The Control of a Continuously Operated Pole-Changing Induction Machine

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28 February 2002

Outline

Pole Changing Techniques for Induction Machines

- Reconfigurable Stator Winding
- Multiple Stator Windings

Experimental Induction Machine with a 3:1 Pole Ratio

- 3phase-12pole Configuration
- 3phase-4pole Configuration
- 9phase-4pole Configuration
- Pole-Phase Variation

Nine Phase Operation

- Coordinate Transformation of Machine Variables
- 9 Phase PWM Techniques

Continuous Operation of a Pole Changing Induction Machine

- Issues During the Pole-Changing Transition
- Proposed Technique for Torque Regulation During Pole-Changing Transient

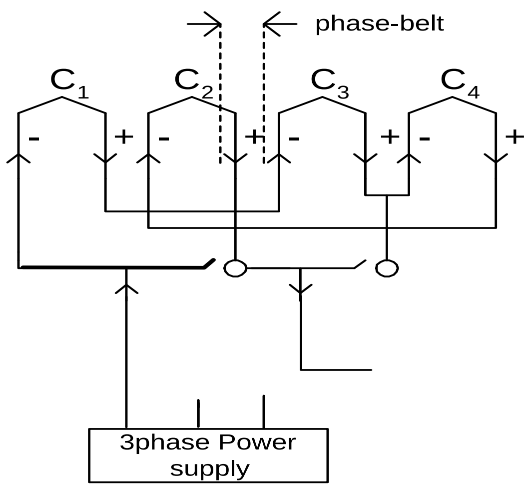
Experimental Setup

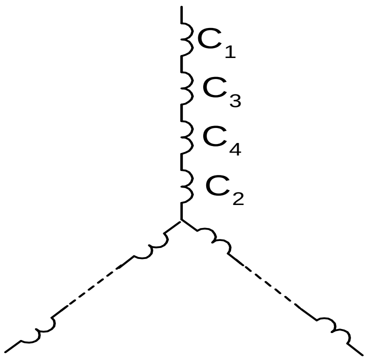
Conclusions

Background

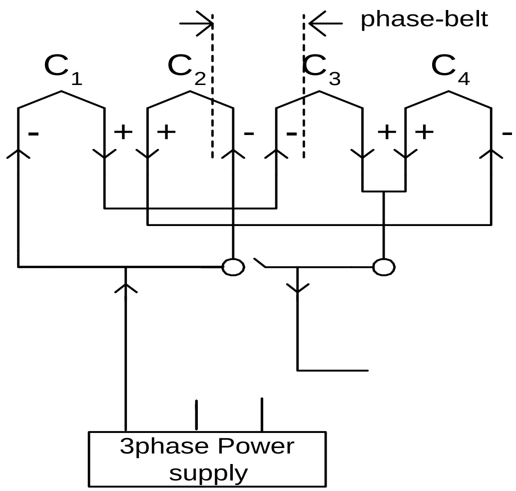
2:1 Pole-changing using Reconfigurable Stator Winding

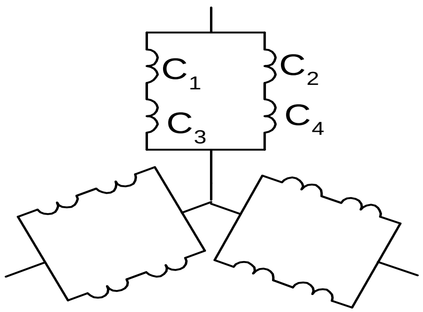
- Series connected phase coils resulting in 8 poles
- Mechanical Contactors





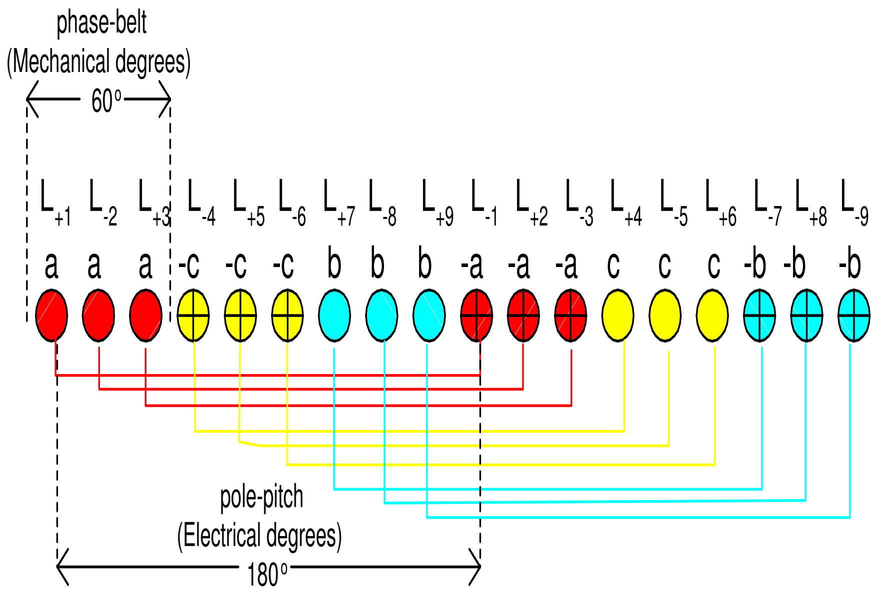
- Series-parallel connected phase coils resulting in 4 poles
- Mechanical Contactors

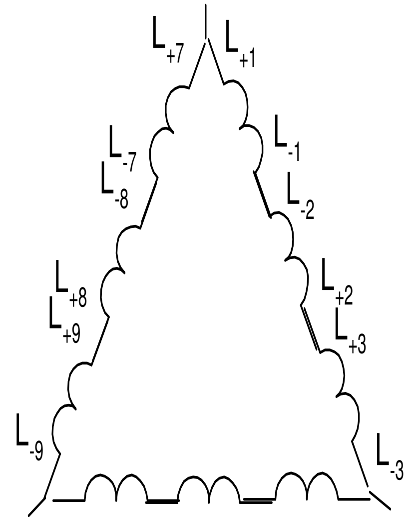




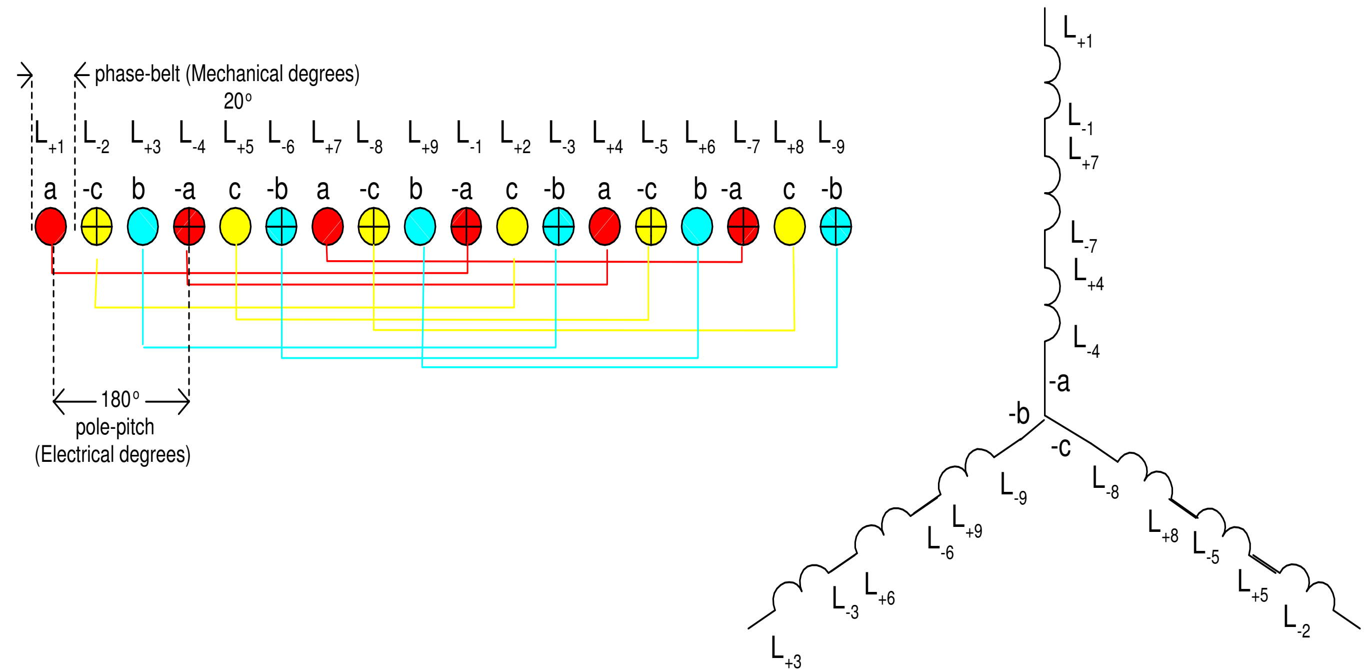
3:1 Pole-changing using Reconfigurable Stator Winding

- Delta connected phase coils resulting in 2 poles
- 60^o Phase Belt



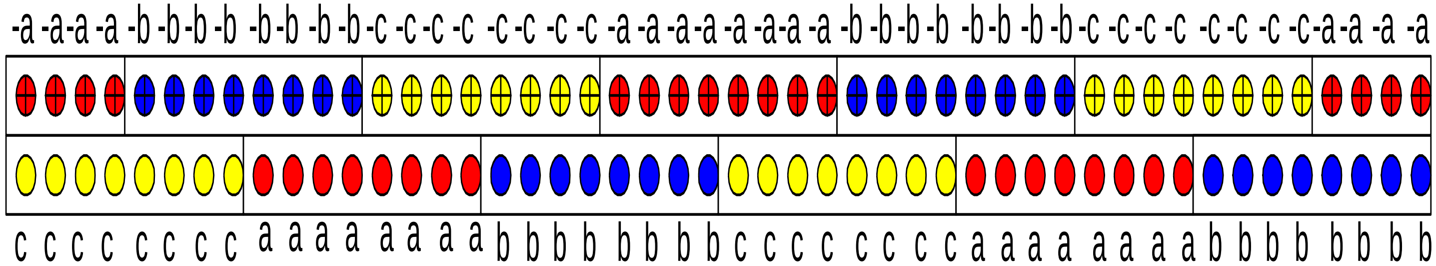


- Wye connected phase coils resulting in 6 poles
- 60^o Phase Belt

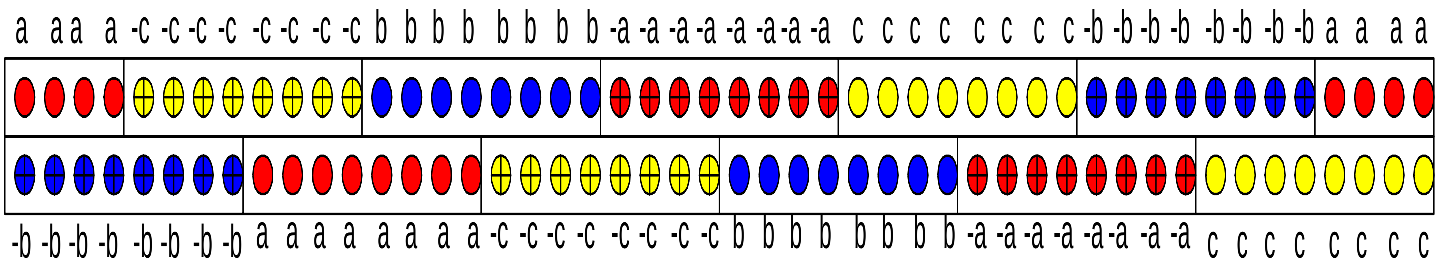


Induction Machine with Dual Stator Windings: Lippo and Osama

- 4 pole configuration
- two 3phase inverters, 6 winding currents:[i_{a1},i_{b1},i_{c1},i_{a2},i_{b2},i_{c2}]



- 2 pole configuration
- two 3phase inverters, 6 winding currents:[i_{a1},i_{b1},i_{c1},$-i_{a2}$,$-i_{c2}$,$-i_{b2}$]



Machine Variables Described in Six Dimensional Space

- Analysis in six-dimensional space too complex

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = [R][I] + \frac{d}{dt}[\lambda] \tag{1}$$

- Transformation to Simplify Analysis: One 6-D Machine mapped into Two independent machines in 3-D

$$\begin{bmatrix} V_{2q} \\ V_{2d} \\ V_{4q} \\ V_{4d} \\ V_{02} \\ V_{04} \end{bmatrix} = [\mathbf{T}] \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} \tag{2}$$

- Use Stator Winding MMF as basis for Transformation

$$\Im_1(\phi) = \sum_{h=1,2,3\ldots} N_{s_h} \cos\left(h(\phi) i_a(t)\right) \tag{3}$$

$$\Im_2(\phi) = \sum_{h=1,2,3\ldots} N_{s_h} \cos\left(h(\phi - \pi) i_a(t)\right) \tag{4}$$

$$\Im_3(\phi) = \sum_{h=1,2,3\ldots} N_{s_h} \cos\quad h(\phi - \frac{\pi}{3}) i_a(t) \tag{5}$$

$$\Im_4(\phi) = \sum_{h=1,2,3\ldots} N_{s_h} \cos\quad h(\phi + \frac{2\pi}{3}) i_a(t) \tag{6}$$

$$\Im_5(\phi) = \sum_{h=1,2,3\ldots} N_{s_h} \cos\quad h(\phi - \frac{2\pi}{3}) i_a(t) \tag{7}$$

$$\Im_6(\phi) = \sum_{h=1,2,3\ldots} N_{s_h} \cos\quad h(\phi + \frac{\pi}{3}) i_a(t) \tag{8}$$

$$\tag{9}$$

- Total MMF of Dual Stator Machine

$$\Im_{Total} = \Im_1 + \Im_2 + \Im_3 + \Im_4 + \Im_4 + \Im_5 + \Im_6 \tag{10}$$

- Total MMF Harmonic Composition (Fourier Series Expansion)

$$\Im_{Total} = \Im_{fundalmental} + \Im_{2nd} + \Im_{3rd} + \Im_{4th} + \Im_{5th} + \Im_{6th} \qquad (11)$$

- The 6-D machine variables are transformed into two sets of 2-D variables.
- One set is based the MMF fundamental component. These machines describe a 2 pole machine.
- The other set is based on MMF 2^{nd} harmonic component. These variables describe a 4 pole machine.
- The 3^{rd} harmonic component of the Total MMF defines the 1-D zero-sequence subspace for the 2 pole machine
- The 6^{rd} harmonic component of the Total MMF defines the 1-D zero-sequence subspace for the 4 pole machine

Transformation Matrix from original six dimensional space to 2 3-dimensional subspaces

$$T = \begin{bmatrix} q_4 \\ d_4 \\ q_2 \\ d_2 \\ 0_4 \\ 0_{\tilde{2}} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & \frac{-1}{2} & \frac{-1}{2} & \frac{-1}{2} & \frac{-1}{2} \\ 0 & 0 & \frac{-\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 1 & -1 & \frac{1}{2} & \frac{-1}{2} & \frac{-1}{2} & \frac{1}{2} \\ 0 & 0 & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \tag{12}$$

Transformation Matrix for arbitrary reference frame rotating at θ_m

$$T(\theta_m) = \frac{1}{\sqrt{3}} \begin{bmatrix} \cos(2\theta_m) & \cos(2\theta_m) & \cos(2\theta_m - \frac{2\pi}{3}) & \cos(2\theta_m - \frac{2\pi}{3}) & \cos(2\theta_m + \frac{2\pi}{3}) & \cos(2\theta_m + \frac{2\pi}{3}) \\ \sin(2\theta_m) & \sin(2\theta_m) & \sin(2\theta_m - \frac{2\pi}{3}) & \sin(2\theta_m - \frac{2\pi}{3}) & \sin(2\theta_m + \frac{2\pi}{3}) & \sin(2\theta_m + \frac{2\pi}{3}) \\ \cos(\theta_m) & -\cos(\theta_m) & -\cos(\theta_m + \frac{2\pi}{3}) & \cos(\theta_m + \frac{2\pi}{3}) & \cos(\theta_m - \frac{2\pi}{3}) & -\cos(\theta_m - \frac{2\pi}{3}) \\ \sin(\theta_m) & -\sin(\theta_m) & -\sin(\theta_m + \frac{2\pi}{3}) & \sin(\theta_m + \frac{2\pi}{3}) & \sin(\theta_m - \frac{2\pi}{3}) & -\sin(\theta_m - \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \tag{13}$$

Transformed Voltage and Flux Linkage Equations

$$v_{q4s} = r_s i_{q4s} + \lambda'_{q4s} + \omega_4 \lambda_{d4s} \quad (14)$$

$$v_{d4s} = r_s i_{d4s} + \lambda'_{d4s} - \omega_4 \lambda_{d4s} \quad (15)$$

$$v_{q2s} = r_s i_{q2s} + \lambda'_{q2s} + \omega_2 \lambda_{d2s} \quad (16)$$

$$v_{d2s} = r_s i_{d2s} + \lambda'_{d2s} - \omega_2 \lambda_{d2s} \quad (17)$$

$$v_{04s} = r_s i_{04s} + \lambda'_{04s} \quad (18)$$

$$v_{02s} = r_s i_{02s} + \lambda'_{02s} \quad (19)$$

$$\lambda_{q4s} = (L_{m4} + L_{ls}) i_{q4s} + L_{m4} i_{q4r} \quad (20)$$

$$\lambda_{d4s} = (L_{m4} + L_{ls}) i_{d4s} + L_{m4} i_{d4r} \quad (21)$$

$$\lambda_{q2s} = (L_{m2} + L_{ls}) i_{q2s} + L_{m2} i_{q2r} \quad (22)$$

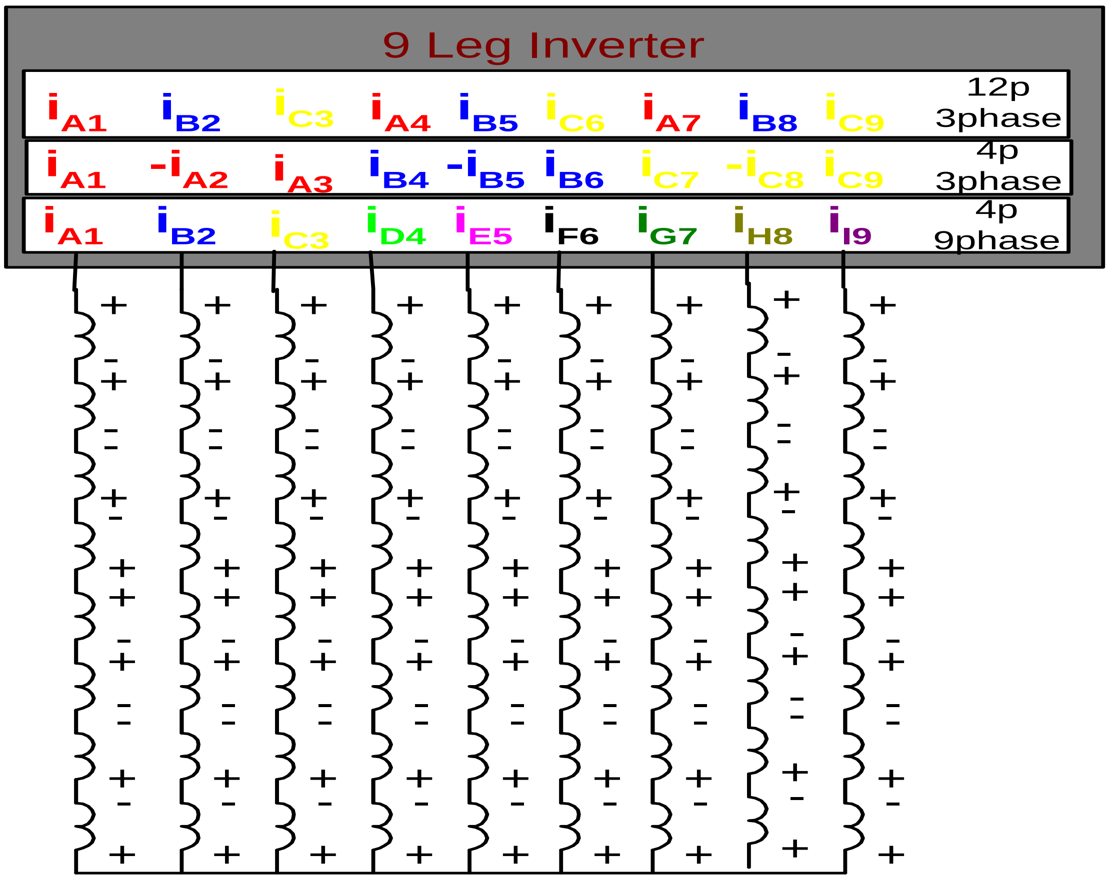
$$\lambda_{d2s} = (L_{m2} + L_{ls}) i_{q2s} + L_{m2} i_{d2r} \quad (23)$$

Transformed Torque Equation

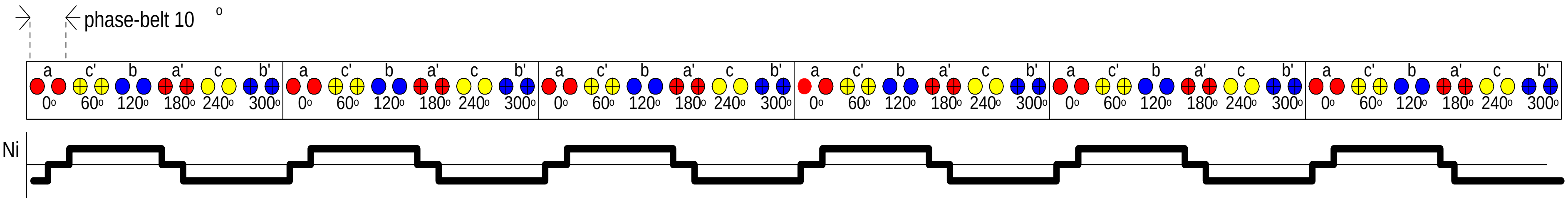
$$T_e = 2(\lambda_{d4s} i_{q4s} - \lambda_{q4s} i_{d4s}) + (\lambda_{d2s} i_{q2s} - \lambda_{q2s} i_{d2s}) \quad (24)$$

Experimental 3:1 Pole Induction Machine

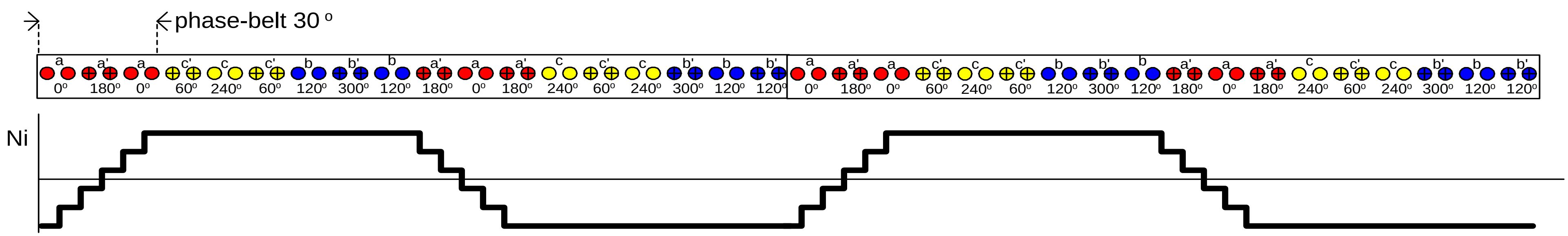
Winding Diagram



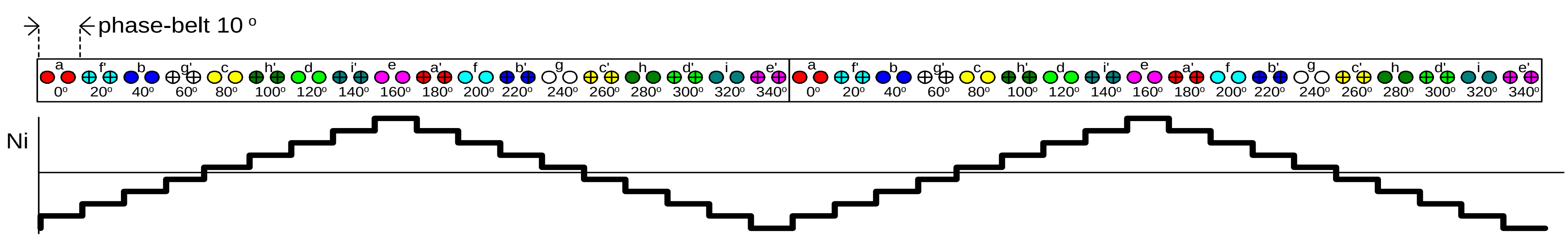
- 3phase-12pole Configuration



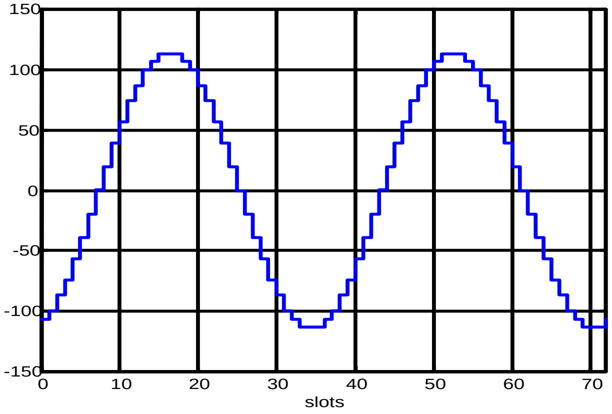
- 3phase-4pole Configuration

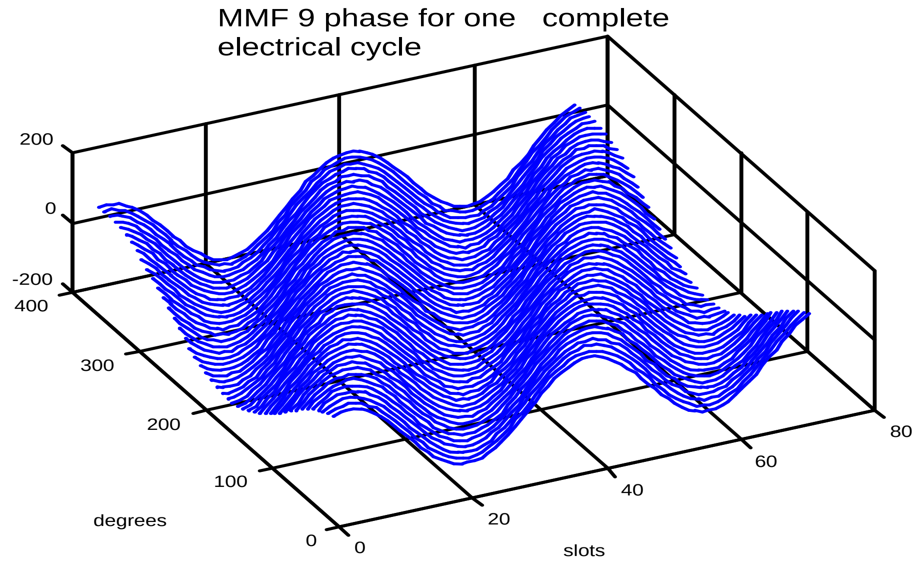


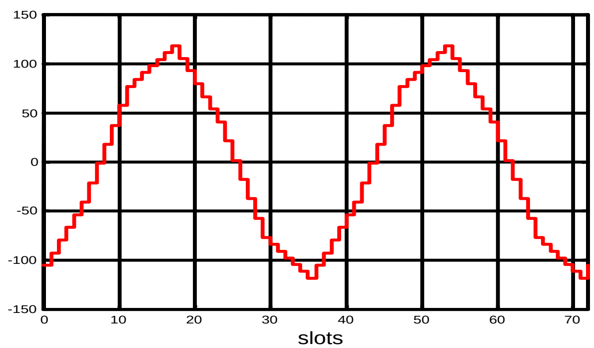
- 9phase-4pole Configuration

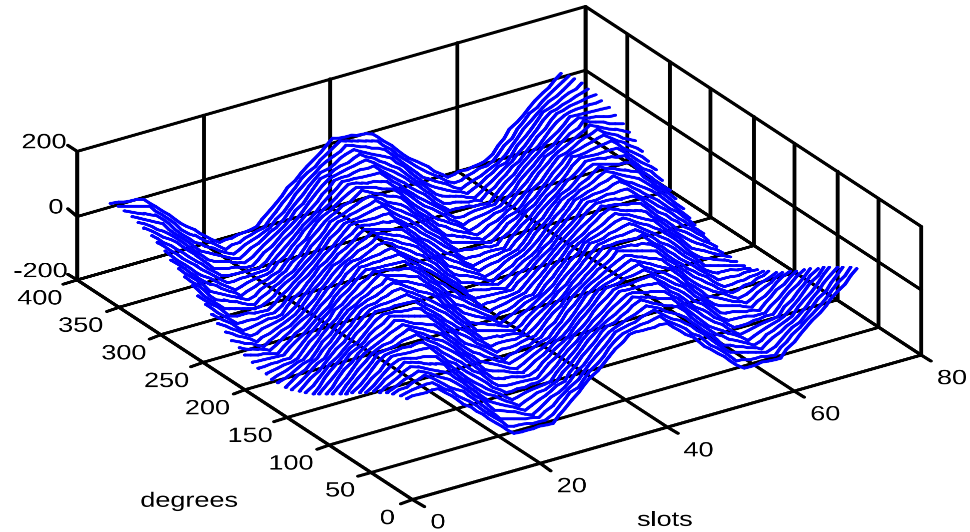


3phase-4pole vs 9phase-4pole MMF







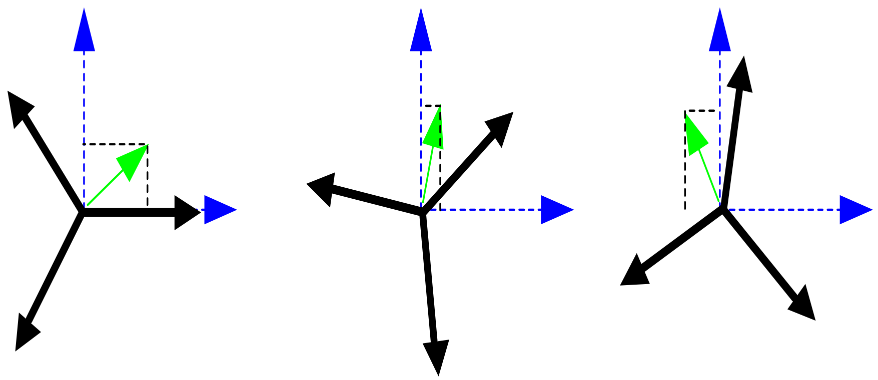


9 Phase Operation

Coordinate Transformation

- 9 dimensional machine variables too complex, transform to 2-D space (for conventional Field Orientation Control)
- Transformation from 9 to 2 dimensions is over defined
- Transformation from 2 to 9 dimensions is under defined
- Add Constraints in order to make transformation unique

- Define a new 9-D coordinate system consisting of three 3phase coordinate systems, rotated 40^o wrt to each other



- Map $\frac{1}{3}$ of the 2-D space vector into each 3phase system
- 2 to 9 transformation

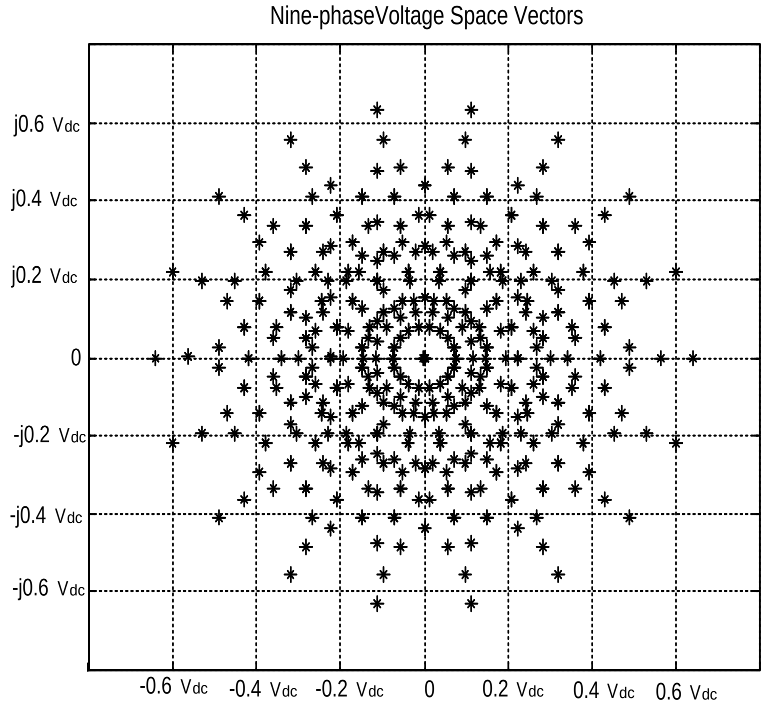
$$\begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \\ f_{ds} \\ f_{es} \\ f_{fs} \\ f_{gs} \\ f_{hs} \\ f_{is} \end{bmatrix} = \frac{3}{2} * \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos(\alpha + \frac{2\pi}{9}) & \sin(\alpha + \frac{2\pi}{9}) & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \cos(\alpha + \frac{4\pi}{9}) & \sin(\alpha + \frac{4\pi}{9}) & 1 & \\ \cos(\alpha + \frac{6\pi}{9}) & \sin(\alpha + \frac{6\pi}{9}) & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos(\alpha + \frac{8\pi}{9}) & \sin(\alpha + \frac{8\pi}{9}) & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \cos(\alpha + \frac{10\pi}{9}) & \sin(\alpha + \frac{10\pi}{9}) & 1 & \\ \cos(\alpha + \frac{12\pi}{9}) & \sin(\alpha + \frac{12\pi}{9}) & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos(\alpha + \frac{14\pi}{9}) & \sin(\alpha + \frac{14\pi}{9}) & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \cos(\alpha + \frac{16\pi}{9}) & \sin(\alpha + \frac{16\pi}{9}) & 1 & \end{bmatrix} * \begin{bmatrix} \frac{f_q}{3} \\ \frac{f_d}{3} \\ \frac{f_o}{3} \\ \frac{f_q}{3} \\ \frac{f_d}{3} \\ \frac{f_o}{3} \\ \frac{f_q}{3} \\ \frac{f_d}{3} \\ \frac{f_o}{3} \end{bmatrix} \quad (25)$$

- 9 to 2 transformation

$$
\begin{bmatrix} f_{q1} \\ f_{d1} \\ f_{o1} \\ f_{q2} \\ f_{d2} \\ f_{o2} \\ f_{q3} \\ f_{d3} \\ f_{o3} \end{bmatrix} = \frac{2}{9} * \begin{bmatrix}
\cos(\alpha) & 0 & 0 & \cos(\alpha - \frac{2\pi}{3}) & 0 & 0 & \cos(\alpha + \frac{2\pi}{3}) & 0 & \\
\sin(\alpha) & 0 & 0 & \sin(\alpha - \frac{2\pi}{3}) & 0 & 0 & \sin(\alpha + \frac{2\pi}{3}) & 0 & \\
\frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 & \\
0 & \cos(\alpha + \frac{2\pi}{9}) & 0 & 0 & \cos(\alpha - \frac{8\pi}{9}) & 0 & 0 & \cos(\alpha + \frac{8\pi}{9}) & \\
0 & \sin(\alpha + \frac{2\pi}{9}) & 0 & 0 & \sin(\alpha - \frac{8\pi}{9}) & 0 & 0 & \sin(\alpha + \frac{8\pi}{9}) & \\
0 & \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 & 0 & \frac{1}{2} & \\
0 & 0 & \cos(\alpha + \frac{4\pi}{9}) & 0 & 0 & \cos(\alpha - \frac{10\pi}{9}) & 0 & 0 & \cos(\alpha \\
0 & 0 & \sin(\alpha + \frac{4\pi}{9}) & 0 & 0 & \sin(\alpha - \frac{10\pi}{9}) & 0 & 0 & \sin(\alpha \\
0 & 0 & \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 & 0 &
\end{bmatrix} \tag{26}
$$

Realization of a 9-D Space Vector Voltage Command Via Pulse Width Modulation (PWM)

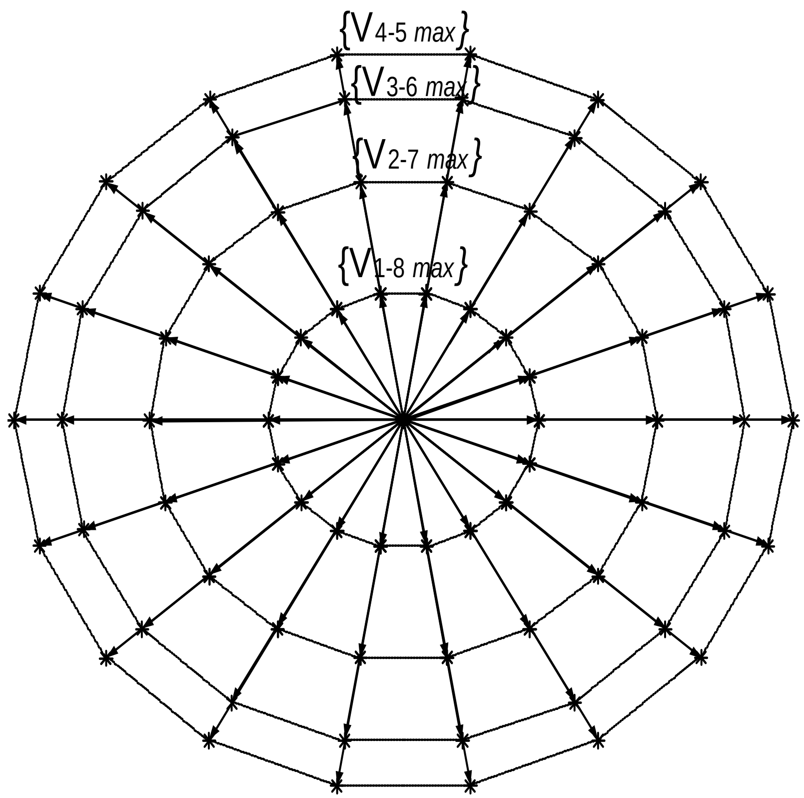
- 512 possible space vectors from a 9-leg inverter



- Extending 3phase Space Vector PWM algorithm for 9phase Space Vector PWM

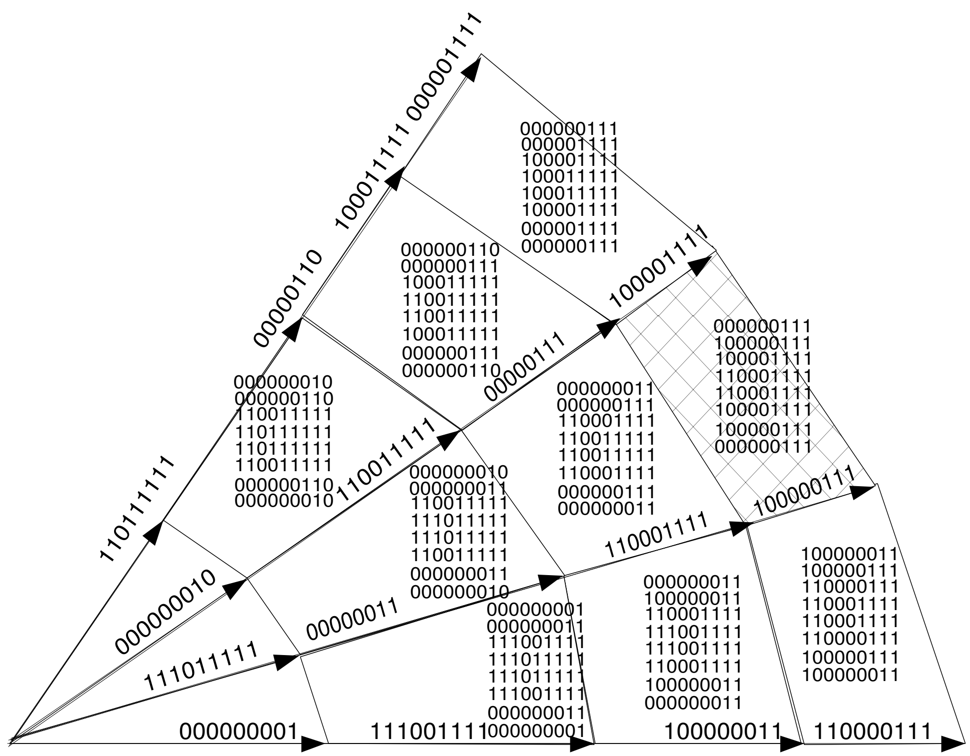
$$V_{n,\ offset} = max \quad \frac{V_1}{V_{dc}} ... \frac{V_n}{V_{dc}} \quad - min \quad \frac{V_1}{V_{dc}} ... \frac{V_n}{V_{dc}} \tag{27}$$

- Only 72 space vectors are used



A new SVPWM for $n > 3$ n-phase Systems

- The Minimum Voltage Difference SVPWM Technique

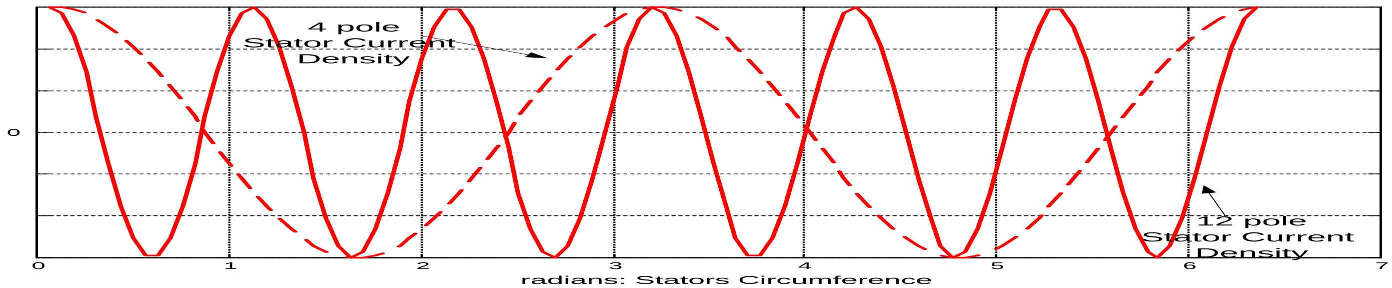


Proposal: The Control of a Continuously Operated Pole-Changing Induction Machine

Goals:

- Decrease the Torque reduction during the pole-changing transition
- Preserve Control during the pole-changing transition

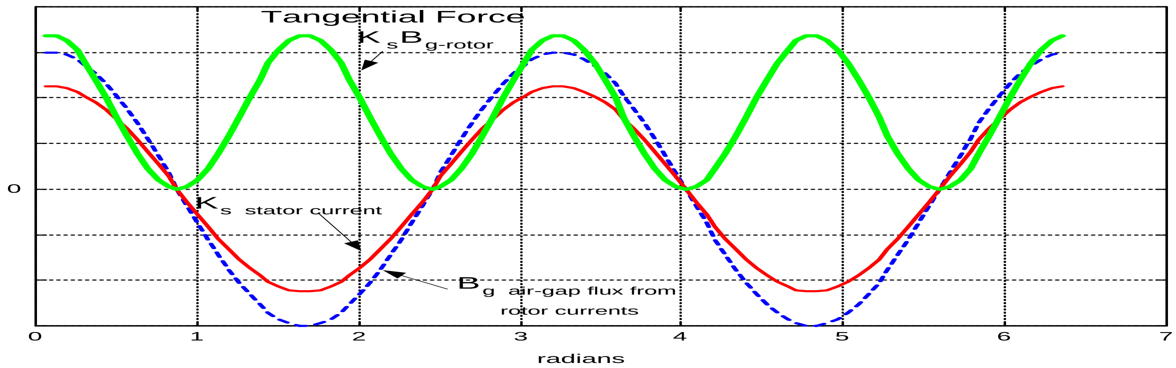
Comparison of 4 pole and 12 pole Stator Current Densities



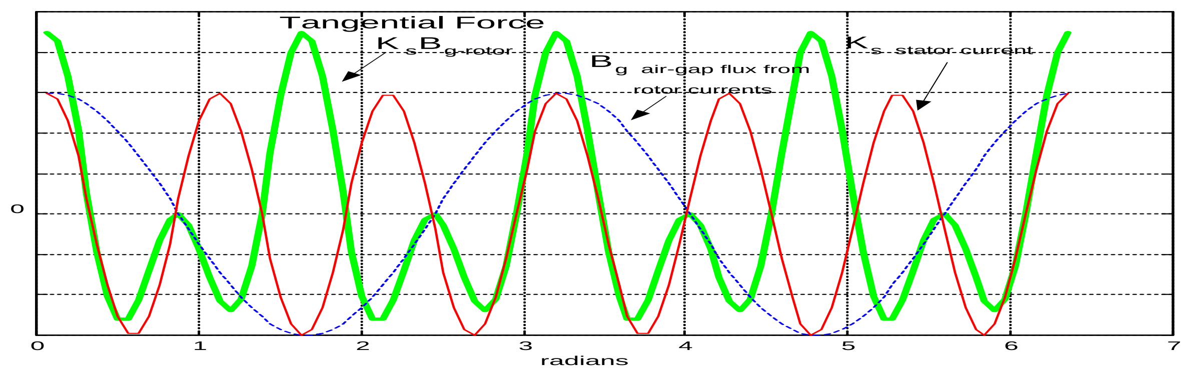
- Interaction between the Stator Current Density and air-gap flux results in a tangential force on the rotor

$$\frac{dF}{d\theta} = B_g K_s(t, \theta) \tag{28}$$

- 4 pole steady state operation



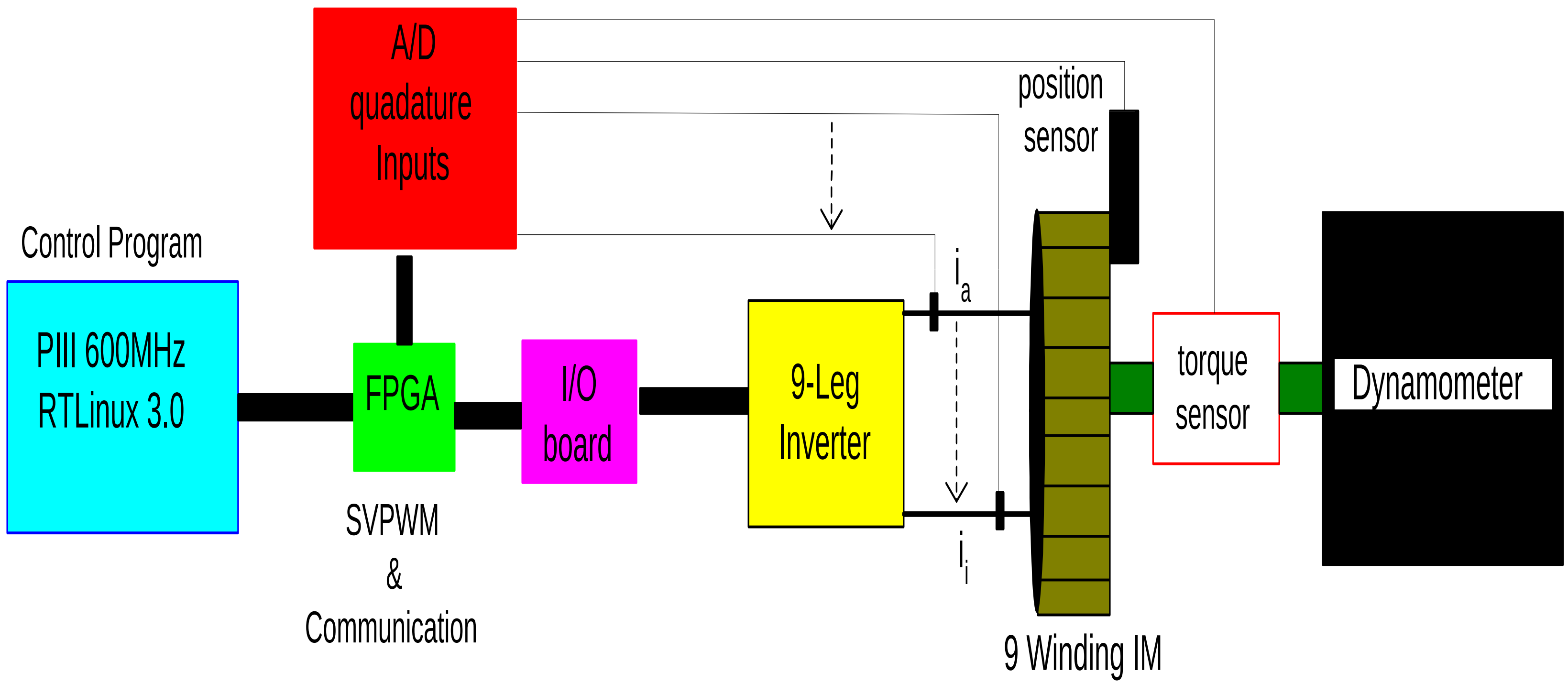
- Transition from 12 poles to 4 poles



Approach:

- Via a coordinate transformation, decouple the machine into two (possibly three) independent machines
- Regulate the two independent torques in order to pole change
- Control each machine separately

Experimental Setup:



Speed-torque curves for the 12 pole and 4 pole configurations

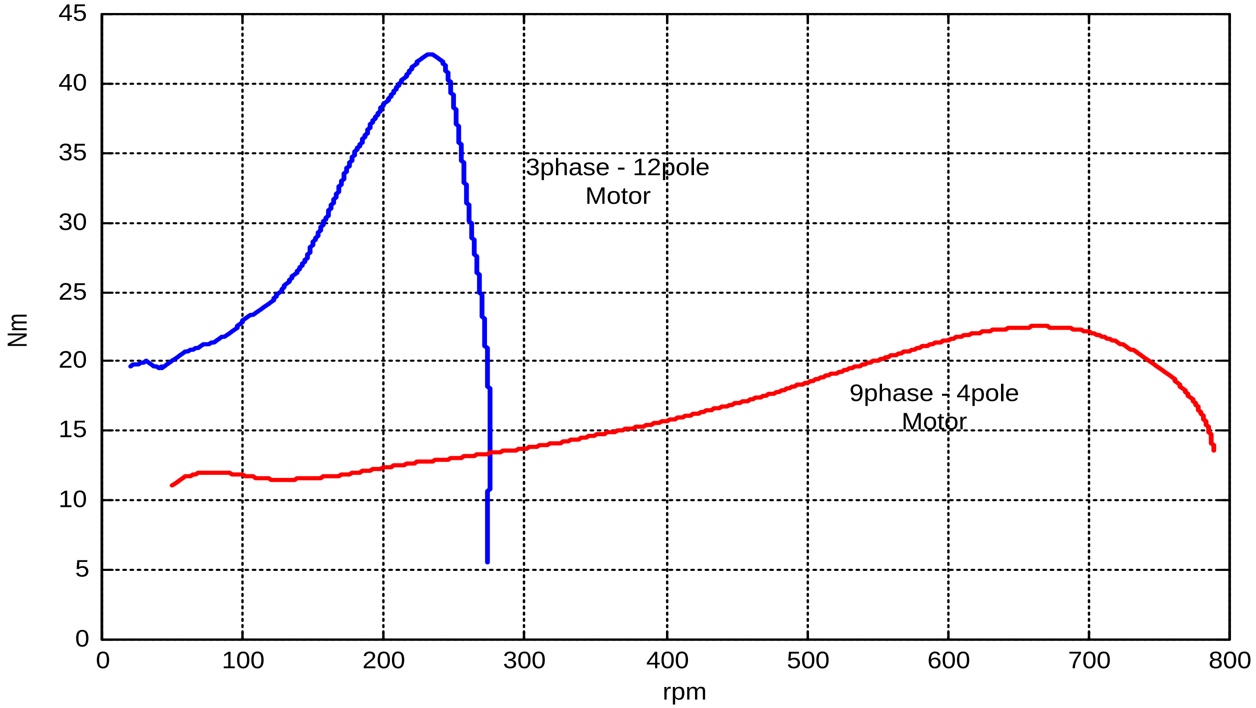


Figure 1: Speed-torque curves for 12 pole and 4 pole configurations

Speed control: 3phase-12pole Induction motor

- Space Vector Field Orientation Control
- 3phase SVPWM

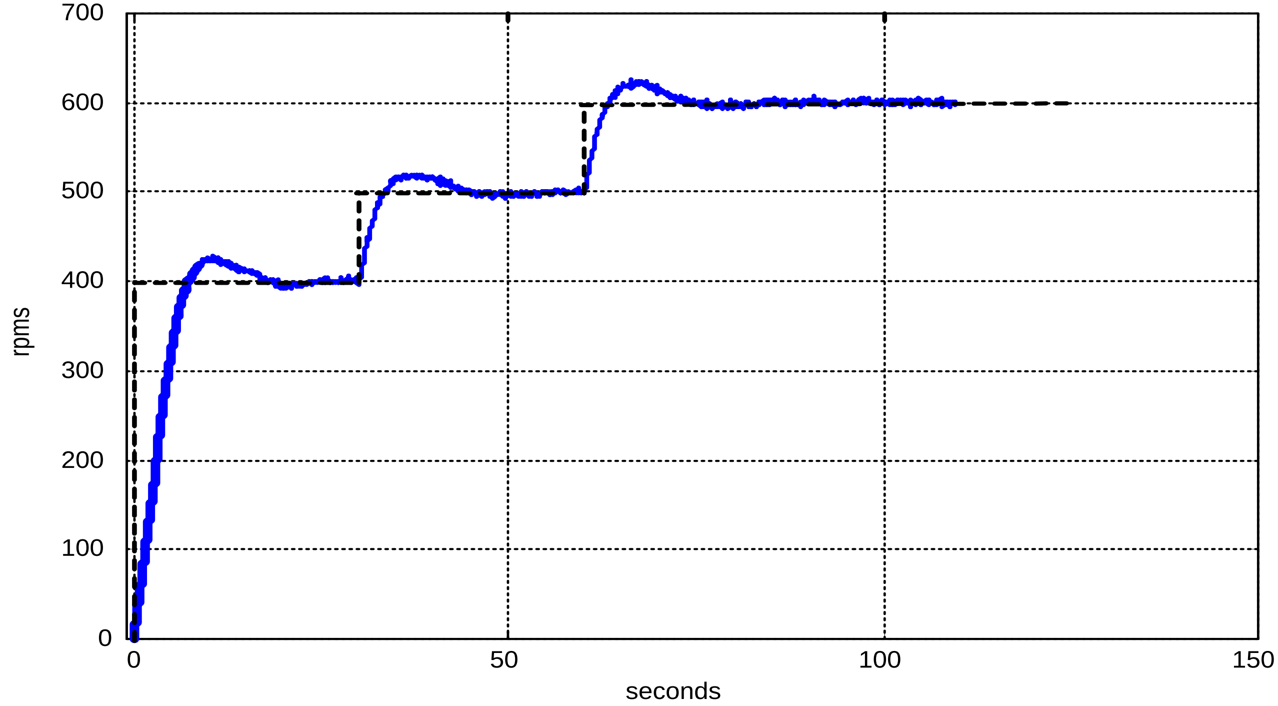


Figure 2: Speed-torque curves for 12 pole and 4 pole configurations

Conclusions:

- A variety of pole changing technique exists
- There are no techniques for regulating torque during the pole-changing transition
- Issues during the pole-changing transition:
  - reduction in torque
  - flux and torque tracking)
- Requirements for a method to decrease torque reduction during the pole-changing transition and preserve control:
  - New PWM scheme
  - Modelling the machine as two independent machines
  - Develop method to analyze a pole-changing machine in terms of Field Orientation Transformation