Starting of Loaded Induction Motors Using Variable-Frequency Drives

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Abstract - Most of the papers dealing with variable frequency drive (VFD) are concerned with speed control rather than the starting period. This paper is mainly concerned with the starting period. The paper presents a proposed control strategy for VFD to enhance the performance of induction motors during the starting period. The main objective of the proposed control scheme is to provide high starting torque while the starting current is maintained within acceptable limits. This is implemented up to the rated speed. Beyond the rated speed, the objective is to target the steady-state operating point following the nominal torque-speed characteristic of the motor. The capabilities of the proposed control scheme in the two regions are examined, and a good performance is confirmed. This scheme is suitable for motors which need high starting torque and have several starting times per day.

Index Terms – Induction motor, starting current, starting torque, variable-frequency drive.

I. INTRODUCTION

Starting of three-phase induction motors is the main topic of many papers [1]–[5]. The methods of starting are direct-online starting, reduced-voltage starting (electromechanical and solid state) and variable-frequency drive (VFD) starting [3], [5]. Direct-online starting method is accompanied with high starting torque and large starting current. High starting torque may cause large stress on the mechanical-system components, and large starting current may cause voltage dips at the point of common coupling with other loads [1], [5]. Reduced-voltage starting methods reduce the starting torque and current. These methods are used to start loads of low starting-torque requirement, such as fans and pumps. However, in case of high-inertia loads, reducing the starting torque increases the acceleration time [3], [5]. VFDs give the most control ability of starting behavior for any type of loads. VFDs, also, give the highest torque per ampere ratio. Therefore, VFD starting is most suitable for starting loads of high starting-torque requirement [5]. The importance of higher cost and space requirement of VFDs is reduced in case of "heavy to start" industrial loads [3]. However, studies on motor starting using VFDs are extremely limited [1]. In [5], a comparison study of all methods of starting is presented. In [1], the factors affecting the motor starting for direct-online starting and VFD starting are studied, where the voltage per hertz control of VFD is considered. However, these studies are based on the equivalent circuit of induction motors. The control in the proposed method is based on the transient model and, thus, it provides better dynamic performance.

In this paper, a proposed control scheme of VFD to start three-phase induction motors is studied. In this scheme, a pulse-width modulation (PWM) converter is controlled to regulate the starting current of the three-phase induction motor (IM) close to an acceptable-overload value, and after that to control the developed torque of the IM according to its reference value. In the control scheme, also, the stator-flux linkage is controlled according to its reference value. Simulation results are obtained to examine the performance of the proposed control scheme for different load types.

II. MODELING OF THREE-PHASE INDUCTION MOTOR

Voltage equations of the IM in the stationary reference frame are given by [6]:

\[
\begin{bmatrix}
\frac{d\omega_m}{dt} \\
\frac{d\omega_s}{dt} \\
0
\end{bmatrix} = \begin{bmatrix}
R_q + pL_s & 0 & pL_m \\
0 & R_r + pL_s & 0 \\
-pL_m & 0 & -R_r - pL, \\
\omega_s L_m & -\omega_s L_m & \omega_s L_r
\end{bmatrix} \begin{bmatrix}
i_q \\
i_r \\
i_m
\end{bmatrix}
\]

where

- \( \omega_s \) = electrical angular speed of the IM
- \( u_{qs}, u_{qs} \) = q-axis and d-axis components of stator voltages
- \( L_s, L_r \) = self inductances of the stator and rotor windings
- \( i_{qs}, i_{qs} \) = q-axis and d-axis components of stator currents
- \( R_s, R_r \) = stator and referred rotor resistances
- \( L_{dx}, L_{dx} \) = stator and referred-rotor leakage inductances
- \( L_m \) = magnetizing inductance.

The equation of motion is given by

\[
\frac{d\omega_m}{dt} = \frac{T_e - T_L - B_m \omega_m}{J}
\]

where

- \( \omega_m \) = mechanical angular speed of the IM
- \( T_e \) = developed torque of the IM
- \( J \) = number of pole pairs
- \( T_L \) = load torque
- \( B_m \) = friction coefficient
- \( J \) = inertia
III. PROPOSED CONTROL SCHEME OF VFD

The proposed control scheme of the system is shown in Fig. 1. In this figure, the stator-voltage vector \( \mathbf{u}_s \) and stator-current vector \( \mathbf{i}_s \) in the stationary reference frame, and the rotor speed \( \omega_m \) are used to estimate the reference stator voltages \( u_{qs-ref} \) and \( u_{ds-ref} \). These reference voltages are required by a PWM technique to determine the switching states of the PWM converter. In this paper, the space-vector PWM (SVPWM) technique is used.

A. Calculation of Stator-Flux

The magnitude of the stator flux linkage \( \lambda_s \) and the angle of the stator flux linkage \( \theta_\lambda \) in the stationary reference frame are determined as [7]:

\[
\lambda_{qs} = \int (u_{qs} - R_s i_{qs}) \, dt , \quad (7)
\]

\[
\lambda_{ds} = \int (u_{ds} - R_s i_{ds}) \, dt , \quad (8)
\]

\[
\lambda_s = \sqrt{\lambda_{qs}^2 + \lambda_{ds}^2} , \quad (9)
\]

\[
\theta_\lambda = \tan^{-1} \left( \frac{\lambda_{qs}}{\lambda_{ds}} \right) . \quad (10)
\]

where \( \lambda_{qs} \) and \( \lambda_{ds} \) are q-axis and d-axis components of stator flux linkage respectively.

B. Reference Stator Currents

The q-axis and d-axis components of reference stator currents are obtained in the stator-flux frame. The reference current \( i_{ds(\lambda)-ref} \), where the subscript \( \lambda \) means stator-flux frame, can be obtained as follows:

\[
i_{ds(\lambda)-ref} = \frac{\lambda_s - L_n i_{ds(\lambda)}}{L_m} \quad (12)
\]

Then, the reference stator current \( i_{qs(\lambda)-ref} \) can be obtained by substituting the values of \( \lambda_{qs-ref} \) and \( i_{ds(\lambda)} \) in (11). Thus,

\[
i_{qs(\lambda)-ref} = \frac{\lambda_{qs-ref} - L_n i_{qs(\lambda)}}{L_s} \quad (13)
\]

where \( \lambda_{qs-ref} \) is the reference stator-flux linkage.

The reference current \( i_{qs(\lambda)-ref} \) can be obtained as follows:

The rated speed \( \omega_{m,\text{rated}} \) is the motor speed at rated load. Motor loads less than the rated load lead to higher motor speeds. Therefore, the rated speed is the minimum steady-state speed. For the rotor speeds less than \( \omega_{m,\text{rated}} \), maximum-possible stator currents are required to obtain high starting torque and low acceleration time. An allowable overload current of VFD can be 150% for 1 minute [8], [9]. The reference current \( i_{qs(\lambda)-ref} \) can be obtained such that the magnitude of the stator current \( |\mathbf{i}_s| \) equal to 1.5 times its rated value \( |\mathbf{i}_{s,\text{rated}}| \). Thus,
\[ i_{qs(\text{ref})} = \sqrt{\left(1.5 \times \left|i_{s(\text{rated})}\right|\right)^2 - \left(i_{ds(\text{ref})}\right)^2} \quad \omega_m < \omega_{m,\text{rated}} \] (14)

For the rotor speed higher than or equal to \( \omega_{m,\text{rated}} \), the objective of the control scheme is to follow the nominal torque-speed characteristic of the IM. This is achieved by choosing the current \( i_{qs(\text{ref})} \) as follows:

The developed torque \( (T_e) \) in the stator-flux frame can be given by [6]

\[ T_e = \frac{3}{2} P \lambda_s i_{qs(\text{ref})} \] (15)

The current \( i_{qs(\text{ref})} \) can be obtained by substituting the values of \( \lambda_s, \text{ref} \) and \( T_{\text{ref}} \) in (15). Thus,

\[ i_{qs(\text{ref})} = \frac{T_{\text{ref}}}{3P \lambda_s, \text{ref}} \quad \omega_{m, \text{rated}} \leq \omega_m \leq \omega_{ms} \] (16)

where \( \omega_{ms} \) is the synchronous speed at the rated frequency.

The reference torque-speed \( (T_{\text{ref}} - \omega_m) \) characteristic is the same as the developed torque-speed \( (T_{\text{e,\text{chara}}} - \omega_m) \) characteristic of the IM, estimated from the steady-state equivalent circuit at rated voltage and frequency. Thus,

\[ T_{\text{ref}} = T_{\text{e,\text{chara}}} (\omega_m) \quad \omega_{m, \text{rated}} \leq \omega_m \leq \omega_{ms} \] (17)

To prevent any oscillation near \( \omega_{m, \text{rated}} \), a condition is used such that once \( \omega_{m, \text{rated}} \) is reached, eqn. (16) is used to calculate \( i_{qs(\text{ref})} \) even if the speed is slightly decreased around \( \omega_{m, \text{rated}} \).

C. Reference Stator-Flux Linkage

During the starting of IM, the highest torque per ampere ratio is required. Therefore, the reference flux linkage is taken equal to the rated value. After starting period, the reference torque \( (T_{\text{ref}}) \) is taken equal to the developed torque \( (T_{\text{e,\text{chara}}}) \) estimated at rated voltage and frequency, (17). Therefore, the reference flux linkage is also taken equal to the rated value. Thus:

\[ \lambda_s, \text{ref} = \lambda_{s, \text{rated}} \quad 0 \leq \omega_m \leq \omega_{ms} \] (18)

D. Current Controllers

The current controllers are PI controllers. The input of these controllers are the differences between the reference currents \( i_{qs(\text{ref})} \) and \( i_{ds(\text{ref})} \) and the stator currents. The output of these controllers are the reference-stator voltages \( u_{qs(\text{ref})} \) and \( u_{ds(\text{ref})} \). The transfer function of PI controller is given by

\[ G(s) = K_p + \frac{K_i}{s} \] (19)

where \( K_p \) and \( K_i \) are proportional and integral gains respectively.

The values of these gains are determined using trial and error, and are given in the Appendix.

IV. Simulation Results

The system is simulated using MATLAB/SIMULINK. Results are obtained for two different loads. The first load is a heavy-to-start load, and its torque \( (T_{L1}) \) is equal to the rated torque of the IM. The second load is a high-inertia load, and its torque \( (T_{L2}) \) is proportional to the square of the angular speed of the IM and reaches the rated-torque value at steady state. Typical Torque-speed characteristics of the IM and the two loads are shown in Fig. 2. Data of simulated system are given in the Appendix.

Results for \( T_{L1} \) in case of direct-online starting of the IM are shown in Fig. 3. Fig. 3(a) shows that the starting current reaches to about 8 times the steady-state current. The phase voltage is shown in Fig. 3(b). Fig. 3(c) shows that the transient developed torque is a large fluctuated torque. Fig. 3(d) shows that the steady-state speed is reached after about 1.2 s.

Results for \( T_{L1} \) in case of VFD starting of the IM with the proposed control scheme are shown in Fig. 4. Fig. 4(a) shows that the starting current is regulated near to the preset value, 1.5 times the rated current. Fig. 4(b) shows the phase voltage applied by the PWM converter. Fig. 4(c) shows that the high transient torque oscillations are eliminated and a nearly constant starting torque, about 1.5 times the rated torque, is obtained. The developed torque has very small values at the beginning of operation because the stator flux is not raised to its final value instantly. Fig. 4(d) shows that the steady-state speed is reached after about 1.4 s. Thus, Fig. 4 shows that the starting current and torque are reduced to acceptable levels without reducing the starting capability or considerable increasing of the acceleration time.

Results for \( T_{L2} \) in case of direct-online starting of the IM are shown in Fig. 5. Fig. 5(a) shows that the starting current reaches to about 8 times the steady-state current. The phase voltage is shown in Fig. 5(b). Fig. 5(c) shows that the transient developed torque is a large fluctuated torque. Fig. 5(d) shows that the steady-state speed is reached after about 1.3 s.

Results for \( T_{L2} \) in case of VFD starting of the IM with the proposed control scheme are shown in Fig. 6. Fig. 6(a) shows that the starting current is regulated near to the preset value, 1.5 times the rated current. Fig. 6(b) shows the phase voltage applied by the PWM converter. Fig. 6(c) shows that the high transient torque oscillations are eliminated and a nearly constant starting torque, about 1.5 times the rated torque, is obtained. The developed torque has very small values at the beginning of operation because the stator flux is not raised to
Fig. 3  Results of direct-online starting of the IM when loaded with $T_{L1}$.

Fig. 4  Results of VFD starting of the IM when loaded with $T_{L1}$. 
Fig. 5 Results of direct-online starting of the IM when loaded with $T_{L2}$.

Fig. 6 Results of VFD starting of the IM when loaded with $T_{L2}$. 
Dynamic performance is examined by changing the load $T_{L1}$ after reaching to the steady state, at the operating point ($P_1$), to half of the rated value, which has the steady-state operating point ($P_2$) as shown in Fig. 7. Dynamic results for both uncontrolled IM and when the proposed control scheme is applied are shown in Figs. 8 and 9 respectively. It can be seen from these figures that the proposed scheme provides a fast and smooth transfer from the point $P_1$ to the point $P_2$. No overshoots occur either in torque or speed.

Fig. 7 Changing of the load $T_{L1}$ to half of the rated value.

Fig. 8 Results of uncontrolled IM when the load is changed from $T_{L1}$ to half of the rated value at time equal to 3 s.

Fig. 9 Results of IM with the proposed scheme when the load is changed from $T_{L1}$ to half of the rated value at time equal to 3 s.
V. CONCLUSION

The paper proposed a control strategy of VFD to enhance the performance of induction motors during the starting period. The main objective is to maximize the starting torque and limit the starting current. To achieve this objective, the stator flux is maintained at its rated value, by controlling the direct component of the stator current, to ensure better utilization of the motor. On the other hand, the quadrature component of the stator current is controlled according to the proposed strategy.

The control strategy is divided into two regions:
1) Below the rated speed, the flux is maintained at its rated value and the stator current is maintained at its permitted overload value. Thus, almost a constant high torque is obtained all through this period. This scheme is thus suitable for motors which need heavy starting torque or for motors which start many times per day.
2) Beyond the rated speed, the flux is maintained at its rated value and the motor is controlled to follow the nominal torque-speed characteristic of the motor. This allows for a gradual descending of the stator current. This may also allows for a smooth change from one operating point to another.

The capability of the proposed control scheme is verified with two different loads; namely a heavy-to-start load and a high inertia load.

REFERENCES

APPENDIX
A. Motor Data:
Y-connected, 100 hp, 460 V, 107 A, 1764 rpm, 4 poles, 60 Hz squirrel-cage induction motor, and has the following parameters:
\[ R_s = 0.06 \, \Omega, \quad R_r = 0.05 \, \Omega, \quad L_{ls} = 0.435 \, \text{mH}, \quad L_{lr} = 0.435 \, \text{mH} \text{ and} \quad L_m = 22.6 \, \text{mH}. \]
Motor inertia = 0.85 kg.m².

B. Motor-load Data:
\[ T_{L1} = 403.8 \, \text{N.m}, \]
Total inertia in case of \( T_{L1} = 1.1 \, \text{kg.m²}, \)
\[ T_{L2} = 0.01185 \omega_m \, \text{m²}, \]
Total inertia in case of \( T_{L2} = 3.55 \, \text{kg.m²}, \)
Total friction coefficient = 0.011 N.m.s/rad.

C. PI controllers Data:
The two PI controllers have the same gain values: \( K_p = 20 \) and \( K_i = 40. \)

D. Other Data:
DC-bus voltage = 650 V,
Switching frequency of PWM converter = 10 kHz.