Pakistan Journal of Applied Sciences 3 (8-9): 579-586, 2003
ISSN 1607-8926

Dynamic Behavior Analysis of Open-circuit Transition Wye-Delta Starter

Saleh A. Al-Jufout
Electrical Engineering Department
Al-Balqa' Applied University, Tafila Applied University College
P.O. Box 92, Tafila 66110, Jordan

Abstract: The mathematical model of the open-circuit transition wye-delta controller has been developed. Two possible delta configurations have been taken into consideration. The dynamic behavior of the motor starting using the open-circuit transition wye-delta controller with different delta configurations has been analyzed. A comparative study between the two delta configurations has been performed and a recommendation to avoid excessive undesirable inrush values of the motor current and the electromagnetic torque has been given. The inrush values of the motor current, electromagnetic torque and acceleration time have been considered as criteria in the comparative study. Curves of the phase currents and electromagnetic torque for motor starting using each of the delta configurations have been illustrated.

Key words: Wye-delta starter, mathematical modeling, delta configurations, inrush current, electromagnetic torque, acceleration time

Introduction

Squirrel-cage induction motors are frequently started by connecting them directly across the supply line. A large starting current of the order of 500 to 800 percent of full-load current may flow and if this causes appreciable voltage drop, it may affect other drives connected to the same line. In addition, if a large current flows for a long time it may overheat the motor and damage the insulation. In such a case, reduced-voltage starting method must be used (Gordon, 1992).

Wye-delta starting method is particularly suitable for applications involving long acceleration time and is the most commonly used method for starting high inertia loads. Wye-delta starter is used with delta-wound motors that have all six leads brought out to facilitate a wye connection for reduced voltage starting. It provides reduced voltage starting by first connecting the motor leads into a wye configuration for starting and then switches the connection to a delta configuration for running.

Typical wye-delta starter is made up of magnetic contactors that switch from wye to delta connection and a timing unit that controls the switching. When the operator presses the start button, the line and wye contactors close and the motor starts. Full voltage is not applied across the winding, but rather it is then reduced by the square root of three. Consequently, starting torque and starting current are approximately one third normal. After the starting period, which

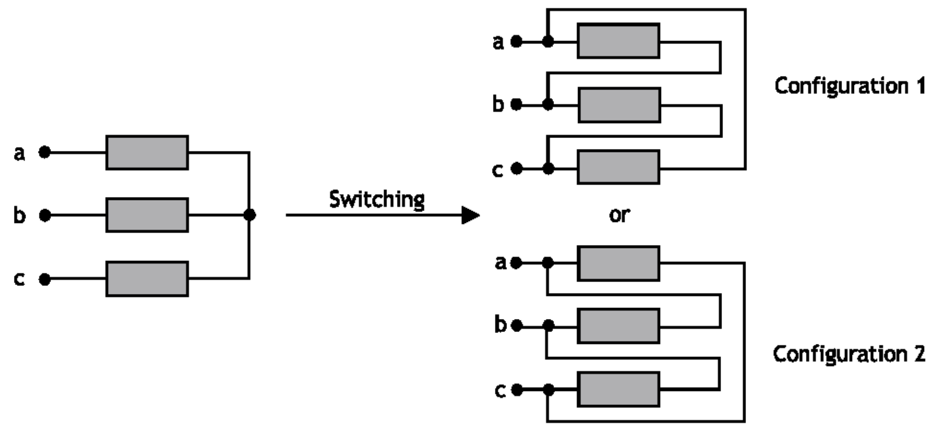

Fig. 1: Connections of the Motor Windings in Wye and the Possible Two Delta Configurations

is determined by a timer setting, the wye contactor opens and a brief time later, the delta contactor closes. This means that the circuit is opened for brief period time before switching to the delta configuration. This open-circuit transition can cause voltage spikes, which may be detrimental to other devices on the power grid.

An appeal of wye-delta starting method is that it does not need accessory voltage reducing equipment such as resistors or transformers. In addition, there is very little noise or vibration associated with this method. The wye-delta starting method seems like an ideal solution until one examines the following points:

- To accomplish wye-delta starting a special (typically more expensive) motor is required. This motor has the ends of its windings drawn out into six leads that are routed to the termination box for connection.
- On a typical three-phase motor, three leads are required to be run from the motor starter to the motor. With a wye-delta system, six leads are needed between the motor and the starter, thus, adding expense.
- If the starting method used is open-circuit transition, a significant spike can be generated on the power system that could cause damage elsewhere.
- Closed-circuit transition wye-delta starting requires an additional contactor and therefore adds additional expense.
- Only two choices of starting torque.

There are two different delta configurations as shown in Fig.1. Literature does not distinguish between the two configurations. Some of them assume the first configuration (Traister, 1994), while others assume the second configuration (Rakosh, 1998). The objective of this paper is to analyze the dynamic performance of the open-circuit transition wye-delta starter with the two different delta configurations.

Wye-delta starter modeling

The three-phase, induction motor can be mathematically modeled by representing it as a system of differential equations for flux-linkages and speed determination (Al-Jufout, 2002). These differential equations are written in a fixed rectangular coordinate system (x, y). To consider the skin effect, the rotor of the machine is represented by two parallel-connected resistive-inductive circuits (Sivokobylenko, 1984). The parameters of the motor equivalent circuit are determined in per unit (pu) by using engineering calculation methods (Sivokobylenko and Kostenko, 1979). The differential equations are solved by using fourth-order Runge-Kutta method.

The difference between the two delta configurations, from mathematical modeling point of view, is that, in the first delta configuration the voltage, which is applied to each of the motor windings, after switching, is larger by the square root of three and leads the phase voltage by 30 degrees. While in the second delta configuration - the voltage is larger by the square root of three and lags the phase voltage by 30 degrees.

The equations of the voltage, applied to the motor terminals, presented in the rectangular coordinate system can be derived from the phase and line-to-line voltage equations:

$$v_a = \frac{V_{max}}{\sqrt{3}} \sin(\omega t), \tag{1}$$

$$v_b = \frac{V_{max}}{\sqrt{3}} \sin(\omega - 120°), \tag{2}$$

$$v_c = \frac{V_{max}}{\sqrt{3}} \sin(\omega + 120°), \tag{3}$$

where

V_{max}: the maximum line-to-line voltage of the power supply.

In rectangular coordinate system, the voltage equations are as follows:

$$V_x = V_a, \tag{4}$$

$$V_y = \frac{V_b - V_c}{\sqrt{3}}. \tag{5}$$

After switching to the first delta configuration the voltage equations are as follows:

$$v_{ab} = V_{max} \sin(\omega t + 30°), \tag{6}$$

$$v_{bc} = V_{max} \sin(\omega t + 90°), \tag{7}$$

$$v_{ca} = V_{max} \sin(\omega t + 150°), \tag{8}$$

In rectangular coordinate system, the voltage equations according to the first delta configuration are as follows:

$$V_x = V_{ab}, \tag{9}$$

$$V_y = \frac{V_{bc} - V_{ca}}{\sqrt{3}}. \tag{10}$$

Similarly, according to the second delta configuration the voltages in phase and rectangular coordinate systems are as follows:

$$v_{ba} = V_{max}\ \sin(\omega t + 150°), \tag{11}$$

$$v_{cb} = V_{max}\ \sin(\omega t + 90°), \tag{12}$$

$$v_{ac} = V_{max}\ \sin(\omega t + 30°). \tag{13}$$

$$V_x = V_{ac}, \tag{14}$$

$$V_y = \frac{V_{ba} - V_{cb}}{\sqrt{3}}. \tag{15}$$

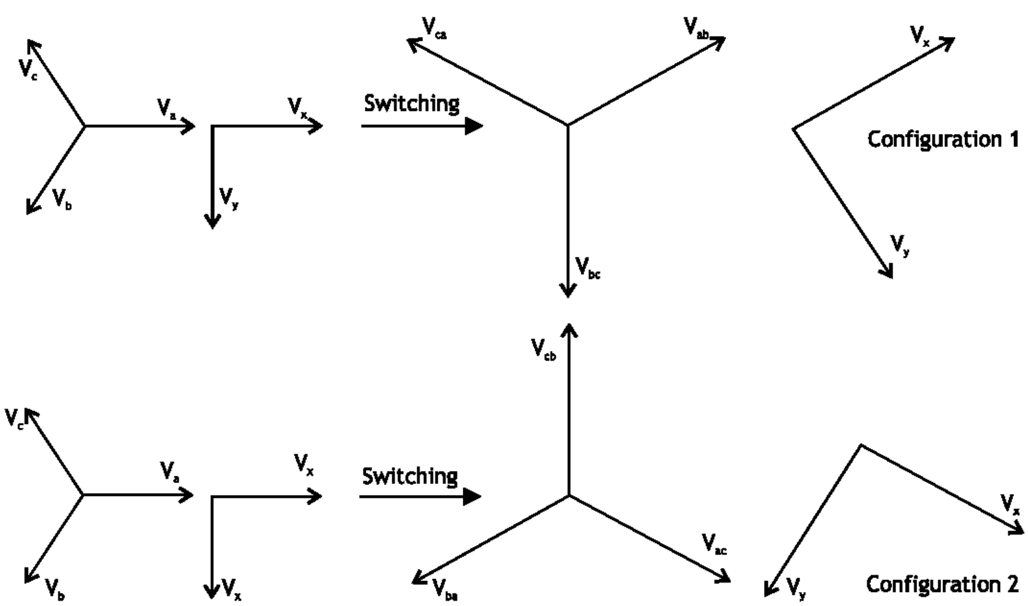

Fig. 2: Phasor Diagrams for Voltages Applied to the Motor Windings in Wye and the Possible Two Delta Configurations

Figure 2 shows the voltage phasor diagrams, which correspond to both the first and the second delta configurations. The duration of the switching process depends on the speed of the contactors operation, which is assumed 20 milliseconds. That means the motor supply will be interrupted for the assumed duration and meanwhile the motor will run down (Al-Jufout, 1999).

To simulate the starting process the initial values of the variables (currents and speed) should be equal to zero (Al-Jufout, 2000). The motor windings are connected in wye configuration and when the motor speed reaches the rated value, the power supply is interrupted for 20 milliseconds. After this period, the voltage is applied, while the motor windings are now connected in one of the above-mentioned delta configurations.

Results and Discussion

The dynamic performance, in each phase, is largely dependent on the instant when the circuit is closed. To consider all possible cases, for a 50 Hz motor, 20 calculations are performed for each period. The absolute values of the phase inrush currents after switching to the first and second delta configurations, at different instants, are shown in Table 1. The switching instants are identified by the voltage phase angle. The sum of the phase inrush currents in each record does not equal to zero, because they might occur at different instants after switching.

As it is shown from the Table, the phase inrush currents can not be used as a criterion to determine the difference between the two delta configurations from dynamic behavior point of view. Thus, the inrush electromagnetic torque (Al-Jufout, 2000) and the inrush generalized current amplitude can be used instead. Where the generalized current amplitude can be calculated by the following formula:

$$I = \sqrt{\frac{2}{3}(i_a^2 + i_b^2 + i_c^2)}, \tag{16}$$

where

i_a, i_b, i_c: the instantaneous values of the phase currents calculated at the same instant of time.

For all cases, listed above in the table, the inrush generalized current amplitude and the inrush electromagnetic torque are 4,72 and 2,10 pu for the first delta configuration and 4,96 and 2,97 for the second delta configuration respectively. Using the second delta configuration, in comparison with the first delta configuration, is associated with an inrush current, which is larger by 5% and inrush electromagnetic torque, which is larger by 41%. In addition to that, using the second delta configuration requires longer acceleration time for the motor to reach the steady-state conditions. This difference in the dynamic behavior is due to that, switching from wye configuration to the second delta configuration looks like applying negative-sequence voltages for the duration of 1,67 ms (50 Hz motor). These negative-sequence voltages induce a three-phase field in the rotor that rotates in the opposite direction of the rotor mechanical direction.

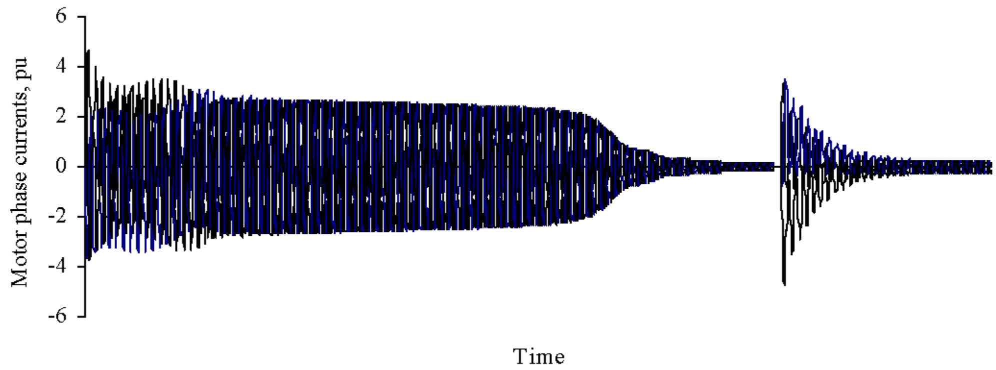

Fig. 3: The Motor Phase Currents during Starting Using Wye-Delta Controller with the First Delta Configuration

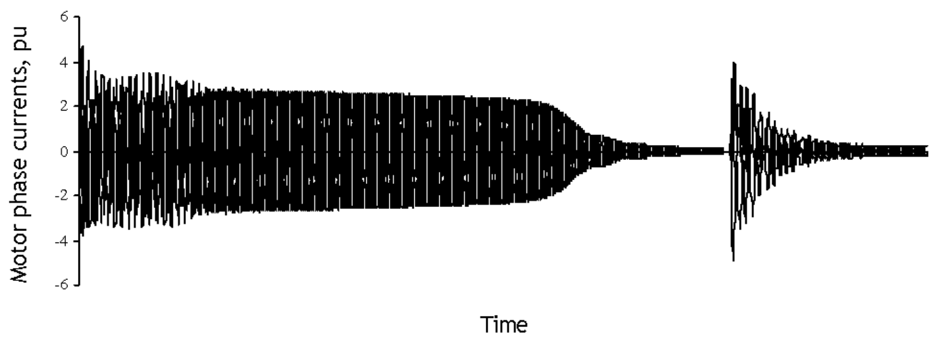

Fig. 4: The Motor Phase Currents during Starting Using Wye-Delta Controller with the Second Delta Configuration

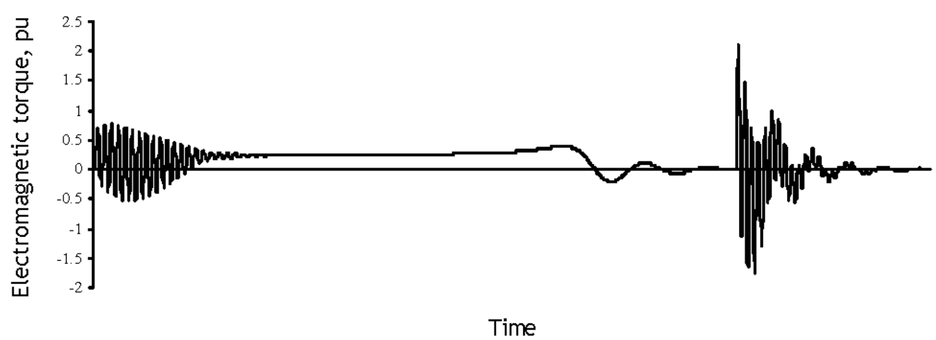

Fig. 5: The Motor Electromagnetic Torque during Starting Using Wye-Delta Controller with the First Delta Configuration

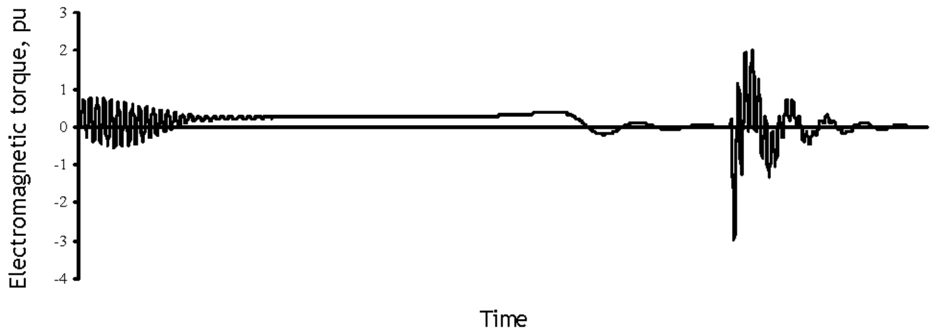

Fig. 6: The Motor Electromagnetic Torque during Starting Using Wye-Delta Controller with the Second Delta Configuration

Table 1: The Inrush Phase Currents after Switching to the First (1) and Second (2) Delta Configurations versus the Phase Angle of Phase (a) Voltage

Phase (a) voltage phase-angle in degrees	Phase (a) inrush current, pu		Phase (b) inrush current, pu		Phase © inrush current, pu	
	1	2	1	2	1	2
0 (360)	3,360	3,980	3,531	4,899	4,720	3,221
18	2,613	4,531	4,115	4,644	4,565	2,411
36	2,559	4,866	4,518	4,158	4,176	3,006
54	3,310	4,951	4,696	3,490	2,874	3,759
72	3,951	4,777	4,625	2,707	2,874	4,370
90	4,421	4,361	4,311	2,712	2,275	4,780
108	4,672	3,742	3,786	3,496	3,054	4,949
126	4,681	2,985	3,102	4,160	3,746	4,857
144	4,446	2,453	2,330	4,647	4,284	4,514
162	3,989	3,264	2,809	4,904	4,617	3,953
180	3,356	3,980	3,524	4,905	4,711	3,229
198	2,612	4,533	4,107	4,651	4,558	2,418
216	2,555	4,869	4,511	4,164	4,171	3,002
234	3,306	4,954	4,690	3,495	3,590	3,757
252	3,947	4,780	4,621	2,712	2,872	4,369
270	4,417	4,363	4,309	2,708	2,274	4,779
288	4,670	3,744	3,784	3,492	3,054	4,948
306	4,680	2,986	3,101	4,156	3,746	4,857
324	4,445	2,448	2,330	4,643	4,284	4,514
342	3,989	3,259	2,810	4,900	4,618	3,952

Fig. 3 and 4 illustrate the phase currents during the entire starting process using wye-delta controller with the first and second delta configurations respectively. Fig. 5 and 6 illustrate the electromagnetic torque.

Based on mathematical modeling, the dynamic behavior of the induction motor starting using open-circuit transition wye-delta starter is analyzed. The two possible delta configurations are taken into consideration. Comparing the motor dynamic behavior in the two cases of the delta configurations leads to that, the delta configuration, which switches the phase voltages to line-to-line voltages, which lag by 30 degrees, is associated with the following:

- larger undesirable inrush current;
- larger undesirable inrush electromagnetic torque;
- longer acceleration time.

Thus, it is recommended to use the delta configuration, which switches the phase voltages to line-to-line voltages, which lead by 30 degrees.

The difference in the dynamic behavior is due to that, using the delta configuration, which switches the phase voltages to line-to-line voltages, which lag by 30 degrees, looks like applying negative-sequence voltages for the duration of 1,67 ms. These negative-sequence voltages induce a three-phase field in the rotor that rotates in the opposite direction of the rotor mechanical direction.

References

Al-Jufout, S.A., 2002. Modeling of the Autotransformer-Type Reduced-Voltage Starter. Proceedings of the 4th International Conference on Quality, Reliability and Maintenance, Professional Engg. Publishing, UK., pp: 337-340.

Al-Jufout, S.A., 2000. Analysis of the Squirrel-Cage Induction Motor Starting Process on the Basis of Computational Modeling. Proceedings of the International Conference on Simulation and Multimedia in Engg. Education, SCS, USA., pp: 205-208.

Al-Jufout, S.A., 1999. Modeling of Transients and Steady-State Operation of the Induction Motor. Proceedings of the 11th European Simulation Symposium, SCS, Germany, pp: 670-674.

Gordon, R.S., 1992. Electric Machines and Drives. Addison-Wesley Publishing Co., USA.

Rakosh, D.B., 1998. Electro-Mechanical Energy Conversion with Dynamics of Machines. New Age International (P) Limited, Publishers, India.

Sivokobylenko, V.F., 1984. Transients in Multi-Machine Power Supply Sys. of Power Stations. DPI, Ukraine.

Sivokobylenko, V.F. and V. Kostenko, 1979. Mathematical Modeling of the Power Station Auxiliaries Electrical Motors. DPI, Ukraine.

Traister, J.E., 1994. Complete Handbook of Electric Motor Controls. PennWell Publishing Co., USA.