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Performance Comparison of Two-leg and Three-leg AC Voltage Controller-Fed Three Phase Induction Motor Drive

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This paper gives the comparison of the starting performance of three phase induction motor fed from three-leg and two-leg ac voltage controller. Optimum firing angles are obtained for both the systems by considering various electrical characteristics like maximum positive and negative torque pulsations, peak starting current and acceleration time. Two group of induction motors are utilized for comparative analysis of performance with the selected optimum firing angle. Result shows that the performances of both the systems are on par. Thus the cost effective, two-leg controller is the better choice for the induction motor starting.

Keywords: Three-leg ac voltage control, Two-leg ac voltage control, Induction motor starting.

1. INTRODUCTION

Starting methods of three phase induction motors are mainly classified in to Direct On Line (DOL) starting and reduced voltage starting. DOL starting is the simplest, economic and reliable method of starting, typically used unless there is either an electrical or mechanical constraint which makes this option unsuitable [1]-[3]. But has several draw backs like, large starting current transient leading to voltage dip and brown out conditions, large torque pulsations resulting in reduced life and reliability of mechanical parts. Reduce voltage starting is again classified in to electromechanical reduced voltage starting and solid state reduced voltage starting. Electro mechanical reduced voltage starters uses mechanical switches or contact and has disadvantages like need for frequent maintenance and inspection, failure in the moving parts etc.[4]-[6]. Solid state reduced voltage starters use power electronic devices to control the voltage. Thyristorized ac voltage controller and Variable Frequency Drives (VFD) come under this. VFD is more costly and is not generally preferred as starting equipment. Thyristorized ac voltage controllers are simple, reliable, economical, and compact and are increasingly used in industries nowadays [7]-[13]. Attempts have been made in the past[14]-[18] to improve the starting performance of ac voltage controller-fed induction motors, but the starting performance comparison of two-leg and three-leg ac voltage controller-fed induction motor is not available in the literature.

The objective of this paper is to compare the starting performance of thyristorized ac voltage controller-fed three phase induction motors with three-leg and two-leg topologies. Two groups of induction motors with group A consisting of three 2.2kW motors (machines AI, AII and AIII) and group B consisting of two 3.7kW motor (BI and BII) are selected for the work. Optimum firing angle is taken as the firing angle at which the negative torque pulsation is zero with minimum acceleration time with satisfactory values for other electrical characteristics considered[19],[20].

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2. SYSTEM MODELLING AND OPEATION

The schematic diagram of thyristorized static switch-fed three phase induction motors in three-leg and two-leg topologies are shown in Figure 1 and Figure 2. Three-leg topology consists of three pairs of back-to-back connected thyristors in series with three phase induction motor, one in each phase forming R, Y, and B phase group, respectively and same firing angle, α with appropriate phase shift is given to all phases. Devices are connected in all the three phases, hence the name three-leg topology or 'α control'. Thyristors in this case is fired in the sequence as marked in Fig. 1. R group thyristor, T1 is triggered at an angle of α and its negative thyristor T4 is fired at (π+ α). Y group thyristor T3 is fired at (2π/3+ α) and its negative thyristor T6 at (5π/3+ α). Similarly triggering pulses to B group thyristors, T5 is given at (4π/3+ α) and T2 at (π/3+ α).

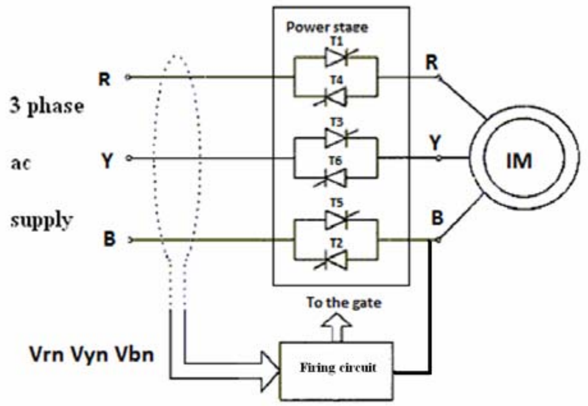


Figure 1. Schematic diagram of three-leg voltage controller-fed induction motor

The two-leg topology has only two pairs of back-to-back connected thyristors and is connected in series with R and B phases, forming R phase and B phase group of thyristors and Y phase is directly connected to the motor. α is taken as the firing angle of phase R group thyristors and β to phase B group thyristors. Thyristors are connected only in two phases, hence the name two-leg topology or ' αβ control'. α is the firing angle to T_{fR} and (π+ α) is the firing angle to T_{bR}. Similarly β and (π+β) are the firing angle to T_{fB} and T_{bB} respectively. Firing pulses are suitably adjusted in certain time sequence to achieve smooth starting of the motor.

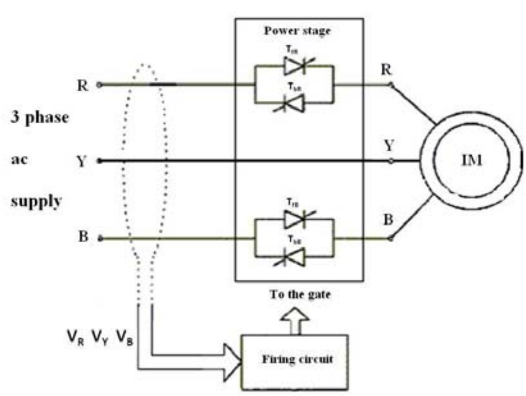


Figure 2. Schematic diagram of two-leg voltage controller-fed induction motor

The matrix differential equation of the motor described in stator reference frame [21] is given by,

$$\begin{bmatrix} \frac{di_{ds}}{dt} \\ \frac{di_{qs}}{dt} \\ \frac{di_{dr}}{dt} \\ \frac{di_{qr}}{dt} \end{bmatrix} = \frac{1}{\sigma} \begin{bmatrix} -\frac{r_s}{L_s} & \frac{\omega_r L_m^2}{L_s L_r} & \frac{r_s L_m}{L_s L_r} & \frac{\omega_r L_m}{L_s} \\ \frac{-\omega_r L_m^2}{L_s L_r} & -\frac{r_s}{L_s} & \frac{-\omega_r L_m}{L_r} & \frac{r_s L_m}{L_s L_r} \\ \frac{r_s L_m}{L_s L_r} & \frac{\omega_r L_m}{L_s} & -\frac{r_r}{L_r} & \frac{\omega_r L_m}{L_r} \\ \frac{\omega_r L_m}{L_s} & \frac{r_s L_m}{L_s L_r} & \frac{\omega_r L_m}{L_r} & -\frac{r_r}{L_r} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} + \frac{1}{\sigma} \begin{bmatrix} \frac{1}{L_s} & 0 & -\frac{Lm}{L_s L_r} & 0 \\ 0 & \frac{1}{L_s} & 0 & -\frac{Lm}{L_s L_r} \\ -\frac{Lm}{L_s L_r} & 0 & \frac{1}{L_r} & 0 \\ 0 & -\frac{Lm}{L_s L_r} & 0 & \frac{1}{L_r} \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \\ 0 \\ 0 \end{bmatrix} \quad \textbf{(1)}$$

Where

$$\sigma = \frac{L_m{}^2}{L_s L_m}$$

r_s and r_r are the stator and rotor resistances respectively, ω_r is the rotor speed, L_m, L_s and L_r are the magnetizing, stator and rotor inductances respectively, i_{ds}
and i_{qs} are the direct and quadrature axis stator currents, i_{dr} and i_{qr} are the direct
and quadrature axis rotor currents, T_L is the load torque and P the number of poles. V_{ds} and V_{qs} are d-axis and q-axis stator voltages and are functions of α.
The electromagnetic torque is governed by the equation,

$$T_e = \frac{3}{2} P L_m \left(i_{dr} i_{qs} - i_{qr} i_{ds} \right) \quad (2)$$

The speed is given by

$$\frac{d\omega_r}{dt} = \frac{T_e - T_L}{J} \quad (3)$$

Equations (1), (2), and (3) are used to develop the motor model in Matlab/Simulink for analyzing the starting transients of the motor drive system.

AC voltage controller-fed induction motors are modeled and simulated in MATLAB Simulink. Even though starting problems are more significant in high rating machines, for demonstration purpose, low rating machines available in the lab set up are used for the simulation work. The machine parameters of the motors were obtained from the manufacturer and subsequently modified through no load and blocked-rotor tests. These values are given in appendix and are used to simulate the machines. Line currents, line voltages, speed and electrodynamic torque waveforms of the motor are analyzed for various firing angles. Positive electrodynamic torque peak, negative electrodynamic torque peak, acceleration time, and peak line current are tabulated in perunit values and are plotted against α to obtain the optimum α. Fine tuning of α is done by repeated simulation on the three-leg topology.

The electrical characteristics under consideration are observed in two-leg topology also and are plotted against firing angle, α with a fixed value of β to obtain the optimum α. This fixed value of β taken initially is the optimum firing angle obtained with α control. Once this optimum α is obtained for a machine, keeping this value constant, firing angle to phase B ie β is varied. Various electrical characteristics are tabulated and plotted against β to get the optimum β value. Finally the machines are simulated with this optimum α,β combination obtained and the performance characteristics were observed. In the previous work[19]-[20], it is found that the optimum firing angles depends largely on machine parameters. This paper concentrates on the performance comparison of three-leg and two-leg topologies with two groups of induction motors, each group consisting of equally rated machines having different motor parameters.

3. RESULTS AND DISCUSSION

Various performance characteristics observed are tabulated for all the machines and values for machine AI is shown in Table 1 and it is seen that optimum α is in between 60^o and 65^o. Performance characteristics under considerations are plotted against firing angle α. Simulation is repeated with the firing angles between 60^o and 65^o. Plots for machine AI in group A machines is shown in Figure 3 as an example.

Table 1. Tabulated data in pu for machine AI for different values of α(α = 0 is the condition of DOL starting)

α (Degrees)	Peak +ve Torque (pu)	Peak –ve Torque (pu)	Acceleration Time (S)	Peak Current (pu)
0	1.75	-0.77	2.77	5.29
30	1.48	-0.50	2.80	5.10
60	0.99	-0.063	2.88	4.32
65	0.88	0	3.10	4.19
75	0.64	0	4.05	3.80
90	0.34	0	6.60	2.68

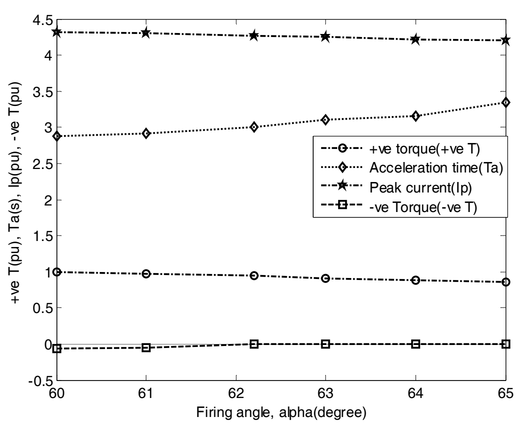


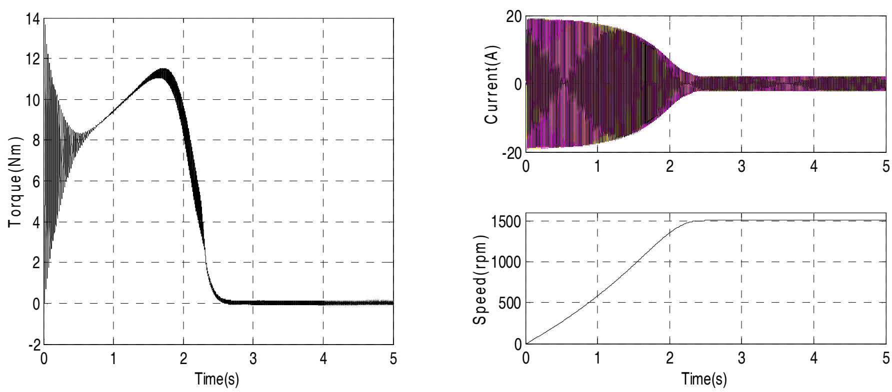
Figure 3. Plots to find optimum α for machine AI

Optimum α in this case is found to be at 62.2^o. Similarly optimum firing angles for machines AII and AIII are obtained and are found to be at 57.55^o and 59.65^o respectively. Line currents, line voltages, speed and torque waveforms with optimum α= 62.2^o for machine AI is shown in Figure 4 and it is seen that motor voltages and currents are sinusoidal under steady state condition. Once the optimum firing angle is obtained for the machine, it can be started like DOL starting, hence the performance values for DOL starting is also given in Table 2 for comparison. Results show that various electrical characteristics considered are significantly reduced with three-leg controller compared to DOL starting.

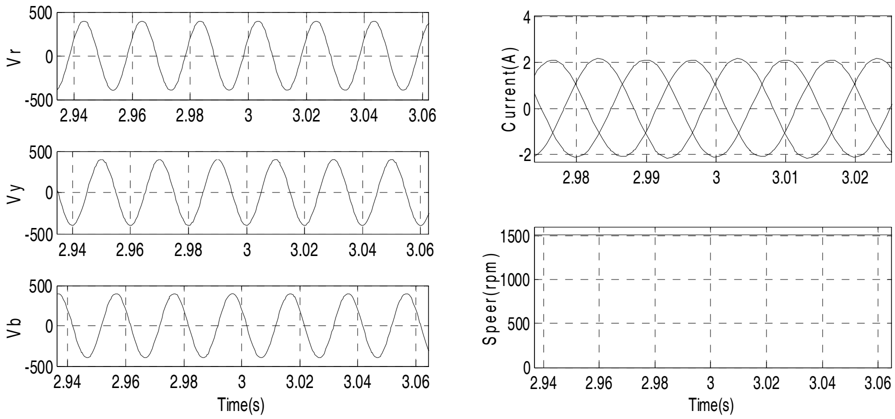
Table 2. Performance values with DOL starting for various machines

Machine	Peak +ve Torque (Nm)	Peak –ve Torque (Nm)	Acceleration Time (S)	Peak Current (A)
AI	25.57	11.3	2.77	23.83
AII	13.32	5.25	2.7	9.5
AIII	26.14	11.42	2.14	28.16
BI	17.22	6.55	1.65	12.63
BII	18.09	6.32	1.95	13.22

For example in machine AI, negative peak torque pulsation for DOL starting is found to be 11.3Nm while that for optimum α is zero. Peak positive torque pulsation is reduced from 25.57Nm for DOL starting to 13.65Nm for optimum α, peak starting current is reduced from 23.83A to 19.2A but acceleration time is increased from 2.77s to 2.8s for optimum α. Also the line voltage and currents are having sinusoidal waveforms at steady state.



(a) (b)



(c) (d)

Figure 4. (a)Transient electromagnetic torque vs time; (b) transient current and speed vs time; (c)steady state line voltage vs time; (d) steady state current and speed vs time for optimum α = 62.2° for machine AI in three-leg topology

The performance characteristics are also analyzed with two-leg topology (α,β control). The plots for finding optimum α,β combination for machine AI is shown in Figures 5-6 and optimum α,β combination is obtained as 55.2° and 62.4°. Similarly α,β values are obtained for other machines also and are 56.5° and 58.5° for machine AII and 59° and 60.7° for machine AIII. Various performance values are observed and are given in Table 3 with the comparison of three-leg and two-leg topology. Line currents, line voltages, speed and torque waveforms of the motor with optimum values of α= 55.2° and β= 62.4° for machine AI are shown in Figure 7.

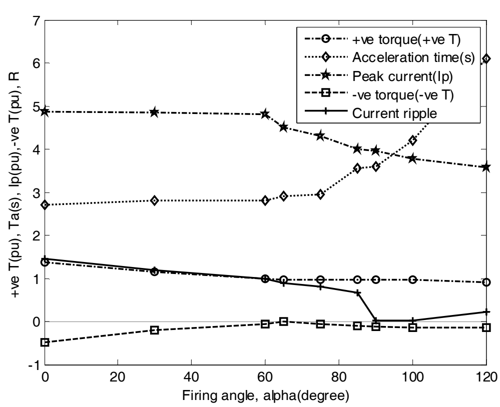


Figure 5. Plots to find optimum α with β = 62.2° for machine AI

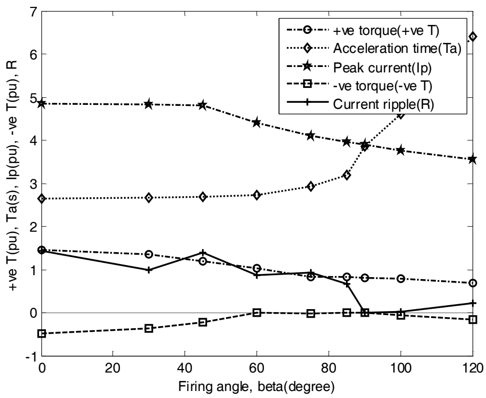


Figure 6. Plots to find optimum β with α = 55.2° for machine AI

From Table 3, for machine AI, it is seen that there is no negative torque pulsation in both two-leg and three-leg topology. Peak positive torque pulsation is 13.65Nm for three-leg controller and 13.9Nm for two-leg controller. Peak starting current is 19.2A for three-leg and 19.3A for two-leg controller and the value of acceleration time is 2.8s where as it is 2.78s for two-leg controller. The comparative values for other machines are also shown in Table 3. Results show that, there is not much difference in their performance values; hence the cost effective two-leg controller is a better choice for AC voltage controller-fed induction motor starting.

Table 3. Comparison of three-leg and two-leg controller for various machines

Machine	Three-leg controller					Two-leg controller				
	α_{opt} (Deg.)	+ve T (Nm)	-ve T (Nm)	Ta (S)	Ip (A)	α_{opt} β_{opt} (Deg.)	+ve T (Nm)	-ve T (Nm)	Ta (S)	Ip (A)
AI	62.2	13.65	0	2.8	19.2	55.2, 62.4	13.9	0	2.78	19.3
AII	57.55	8.05	0	2.9	8.08	56.5, 58.5	8.17	0	2.88	8.14
AIII	59.65	14.77	0	2.4	21.47	59.0, 60.7	14.85	0	2.25	21.75
BI	56.2	10.71	0	1.74	10.84	56.1, 56.8	10.76	0	1.73	10.9
BII	53.65	11.73	0	2.1	11.63	53.1,53.9	11.79	0	2.09	11.67

(+ve T–Peak positive torque pulsation in Nm; -ve T–Peak negative torque pulsation in Nm; Ta–Acceleration time in seconds; Ip–Peak positive current in A; $\alpha_{opt.}$ and $\beta_{opt.}$; Optimum firing angles in degrees.)

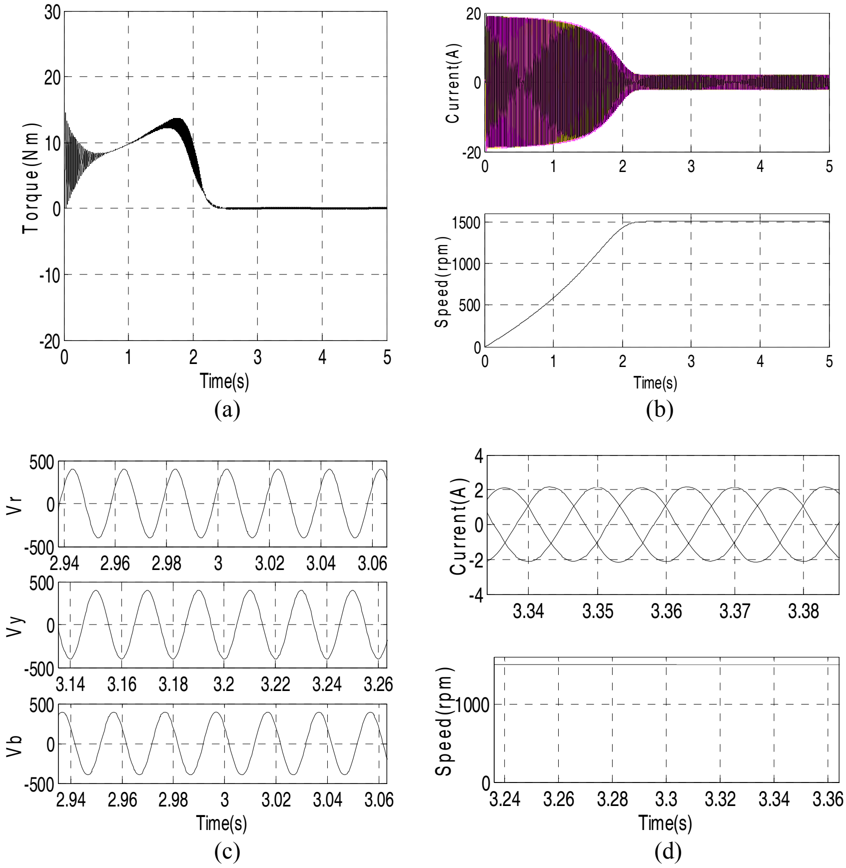


Figure 7. (a) Transient electromagnetic torque vs time; (b) transient current and speed vs time; (c)steady state line voltage vs time; (d) steady state current and speed vs time for optimum α = 54.5° and β = 61.5° for machine AI in two-leg topology

Analysis has been done for group B machines also, and similar results are obtained. The comparative performances for all the machines are shown in Table 3. It is noted that the performance with both the systems are on par. Thus the two-leg topology with only two groups of thyristors is cost effective and is the preferred method of starting compared to three-leg topology.

4. CONCLUSIONS

Starting performance of three phase ac voltage controller-fed induction motors are compared under three-leg and two-leg topologies. Performances of the motors are analyzed and optimum angles are obtained by considering different electrical characteristics. Optimum firing angle is taken as the firing angle at which the negative torque pulsation is zero with minimum acceleration time and other electrical characteristics under considerations are having satisfactory values. Two groups of induction motors with each group having same rated motors with different motor parameters are used for the simulation work. Results show that there is a significant improvement in the performance characteristics under three-leg and two-leg topologies compared to DOL starting. Among the topologies compared, the performances were on par and hence the cost effective two-leg controller is preferred over three-leg controller.

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APPENDIX

Table 4. Induction motor parameters for various machines

Machine	Motor rating	Stator resistance Rs(Ω)	Rotor resistance Rr(Ω)	Magnetizing inductance Lm(mH)	Stator/Rotor inductance Ls/Lr(mH)
AI	2.2kW,415V, 50Hz,4.5A	3.3	2.2	324.5	17.7
AII	2.2kW,415V, 50Hz,4.5A	8.0	7.0	1139.1	40.6
AIII	2.2kW,415V, 50Hz,4.5A	3.35	1.76	439.5	15.43
BI	3.7kW,400V, 50Hz,7A	6.2	5.23	692.73	30.42
BII	3.7kW,400V, 50Hz,7A	6.42	5.0	614.9	27.63