REGENERATIVE BRAKING OF SENSORLESS VECTOR CONTROLLED THREE PHASE INDUCTION MOTOR DRIVE FED FROM MULTILEVEL INVERTER FOR ELECTRIC VEHICLE APPLICATIONS

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Abstract

Few industrial applications are capable of returning energy into the ac distribution system on a continuous basis. For example, mining companies usually transport their product downhill for few kilometers before processing it. In such cases, the drive maintains the transportation belt conveyor at constant speed and takes the kinetic energy. Due to the large amount of energy and the continuous operating mode, the drive should be capable of taking the kinetic energy, transforming it into electrical energy, and sending it into the ac distribution system. This would make the drive a generator that would compensate for the active power required by other loads connected to the electrical grid. The system we have considered up to now uses a sensor to measure position of the rotor. In many cases it is impossible to use sensors for speed measurement, perhaps because it is either technically impossible or extremely expensive. For example, we can mention the pumps used in oil rigs to pump out the oil. These have to work under the surface of the sea, sometimes at depths of 50 meters, and getting the speed measurement data up to the surface means extra cables, which is extremely expensive. Cutting down the number of sensors and measurement cables provides a major cost reduction. The two level inverters with levels 0 or have some limitations in operating at high frequency in high-power and high –voltage applications due to switching losses and constraints of device ratings. The multilevel inverters can alleviate this problem. It is easier to produce a high- power, high- voltage inverter with multilevel structure because of the way in which device voltage stresses are controlled in the structure. Increasing the number of voltage levels in the inverter without requiring higher ratings on individual devices can increase the power rating. The unique structure of multilevel voltage source inverter's allows them to reach high voltages with low harmonics without the use of transformers or series connected synchronizing devices. As the number of voltage level increases, the harmonic content of the output voltage waveform decreases significantly. The behaviour of Induction motor during motoring and re-generating mode with accurate speed control without the aid of sensors, when fed by a multilevel inverter with space vector pulse width modulation (SVM) is presented in this paper.

Keywords: Induction Motor Drives, Vector Control, Sensor less Control, Multilevel Inverter, Extended Kalman Filter, State Vector, Re-generation, Pulse Width Modulation, Rotor speed estimation, Space Vector Modulation.

I. INTRORDUCTION

The block diagram for the proposed scheme is given in Fig.1. The three phase AC voltage is fed to a voltage source controlled rectifier; which is a combination of un-controlled diode bridge rectifier and controlled thyristor bridge rectifier. The output rectified output is filtered through an Inductor and fed to three level neutral point clamped voltage source inverter which is space vector pulse width modulated. Therefore the harmonics in the stator currents are reduced substantially. For sensorless operation Extended Kalman Filter (EKF) based vector control is employed. A Bi-directional DC Chopper can be placed in between the controlled rectifier and the Voltage Source Inverter, to enhance the voltage levels. Proposed Induction motor control circuitry can be used for traction purpose or in Hybrid Electric Vehicles.

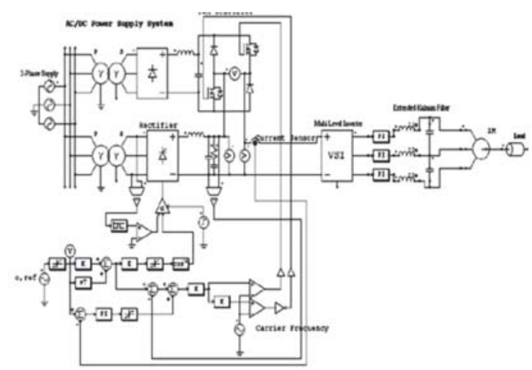


Fig. 1. Circuit Diagram of EKF Based Sensorless Vector Controlled Induction Motor for Motoring & Regenerating Operation

II. THREE PHASE INDUCTION MACHINE DYNAMIC MODEL

Synchronously Rotating Reference Frame Dynamic Model (Kron Equation) is considered, because all the sinusoidal variables in stationary reference frame appear as DC quantities. The Induction motor dynamic model, per phase equivalent circuits are shown in Fig2.a & Fig2.b

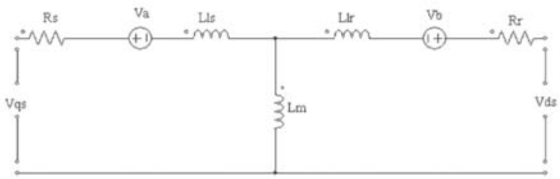


Fig. 2(a). Dynamic Equivalent circuit of Machine q^e-axis circuit

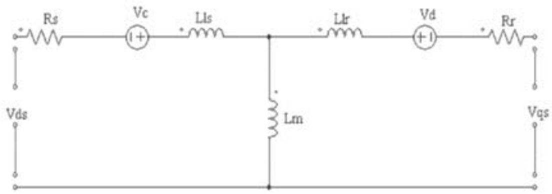


Fig. 2(b). Dynamic Equivalent circuit of Machine d^e-axis circuit

Where $Va = \omega_e \psi_{ds}$; $V_b = (\omega_e - \omega_r)\psi_{dr}$; $V_c = \omega_e \psi_{qs}$ & $V_d = (\omega_e - \omega r)\psi_{dr}$

The voltage equations are as follows:

$$\begin{bmatrix} Vqs \\ Vds \\ Vqr \\ Vdr \end{bmatrix} = \begin{bmatrix} Rs+sLs & \omega_e Ls & sLm & \omega_e Lm \\ -\omega_e Ls & Rs+sLs & -\omega_e Lm & sLm \\ sLm & (\omega_e-\omega_r)Lm & Rr+sLr & (\omega_e-\omega_r)Lr \\ -(\omega_e-\omega_r)Lm & sLm & -(\omega_e-\omega_r)Lr & Rr+sLr \end{bmatrix}$$

For a singly fed squirrel cage Induction motor ;

$V_{qr} = V_{dr} = 0$

Air gap Power, $P_g = 3V_m I_s \sin\theta$

Torque developed is given by,

$$Te = \frac{P}{2} \times \frac{3}{2} \times \psi_m I_r$$

III. MACHINE MODEL FOR EXTENDED KALMAN FILTER METHOD

The block diagram for Extended Kalman Filter for speed estimation is shown in Fig. 3. where the machine model is indicated on the top. The EKF algorithm uses the full machine dynamic model. The augmented machine model is given by T

$$\frac{dX}{dt} = AX + BV_s \qquad (1)$$

$Y = CX$

Where

$$A = \begin{bmatrix} \frac{-(L_m^2 R_r + L_r^2 R_s)}{\sigma L_s L_r^2} & 0 & \frac{L_m R_r}{\sigma L_s L_r^2} & \frac{L_m \omega_r}{\sigma L_s L_r} & 0 \\ 0 & \frac{-(L_m^2 R_r + L_r^2 R_s)}{\sigma L_s L_r^2} & \frac{-L_m \omega_r}{\sigma L_s L_r} & \frac{L_m R_r}{\sigma L_s L_r^2} & 0 \\ \frac{L_m R_r}{L_r} & 0 & \frac{-R_r}{L_r} & -\omega_r & 0 \\ 0 & \frac{L_m R_r}{L_r} & \omega_r & \frac{-R_r}{L_r} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$X = \begin{bmatrix} i_{ds}^s & i_{qs}^s & \psi_{dr}^s & \psi_{qr}^s & \omega_r \end{bmatrix}^T$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$V_s = \begin{bmatrix} v_{ds}^s & v_{qs}^s \end{bmatrix}^T$ and

$V_s = \begin{bmatrix} v_{ds}^s & v_{qs}^s \end{bmatrix}^T$ is the input vector.

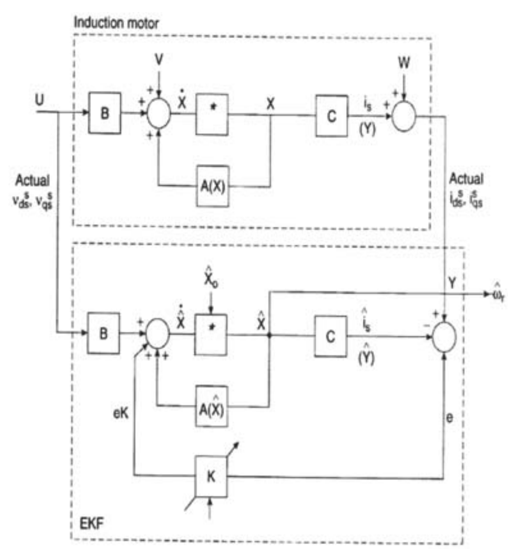


Fig. 3. Extended Kalman Filter for Speed Estimation

Equation (1) is of the fifth order, where ω_r is a state as well as a parameter. If speed variation is negligible, then $d\omega_r/dt = 0$. This is a valid consideration if the computational sampling time is small or load inertia is high. With ω_r as a constant parameter, the machine model used in the EKF is linear.

IV. NEUTRAL-POINT-CLAMPED (NPC) MULTILEVEL INVERTER WITH SPACE VECTOR MODULATION.

A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of a multilevel converter can be briefly summarized as follows.

Staircase waveform quality:

Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stresses; therefore electromagnetic compatibility (EMC) problems can be reduced.

Common-mode (CM) voltage:

Multilevel converters produce smaller CM voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive can be reduced. Furthermore, CM voltage can be eliminated by using advanced modulation strategies.

Input current:

Multilevel converters can draw input current with low distortion.

Switching frequency:

Multilevel converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency.

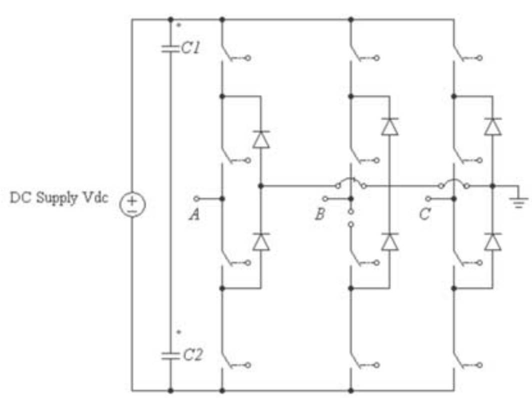


Fig. 4. Three level Neutral-Point-Clamped inverter.

One of the multilevel structures that has gained much attention and widely used is the Neutral-Point-Clamped Multilevel Inverter or also known as Diode Clamped Multilevel Inverter. A NPC multilevel inverter synthesizes the small step of staircase output voltage from several levels of DC capacitor voltages. The structure of a 3-level NPC is shown in Fig. 4. For regeneration application, Bi-directional switches are employed. The DC bus voltage is split into 3 levels by using two DC capacitors, C1 and C2. Each capacitor has Vdc/2 volts and each voltage stress will be limited to one capacitor level through clamping diodes. The output voltages VA, VB and VC have three states.

The main merits of NPC are;

- For a high m-level, the distortion level of the harmonics content is so low that the use of filter is unnecessary.
- Constraints imposed on the switches are low because the switching frequency may be lower than 500Hz.
- Reactive power flow can be controlled.

High efficiency and simple control.

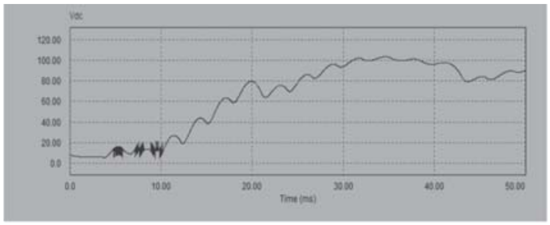
V. SPACE VECTOR MODULATION

Space Vector Modulation is a technique where the reference voltage is represented as a reference vector to be generated by the power converter . For the operation of 3-level inverter, there are 3 switching states for each inverter leg; [1], [2] and [3]. [1] denotes that the upper two switches in leg A are on and the inverter terminal voltage, VAN is +Vdc/2, while [3] means that the lower two switches are on with a terminal voltage of -Vdc/2. Switching state [2] signifies that the inner two switches are on with the terminal voltage equals to zero.

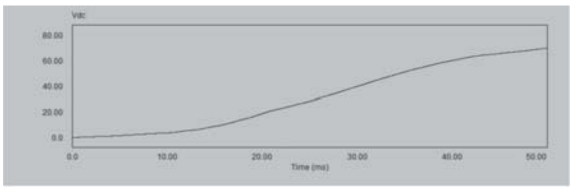
Space Vector Modulation has been chosen as the modulation technique for the inverter as it enables it to be operated at power system frequency without high frequency component which usually produces in PWM as carrier frequency. This is the main reason which makes SVM more attractive to be used in high power and voltage applications.

VI. RESULTS AND DISCUSSION

Simulation is carried out using PSIM and the various stage outputs are given below. The rectified output for during motoring mode is shown in Fig. 5(a) Without Inductive filter the rectified output is more distorted as shown in Fig. 5(b) The insertion of Inductor reduces the total harmonic distortion by 17%.



(a)



(b)

Fig. 5. (a) Rectifier Output without Inductive Filter (b). With Inductive Filter

NPC Three Level Inverter Output

Fig. 6. and Fig. 7. shows the output voltage and currents of three level NPC Inverter

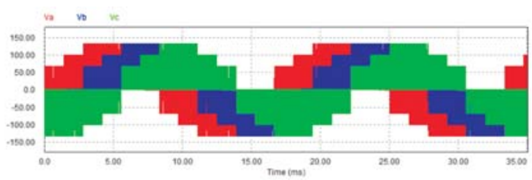


Fig.6. NPC Three level Inverter (Three Phase Output Voltages)

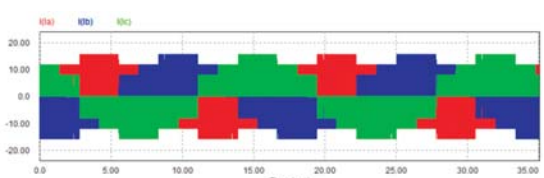


Fig. 7. NPC Three Level Inverter (Three Phase Output currents)

From the above waveforms it is evident that the distortion is alleviated and therefore losses are minimized and hence the system is more efficient.

Fig. 8. shows the deviation between the estimated and the actual motor speeds. The settling time is 0.2secs, therefore the dynamic response of the proposed system is faster. The error between the estimated and the actual values of speed is approximately 7%.

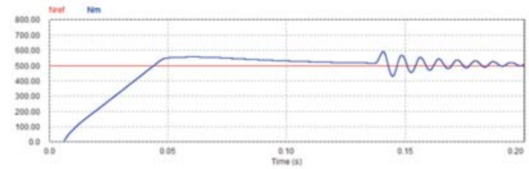


Fig.8. Estimated Speed (Nref) and Actual Speed (Nm) of the Induction motor With EKF

The electromagnetic torque is as shown in Fig. 9. The slip is negative at 0.104 sec., therefore the torque becomes negative after 0.104 Sec., Hence the Induction motor operates in regenerative mode. Now the Inverter will act as a converter and the controlled converter acts as an inverter. Therefore the power flow is from load to source side. This power can be used to drive the other loads.

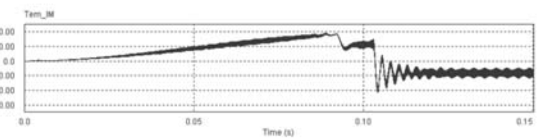


Fig. 9. Electromagnetic Torque

VII. CONCLUSION

The proposed circuitry can be used for traction purpose. Since EKF based sensorless vector control is used, the speed estimation and speed control over wide range including zero speed is possible. The dynamic response is better and the system is more efficient. The major drawback of the scheme is multilevel inverter circuit requires more solid state switches and hence the device switching losses are more. In future Zero Voltage and Zero Current switching can be employed to alleviate the losses.

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