

Acknowledgement

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Abstract

Computer Simulations enable engineers to study the behavior of complex and powerful systems without actually building or operating them. PSpice is one of the most widely used general-purpose simulation programs which is more specialized towards the power electronics and motor drives application area. SPICE means “Simulation Program with Integrated Circuit Emphasis”. The PSpice model consists of three main Components – PWM Generator, Inverter and Induction Motor. Using this model, one can study the torque, rotor speed, stator currents and voltages of Induction Motor, varying with respect to time.

Chapter 1. Various Methods of Speed Control of Induction Motor

The speed of induction motor is given by,

$$N = (1-S) * N_s \text{_____} (1.1)$$

Where S = Slip

N_s = Synchronous Speed of motor

$$= 120 * f / P$$

P = No. of poles

f = Supply frequency

Hence,

$$N = (1-S) * 120 * f / P \text{_____} (1.2)$$

From this equation 1.2, the motor speed can be varied by

- Varying the number of poles P.
- Varying the frequency of stator supply voltage.
- Varying the slip of the motor at constant supply frequency.
- The pole control method is not preferable in practice as it is a mechanical means for varying the speed.
- The slip can be varied by varying the stator supply voltage, rotor resistance in slipping induction motor etc.

- The speed control methods other than variable frequency control suffer from the following drawbacks:
 - Low operating efficiency.
 - Rotor heating which demands motor cooling.
 - Low operating power factor.
 - Low torque per ampere.
 - Low starting torque.
 - Limited speed control range.

- Apart from the above conventional methods, the frequency control method has following important advantages:
 - Constant maximum torque throughout the speed range.
 - Speed control range from 2-3 times the synchronous speed down to zero speed.
 - High torque per ampere throughout the speed range.
 - Constant slip throughout the speed range, hence higher efficiency of operation.
 - Improved operating power factor.

In this frequency control method, the frequency of the stator supply is varied to vary the speed. To keep the airgap flux constant throughout the speed range and to achieve the maximum breakdown torque, the stator supply must also be varied along with the stator supply frequency so that V_s/f ratio remains constant.

Chapter 2. PWM Generator

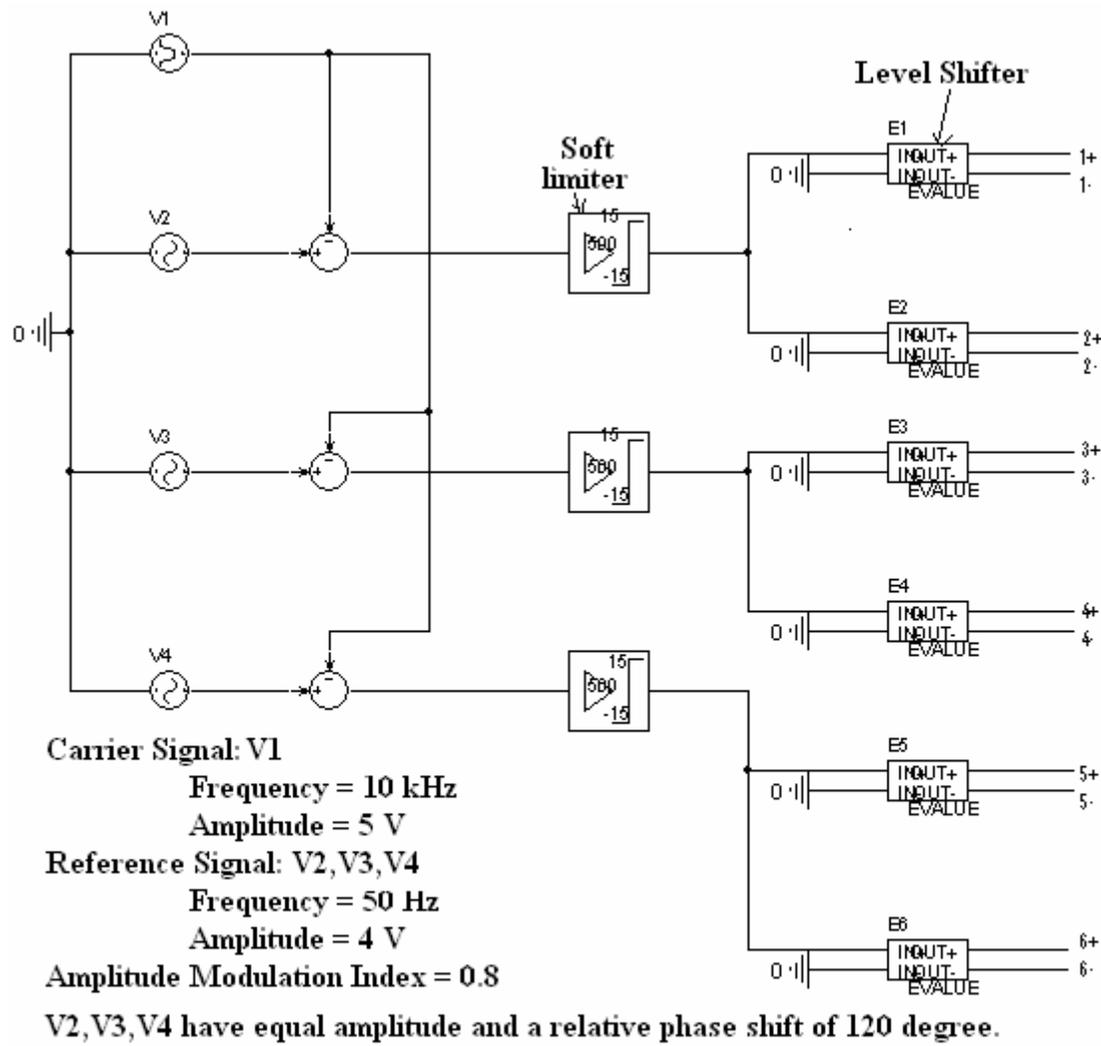


Figure 2.1 PWM Generator

- V1 is a triangular carrier signal, which is compared with a sinusoidal reference signal. The output of the comparator is shown in figure 2.2.

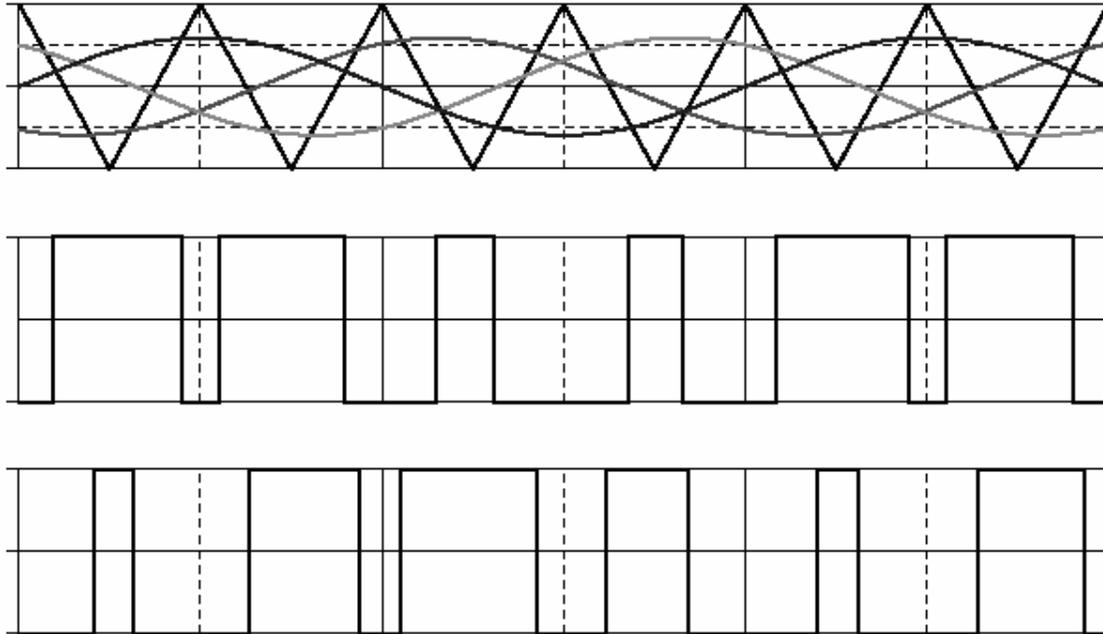


Figure 2.2 Pulse Width Modulation

- The output of comparator is high when the instantaneous reference voltage is higher than the carrier voltage and vice versa.
- Feeding the difference of the carrier wave and the reference wave into a soft limiter generates the primary PWM signal.
- The result of the soft limiter is an output signal with smooth transitions, which is crucial to avoid convergence problems in PSpice.
- The soft limiter used in the model has an upper and lower limit of ± 15 V and a gain (steepness control for the tanh function) of 500.
- Following each soft limiter, there are two voltage controlled voltage sources (level shifters) that generate isolated gate-source voltages of 15 V for the on condition and 0 V for the off condition of the MOSFETs.

Chapter 3. Three-phase Inverter with Mosfets

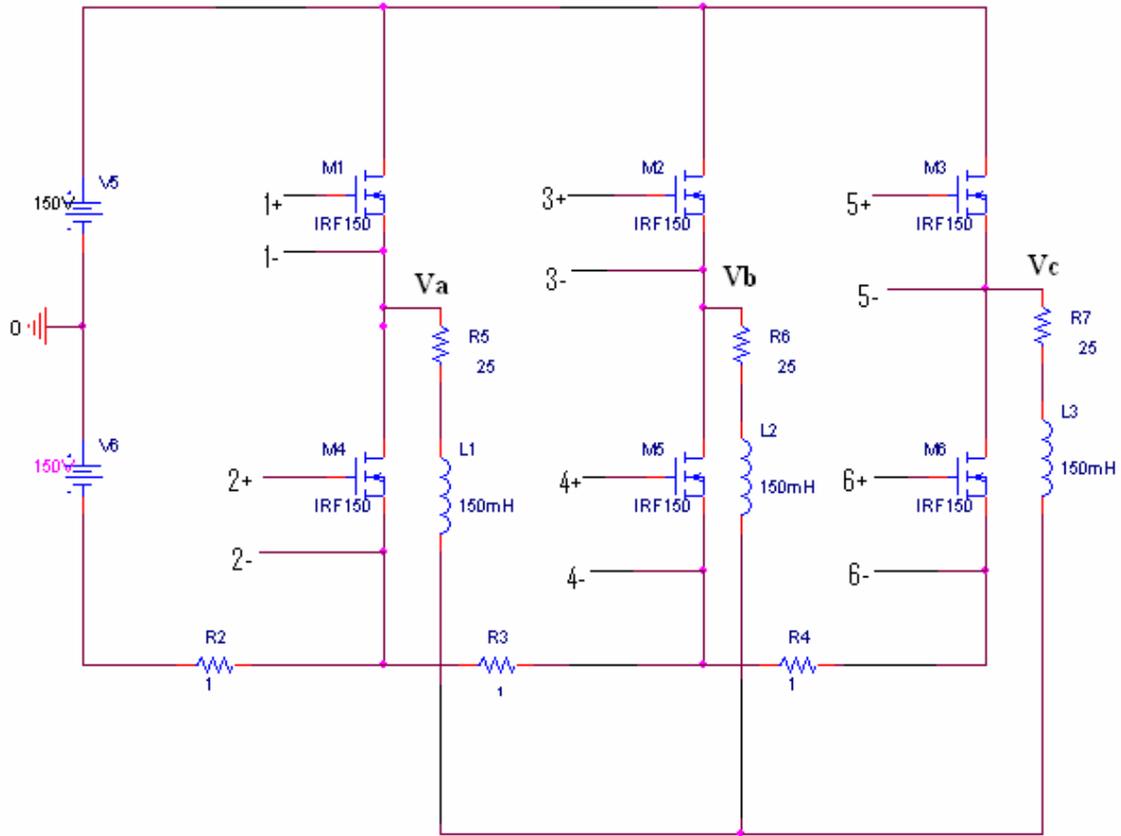
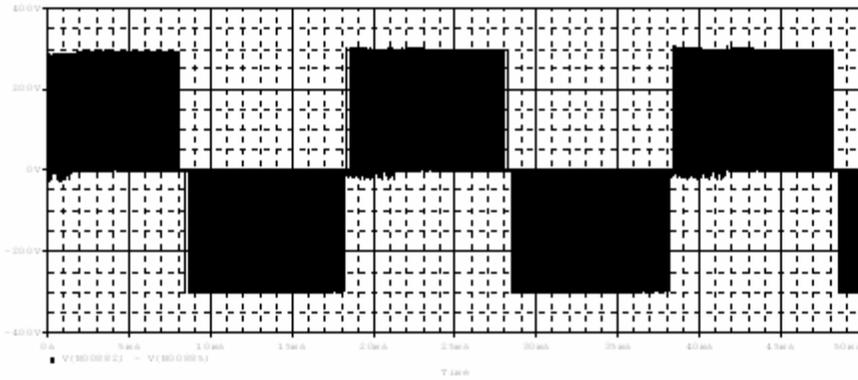


Figure 3.1 Circuit for a 3-phase inverter with MOSFETs.

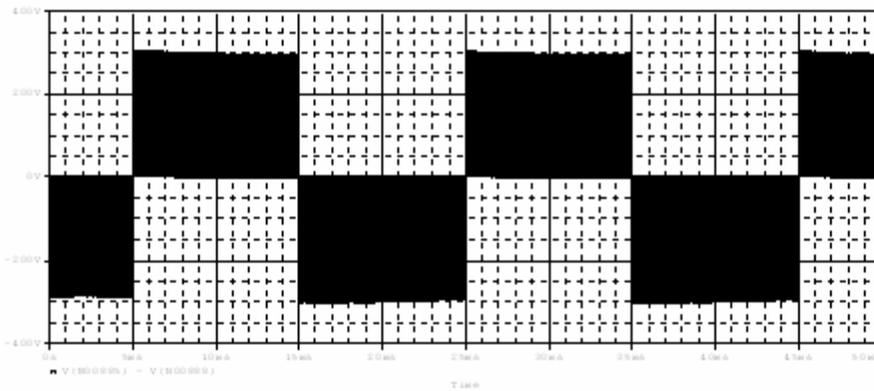
- Figure 3.1 shows a complete 3-phase inverter bridge using six power MOSFETs.
- The six outputs of PWM generator are given to the gate terminals of six MOSFETs, so that 3 AC voltages (V_a , V_b and V_c) of magnitude 300 V (p-p) at 120 degree phase displacement are generated.

Output Voltage of Inverter :

Vab:



Vbc:



Vca:

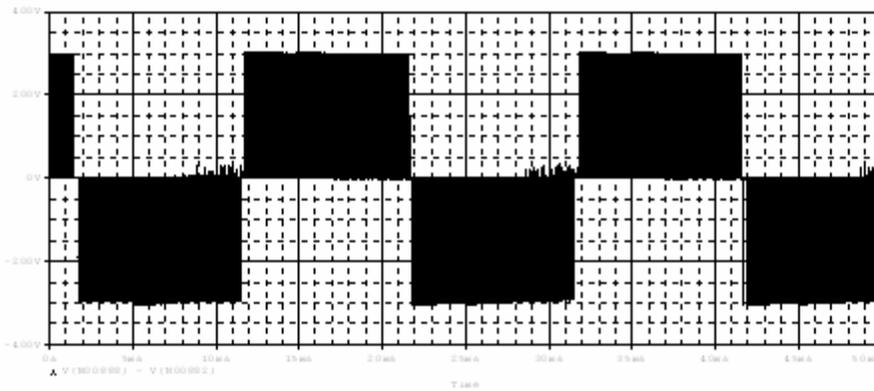


Figure 3.2 Output Voltages of Inverter

Output Currents of Inverter

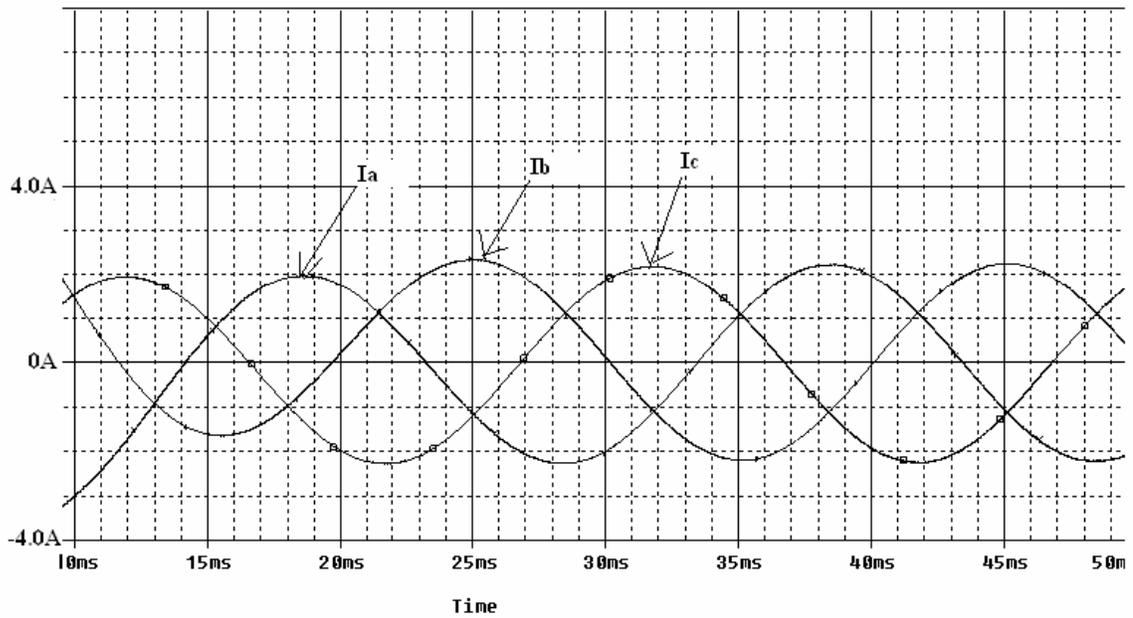


Figure 3.3 Output Currents of Inverter

- Due to the inductors contained in the load, the current cannot instantaneously change and follow the PWM signal. Therefore the load current is an almost pure sinusoid with very little ripple.

Chapter 4. ABC-DQ Transformation

- Transformation in electrical machines is usually carried out for the purpose of obtaining new equations which are fewer in number and are more easily solved.
- For example, a 3-phase machine requires three voltage equations whereas its equivalent 2-axis model requires two voltage equations which can be solved more easily as compared to three voltage equations. Thus the complexity of equations can be reduced.
- Further, the circuit equations for a 3-phase machine are more complicated because of the magnetic coupling among the 3-phase winding, but this is not the case in the equivalent 2-axis model in which mmf acting along one axis has no mutual coupling with the mmf acting along the other axis.
- A transformation can be arbitrarily selected purely on mathematical grounds to get the suitable matrix, which results in simplifying the process of obtaining the solution of a problem.
- In the case of winding on the stator, a transformation must be made to the equivalent coils d^s and q^s in such a manner that the magnitude and direction of mmf set up by 3-phase currents i_{as} , i_{bs} , i_{cs} and two coil currents i_{qs} and i_{ds} are identical.

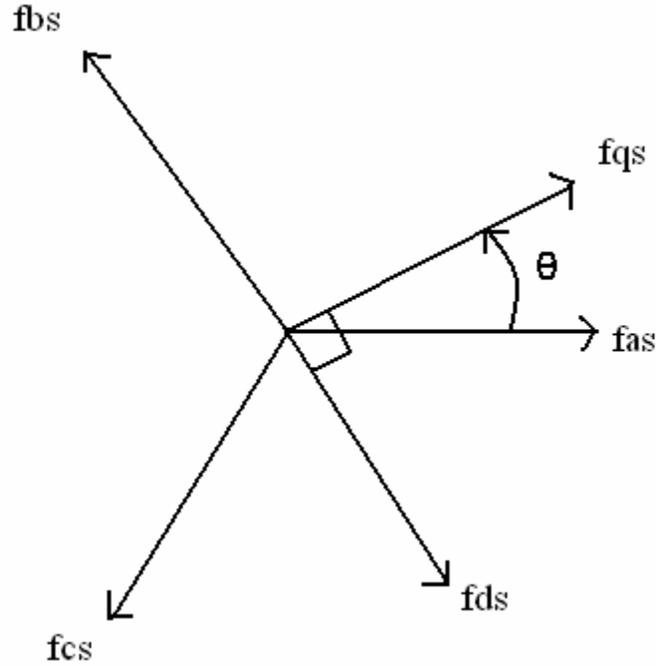


Figure 4.1 Transformation from ABC to DQ.

- Consider a symmetrical 3-phase induction machine with stationary as-bs-cs axis at 120° angle apart as shown in figure 6. Here f denotes voltage, current or flux linkage.
- We have to transform the 3-phase stationary reference frame (as-bs-cs) variables into 2-phase stationary reference frame (d^s-q^s) variables.
- Here, θ is the angle between f_{as} and f_{q^s}. Now, writing the voltage equations,

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-120) & \sin(\theta-120) & 1 \\ \cos(\theta+120) & \sin(\theta+120) & 1 \end{bmatrix} \begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{os}^s \end{bmatrix} \quad (4.1)$$

Taking the inverse of the matrix, we get,

$$\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{os}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad (4.2)$$

- The equations can be written in simplified form as,

$$V_{qs}^s = (2/3)*\cos\theta*V_{as} + (2/3)*\cos(\theta-120)*V_{bs} + (2/3)*\cos(\theta+120)*V_{cs} \quad (4.3)$$

$$V_{ds}^s = (2/3)*\sin\theta*V_{as} + (2/3)*\sin(\theta-120)*V_{bs} + (2/3)*\sin(\theta+120)*V_{cs} \quad (4.4)$$

- Considering stationary reference frame and $\theta=0$,

$$V_{qs}^s = (2/3)*V_a - (1/3)*V_b - (1/3)*V_c \quad (4.5)$$

$$V_{ds}^s = (-1/\sqrt{3})*V_b - (1/\sqrt{3})*V_c \quad (4.6)$$

The ABC-dq transformation is realized by the following model, in which summation and gain blocks are used to process the transformation equations.

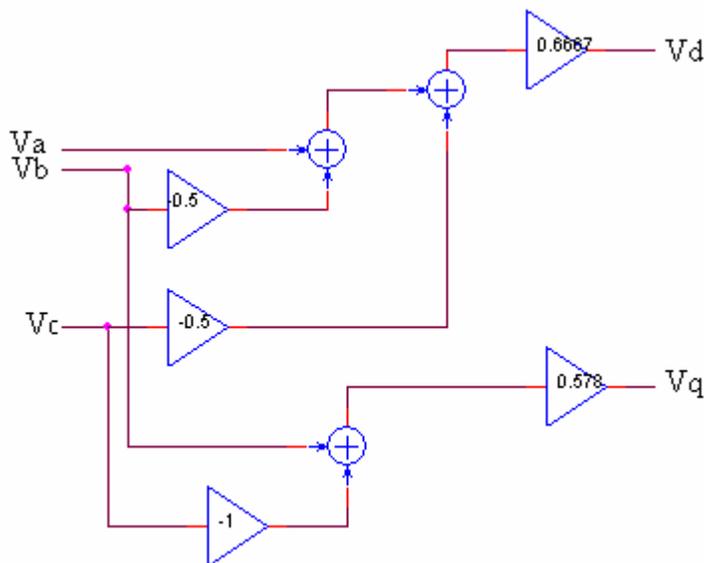


Figure 4.2 ABC-dq Transformation

Chapter 5. Electrical and Mechanical Model of Induction Motor

5.1 Electrical Model

- The electrical transient model in terms of currents and voltages can be given in matrix form as

$$\begin{bmatrix} V_d \\ V_q \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{stat} + pL_s & 0 & pL_m & 0 \\ 0 & R_{stat} + pL_s & 0 & pL_m \\ pL_m & \omega_e L_m & R_{rot} + pL_r & \omega_e L_r \\ -\omega_e L_m & pL_m & -\omega_e L_r & R_{rot} + pL_r \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \\ I_{rd} \\ I_{rq} \end{bmatrix}$$

$$L_s = L_m + L_{s1} \quad L_r = L_m + L_{r1} \quad p = d/dt \quad \text{_____}(5.1)$$

- The electrical model shown in figure 5.1 implements the equation system shown above.
- This circuit resembles the T-equivalent circuit for the steady state analysis of induction motor.
- The equation system and the model are formulated for the stationary reference frame. This reference frame assumes that the frame of the machine is stationary and the voltages and currents of the rotor are equivalent ac values with stator frequency.

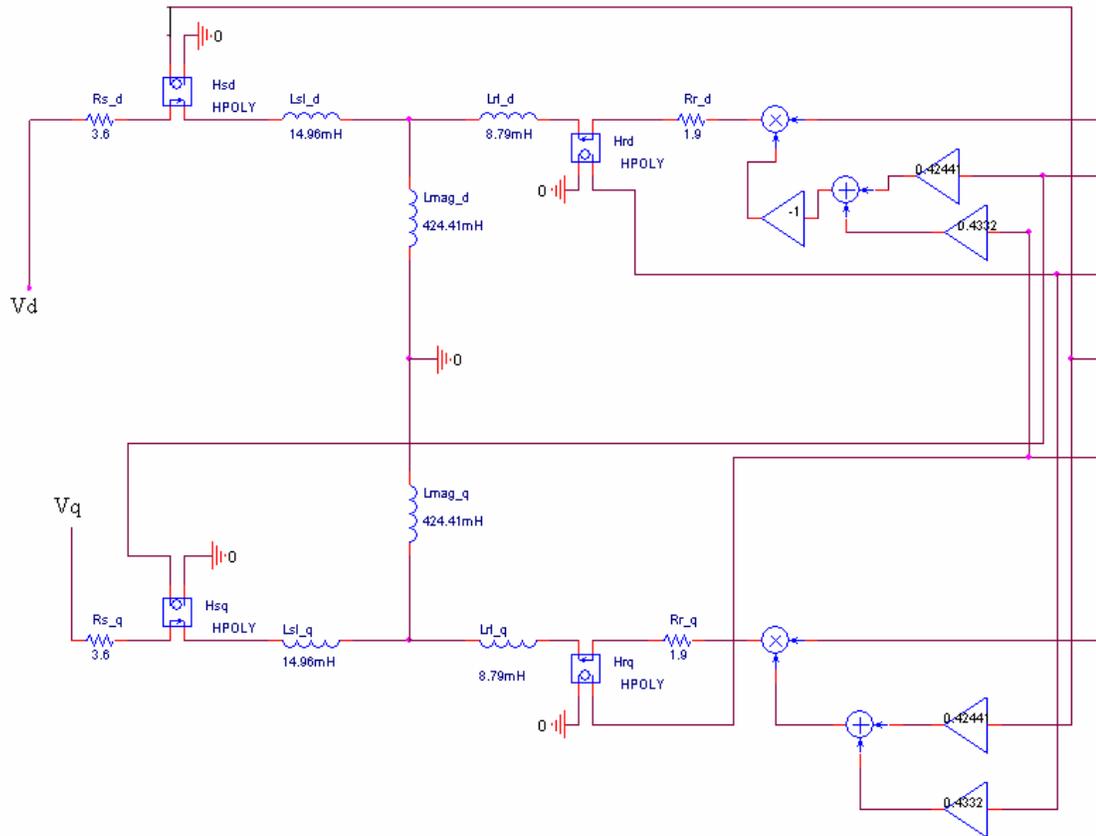


Figure 5.1 Electrical Model of Induction Motor

5.2 Mechanical Model

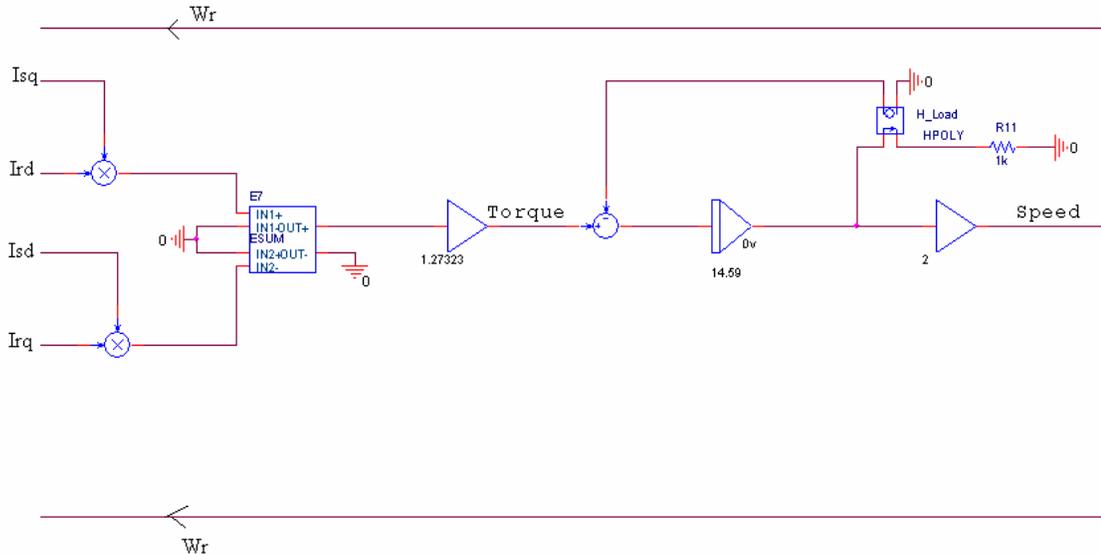


Figure 5.2 Mechanical model of Induction Motor

- This circuitry calculates the internally generated electromagnetic torque using the rotor and stator currents as input values.
- The equation for the electromagnetic torque is given by,

$$T_e = (3/2) * (P/2) * L_m * [(I_{sq} * I_{rd}) - (I_{sd} * I_{rq})] \quad (5.2)$$

The factor 3/2 accounts for the fact that the real motor is a three phase machine.

- Using the generated torque, the load torque and the moment of inertia, the angular speed can be calculated as follows:

$$2H * (dW_r/dt) = T_e - T_L \quad (5.3)$$

Where H = Inertia Constant

$$= J * W_{bm}^2 / (2 * S_b)$$

J = Moment of Inertia

S_b = Base volt-ampere

$$W_{bm} = (2/P) * W_b$$

$$W_b = 2\pi f_{rated}$$

f_{rated} = Rated frequency of machine

Chapter 6. Torque and Speed Waveforms at Different Frequencies

The different parameters of induction motor are as below:

Poles = 4

$R_{stat} = 3.6 \Omega$

$R_{rot} = 1.90 \Omega$

$L_{sl} = 14.96 \text{ mH}$

$L_{rl} = 8.79 \text{ mH}$

$L_m = 424.41 \text{ mH}$

$J = 0.01 \text{ kg-m}^2$

Gain of integrator block = 14.59

For 5 kHz

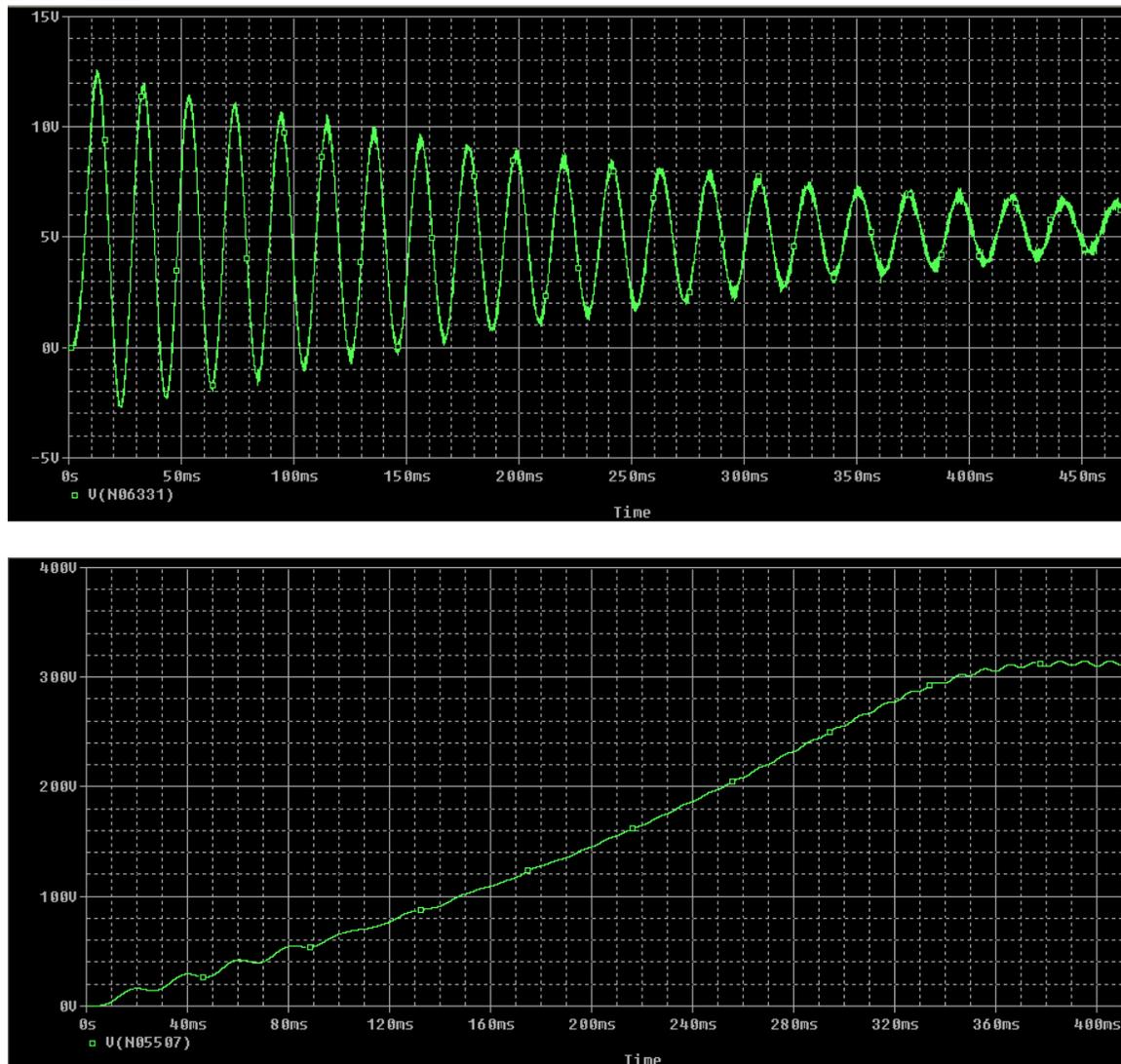


Figure 6.1 Torque and Speed Waveforms at 5 kHz Carrier Signal Frequency

For 10 kHz

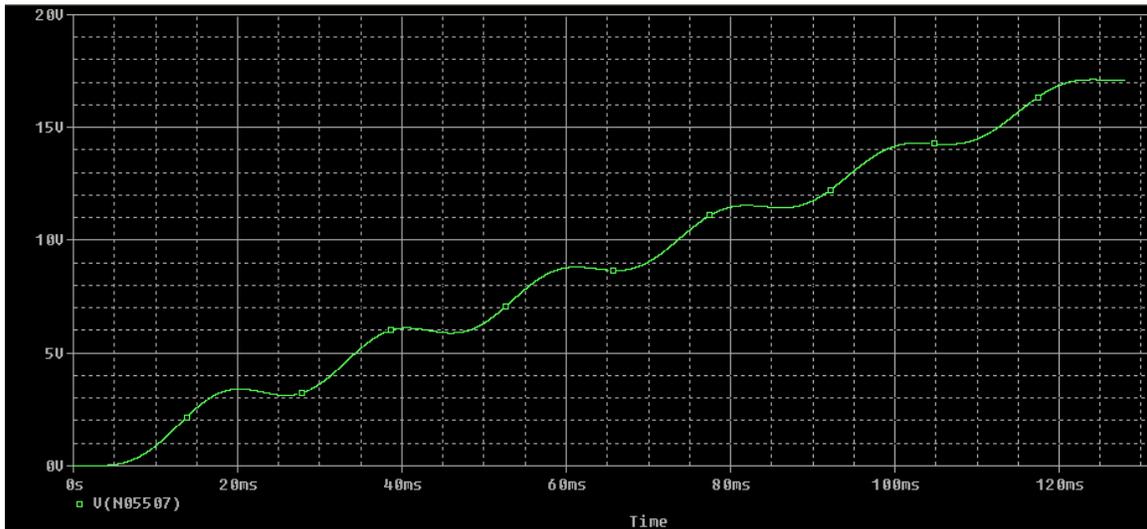
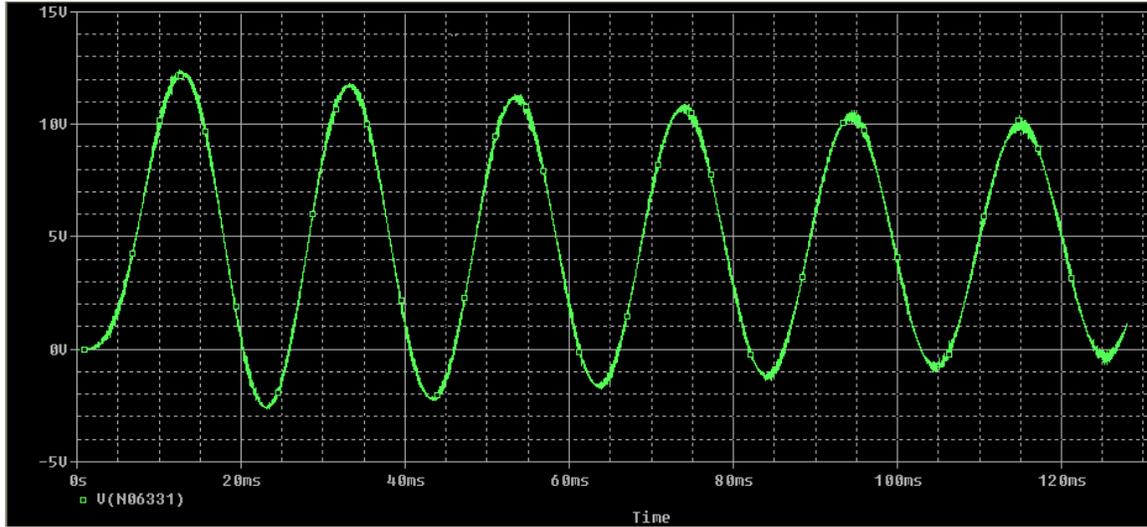


Figure 6.2 Torque and Speed Waveforms at 10 kHz Carrier Signal Frequency

For 20 kHz

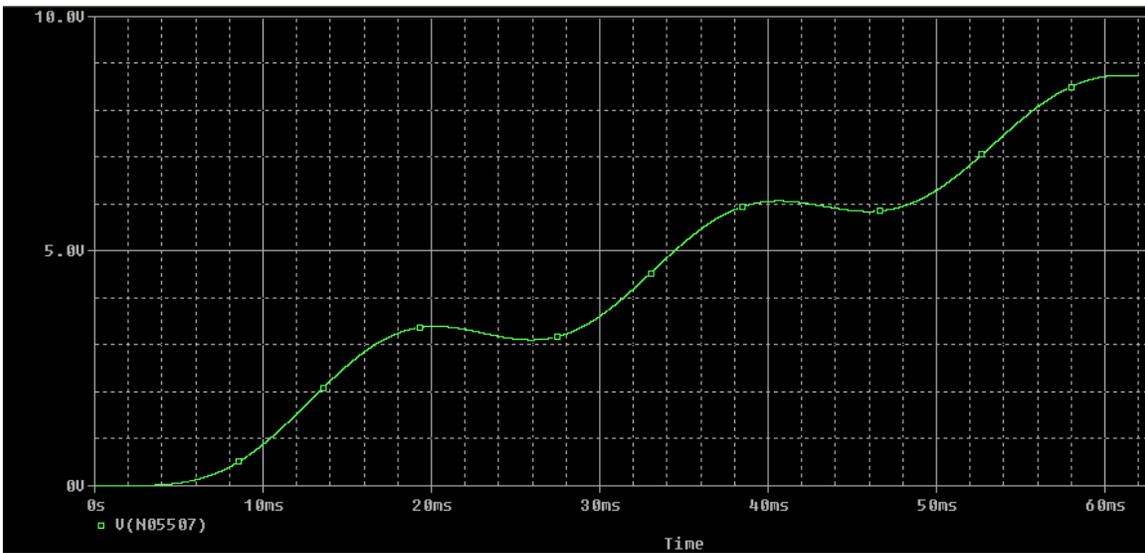
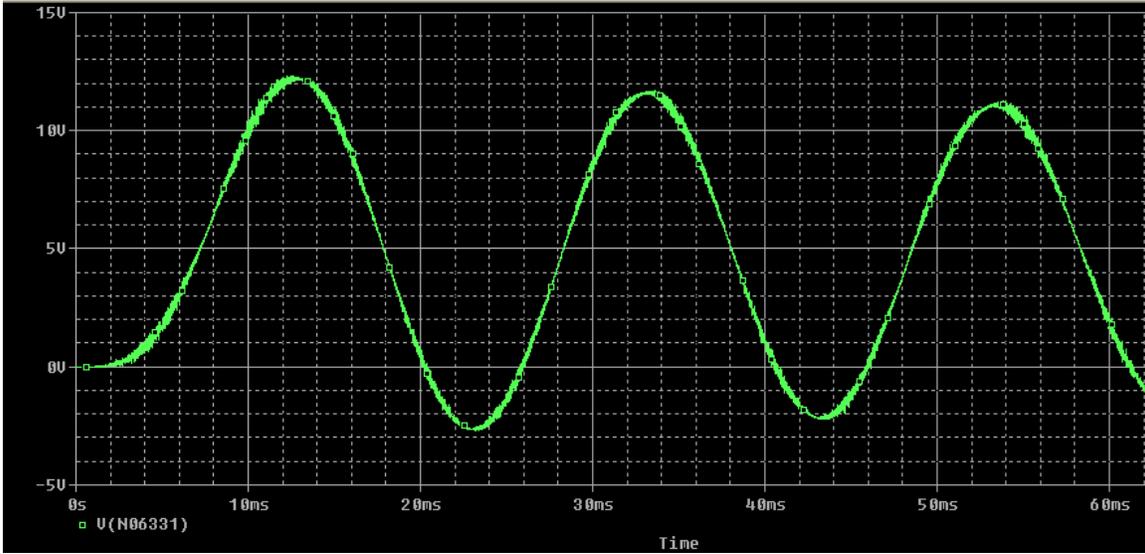


Figure 6.3 Torque and Speed Waveforms at 20 kHz Carrier Signal Frequency

Conclusion

From the output waveforms of the inverter, it can be seen that the current traces are almost perfect sinusoids, despite the fact that the input voltage is the PWM waveform. Due to the inductors contained in the load, the current cannot instantaneously change and follow the PWM signal. Therefore the load current of inverter is an almost pure sinusoid with very little ripple. Also, the trace for the torque shows no high frequency ripple. The reason for this is that the motor windings are inductive and represent a low pass filter for the applied voltages. The waveforms of speed show that it starts rising in the beginning and then becomes almost constant.

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