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Torsional Torques Reduction in Starting of Three-Phase Induction Motor

By

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Abstract:

This paper proposes a simple starting method for three-phase induction motor. The technique has the advantages of alleviating torsional toques in sub/super synchronous range. The feasibility of the proposed method was validated by a rigorous simulation work.

Keywords:

Torsional torques, Natural frequency, Large three-phase induction motors

1. Introduction:

Direct starting of a three-phase Induction Motor (IM) has serious impacts on the operation of the power system and nearby equipments [1,2] in terms of:

Hugh starting currents, nearly 5 to 12 times full load,

Flicker/dip in the grid voltage,

Malfunction of nearby loads, such as loss of synchronism of synchronous motors, a large dip in the lighting loads.

Direct starting also stresses the mechanical system composed of motor, shaft and load. This is attributed to pulsations in electromagnetic torque during starting.

Numerous starting techniques were reported in the literature [1-9] for the three-phase induction motor. Most of these techniques are focused in reducing the stress on the grid by reducing the starting currents.

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Some techniques are proposed to provide soft starting for loads such as conveyor belt. These techniques achieve the soft starting by applying reduced voltage at the motor terminals. This voltage increases gradually with/out conjunction to motor speed through controlling the thyristors firing angle. However, these methods are not paying attention to the stress on motor shaft. Moreover, these methods aggravate the stress on the utility grid by reducing the input power factor and increase the magnitude/number of injected harmonics particularly low order harmonics [7,9].
In the large IM, the pulsations in motor electromagnetic torque during the direct start/conventional soft starting stress the shaft to/beyond the limit. Thus the frequent starting may result in mechanical failure and economical losses[3]. This phenomena was investigated in [1,3,7], however no remedy was presented.
A simple, reliable and robust starting method is proposed here. The proposed method has the advantages of reducing electrical stress on utility grid and mechanical stress on motor-load system. Moreover, the proposed technique reduces torsional torque for mechanical systems with natural frequency in sub/super synchronous range.

2. System Modeling:

The system under concern, Figure (1), comprises a large three-phase squirrel cage driving an inertia load through elastic shaft.

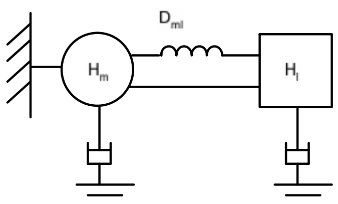


Figure (1) System under concern

2.1. Electrical model:

The induction motor modeled in d-q synchronously rotating frame [4] is given in (1), Appendix A. Equation (1) has time variant coefficient due to variation in the motor speed, ω_m, and the slip, s. These variations are not so fast due to the presence of the large inertias of the motor and load. Therefore, they are assumed constant during the small interval of integration.

$$\begin{bmatrix} \frac{X_{ss}}{\omega_o} & 0 & \frac{X_m}{\omega_o} & 0 \\ 0 & \frac{X_{ss}}{\omega_o} & 0 & \frac{X_m}{\omega_o} \\ \frac{X_m}{\omega_o} & 0 & \frac{X_{rr}}{\omega_o} & 0 \\ 0 & \frac{X_m}{\omega_o} & 0 & \frac{X_{rr}}{\omega_o} \end{bmatrix} \begin{bmatrix} \dot{i}_{qs} \\ \dot{i}_{ds} \\ \dot{i}_{qr} \\ \dot{i}_{dr} \end{bmatrix} = \begin{bmatrix} -r_s & -\frac{\omega_e}{\omega_o}X_{ss} & 0 & -\frac{\omega_e}{\omega_o}X_m \\ \frac{\omega_e}{\omega_o}X_{ss} & -r_s & \frac{\omega_e}{\omega_o}X_m & 0 \\ 0 & -sX_m & -r_r & -sX_{rr} \\ sX_m & 0 & sX_{rr} & -r_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} \qquad (1)$$

2.2. Mechanical model:

The motion of the rotating masses including torsional dynamics of the shaft is expressed in terms of θ and ω angular position and velocity of each mass by (2) [5].

$$\begin{bmatrix} \dot{\omega}_m \\ \dot{\theta}_m \\ \dot{\omega}_l \\ \dot{\theta}_l \end{bmatrix} = \begin{bmatrix} \frac{-(D_m+D_{ml})}{2H_m} & -\frac{k_{s\ 0}}{2H_m} & \frac{D_{ml}}{2H_m} & \frac{s\ 0}{2H_m} \\ 1 & 0 & 0 & 0 \\ \frac{D_{ml}}{2H_l} & \frac{K_{s\ 0}}{2H_l} & \frac{-(D_m+D_{ml})}{2H} & -\frac{s\ 0}{2H_l} \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \omega_m \\ \theta_m \\ \omega_l \\ \theta_l \end{bmatrix} + \begin{bmatrix} \frac{\omega_o}{2H_m} & 0 \\ 0 & 0 \\ 0 & -\frac{\omega_o}{2H_l} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_e \\ T_l \end{bmatrix} \quad (2)$$

The electromagnetic torque T_e in (2) is defined by (3) [5], and given in p.u. values.

$$T_e = X_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (3)$$

The natural frequency mode f_o of the mechanical system is calculated by [6],

$$f_o = \frac{1}{2\Pi} \sqrt{ o \frac{K_s (H_m + H_l)}{2 H_m H_l} } \quad (4)$$

The values of the motor speed and slip in (1) are updated at each interval according to the values obtained by solving the mechanical equations of the rotating masses (2) and (3).

The shaft (torsional) torque is calculated by,

$$T_s = K_s (\theta_m - \theta_l) \quad (5)$$

3.Spectrum of electromagnetic torque:

The electromagnetic torque in the induction motor is developed due to the interaction of the stator and rotor currents. During the starting period, these currents contain various frequency components:

a. A supply frequency component in the stator currents
b. A slip frequency component in the rotor currents.
c. DC components in the stator currents
d. DC components in the rotor currents.

These current components interact with each other and produce the following torque components:

1. A unidirectional component, this torque component results from the interaction between the magnetic fields established by the supply frequency stator current component and slip frequency rotor current component (a &b).
2. A supply frequency oscillatory torque component, which is produced by the interaction of the magnetic fields created by the slip frequency rotor current component and DC stator current component (b &c).
3. A slip frequency component is produced by the interaction of the rotating field

established from the DC current component flowing in the rotor circuit, which rotates with the rotor speed "ω_m", and the synchronously rotating magnetic field of the stator (a &d). The speed of this component ω_{slip} is given in (6) as a product of the synchronous frame speed ω_e and the motor slip s,

$$\omega_{slip} = \omega_e - \omega_m = s\omega_e \tag{6}$$

4. A rotor frequency component is produced by the interaction of the stationary magnetic fields, which are established by the DC current components flowing in the stator and rotor circuits (c & d).

The DC current component in the rotor circuit rotates with the rotor, therefore, the rotor frequency torque component has the same speed as the rotor ω_m.

The slip and the rotor frequency torque components have a potential impact on the shaft torque if their frequencies coincide with the natural frequency of the motor/load system. Usually the impact of the rotor frequency torque component is ignored because it results from the interaction of decaying DC components.

In the direct starting and conventional flux weakening, the frequency of the applied voltage is kept constant at its rated value. Therefore, the slip and the rotor frequency torque components will result in high torsional torques, when their frequencies coincide with the motor/load system natural frequency.

4. Proposed starting technique:

In the proposed method, the motor starts with rated voltage while the frequency is ramped down from high value to the rated frequency. The starting frequency value and the slope of the frequency ramp are depending on some criteria such as:

1. Load torque, whether the load requires high or low starting torque.
2. The value of the natural frequency of the motor/load system, when the motor is driven an inertia load.

The proposed technique is themed flux weakening; therefore it naturally has the ability for soft starting, which is mandatory for conveyor belt loads.

5. Results and discussions:

Equations (1)-(4) are solved in Matlab environment for two distinct scenarios:

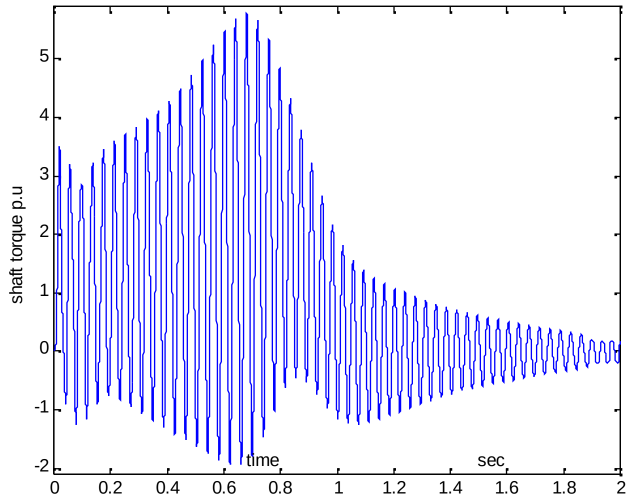
1. Case 1, the natural frequency of the mechanical system is in the sub-synchronous region.
2. Case 2, the natural frequency of the motor-load system is in the super synchronous region

The data of cases 1 and 2 respectively is given in Appendix I.

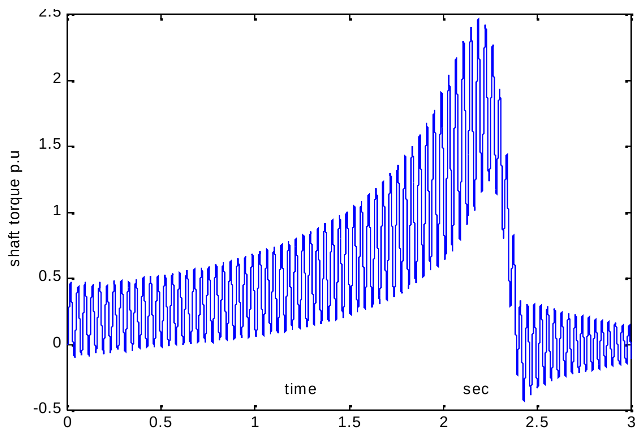
The results of each case with direct starting and proposed method are given in the following figures

5.1.Case 1:

The motor/load system has a natural frequency of 26Hz, (4), while the supply frequency is 60Hz. In the proposed method, the starting value and slope of the frequency ramp are chosen to be : 120Hz and 25Hz/sec respectively. The torsional torque and phase current for direct starting and proposed method are shown in Figures (2) and (3) respectively.

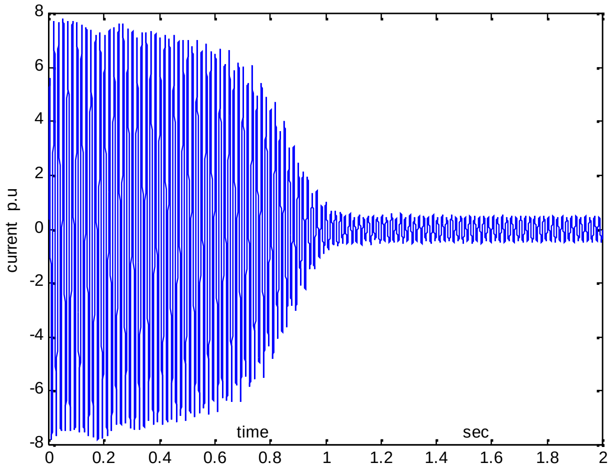


a- Torsional torque with direct starting

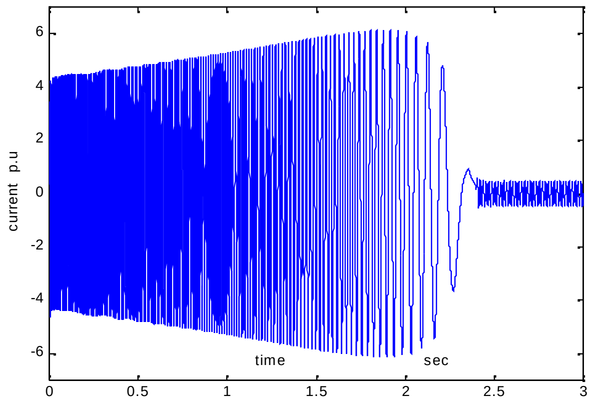


b-Torsional torque with proposed starting method

Figure (2): Torsional torques with a-direct starting b-proposed starting method



a- Phase current with direct starting



b-Phase current with proposed starting method

Figure (3): Phase current with a-direct starting b-proposed starting method

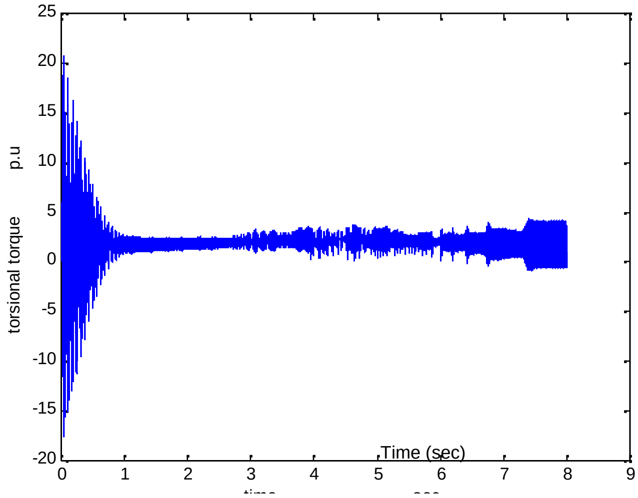
The advantages of the proposed starting method in reducing electrical and mechanical stresses are shown in Figures (2) and (3) respectively. 58.3% and 25% reduction in torsional torque and phase current are achieved with the proposed method, Figures (2) and (3). Moreover, the proposed starting technique provides smooth build up for motor speed, which is convenient for production lines in drug industry.

5.2. Case 2:

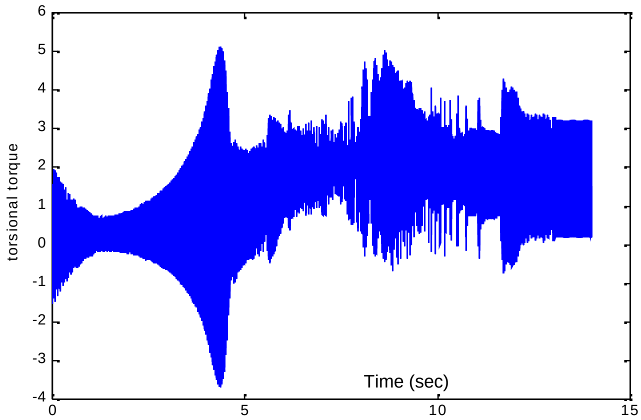
The motor/load system has a natural frequency of 74Hz, (4), while the supply frequency is 60Hz. In the proposed method, the starting value and slope of the frequency ramp are chosen to be : 120Hz and 10Hz/sec respectively.

The slope of frequency ramp is lower in case 2 than 1, this to provide adequate reduction in torsional torque.

Figures (4) and (5) show the torsional torque and phase current for direct starting and proposed method respectively.

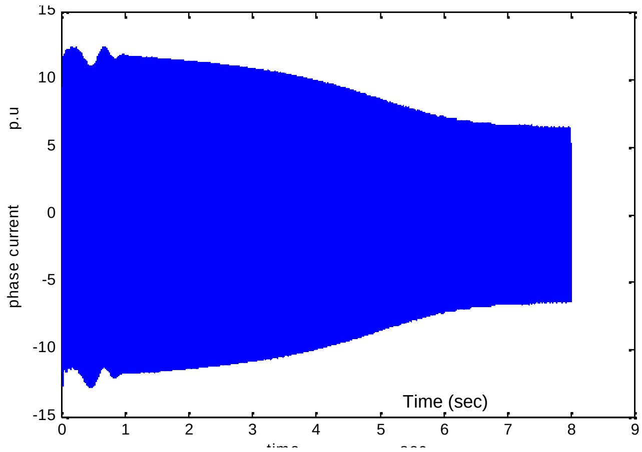


a- Torsional torque with direct starting

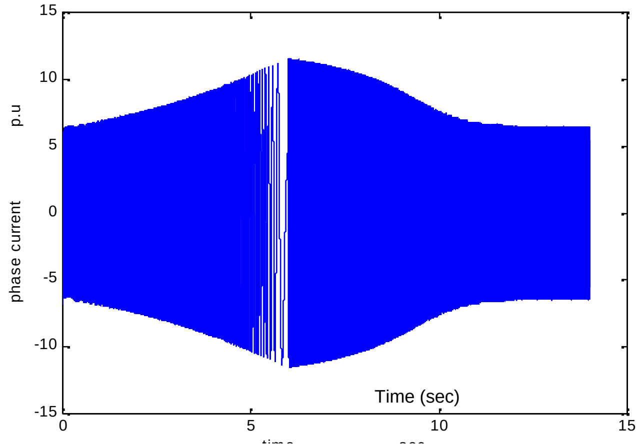


b-Torsional torque with proposed starting method

Figure (4): Torsional torques with a-direct starting b-proposed starting method



a-Phase current with direct starting



b-Phase current with proposed starting method

Figure(5): Phase current with a-direct starting b-proposed starting method

Figure (4) shows that the proposed starting method achieves significant reduction in torsional torque compared with direct The torsional torque reaches around 20pu for direct starting, which possibly damage the mechanical system particularly in the case of frequent starting [8]. The proposed starting technique manages to reduce the torsional torque to 5p.u. In other words it achieves around 75% in the amplitude of the torsional, which could reduce the burden on the mechanical system. Figure (5) indicates that the proposed starting scheme has less advantages regarding motor current for the super-synchronous case, which may be attributed to the prolonged starting time.

6. Conclusions:

The following conclusions are obtained :

- The electromagnetic torque have various frequency components that result from interaction between stator and rotor currents
- Large torsional torques are produced when the system natural frequency coincide to a component or more of motor toque components.
- Direct starting stresses the mechanical and electrical systems. The consequences are not only restricted on the motor but extended to nearby appliances.
- The proposed starting method reduces the electrical and mechanical stress significantly, particularly when the motor is loaded by large inertia loads.
- The proposed starting scheme reduces torsional torques on load and connecting shaft irrespective to the natural frequency mode of the mechanical system; whether it in sub/super synchronous zone.
- The value of the starting high frequency and slope of the frequency ramp in the proposed method vary according to the load requirements.

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Nomenclatures:

ω_e	Speed of synchronously rotating frame (rad/sec)
ω_m, ω_l	Motor and load speed (rad/sec)
θ_m, θ_l	Rotor and load position respectively (rad)
ω_o	Base speed (rad/sec)
D_m, H_m	Damping coefficient and inertia constant of the motor respectively (p.u.)
D_l,H_l	Damping coefficient and inertia constant of the load respectively (p.u.)
D_{ml}	Stiffness of shaft section connecting motor with the load (p.u.)
f_o	Natural frequency (Hz)
K_s	Stiffness of shaft section connecting motor with the load (p.u/rad)
T_e,T_L	Motor and load torque respectively (p.u.)
T_s	Shaft torque (p.u.)

S Slip
v, i Instantaneous value of the voltage and current respectively (p.u)
r,X Resistance, and reactance respectively (p.u.)

Subscripts

d-q d-q axis of synchronously rotating frame respectively
r, s rotor and stator respectively

APPENDIX A

<u>Data for case 1:</u>

A. Electrical data **:**

r_s=0.0453 p.u r_r=0.0272p.u.X_{ss}=2.1195 p.u., X_{rr}=2.0742 p.u., X_m=2.042 p.u., ω_o =377.0 rad/sec.

B. Mechanical data :

D_{ml}=0.002 p.u, D_m=0.0, D_l =0.0, K_s=30 pu/rad, H_m=0.3 sec, H_l=0.75 sec.

<u>Data for case 2:</u>

A. Electrical data :

r_s=0.0144 p.u, r_r=0.0278p.u.,X_{ss}=2.0912 p.u., X_{rr}=2.0912 p.u., X_m=2.0356 .p.u, ω_o =377.0 rad/sec.

B. Mechanical data :

D_{ml}=0.0 ,D_m=0.0164, D_l =0.0164, K_s=1.2295e+003 pu/rad, H_m=0.3981 sec , H_l=3.5406 sec