Investigation of Induction Motors Starting and Operation with Variable Frequency Drives

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Abstract — **Induction machines are most widely used in various industrial applications. Variable frequency drives (VFDs) provide flexibility in speed control and improve starting and operating performance of induction motors. However, investigation of induction motor starting with VFDs is not considerably carried out. In some cases motor performance is different from that expected, which causes confusion to field engineers. In this paper, theoretical derivation of starting parameters of induction motors using the equivalent circuit is conducted for cross-line and VFD starting. Cross-line starting is considered as one special scenario of VFD starting with a starting frequency of 60Hz. An industrial distribution system in the oil field is used as a case study for the cross-line starting. Factors that could significantly affect the starting performance are studied. A two-pole squirrel-cage induction motor is used in the case study for VFD starting. The relationship between the starting frequency, starting current and required starting voltage is derived mathematically. It is found that although both starting voltage and current are functions of starting frequency the required starting voltage shows large variation at the lower starting frequency between 2Hz – 10Hz. The induction motor torque characteristics of speed control during normal operation with VFDs are also discussed.**

Keywords - Variable frequency drives, induction motors, motor starting, cross-line starting, torque

I. INTRODUCTION

Motor staring has been investigated for decades [1-11]. Traditional motor starting methods for induction motors are the cross-line starting and reduced voltage starting. With the advanced technology development of Variable Frequency Drives, VFDs are widely used in various industrial areas and introduce flexible starting and operation features. Understanding motor starting with variable frequency drives becomes essential for proper system operation, troubleshooting and maintenance.

The cross-line starting method applies the network voltage and frequency to the motor terminal. It is the simplest motor starting method with the lowest equipment cost. The motor generates the highest starting torque and the highest inrush current compared to other starting methods, and provides the shortest acceleration time. Such high starting torque is desired for a high inertia load, but will put large amount of stress on the mechanical parts of the equipment. Application of this method must be carefully evaluated if the possibility of mechanical system damage exists. The starting current is typically 5 to 7 times of the motor full-load current. This could cause large voltage sag during the starting transient and disturb the operation of distribution network [1-11]. Reduced voltage starting method is also used for the induction motor starting, but it is not within the scope of this paper.

Variable frequency drives are widely used in industry. The motor is started using a low starting frequency of the drive, such as 7Hz, in order to reduce the starting current and voltage sag introduced to the power system. Typical starting current with a VFD is about 1.5 times motor full-load current, which is 4 times smaller than that of the cross-line starting. VFD starting method provides the best overall control and flexibility during the motor starting but with higher cost.

The cross-line starting is a mature topic. However, theoretical investigation regarding the motor starting with VFDs has not been considerably investigated. Electrical parameters of induction motors using the cross-line starting and VFD starting are not compared although they are practically linked together. In this paper theoretical derivation is carried out based on the traditional equivalent circuit of induction motors. Calculations of the starting voltage, starting current and starting torque are derived mathematically for both starting methods. Case studies for the cross-line and VFD starting are performed and analyzed.

II. STARTING PARAMETERS OF INDUCTION MOTORS

A. *Cross-Line Starting*

Cross-line starting applies full voltage at rated frequency to the motor terminal to start an induction motor. If there are no electrical or mechanical constraints, it can be typically used in most cases. The traditional equivalent circuit of induction motors is shown in Figure 1.

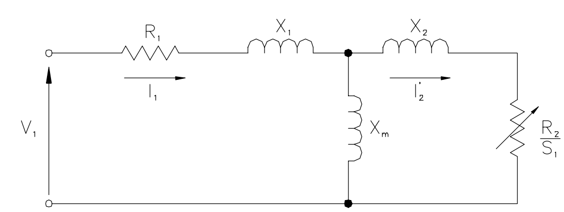

Figure 1 Equivalent circuit of Induction motors

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Electrical parameters of induction motors during normal operation and motor starting can be calculated using the equivalent circuit. Generally, the motor impedance Z_{motor}, stator current I_1, rotor current I_2' and the electromagnetic torque T_{em} can be calculated using the following equations:

$$Z_{motor} = (R_1 + jX_1) + \frac{\left(\frac{R_2}{S_1} + jX_2\right)(jX_m)}{\frac{R_2}{S_1} + j(X_2 + X_m)} \quad (1)$$

$$I_1 = \frac{V_1}{Z_{motor}} = \frac{V_1}{(R_1 + jX_1) + \frac{\left(\frac{R_2}{S_1} + jX_2\right)(jX_m)}{\frac{R_2}{S_1} + j(X_2 + X_m)}} \quad (2)$$

$$I_2' = \frac{jX_m}{\frac{R_2}{S_1} + j(X_2 + X_m)} I_1 \quad (3)$$

$$\Omega_1 = \frac{2\pi n_1}{60} = \frac{4\pi f_1}{p} \quad (4)$$

$$T_{em} = \frac{P_{em}}{\Omega_1} = \frac{\frac{p_{cu2}}{S_1}}{\Omega_1} = \frac{3I_2'^2 R_2}{\Omega_1 S_1} \quad (5)$$

Where

- R_1 and X_1 – resistance and leakage reactance of the stator,
- R_2 and X_2 – resistance and leakage reactance of the rotor referred to the stator side,
- X_m – magnetizing reactance,
- Z_{motor} – motor equivalent impedance,
- V_1 – voltage per phase at the motor terminal with the power system frequency of 50Hz/60Hz,
- I_1 – stator current,
- I_2' – rotor current referred to stator side,
- T_{em} – electromagnetic torque,
- f_1 – starting frequency,
- S_1 – slip,
- p – pole number of induction motors.

The electromagnetic torque can be expressed as a function of the motor terminal voltage per phase and also as a function of the stator current. It can be derived by submitting Equations (2), (3) and (4) in Equation (5) as follows:

$$T_{em} = \frac{3pR_2}{4\pi f_1 S_1} \left| \frac{jX_m}{\left(\frac{R_1 R_2}{S_1} - X_1 X_2 - X_m(X_1 + X_2)\right) + j\left(R_1 X_2 + \frac{R_2 X_1}{S_1} + X_m\left(R_1 + \frac{R_2}{S_1}\right)\right)} \right|^2 \times V_1^2 \quad (6)$$

$$T_{em} = \frac{3pR_2}{4\pi f_1 S_1} \left| \frac{jX_m}{\frac{R_2}{S_1} + j(X_2 + X_m)} \right|^2 \times I_1^2 \quad (7)$$

Although the torque is the ultimate parameter to start the motor and turn electrical energy into mechanical force, the motor terminal voltage and stator current can be easily measured by field engineers. Therefore, the motor terminal voltage, stator current and electromagnetic torque are used to investigate motor starting. The starting voltage, starting current and starting torque can be calculated based on Equations (1)-(7) considering the slip S_1 is equal to 1. Motor starting voltage V_{st} and starting current I_{st} for the cross-line starting can be determined by

$$V_{st} = V_1 \quad (8)$$

$$I_{1st} = \frac{V_1}{(R_1 + jX_1) + \frac{(R_2 + jX_2)(jX_m)}{R_2 + j(X_2 + X_m)}} \quad (9)$$

The starting torque as the function of the motor terminal voltage and starting current can be expressed as follows:

$$T_{st} = \frac{3pR_2}{4\pi f_1} \left| \frac{jX_m}{(R_1 R_2 - X_1 X_2 - X_m(X_1 + X_2)) + j(R_1 X_2 + R_2 X_1 + X_m(R_1 + R_2))} \right|^2 \times V_1^2 \quad (10)$$

$$T_{st} = \frac{3pR_2}{4\pi f_1} \left| \frac{jX_m}{R_2 + j(X_2 + X_m)} \right|^2 \times I_{1st}^2 \quad (11)$$

Due to the constant frequency f_1 of the power supply for the cross-line starting, the resistance and reactance in Equations (10) and (11) are constant. The starting torque is strictly proportional to the square of the motor terminal voltage and also proportional to the square of the motor starting current.

B. Motor Starting with Variable Frequency Drives

Variable frequency drives allow the motor to start and operate on a constant volt per hertz level, i.e.,

$$\frac{Voltage}{Frequency} = \frac{Volts}{Hz} = cons\tan t \quad (12)$$

Therefore, the voltage and frequency applied to the motor terminal are varied correspondingly and their ratio is constant. For example, if the motor terminal voltage is 480V at 60Hz, the practical motor terminal voltage at 6Hz with a VFD is 48V.

The equivalent circuit of induction motors can be used to study the VFD starting. However, the voltage applied to the motor terminal in this case should be calculated using Equation (12). The practical motor terminal voltage $V_{1\text{-}VFD}$ using VFD starting can be determined by

$$V_{1-VFD} = \frac{V_1}{System\ Frequency} \times Starting\ Frequency = \frac{V_1}{f_{sys}} \times f_1 \quad (13)$$

where

- f_{sys} – system frequency, 50Hz/60Hz
- f_1 – starting frequency of VFDs
- V_1 – voltage per phase at the motor terminal with system frequency of 50Hz/60Hz.

For the cross-line starting parameters in Equations (9) and (10), the motor starting frequency is equal to the system frequency, the motor terminal voltage is V_1. Therefore, cross-line starting is a special scenario of VFD starting.

In the equivalent circuit of induction motors, the resistances R_1 and R_2 are constant values and independent of the frequency. However, the reactance values X_1, X_2 and X_m are function of the frequency, which can be calculated as follows:

$$X_1 = 2\pi f_1 L_1 \quad (14)$$

$$X_2 = 2\pi f_1 L_2 \quad (15)$$

$$X_m = 2\pi f_1 L_m \quad (16)$$

where

L_1, L_2 and L_m – Stator leakage inductance, rotor leakage inductance referred to the stator, and magnetizing inductance, respectively. Inductances are considered to be constant.

f_1 – frequency at the motor terminal

For the cross-line starting f_1 is the system frequency of 50Hz/60Hz. For the VFD starting f_1 is the starting frequency of the drive such as 7Hz, 10Hz etc.

Substituting Equations (13)-(16) in Equations (9)-(11), the starting voltage and starting current for the VFD starting can be calculated as follows:

$$V_{st-VFD} = \frac{V_1}{System\ Frequency} \times Starting\ Frequency = \frac{V_1}{f_{sys}} \times f_1 \quad (17)$$

$$I_{1st-VFD} = \frac{\left(\frac{V_1}{f_{sys}} \times f_1\right)}{(R_1 + j2\pi f_1 L_1) + \frac{(R_2 + j2\pi f_1 L_2)(j2\pi f_1 L_m)}{R_2 + j2\pi f_1 (L_2 + L_m)}} \quad (18)$$

The starting torque as a function of the motor terminal voltage or starting current for the VFD starting can be determined by

$$T_{st} = \frac{3pR_2}{4\pi f_1}\left|\frac{jX_m}{(R_1R_2 - X_1X_2 - X_m(X_1 + X_2)) + j(R_1X_2 + R_2X_1 + X_m(R_1 + R_2))}\right|^2 \times \left(\frac{V_1}{f_{sys}} \times f_1\right)^2$$
$$= \frac{3pR_2}{4\pi f_1}\left|\frac{jX_m}{[R_1R_2 - (2\pi f_1)^2(L_1L_2 + L_mL_1 + L_mL_2)] + j2\pi f_1[R_1L_2 + R_2L_1 + L_m(R_1 + R_2)]}\right|^2 \times \left(\frac{V_1}{f_{sys}} \times f_1\right)^2 \quad (19)$$

$$T_{st} = \frac{3pR_2}{4\pi f_1}\left|\frac{jX_m}{R_2 + j(X_2 + X_m)}\right|^2 \times I_{1st-VFD}^{\ 2}$$
$$= \frac{3pR_2}{4\pi f_1}\left|\frac{j2\pi f_1 L_m}{R_2 + j2\pi f_1 (L_2 + L_m)}\right|^2 \times I_{1st-VFD}^{\ 2} \quad (20)$$

Equations (19) and (20) indicate that the starting torque for VFD starting is not only determined by the motor terminal voltage and motor starting current, but also a function of the starting frequency of the drive.

III. CASE STUDY FOR CROSS-LINE STARTING

A case study for a 4.16KV motor control center (MCC) of an industrial distribution system in the oil field is used to investigate the cross-line starting and its influence on the motor protection and distribution system.

The single-line diagram of the MCC is shown in Figure 2. It consists of two water injection pumps rated at 1750HP and 1500HP. Nuisance tripping of the breaker in the MCC was experienced when one water injection pump started while the other pump was in operation. The second pump was able to start only after the first pump was started and stabilized after 30 minutes of operation. The motor starting and protective device coordination at the MCC bus were performed in order to solve the problem. It was found that the problem was caused by improper relay settings interfering with the motor starting transient. The time-current characteristic (TCC) curve of the motor starting was overlapping with the TCC curve of the relay. The relay tripped the whole MCC when attempts to start the motor were made.

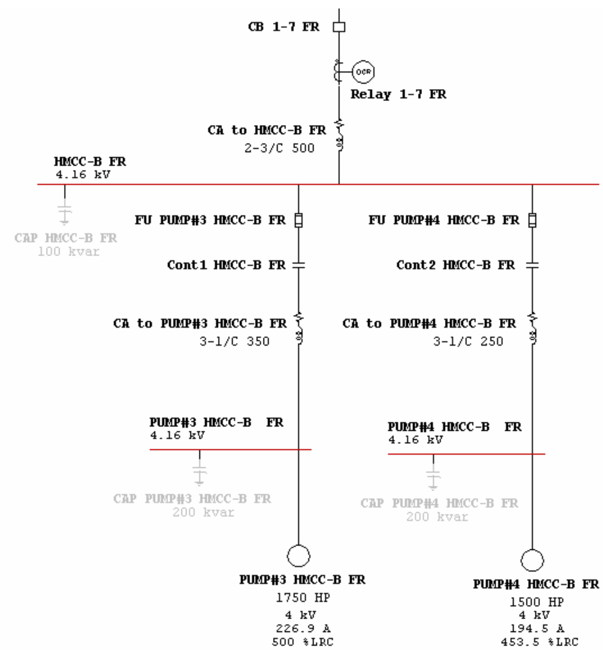

Figure 2 Single-line diagram of the 4.16KV motor control center with two water injection pumps

The simulation was performed for the case where 1750HP pump was started with 1500HP pump in operation. It was assumed that the locked rotor current was 5 times nameplate full-load current for 1750HP pump. The moment of inertia WR^2 is assumed to be 502 lb-ft^2. A power study of the system indicated that the MCC bus voltage before the motor starting was 93.54% of nominal bus voltage. The simulated motor electromagnetic torque and load torques, acceleration torque, motor current and MCC bus voltage are shown in Figures 3-6. The total motor starting time is 5.8 seconds using the 502 lb-ft^2 inertia and pre-starting MCC bus voltage equal to 93.54% of nominal bus voltage.

The acceleration torque shown in Figure 4 is the difference between the motor electromagnetic torque and load torque curves (Figure 3). Water injection pumps are centrifugal pumps. The motor starting current (Figure 5) is slowly decreased during 0-5 seconds and quickly drop to full-load amps after that. The MCC main bus voltage (Figure 6) decreased to 86.45% at the starting transient, and slowly recovered and stabilized at 92.67%. It is about 1% lower than

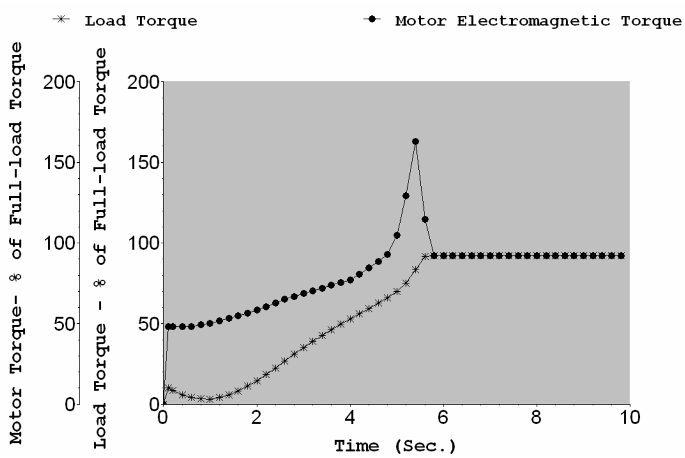

Figure 3 Load torque and motor electromagnetic torque during the motor starting for 1750HP water injection pump

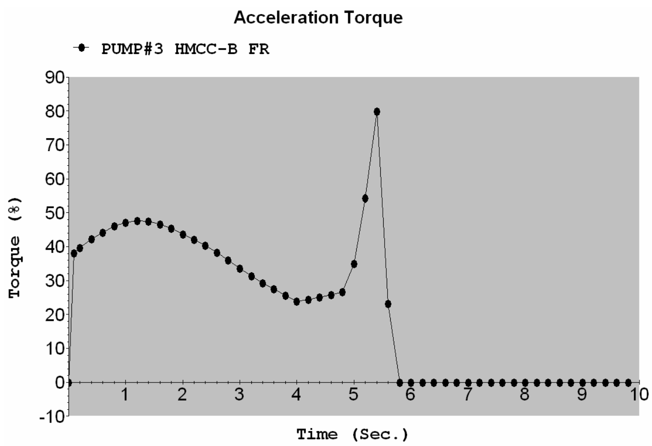

Figure 4 Acceleration torque during the motor starting for 1750HP water injection pump

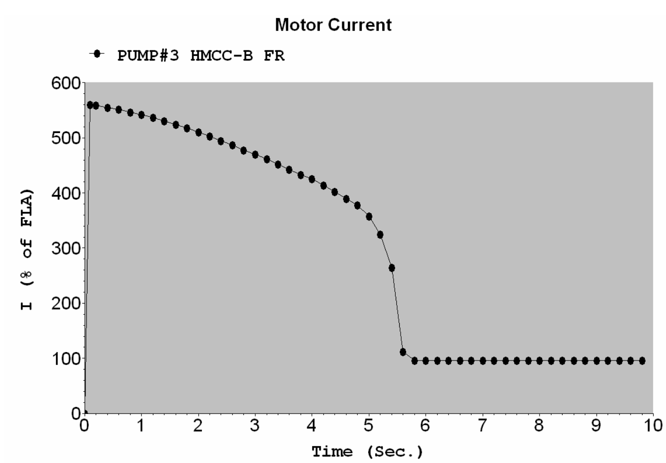

Figure 5 Motor starting current for the 1750HP water injection pump

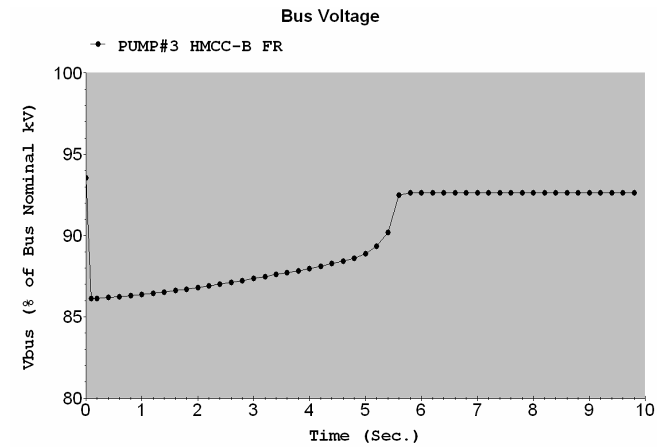

Figure 6 Voltage at the MCC main bus, HMCC-B FR

the bus voltage before the motor starting. Since there are no long cables between the motor terminal and the MCC main bus, the pre-starting MCC bus voltage can be considered equal to the motor terminal voltage.

Two external factors that could significantly affect the motor starting time are:

- Inertia of loads, and
- Motor terminal voltage, which is the same as the pre-starting MCC bus voltage in this case study.

Different inertia of loads and pre-starting MCC bus voltages were used for 1750HP pump in the motor starting simulation to investigate such influence. Table I summarizes different MCC bus voltages result in different motor starting time. Table II indicates that inertia of loads will determine the motor starting time using the same pre-starting bus voltage.

TABLE I. MCC BUS VOLTAGE VS. MOTOR STARTING TIME

MCC Bus Voltage in % of nominal bus voltage	Starting Time in Seconds
93.54	5.8
94.14	5.4
95.26	4.6

TABLE II. INERTIA OF LOADS VS. MOTOR STARTING TIME

WR^2, Moment of Inertia of loads, in lb-ft^2	Starting Time in Seconds	MCC Bus Voltage in % of nominal voltage
502	5.8	93.54
402	4.8	93.54
302	3.6	93.54
202	2.4	93.54

IV. CASE STUDY FOR VFD STARTING

A 2-pole squirrel-cage induction motor is used as a case study for the motor starting with VFDs. Nameplate data for the motor are 3764V@87Amps@540HP@60Hz. It is assumed the locked rotor current is 5 times the nameplate current for the cross-line starting. The resistance and reactance of the motor in p.u., in Ohm and mH are given in Tables III and IV.

TABLE III. IMPEDANCE OF INDUCTION MOTOR IN P.U.

R_1	0.01885 p.u.
X_1	0.04355 p.u.
X_m	1.8315 p.u.
R_2	0.03185 p.u.
X_2	0.07345 p.u.

TABLE IV. IMPEDANCE OF INDUCTION MOTOR IN OHMS AND MH

R_1	0.4708485 Ohms
L_1	2.88554 mH
L_m	121.3516 mH
R_2	0.795572 Ohms
L_2	4.86666 mH

The starting torque requirement from a motor is determined by the nature of the load. Centrifugal pumps typically require 30% of the running torque or less to start. Once the pump begins to turn, the torque drops a little and then increases with the square of the speed. NEMA requires that a standard motor should have adequate torque at 90% and 100% rated voltage to start a fully loaded pump, fan or compressor. The cross-line starting will produce the greatest torque, typically 1.5 to 2.5 times the full load running torque. For the worst case scenario the motor starting is for high inertia loads instead of centrifugal pumps, the required starting torque using VFD starting could be equal to the starting torque of the cross-line starting. In order to obtain the same starting torque, the starting current and the required starting voltage for VFD starting are calculated.

The starting current as a function of starting frequency of VFDs is shown in Figure 7. The starting current is expressed by times nameplate motor current. It is found that starting currents range between 1.5 to 2.1 times rated current for starting frequencies between 5Hz and 10Hz. For the starting frequency lower than 5Hz the motor will require less than 1.5 times rated current to start. At 2Hz only the rated motor current is required to generate the same starting torque. Figure 7 also shows the motor starting current is 5 times rated current at 60Hz starting frequency.

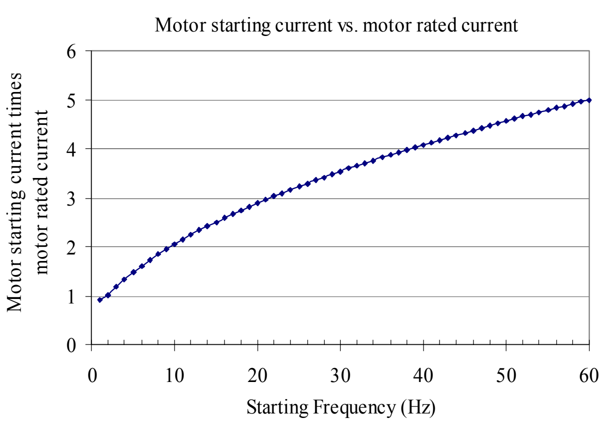

Figure 7 Motor starting current times rated current as a function of the starting frequency of VFDs

The required starting voltage at the motor terminal as a function of starting frequency of VFDs is calculated. It is expressed by times motor rated voltage at 60Hz as shown in Figure 8. It varies almost linear with the starting frequency of VFDs to generate the same amount starting torque.

The required starting voltage is also expressed by times the practical motor terminal voltage with VFDs as shown in Figure 9. This voltage is converted from motor rated voltage at 60Hz to the corresponding starting frequency using Equation (13). Figure 9 indicates the motor requires more voltage to start when starting frequency of VFDs is 10Hz or lower. At 5Hz starting frequency, the motor needs 1.4 times of the converted rated voltage to produce the same starting torque. At 2Hz starting frequency, 2.2 times of the converted rated voltage is required at the motor terminal. The required starting voltage shows large variation at the lower starting frequency between 2Hz – 10Hz. This explains why the voltage boost function of VFDs is required during motor starting for some applications.

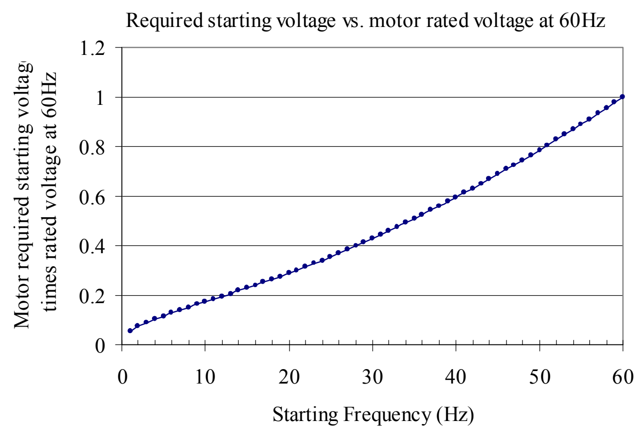

Figure 8 Required starting voltage times the motor rated voltage at 60Hz as a function of the starting frequency of VFDs

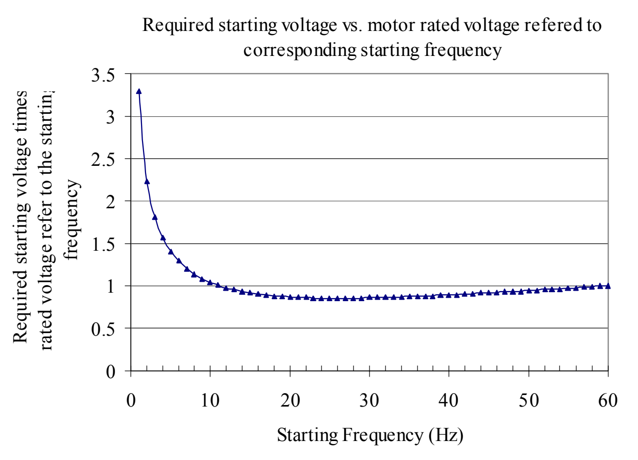

Figure 9 Required starting voltage times converted motor rated voltage from 60Hz to starting frequency as a function of starting frequency of VFDs

Operation of induction motors with VFDs provides flexible speed control. The torque-speed characteristics of induction motors operating with VFDs are a family of torque curves. Each frequency and voltage combination produced by the VFDs will create a different torque-speed curve for the motors. The typical motor torque-speed characteristics with VFDs are shown in Figure 10.

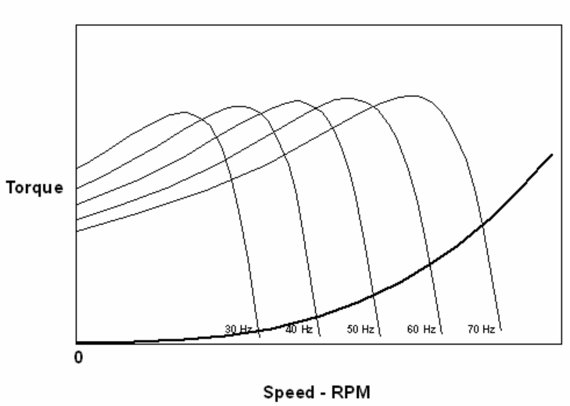

Figure 10 Torque-speed characteristics of induction motors operating with VFDs

V. CONCLUSIONS

Cross-line and variable frequency drive starting of induction motors are investigated in this paper. Theoretical derivation of electrical parameters for both starting methods is conducted based on traditional equivalent circuit of induction motors. The calculation of starting voltage, starting current and starting torque is derived mathematically. Case studies are performed for each starting method. It can be concluded that

- Cross-line starting can be considered as a special scenario of VFD starting with the starting frequency of 50Hz /60Hz.
- Inertia of loads and motor terminal voltages are two external factors determining motor starting time.
- In order to produce the same starting voltage as the cross-line starting for high inertia loads, the required starting voltage at the motor terminal shows large variation at the starting frequency of VFDs between 2Hz–10Hz. This explains why the voltage boost function is required during VFD starting in some applications.

The investigation and conclusions in this paper provide highly valuable information for field engineers dealing with induction motor starting and operation with variable frequency drives.

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BIOGRAPHIES

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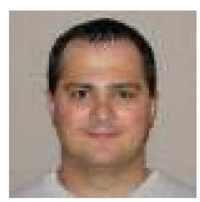

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