown that the control system of AC induction machine can be improved by boosting the stator voltage at low frequency.

Key words: AC Induction Machine, V/Hz control, Rotor speed, Stator current, Transient stability.

INTRODUCTION

The implementation of induction machines was first operated in the end of fifties and early sixties by using constant voltage rate per hertz (Miokrytzki 1968). However, this technique was limited due to poor performance in low speed range and difficulties of supplying constant voltage for different speed range. The development of power electronics gives big support for the AC induction machine. Recently, the PWM-inverter uses to maintain a constant volt per hertz at low speed range (Zhang 1996). Although the machine is operating at a very low speed (frequency of less than one Hz) but still remains as a mainly challenge due to non-linearity of the inverter when low output voltage is required (Lipo and Jezernik 2002). These modern techniques use inverters to control the machine at low frequency and to make sure the machine is still worked in stable situation. Various speed control techniques applied by modern-age VFD are mainly classified in the following three categories (Swarupa, Das, and Gopal 2009):

1. Scalar Control (V/Hz Control).
2. Vector Control (Indirect Torque Control).
3. Direct Torque Control (DTC).

Swarupa *et al.*(Swarupa, Das, and Gopal 2009) discussed in details each type of control. However, scalar control is widely used as it can be implemented without requiring any feedback devices. Besides that, this type of control offers a low-cost and is not complicated model. The disadvantage of this method is that the torque developed is not controlled directly, which reduce the performance of the machine.

Several applications such as an electric vehicle, which requires a low and high speed control (Guidi, Kubota, and Hori 1997), the induction machine is controlled based on sensor signal of V/Hz. Therefore, the development of fast control method is still necessary for the induction machine. The main factor of using induction machine in wide applications is that can handle the heavy load under a variant speed. Figure 1 illustrates the equivalent circuit of single phase induction machine.

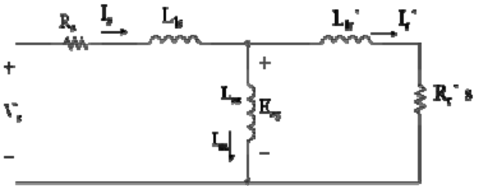

Fig. 1: Single phase equivalent circuit of the induction machine.

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This paper describes the design of a 3-phase AC induction motor drive with Volts per Hertz scalar control in open-loop (V/Hz). The voltage V_a magnitude is varied by maintaining the E_g / f ratio and constant air gap flux, Φ_{ag} for small value of slip (S) it can be shown that the relationship between the electrical torque and slip speed is linear. In order to ensure that Φ_{ag} is at its rated value and constant, when the voltage is changed, the frequency has to be changed following equation 1.

$$E_{ag} = k\, f\, \Phi_{ag} \tag{1}$$

Additionally, to maximize the torque capability under variance operation, it is necessary to maintain the magnetic flux at its rated value at any frequency. This can be proven from the steady state equivalent circuit by maintaining the magnetizing current I_m at its rated value (Idris and Yatim 2002). Figure 2 shows the relationship between the torque and speed signals.

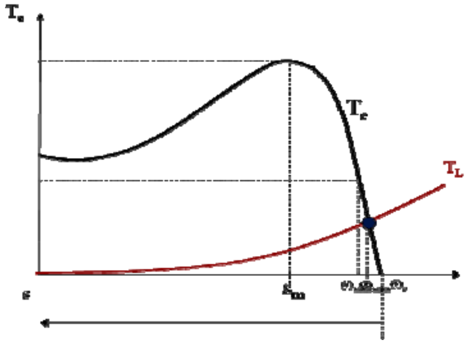

Fig. 2: The Relationship between torque and speed.

At high speed operation, the E_g is dropped as the stator leakage and resistance are low value. Therefore, E_{ag}/ f is constant by maintaining V_s/ f constant as shown in equation 2. However, the back emf is base at low speed operation; therefore, the voltage will drop gradually at the stator side if the mmf is not enough. Thus, the flux is reduced below the rated value as well as torque capability.

$$\frac{E_{ag}}{f} \approx \frac{V_s}{f} \tag{2}$$

The performance can be improved by boosting the voltage at low frequency and/ or controlling the stator current. The injection of low frequency boost-voltage, offers the variety of operation from zero up to maximum torque at rated speed, thereby compensating for the low frequency stator impedance drops associated with the basic V/Hz control (Ogbuka and Agu 2011).

RESULT AND DISCUSSION

An open-loop constant V/Hz 3-phase induction motor drive is demonstrated by using MATLAB/ SIMULINK software, as shown in figure 3.

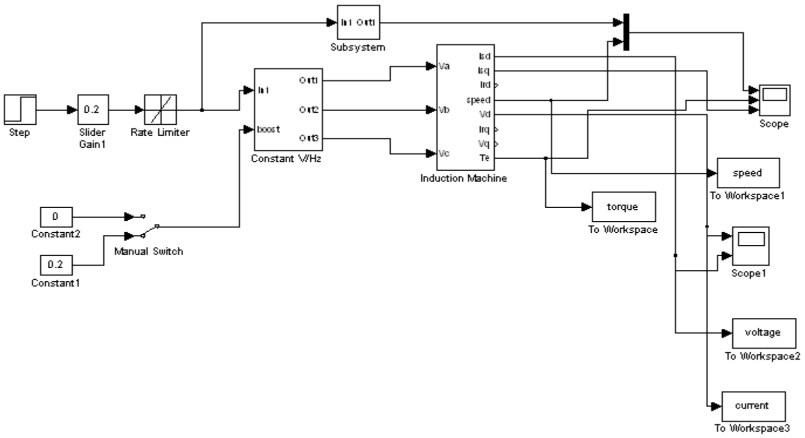

Fig. 3: Block diagram Simulation model for an open-loop constant V/Hz induction motor drive.

The parameters of rated power, number of poles and rated speed for the machine are given as 1.5Kw, 4 pole, and 1410 rpm, respectively. The load constant is set to be same as the torque at the rated speed, which can be calculated as follows:

$$T_{rated} = \frac{P_{rated}}{W_{rated}}$$

$$W_{rated} = N_{rated} \times \frac{2\pi}{60} = 1410 \times \frac{2\pi}{60} = 147.58 rad/\sec$$

$$\therefore T_{rated} = \frac{1.5 \times 10^3}{147.58} = 10.16 N.m$$

The specifications of the simulation are given as follows:

3-phase Induction machine
Stator resistance =0.25Ω
Rotor resistance = 0.2Ω
Stator self inductance = 971mH
Rotor self inductance = 971mH
Mutual inductance = 955mH
Number of poles = 4
Moment of inertia = 0.04kg.m^2
Load torque = 0-10Nm
Load constant = 0.05
Rated frequency = 50Hz
Voltage, V_m at rated frequency = 239V
Voltage boost at low frequency =0.2

The open-loop model is simulated under two different operation conditions to ensure the enhanced control model is widely significant. The next section discusses the output result without load and with load, which is equal to the rated torque.

A. Without load:

The wave forms of the speed, electrical torque, q component of the stator current I_{sq} and d component stator current I_{sd} and voltage V_d are obtained with and without load. However, the machine has been loaded with T_{load} ratio to evaluate the difference without and with load. As it can be shown in figures 4 and 5, there are three parts, the first part at the low speeds with 0.1 adjustable amounts,

w= (2*pi*50*0.1)/2=15.7 rad.s^{-1}

The second part at full speed with one adjustable amount of the slide

w= (2*pi*50*1)/2=157 rad.s^{-1}

The third part also at low speed with 0.15 adjustable amount of the slide

w= (2*pi*50*0.2)/2=31.4159 rad.s^{-1}

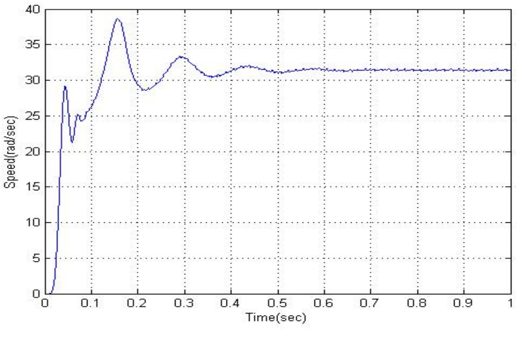

Fig. 4: Rotor speed.

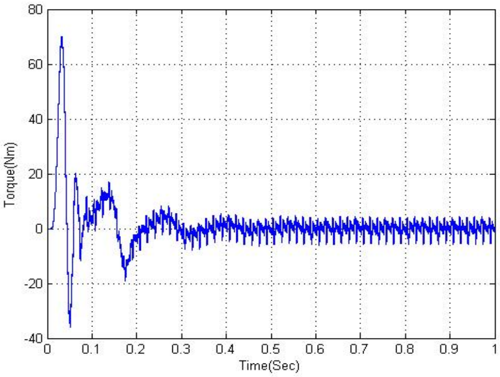

Fig. 5: Electrical torque.

Torque signal is damped after about 0.5 millisecond of load applied, and that is considered as a good and fast transient response of the machine.

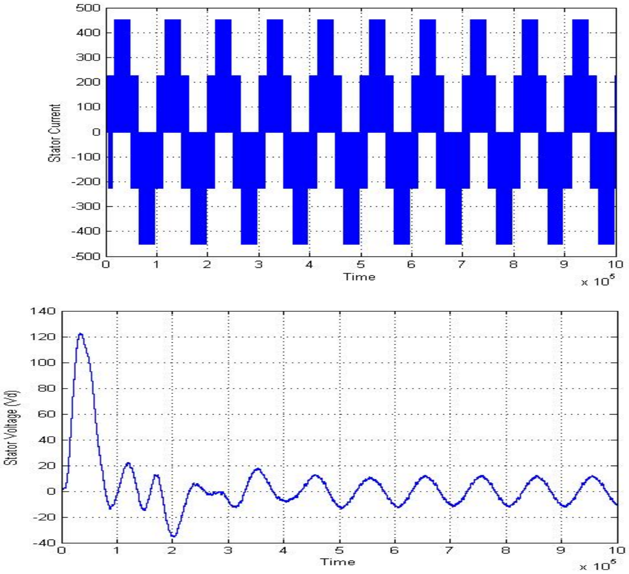

Fig. 6: Stator current I_{sd} and voltage V_d (d component).

B. With Load Equivalent To The Rated Torque:

The simulation was done with the present of load equivalent to the rated torque at low speed w=31.4 rad.s^{-1}. The voltage is obviously dropped in the stator when the load is connected to the rotor. Likewise, this will affect the performance of the motor and could lead to stop the rotor or lose its operation. Although, the speed cannot exceed the speed limit values that load required. In simulation, this phenomena can be clearly proven when the simulation is stopped (the machine did not work in that value of speed and torque because the torque cannot supply the load at this speed value). In this developed model, the control is given by boosting the voltage at the stator side, and the motor was successfully reduced its speed without any violation. It can be shown in the figures 7 to 10 that the speed, electrical torque, q component of the stator current I_{sq} and d component stator current I_{sd} and voltage V_d, respectively, before and after boosting the voltage. The time for transient analysis was around 5 sec to show the damping of the motor signals which was stable under all conditions.

In this case, the unstable situation has high slip speed and that reduce the efficiency of the machine due to the drop voltage which reduced the slip speed, and the boost voltage was induced to support the load.

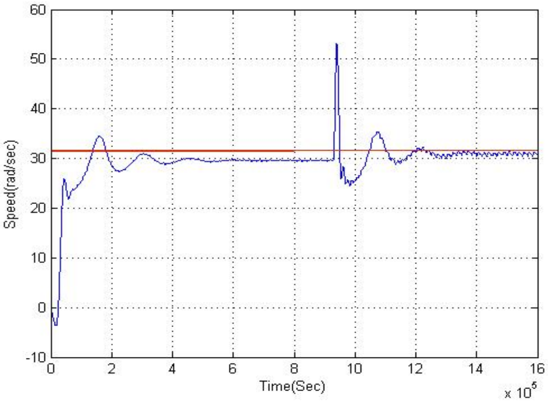

Fig. 7: Rotor speed before and after implementation.

The rotor speed has reduced when the load torque applied due to the drop voltage that occurs in the stator. Therefore, at low frequency, it does need to compensate that drop voltage which happened when load was applied. In addition, a high slip speed was detected that can lead to loss machine synchronism. However, the implemented solution can stabilize the induction machine by using boost voltage for compensation, I_s and R_s. The overshot response happened in small time when we connect the new circuit model with the motor. On the other hand, the transient signal is still in good criteria, and snubber circuit can be introduced to eliminate this overshot current.

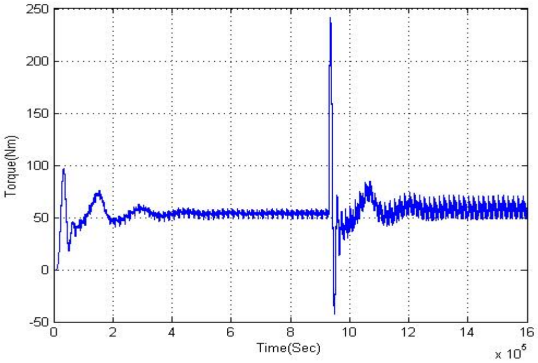

Fig. 8: Electrical torque before and after implementation.

The torque has been increased after boosting stator voltage at rated value that can supply the load. It means that the torque can supply the load in good operating point (peck-peck is in better range comparing to the result in figure 5). Moreover, the motor is still operating in stable condition as shown in figure 8 the electrical torque.

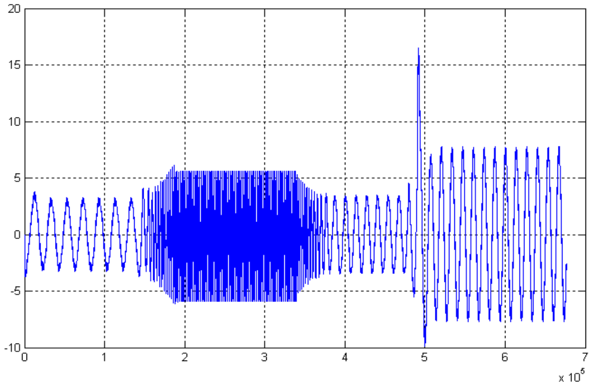

Fig. 9: Stator current I_{sq} (q component) before and after implementation.

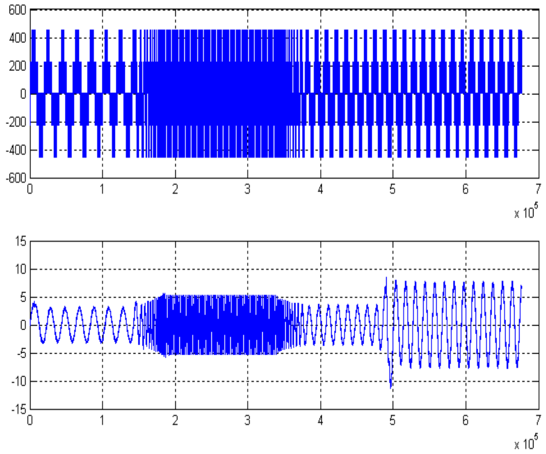

Fig. 10: Stator current I_{sd} (d component) and voltage V_d before and after implementation.

Conclusion:

The main objective was successfully done by using enhanced V/Hz method to control the induction machine speed when the load is applied. From the simulation results in figures 4, 5 and 6 it can be seen that the assumption of negligible stator resistance and leakage inductance is valid, and the simulation will not stop as it is clearly seen in figure 4 when the mechanical speed is nearly close to the stator speed. When the load torque is implemented in the simulation, it can observe that at the high speed the simulation will continue at rated load and high speed as well. Where the speed decreased to low speed of the present of load, the simulation was stopped, but at this speed where the simulation is stopped, the implementation of boost the voltage the motor could support the load without losing its synchronism. On another word, the voltage boosted can compensate the voltage drop in stator resistance and leakage inductance.

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