A Comparative Study between V/F and IFOC Control for Three-Phase Induction Motor Drives

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Abstract: The voltage/frequency "(V/F) control" method is considered as widely used method in industrial application for control the induction motor (IM) due to its simplicity and lower the cost. The main problems in this method are the slow response, and it cannot be applied in the applications that required smooth speed control. To solve these problems, a robust control method of indirect field-oriented control (IFOC) was developed. In this paper, a comparative study of classical V/F control and IFOC of 3-ph IM is done. The principle action for both methods are studied and then they implemented and simulated using "MATLAB/Simulink" software for a 10 HP (7.457kw) 3-ph squirrel cage type IM. Besides, the sinusoidal pulse width modulation (SPWM) technique with a proportional-integral (PI) controller has been used to control the VSI inverter in the V/F method. While, the space vector PWM (SVPWM) technique has been used to control the VSI inverter in the IFOC method. The 3-ph IM has been achieved to its desired speed with good transient time and steady state response when the step change in the torque load has applied. Therefore, the IFOC method provides smooth speed control, high performance, and fast response under different dynamic conditions compared to classical V/F method.

1. Introduction

Today, all industrial electrical are required induction motors (IMs) in their applications such as air compressors, blowers, cranes, industrial sectors, etc. [1]. The electrical isolation of the stationary and rotating parts of the IM represent the major benefit of using this motor. Therefore, the mechanical commutator is not required, this led to minimizing the weight and inertia constant with higher efficiency capability [2-4]. Furthermore, the IM is supplied with a three-phase voltages source inverter (VSI) of variable frequency and magnitude to control its speed. However, there are many methods used to control the IM speed such as pole changing methods, frequency variation, variable rotor resistance, variable stator voltage, constant V/F control, slip recovery method etc. [5-7]. The variable frequency drive methods are most widely used in industrial application for control the IM as shown in Figure 1. Several researchers have applied the voltage/frequency (V/F) and FOC methods to control the IM speed [8-10]. Firstly, the V/F represents the scalar control method, which has great applications in industrial processes by maintaining a stable V/F ratio due to its simplicity. However, by maintaining the magnetic flux at the rating value, the V/F ratio kept as constant. Hence, to achieve this requirement, it is necessary to change the terminal voltage with any change in frequency. For this reason, the PWM technique is used to control the voltage and frequency of an inverter that supplied the IM [11-14]. More advantages of this method are considered such as simple, low cost, higher efficiency with closed-loop control. Nevertheless, this method in the transient state conditions takes a relatively long time (Slow response), and it failed in applications that require precise speed control. For this reason, the FOC method is commonly used for controlling the IM due to its higher performance with fast response and has precise control. This method based on obtaining the phase and magnitude of currents or voltages [15-18]. Thus, the position of voltage, current, and flux vectors are...
estimated depending on the Park and Clarke transformation. Therefore, the torque and flux of IM are generated correctly. In this paper, the IM is controlled using both V/F and IFOC control methods based on "MATLAB/Simulink" software. In V/F method a sinusoidal pulse width modulation (SPWM) technique is used to control the output frequency and voltage of the inverter. This technique is integrated with a robust Proportional-Integral (PI) controller to obtain a closed-loop control drive. On the other hand, the IFOC is implemented with SVPWM technique. Motor signatures have been taken for analysis study such as the "line currents", "rotor speed" and "electromagnetic torque".

**Figure 1.** Variable frequency drive methods.

### 2. Scalar V/F Control Method

#### 2.1 Principle Action of V/F Method

In some industrial units, IM control look to be complicated because of non-linearity specialty of the motor. In general, three phase IM can be considered as a self-starting constant speed because of the rotor speed alteration in proportional to the frequency change of the source voltage as express in equations below \[19,20\]:

\[
N_S = \frac{120f}{2P} \tag{1}
\]

where \(N_S\) is the synchronous speed, \(P\) is the number of pole pairs, and \(f\) is the supply frequency. In addition, the rotor speed is given by:

\[
N_r = (1 - S) \cdot N_S \tag{2}
\]

where \(S\) is the slip and \(N_r\) is the actual rotor speed. The basic principle of AC motor control in a way of V/F depends on the equivalent circuit of the IM in a steady state, because when applying balanced 3-ph voltage, 3-ph balanced currents passive will produce magnetic flux through the air gap. It has an angle velocity related to the angular velocity of the voltage applied. So, the flux in the air gap will than induce an electric current in the rotor. The "V/F control" can be completed to solve the control difficulties of IM depending on PWM technique for controlling the ON/OFF switches of a 3-ph inverter circuit [20]. Moreover, by vary the supply voltage the flux remains constant by simultaneously varying the supply frequency, therefore the ratio V/F remains constant. Hence, the developed torque can be kept constant over the entire speed range. So, this method is the most widely used in speed control of IM. Figure 2 shows 3-ph IM controlled by V/F control.
2.2 Closed loop V/F Control with SPWM Technique

Closed-loop control drive is desired in different applications where fixed operation are important. In this case, it has been used to be sure that the 3-ph IM operated with the desired speed [21]. This makes the three-phase VSI inverter that fed IM having a much-combined building in the typical of various automation operation [22]. To enhance the inverter execution in comparison with the requirements of working state, a system controller with preferable algorithm are presented. Therefore, in this paper, the SPWM has been utilized to control the inverter outputs. A 3-ph sine wave voltages of changeable frequency and amplitude "(control signals)" are comparison with a carrier wave in fixed amplitude \((V_{cr})\) and variable frequency "(\(f_r\))" to construction the suitable PWM signals to the inverter as presented in Figure 3. In order to implement a robust closed loop V/F control a "Proportional-Integral" (PI) controller is used as a feedback loop controller which is widely utilized in controlling industrial processes because of simplicity of design, flexibility, ability of control and high compatibility [23]. The general equation of the PI controller can be expressed as in (3). The schematic block diagram of 3-ph IM in "close-loop V/F control" is shown in Figure 4.

![Figure 2. Three-Phase IM controlled by V/F control strategy](image)

\[ u(t) = K_p \ e(t) + K_i \int e(t) \, dt \]  

(3)

where \(e(t)\) is the error, \(K_p\) is the proportional gain and \(K_i\) is the integral gain. In this work, the parameters of PI controller have been tuned by trial and error method. By this method through the close loop IM step response until a minimum of overshoot with good rise time and steady-state error is achieved.

![Figure 3. SPWM principle for 3-ph VSI.](image)
3. Vector IFOC Control Method

3.1 Principle Action of IFOC Method

In IFOC control of the 3-IM, \( i_d \) produced the required flux, while \( i_q \) represent the torque-producing [24,25]. Thus, according to this idea, the stator currents can be controlled independently and then, the IM will be controlled similar to the separately excited DC motor. There are two basic strategies of FOC: direct and indirect method [21-22]. The first type depends on measuring the flux in stator-rotor gap directly, while the second type estimates the magnetic flux from the applied voltages and resultant currents through the motor. So, the behavior of the indirect type very much depends on the parameters of the machine, as opposed to the direct type. Therefore, in this work, the IFOC is used to control the IM due to its higher performance as presented in Figure 5. IFOC overcome the problems in the scalar V/F control method due to provide a constant reference values for the torque and flux components of the IM. Furthermore, the rotor speed is detected by a speed sensor and compared with its reference and the error is passed through PI1 controller to obtain reference \( i_q \). Then, this current is compared with generated \( i_q \) and used to obtain \( V_q \) through the PI2. At the same time, \( V_d \) is obtained using the PI3 which its input the difference error between the reference and actual stator current \( i_d \). Also, the VSI inverter is provided by a suitable gate signals to control its power switches using SVPWM technique as described in section 3.2.

Figure 4. block diagram of close-loop V/F control of 3-ph IM.

Figure 5. IFOC control method of the IM.
3.2 SVPWM Technique

As discussed before, the 3-IM that operated with FOC control method can be controlled with SVPWM technique to provide a suitable gate signal to his VSI inverter. The VSI inverter has six semiconductor switches that control the supplied power of the inverter (S₁ to S₆), as shown in Figure 6 [25]. The SVPWM mechanism can be summarized as following:

**Step 1:** in this step, \( V_{\text{ref}} \), and the angle (\( \alpha \)) is calculated from \( V_d \) and \( V_q \).

**Step 2:** in this step, the time periods \( T_1 \), \( T_2 \), and \( T_0 \) are calculated according to the time division that indicated as following:

\[
T_1 = \frac{\sqrt{3} T_z |\bar{V}_{\text{ref}}|}{V_{dc}} \sin \left( \frac{n}{3} \pi - \alpha \right) \quad (4)
\]

\[
T_2 = \frac{\sqrt{3} T_z |\bar{V}_{\text{ref}}|}{V_{dc}} \sin \left( \alpha - \frac{n - 1}{3} \pi \right) \quad (5)
\]

\[
T_0 = T_z - (T_1 + T_2) \quad (6)
\]

where \( n \) is the sectors number (from 1 to 6)”, "the angle (\( \alpha \)) is \( 0 \leq \alpha \leq 60^\circ \) and \( T_z \) is the switching time (\( T_z = 1/f_z \)”). Figure 7 shown the timing period for sector 1.

**Step 3:** the switching time of each switching device (\( S_1 \) to \( S_6 \)) is calculated. Also, the time periods are apportioned into seven sub-periods, stratify zero state vector in part one for” (1/4th “). In the second and third parts stratify active state vectors for” (1/2th “), then stratify zero state vector again for” (1/4th “). This procedure is repeated in the other half of the switching period [24].

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**Figure 6.** the "sectors and switching vectors"
The principle operation of VSI inverter during SVPWM has divided into the eight switching vectors that generated by 3-ph VSI inverter have six non-zero (V1 to V6) which are divided the complex plane into six sectors of a hexagonal. While the center of the hexagonal is located by two zero vectors and the angle between the two non-zero vectors is 60°. In SVPWM, the "Vref" is generated by switching between two nearest active space vectors and one zero vector. Therefore, the voltage output from VSI is controlled by controlling the frequency value of (Vref).

4. Simulation Results and Discussion

In order to verify the comparison process of the performance between the scalar V/F and vector IFOC control methods, "MATLAB/ Simulink" software is used. Figure 8 shows the Simulink model for close-loop V/F control method. It consists of four blocks, PI controller block, VSI block, Vabc to Vd, Vq block and IM block.

The VSI consists of six-switch three-phase SPWM inverter, Input supply voltage of 3-phase, 380 V, 50 Hz, IM of 10hp, 380 V, 50 Hz, 1500 rpm, and 4 poles. Thus, the stator currents, rotor speed, and torque waveforms are shown in Figures 9-11, respectively. However, the rotor speed increases approximately linearly and reaches the reference speed at steady state. At starting period, the torque increases and reduces to a small value when the rotor speed reaches its reference. It is noticed that the developed torque increases when load torque is increased while the speed is hunted through a transient period and the line current is changed with load change.
Figure 9. the electromagnetic torque of 3-IM at step change of the load torque.

Figure 10. the rotor speed of 3-IM at step change of the load torque.

Figure 11. the rotor speed of 3-IM at the load torque (9) N.M.
On the other hand, the IFOC control is simulated with "MATLAB/Simulink" software as shown in Figure 13. In addition, SVPWM method is used to find the trigger signals for the VSI used. The same motor used in previous subsection is used in this simulation. In this paper, the IFOC control has been written in the "m-file function of MATLAB/Simulink". Also, the SVPWM control has built in "MATLAB" as discussed in section (3.2). And, the PI gains has been tuned using trial and error method and their parameters are shown in Table 1.

Figure 13. Simulink model using IFOC control 3-IM drive.

Table 1. PI controller parameter

| PI    | Kp  | Ki  |
|-------|-----|-----|
| PI₁   | 10  | 23.5|
| PI₂   | 0.91| 19.7|
| PI₃   | 3.4 | 18  |

The electromagnetic torque wave reaches to the steady state conditions with 17N.m for 0.3sec time as shown in Figure 14. Also, the motor response in Figure 15, has been reached to the stable condition after 0.3sec and reaches its state speed 1500 rpm. When a full load torque is applied at 1 sec and removed at 2 sec, the motor speed remains constant at rated speed with a small disturbance during 0.1sec.
Figure 14. The electromagnetic torque of 3-IM at step change of the load torque.

Figure 15. The rotor speed of 3-IM at step change of the load torque.

Figure 16. The line current of 3-IM at step change of the load torque.
Figure 17. the rotor speed for V/F and FOC controllers.

5. Comparison of the results of FOC and V/F techniques
Through the results, we note that the motor speed when applied a load of (17) N.M, it returns to (1500) R.P.M, when using the Field Oriented Control (FOC) Technique. While the motor speed when in use Scalar Control (V/f) becomes (1491) RPM, under the same operation conditions.

6. Conclusion
In this paper, both scalar V/F and vector IFOC control methods for drive the 3-IM are presented. The theoretical analysis for both methods have been done with their VSI inverter circuit control to show the differences between them. As result, the SPWM technique has been used to control the V/F inverter circuit, while the SVPWM technique has been used to control IFOC inverter circuit. The both methods are modelled and simulated using "Matlab/Simulink " software. The simulation results have been shown that the IFOC control method has good performance, precise speed control, and fast in response for step change in the load torque compared with the scalar V/F control.

For future work, two control methods (V/F and FOC) can be implemented inside the programmable logic controller (PLC) to control the speed of the IM.

References
[1] Suetake M, da Silva IN, Goedtel A. “Embedded DSP-based compact fuzzy system and its application for induction-motor speed control” IEEE Trans Ind. Electron, Vol.58 No., pp.750–60, 2011.
[2] Marino R, Tomei P, Verrelli CM. “An adaptive tracking control from current measurements for induction motors with uncertain load torque and rotor resistance” Elsevier Publisher Automatica, Vol. 44:pp.2593–9, 2008.
[3] M.S.Aspalli., Asha.R and P.V. Hunagund, "Three Phase Induction Motor Drive Using IGBTs and
Constant V/F method", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 1, No. 5, pp. 463-469, November, 2012.

[4] R. Thejaswini and R. Sindhuja, "Voltage/Frequency Control of an Induction Motor Using FPGA", International Journal of Emerging Engineering Research and Technology Vol. 2, No. 2, pp. 101-106, May 2014.

[5] Deepali Shirke and Haripriya Kulkarni, "Microcontroller Based Speed Control of Three Phase Induction Motor Using V/f method", International Journal of Scientific and Research Publications, Vol. 3, No. 2, pp. 1-6, February, 2013.

[6] Ahmed J. Chasib, Ali K. Abdulabbas and Adel A. Obed, "Independent Control of Two-PMSM Fed by Two SVPWM Inverters with Fault Tolerant Operation", Basrah Journal for Engineering Sciences, Vol. 16, No. 1, pp. 51-61, 2016.

[7] Dos Santos TH, Goedtel A, da Silva SAO, Suetake M. "Scalar control of an induction motor using a neural sensor less technique" Elsevier publisher, Elect. Power Syst. Res. Vol. 108, pp.322–30, 2014.

[8] Alsofyani IM, Idris NRN "A review on sensorless techniques for sustainable reliability and efficient variable frequency drives of induction motors" Elsevier publisher, Renew Sustain Energy Rev. Vol. 24, pp.111–21. 2013.

[9] Sarhan H. "Efficiency optimization of vector-controlled induction motor drive," Elsevier publisher Int. J Adv. Eng. Technol., Vol.7, pp.666. 2014.

[10] Ilango GS, Rajasekar N. "An improved energy saving v/f control technique for solar powered single-phase induction motor" Elsevier publisher Energy Convers Manag., Vol.50, pp.2913–8. 2009.

[11] Lee DC, Kim YS. "Control of single-phase-to-three-phase AC/DC/AC PWM converters for induction motor drives" IEEE Trans Ind. Electron Vol. 54, pp.797–804. 2007.

[12] Coman CE, Agarlit SC, Andreescu GD. "V/f control strategy with constant power factor for SPMSM drives, with experiments" Applied Computational Intelligence and Informatics (SACI) IEEE, In. Proceedings of the 8th International Symposium, pp.147-151; 2013.

[13] Lima F, Kaiser W, da Silva IN, de Oliveira AAA. Jr, "Open-loop neuro-fuzzy speed estimator applied to vector and scalar induction motor drives" Elsevier publisher, appl. Softw. Comput. 2014;21:469–80.

[14] Ali JA, Hannan MA, Mohamed A. "Rule-based fuzzy and V/f control for induction motor speed responses using SVPWM switching technique" Elsevier publisher, Przegląd Elektrotech, Vol. 91, pp.133–6, 2015.

[15] Gonzalez-Prieto, I., Duran, M. J., Aciego, J. J., Martin, C., & Barrero, F. "Model predictive control of six-phase induction motor drives using virtual voltage vectors" IEEE Transactions on Industrial Electronics, Vol.65. No.1, pp.27-37. 2017.

[16] Zeb, K., Ali, Z., Saleem, K., Uddin, W., Javed, M. A., & Christofides, N. "Indirect field-oriented control of induction motor drive based on adaptive fuzzy logic controller" Electrical Engineering, Vol.99, No.3, pp.803-815.2017.

[17] Bondarko VA. "Adaptive vector control of an induction motor on the basis of the method of recurrent objective inequalities" Autom. Remote Control, Vol.71, pp.1849–63. 2010.

[18] Pal, A., Das, S., & Chattopadhyay, A. K. "An improved rotor flux space vector based MRAS for field-oriented control of induction motor drives" IEEE Transactions on Power Electronics, Vol. 33, No.6, pp.5131-5141. 2017.

[19] Smith, A., Gadoue, S., Armstrong, M., & Finch, J. "Improved method for the scalar control of induction motor drives" IET electric power applications, Vol.7, No.6, pp.487-498.2013.

[20] R. Thejaswini and R. Sindhuja, "Voltage/Frequency Control of an Induction Motor Using FPGA", International Journal of Emerging Engineering Research and Technology Vol. 2, No. 2, pp. 101-106, May 2014.

[21] Ravi Prakash, Prof. Rishi Kumar Singh and Rajeev Ranjan Kumar, " Variable Voltage Variable Frequency Speed Control of Induction Motor Using FPGA- Xilinx", International Research Journal of Engineering and Technology, Vol.2, No. 03, pp. 1268-1273, July,2015.
[22] C. S. Sharma and Tali Nagwani, “Simulation and Analysis of PWM Fed Induction Motor Drive”, International Journal of Science, Engineering and Technology Research (IJSETR), Vol. 2, pp. 359-366, Feb. 2013.

[23] Madhavi L. Mhaisgawali and S. P. Muley, "Speed Control of Induction Motor using PI and PID Controller", IOSR Journal of Engineering (IOSRJEN), Vol. 3, No. 5, pp. 25-30, May, 2013.

[24] Sharma A, Singh A and Yadav P, "Analysis of 3 Level SVPWM Based Open Loop and Closed Loop V/F Control of Induction Motor", Int. J. of Eng. Research & Techno. (IJERT), Vol. 4, No. 4, pp. 1362-1365, 2015.

[25] Gerald M B J and Mahadevan K, "A Reliable Vector Control Method: IFOC for Three Phase Induction Motor Drives Using SVPWM", ARPN J. of Eng. and App. Sci., Asian Research Publishing Network, Vol.10, No. 6, pp. 2670-2674, 2015.