Performance Improvement of ZSI Based PMS Motor Drive System for Electric Vehicles

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Abstract. In traction system the choice of motor is very important, multipurpose motors are available in the market. By considering the motor parameter like high power to weight ratio, high torque to current ratio with that high efficiency and robustness. Owing all the advantages the motor chosen is PMSM (Permanent magnet synchronous motor) for the variable speed modern drive which is most widely used in EV’s (Electric vehicle and in Hybrid electric vehicle). Without weakening the field by controlling the DC-link voltage the PMSM machine can run at high speed by implementing ZSI to the drive system. Z source inverter working principle and modulation method is discussed in this study. By considering the Limitation of Maximum voltage and available line current a new Vector control scheme is developed for PMSM drive voltage boosting. At last the proposed system implementation effectiveness and reliability is tested by several simulation and experimental results.

1. INTRODUCTION

Increase in population is proportionally increased in internal combustion engine Automobile. This leads demand in natural resources and drastic increase in the price of petroleum products. By concerning the global problem all the IC engines should be replaced with Electric Motor which turns our attention to the research area Electric Vehicle (EV). The EV’s are Eco friendly and no emission to the environment. In Idle speed it will not consume energy and also it will not produce any sound at the time of running.

A drive system is necessary for the Electric vehicle to control the speed from stand still to the maximum speed to propel the vehicle. Multiple motor and their drive system are available in market out of which Permanent magnet synchronous motor is very popular and attractive because of their reliability, high power density and efficiency [5][6][10]. To operate the motor in high-speed region, field weakening control scheme is utilized since the PMSM machine have a short constant-power region due to their limited field weakening capability [5], still it requires some more current to reduce the magnetic flux of the machine. In reference [6][11], De-Link voltage is changed with boost converter connected in series with the PWM inverter for the rated speed of PMSM drive system. Z source inverter existing PWM technique total harmonic distortion is bigger due to unsymmetrical shoot through is discussed in [1]. Different modulation strategies impedance source network to generate DC to AC voltage is discussed in [2], MPC model predictive control discuss about the fast torque control of PMSM machine [4], Fuzzy logic based vector control led PMSM machine speed control using DS1103 discussed in this paper [3].
A competitive alternative topology is introduced in single stage power converter and Z-source inverter due to the defects in tradition voltage inverter because of the complexity of the circuit and and control, the two stage system requires more space and proposed single stage ZSI is discussed in [7] [8] [12]. Both the buck and boost capabilities advantages adopted in the different applications are discussed in [7] and the same is discussed with Ac induction motor drive in [12]. A birectional Z source inverter with the steady state operating principle and voltage boosting modified vector control scheme of permanent magnet synchronous motor drive is presented in the paper.

Z source inverter both direction topologies has discussed in [20]. The discontinuous induction current causes unstable and un controllable ZSI, it can be overcome by operating the ZSI in Low load power factor or with small inductance [28], The system bidirectional power flow is discussed in [21]. The proposed circuit ZSI is used to feed current to PMSM machine as current fed Z-source DC/DC converter under the condition of reverse power flow. The complicated operation and increase in number of switches and their mode of operation are compared to [20]. Z source inverter, Pulse width modulation traditional inverter and DC/DC boosted PWM inverter are compared in [22] [29]. As per the comparison the ZSI Conversion efficiency of inverter and motor system efficiency is better when compared to the earlier two existing inverter system. In this survey PMSM drive system is controlled by Bi-directional Z source inverter as a single stage converter instead of a two stage converter (DC/DC converter bidirectional and VSI).

2. BIDIRECTIONAL Z-SOURCE INVERTER

The proposed drive system is shown in the figure which consists of Permanent magnet synchronous motor connected with conventional voltage source inverter with a impedance network. The power to the circuit is fed by the Battery pack connected to it. The bidirectional power flow system ability is enabled by introducing switch S7. A PN junction diode is connected Anti parallel to S7 which eliminates the discontinuous inductor current caused by undesirable mode of operation. To achieve the required property two similar inductors and capacitors are connected in specific manner as shown in Fig.1

![Bidirectional ZSI for PMSM drive](image)

To maintain the output voltage the active states should be kept as same and partially replace the traditional zero states or the zero state to be shoot-through entirely based on voltage level required to boost base on our need. Each operating state characteristics are described separately as shown below

From the equivalent circuit based on symmetry we have

\[ V_{c1} = V_{c3} = V_{c2}, \quad v_{l2} = v_{l1} = v_{l3} \]
2.1 Bidirectional ZSI PWM control strategy

Traditional voltage source converter uses various Pulse width modulation control methods at present. Traditional PWM methods will not use the shoot through state so to control the ZSI DC boost PWM methods need to be modified. The method we require is controllability in wide range AC output voltage and less harmonic. A technique that bridges PWM and Space vector control is space vector pulse width modulation (SVPWM) technique. Four PWM control methods are existing, Maximum constant boost control method is discussed in [23]. Simple boost control method is discussed in [15], Modified space vector control method discussed in [31] and maximum boost control method is discussed in [30]. In this paper for attaining variable speed application shoot through is control by using MSVPWM method.

While inverter is operated in shoot through state switch S7 has to be kept in OFF in the mode analysis of ZSI. Switch position remains in ON state when the inverter is operated in its non-shoot through states. Boost capacitor is used in non shoot through state when inverter is operated in regenerating mode. In the different mode of operation whenever reverse current is monitored the switch S7 is closed permanently since because the battery receives constant reverse current.

3. PMSM DRIVE SYSTEM DESIGN

3.1 Current and Voltage Range

The rotor reference frame steady state voltage equation of PMSM is,

\[ T_e = P \left[ i_{sq} \lambda_{pm} + i_{sq} (L_d - L_q) i_{sd} \right] \]

\[ \frac{v_{sd}}{v_{sq}} = \begin{bmatrix} L_d P + R & -L_q \omega_e \\ L_q P + R & L_q P \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ \lambda_{pm} \omega_e \end{bmatrix} \]

Where, d- and q-axis current are the \( i_{sd} \) and \( i_{sq} \) currents; d- and q-axis voltages are \( v_{sd} \) and \( v_{sq} \) voltages; d- and q-axis inductances are the \( L_d \) and \( L_q \) Stator resistance is the R; Electrical angular frequency is \( \omega_e \); number of pole pairs is P and electromagnetic torque \( T_e \) d/dt is the derivative operator of p; flux linkage is PM respectively.

\( v_{s max} \) maximum available voltage and \( i_{s max} \) maximum line current amplitude of the motor with that we can get the following equation

\[ v_{sq}^2 + v_{sd}^2 \leq v_{s max}^2 \]  \( (4) \)

\[ i_{sq}^2 + i_{sd}^2 \leq i_{s max}^2 \]  \( (5) \)

In high speed operation by neglecting the armature resistance drop, in steady state the derivative operator P becomes zero by substituting (4) and (5) into (2), With that we can obtain an voltage constraint equivalent as follow,
\[(i_{sq}L_q)^2 + (\lambda_{pm} + L_d i_{sd})^2 \leq \frac{v_{e,max}^2}{\omega_e}\]  

(6)

### 3.2 Maximum Torque per Ampere Operation (MTPA)

Motor parameters depend on the MTPA trajectories; MTPA operation can be done and IPM motor has a saliency \((L_q, L_d)\) With the reluctance torque

The following equation obtains the operating point as follows. The operating point can be obtained by the following equations simplified is,

\[i_{sq} \leq \sqrt{i_{s,max}^2 - i_{sd}^2} \]  

(7)

\[i_{sd} = -i_{sq} \frac{(L_q - L_d)}{\lambda_{pm}} \]  

(8)

### 3.3 Current Range of the Battery

To run a motor above its rated speed with constant power and also to operate below rated speed with the same power when current of the battery is limited. When motor draws the rated current that value corresponds to the DC-link Current. \(I_{BT,max}\)\([32-35]\)

Current value is limited by considering the parameters and characteristics of the battery. The below equation defines the maximum torque output of the machine.

\[T_{max} = \frac{I_{BT,max} V_{in}}{\eta \omega_e} \]  

(9)

Constant torque can be achieved only if the current of the battery is not limited; if the current of the battery is limited then \(I_{DC}\) DC-Link current is as follows

\[I_{DC} = I_{BT,max} \eta \frac{V_{in}}{V_{DC}} \]  

(10)

Therefore the VDC DC-link voltage increases as the \(I_{DC}\) decreases. In other words, current \(I_{BT,max}\) for the constant battery the current limited circle shrinks as the speed increases.

### 4. CONTROL DESIGN
Fig.3 Control scheme PMSM with Bi-directional ZSI

Fig. 4 Functional diagrams a) $i_{sq}$ current calculator b) voltage command generator DC-link

Fig.3 show the functional diagram of $i_{sq}$ bound calculator. The q-axis current is the output maximum amplitude and rotor speed is the input parameter. Maximum line current of the motor is limited using speed PI controller in the zero d-axis control modes such that current of the battery will not exceed the limit. Fig. 4(b). Shows the command block of the DC-link, $\omega_r$ rotor speed is less than the rated speed $\omega_b$ Z source inverter will operate without the DC-link voltage command and boost which are equal to the applied input voltage. In the high speed operation the rated input voltage should apply higher. Feedback signal cannot be selected because of the DC-link voltage in the shoot through state of Z source inverter. The duty ratio $D_o$ shoot through time by controlling it $V_c$ capacitor voltage of the Z-source can be increased. So in this paper, $V_c$ is selected as feedback signal to control $V_{dc}$ indirectly. In order to overcome the nonlinear problem between $V_{dc}$ and $V_c$, a linear capacitor voltage controller [9] is adopted. The task of shoot through controller in Fig.3 is to generate $D_o$.

5. SIMULATION RESULTS

Saber software is used to take the simulation result. Bidirectional ZSI based proposed PMSM drive system for an electric vehicle by considering the PMSM parameters like, battery, Z-source network, Transmission system are listed in the Table 1.

| Component      | Parameter                  | Value       |
|----------------|----------------------------|-------------|
| Transmission system | Ratio                      | 1:2         |
|                | Efficiency                 | 0.91        |
| PMSM           | rated speed                | 51 rad/s    |
|                | rated torque               | 339 Nm      |
|                | d-axis inductance (L_d)    | 9 mH        |
|                | q-axis inductance (L_q)    | 8.5 mH      |
|                | flux of field              | 0.7 Wb      |
|                | rated output power         | 17 kW       |
|                | armature resistance (R)    | 0.4375 ohm  |
|                | pole number                | 8           |
| Battery        | rated capacity             | 100 A h     |
|                | rated voltage (EBT)        | 410 V       |
The electric vehicle proposed drive system dynamics and effectiveness are simulated extensively through saber. The table 1 list all the parameters. The different operating mode of the system is detail shown in Fig. 5. ZSI driven PMSM characteristics and simulation results are shown in Fig.7. The rated torque is achieved in the time interval of 0.4-3.9 s in the acceleration mode. 3.9-4.2s time interval requires to reach the rated speed in cruise mode. 4.2-11s requires to decrease in torque in acceleration mode. 11-12s, time interval to reach the maximum speed in cruise control mode. 12-18s required to reach maximum speed to rated speed in regenerative braking mode. 20-23.5s time intervals required for regenerative braking mode with the rated torque. 18-20s time intervals with the rated speed requires in cruise operation mode. Here, a dip is observed in the battery current and the q-axis current waveforms at 3.9 s. This is because the vehicle’s resistance decreasing significantly during the time interval (3.9-4.2 s), where the vehicle is in cruise operation mode. The shoot-through time duty ratio, boost factor, DC-link voltage and capacitor voltage of PMSM driven by ZSI against speed characteristics presented in Fig. 7.

| Vehicle | aerodynamic drag coefficient | 0.3 |
|---------|-------------------------------|-----|
|         | gross mass                    | 990 kg |
|         | rolling resistance coefficient| 0.015 |
|         | radius of wheels              | 0.288 |
|         | frontal area                  | 1.7 m² |

| Z-source network | Capacitor | 300 µF |
| Z-source network | inductor  | 36.5 µH |
Fig. 7 (a) speed characteristics vs shoot-through and Boost factor time duty ratio (b) speed characteristics vs capacitor voltage versus and DC-link voltage and

Fig. 5 - 7, one finds the following mentioned below,

▪ Above the rated speed the d-axis current kept zero. Hence there is no additional current required to reduce the flux of the motor.

▪ Since $i_{BT}$ is negative bidirectional power flow is possible in regenerative braking mode.

▪ Input voltage and DC-link voltage are equal at rated speed while ZSI working in non-shoot through mode.

Using the table 1 parameters the bidirectional Z source inverter prototype for PMSM drive is designed and implemented in the laboratory set up. For the switching frequency generation the TMS320F2808 board has chosen to generate 10KHZ system frequency for testing the proposed control methods and realization. Code generation is done with code composer studio for the real time control. DAC 12 bit resolution is used to find the wave forms and inspect in oscilloscope. System functional block is shown in the Fig.7. Laboratory setup is shown in Fig.8. Bidirectional ZSI switches (S1–S7) and intelligent power module PM800HSA120 is used. Fig. 9 shows the d-axis current, stator current, speed command and motor speed, DC-link voltage and battery voltage; motor speed and capacitor voltage short-through time duty ratio; respectively, which are quite consistent with the simulation results.
Fig. 9 Experimental result of characteristics for PMSM driven by ZSI (a) motor speed and Speed command (b) current d-axis (c) capacitor voltage, motor speed and Short-through time duty ratio (d) battery voltage, Stator current, DC-link voltage and

6. CONCLUSION
The bidirectional Z source inverter is presented in the paper. The main focus is to increase the speed range of permanent magnet synchronous motor by reducing the amplitude of the current in the high speed region, this is achieved by gating simultaneously both the lower and upper switches of the same phase leg, when the speed of the machine goes higher than the rated speed. The shoot through of the circuit no longer disturbs the system and hence the reliability goes higher. It is a stable low cost single stage highly efficient system. The experimental result is compared with the simulated result and the simulated results were validated. In the proposed system the D-axis current is totally eliminated in the constant power region, obviously in the flux weakening operation the copper loss of the motor will be reduced.

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