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Digital Implementation of DSVPWM Control for EV fed through Impedance Source Inverter

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ABSTRACT

In this paper, a new space vector modulation technique is proposed for speed control of Induction Motor using Z-source inverter powered by a low voltage DC source. The zero states of conventional space vector modulation are used for boosting the DC-link voltage to the required level. The proposed SVM technique estimates the required shoot through period of the Z-source inverter to maintain the DC-link voltage constant at the desired level through capacitor voltage control. A 32 bit DSP (TMS320F28335) is used to implement the proposed space vector modulation method. The power structure and the modulation technique is well suited for electric vehicle application.

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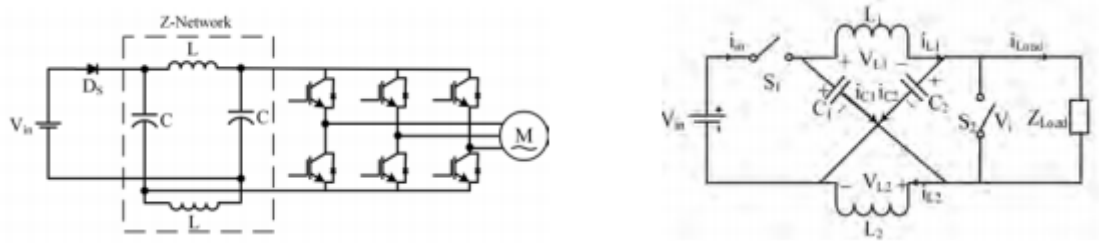
1. INTRODUCTION

The oil bill has risen to approximately 10 times of itself in the last one decade. Strict enforcement of environmental laws and the ever increasing fossil fuel prices have led to spout in research and development of Electric Vehicles. For boosting the low voltage from battery, the electric drive employs a DC-DC boost converter followed by a DC-AC power converter [1] -[2]. Several other domestic and industrial applications work on the similar concept [3] -[4]. There are some operational limitations of the traditional voltage source inverter (i.e. the output voltage is always lower than the DC link voltage). Therefore, to get the desired boosted AC voltage, integration of DC-DC boost converter between the DC source and the inverter is necessary. The additional boost converter lowers the efficiency and increases the cost of the system. In order to ensure operation of the inverter to be safe, dead time has to be maintained, which leads to distortion in the output voltage waveform. The VSI fed drive is driven under current regulation (Load changing). If the DC-bus voltage drops down, the current regulator can saturate. For induction motor under standard V/f control, the VSI may not be able to supply the required voltage to the motor at a certain speed if the DC-bus voltage drops down [5]. Therefore, during a voltage drop, capacitor (DC-bus) voltage needs to be controlled (regulator). The Impedance or Z-source inverter is a possible solution for such problems [6]. The need of additional switching devices used for boost DC-DC converter is eliminated by voltage boosting and three phase inverter, thus minimising cost and improving the overall efficiency of the drive. The high performance Digital Signal Processors (DSPs) are used to minimize control loop delays and perform high-resolution control, multi operations [7]. High reliability and improved dynamic response are additional features of Z-source inverters.

This paper summarizes the implementation of a new SVPWM (DSVPWM) based capacitor voltage control with IFOC for ZSI fed induction motor drive. It uses minimum number of components and employs a

DSP (TMS320F28335) developed by Texas Instruments for power electronics and motion control applications.



(a) Schematic of a ZSI Fed Induction Motor (b) Simplified Equivalent Circuit of the ZSI

Figure 1. Z-Source Inverter

2. Z-SOURCE INVERTER

The Z-source inverter was developed in order to deal with problems in functioning of voltage source and current source inverters. A Z-network is injected between DC source and 3-legs of inverter switches as shown in Figure 1(a). where DC source employed can be a battery, diode rectifier, or fuel cell etc. Following are the attributes of a Z-source system [8] :

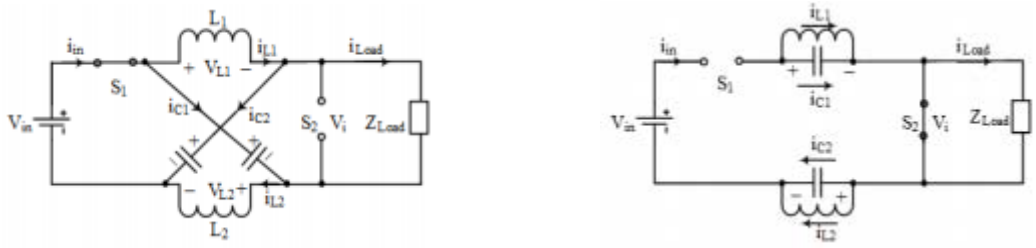
- Being a filter of second order, Z-network is more effective than capacitor filter in suppressing the voltage ripples used in the traditional PWM inverters.
- The in-rush current and current harmonics is limited by the inductor.
- Boosting of voltage across the DC-link is facilitated by the Z network.
- Instead of damage to the power circuit, the shoot-through state facilitates boosting in output voltage.

Figure 1(b) shows the Z-source inverter topology, which consists of two capacitors (C1 and C2) and two inductors (L1 and L2) connected in a cross shape to link the DC-AC converter to the DC source voltage. The Z-source inverter can make a required AC voltage from a low voltage DC source. The ZSI has one extra switching state is shoot-through (ST) state which is in addition to the eight conventional non-shoot through states. The shoot-through state will short the top and bottom switching device of any phase leg of the inverter through load terminals. The ZSI has two operating modes: shoot-through mode and nonshoot-through mode, as shown in Figure 2. During the shoot-through switching state, the input diode is reverse biased; the input DC source is cut off from the load, and the two capacitors energy discharge to the inductors and to the load. During the nonshoot-through switching states, the input diode turns ON, and the DC input voltage source plus the inductors is charged the capacitors and shift energy to the load, as a result the DC-bus voltage is boosted.

3. PWM TECHNIQUE

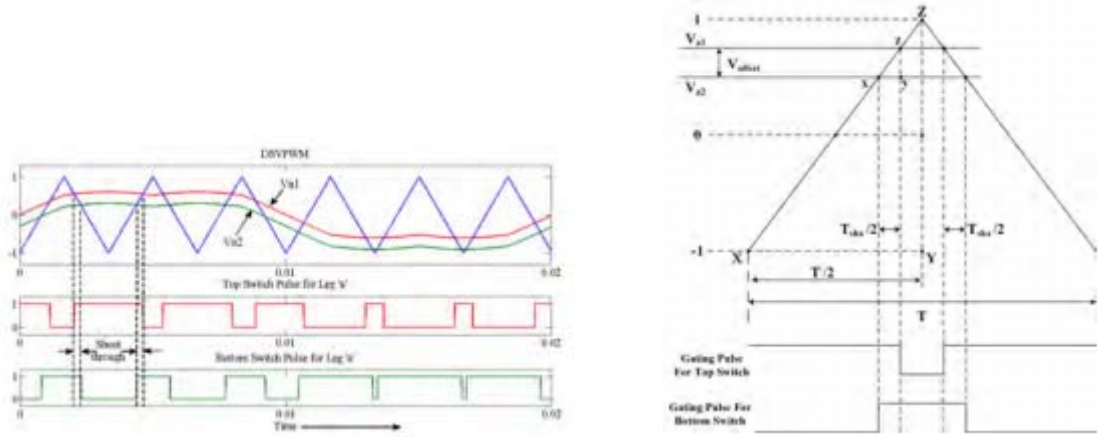
In inverters, there are many PWM techniques in use. Sinusoidal Pulse width modulation (SPWM) technique is the most basic technique in practical applications. The Space vector Pulse width modulation (SVPWM) is an advanced computation-intensive PWM technique, preferred in real-time realization, being widely used in voltage source inverters. This technique generates reference three phase signals by sharing the space vector among the active and zero vectors such that the harmonic content is optimized. The maximum inverter line-to-line voltage generated by the SVPWM scheme is 15.5% higher than that of the SPWM for a given DC bus voltage.

In SVPWM technique for VSI, eight switching states (six active + two zero/null) are realised. During the six active states, the supply is connected to the load and during the two zero/null states, the load terminals are shorted by the switching devices. In the ZSI, an extra state called shoot-through state is realised during which upper and lower switching devices of the same leg are turned-on. This state is forbidden in traditional VSI as it leads to supply short-circuit and results in high and device damaging surge current.



(a) Non Shoot-Through State (b) Shoot-Through State

Figure 2. Z-Source Inverter Circuit for Different Mode of Operation



(a) DSVPWM Pulses for Phase A (b) Generating DSVPWM shoot-through in leg A of inverter

Figure 3. DSVPWM

In ZSI, the advantage of having Z-network between the supply and the inverter switches is that the rise in the shoot-through state current is limited by the inductor of the Z-network. In addition to this, the inductor in Z-network stores energy during this state to boost the capacitor voltage and helps in regulating it. This shoot-through state sometimes also called the third zero state is generated in seven different ways: shoot-through via any phase, combinations of any two-phase legs and all three phase legs. Its duration can be adjusted/controlled for different output voltage gain by different methods. There are two shoot-through methods.

In the Simple Boost Control (SBC) method, the resulting voltage stress across the switches is higher as some portion of traditional zero states is not utilized. The Constant Boost Control (CBC) method, though minimizes the voltage stress across the switches, causes shoot-through duty ratio to vary in each cycle, thus increasing the ripple content in inductor current.

The Double Space Vector Pulse Width Modulation (DSVPWM) technique uses two sets of three phase signals as reference signals and a high frequency triangular wave as carrier signal. Let V_{a1},V_{b1},V_{c1} be the first set of reference signals generated by SVPWM technique for required modulation 'm' of input voltage. Let V_{a2}, V_{b2}, V_{c2} be the second set of reference signals generated by adding a finite negative DC offset (V_{offset}) to the first set.

The reference signals V_{a1} and V_{a2} will generate pulse for top switch and bottom switch of leg 'a' respectively as shown in Figure 3(a). The offset results in a shoot through time T_{sha} per switching period in that leg. For high switching frequencies, the reference signals V_{a1} and V_{a2} can be approximated as constant during a switching cycle.

The relation between the shoot through time T_{sha} and $V_{off\ set}$ can be established as follows: In Figure 3(b), consider similar triangles 'xyz' and 'XYZ'.

$$xy = \left(\frac{yz}{YZ}\right) * XY$$

$$\frac{T_{sha}}{2} = \left(\frac{V_{offset}}{1-(-1)}\right) * \left(\frac{T}{2}\right) \quad (1)$$

Shoot through time of leg-a,

$$T_{sha} = \left(V_{offset}\right) * \left(\frac{T}{2}\right) \quad (2)$$

The shoot through time in all three legs of the inverter remains same whereas the instants at which they occur during a switching period vary. So, the shoot through time in leg b and c is

$$T_{shb} = T_{shc} = T_{sha} = \left(V_{offset}\right) * (T/2)$$

The total shoot through time T_{sh} per switching period can be written as

$$T_{sh} = 3 * T_{sha} = 3 * \left(V_{offset}\right) * \left(\frac{T}{2}\right) \quad (3)$$

The shoot through duty ratio D_{sh} can be defined as

$$D_{Sh} = \frac{shoot-through\ time\ (T_{sh})}{total\ switching\ time\ (T)} = 3 * \frac{V_{offset}}{2} \quad (4)$$

The DSVPWM technique introduces $V_{off\ set}$ to extend the pulse width of the bottom switch into the top switch pulse width to result in shoot-through time. When the ZSI is operated at a SVPWM modulation index of 'm', the minimum pulse-width of the top switch is (1 - m) * T/2 and it occurs in a switching period during the negative half cycle of the fundamental wave. The bottom switch pulse width during this switching period is (1 + m) * T/2 when V_{offset} is zero. As V_{offset} increases, the bottom switch pulse width increases from (1 + m) * T/2 to a maximum of T at a maximum offset voltage V_{offset_max}. On further increase in V_{offset}, SVPWM operation enters over-modulation region. So, the maximum limit V_{offset_max} can be obtained as follows:

At maximum offset voltage V_{offset_max} condition, if T_{sha_max} is the maximum shoot through time of leg a,

$$T_{sha\_max} = T - (1+m) * \frac{T}{2} = (1-m) * \frac{T}{2} \quad (5)$$

From (2)

$$T_{sha\_max} = \left(V_{offset\_max}\right) * \frac{T}{2} \quad (6)$$

Substituting in (5),

$$\left(V_{offset\_max}\right) * \frac{T}{2} = (1-m) * \frac{T}{2} \quad (7)$$

$$V_{offset_{max}} = 1 - m \quad (8)$$

From (4) and (8), the maximum shoot-through duty ratio D_{sh_max} is

$$D_{sh\_max} = 3 * \frac{(1-m)}{2} \quad (9)$$

$$B = \frac{1}{1-(2T_{Sh}/T)} \quad (10)$$

From (9) and (10), the maximum boost factor B_{max} is

$$B_{max} = \frac{1}{3m - 2} \tag{11}$$

For SBC control method, the maximum boosting factor that can be obtained is

$$B_{\max\_SBC} = \frac{1}{2m - 1} \tag{12}$$

A comparison among SBC and DSVPWM boost control methods for maximum boosting factor Bmax variation with modulation index m using equations (11) and (12) is shown in Figure 4. The advantage of DSVPWM technique is that the maximum boosting factor is higher than that of SBC boost control method.

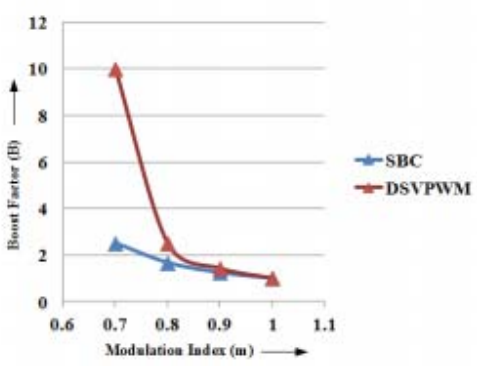


Figure 4. Comparison between Control Methods

The over-all voltage gain of the ZSI using DSVPWM is given as

$$\frac{\hat{V}_{Ph1}}{V_{in}} = \frac{2}{3} m * B \tag{13}$$

$\hat{V}_{Ph1}$ - peak of the fundamental component of phase voltage, V_{in}- input DC source voltage.
Modulation index 'm' of SVPWM technique is defined as

$$m = \frac{\hat{V}_{Ph1}}{V_{dp}} \tag{14}$$

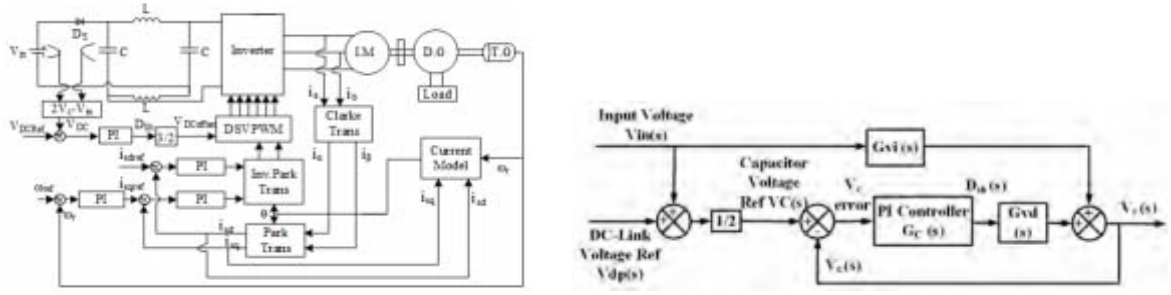
$V_{dp}(s)$ is DC-link voltage Substituting Z-network boost factor B definition from (10) and shoot-through duty ratio D_{sh} from (4) in (13), we get

$$\frac{\hat{V}_{Ph1}}{V_{in}} = \frac{2}{3} m * \frac{1 - D_{Sh}}{1 - 2 * D_{Sh}} \tag{15}$$

4. CAPACITOR VOLTAGE CONTROL

The DC-link voltage is a pulsating value and its control is difficult. So, it is controlled by employing the capacitor voltage control. The capacitor voltage control is worked out for a ZSI fed induction motor drive realizing IFOC along with DSVPWM technique shown in Figure 5(a). The capacitor voltage control block diagram is as shown in Figure 5(b). The error in the capacitor voltage due to change in loading is fed to a PI controller $G_c(s)$ to obtain the appropriate V_{offset} value. This V_{offset} value is used to generate the two sets of reference signals as mentioned in DSVPWM technique. The gating pulses obtained from the DSVPWM technique result in both required modulation index 'm' and shoot-through duty ratio 'D_{sh}'. The shoot-through duty ratio calculator uses equation (4) to calculate D_{sh} from the V_{offset} value obtained from the PI controller.

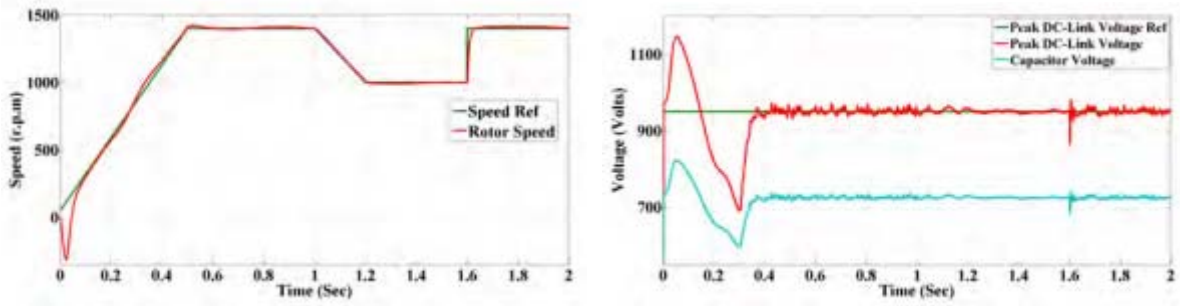
It is necessary to establish capacitor voltage $V_c(s)$ to shoot-through duty ratio $D_{sh}(s)$ plant transfer function $G_{vd}(s)$ to tune the PI controller $G_c(s)$ for DC-link voltage compensation.



(a) Schematic Diagram of ZSI fed Induction Motor Coupled with DC generator

(b) Block Diagram for Capacitor Voltage Control

Figure 5. Schematic Diagram of ZSI



(a) Induction Motor Rotor Speed

(b) DC-Link Voltage Response

Figure 6. Response of ZSI Fed Induction Motor Drive with Speed Changes.

Using the Table.1(a), Table.1(b) parameters and transfer function $G_{vd}(s)$, the compensator (PI controller) is designed for the response: (i) Overshoot less than 10%, (ii) Rise time less than 0.01 seconds, (iii) Settling time less than 0.05 seconds, (iv) Steady-state error less than 1%.

Using SISO-tool MATLAB/Simulink the Phase Margin (PM) and Gain Margin (GM) are found to be 59.5 deg & 12.3 db, respectively. Hence the developed mathmatical model with the designed circuit parameters is quite stable system.

The controller (PI) is tuned and its (G_c) values are

Kp= 0.0075, Ki= 0.095

Table 1. Z-Source Inverter and Induction Motor Parameters

(a) ZSI Parameters

Parameters	Value
Input Voltage V_{in}	400 V
Capacitor Voltage V_c	500 V
Peak DC link voltage V_{dp}	600 V
ZNetwork Capacitor $C_1 = C_2$	1000μF
ZNetwork Inductor $L_1 = L_2$	2 mH
Switching frequency f_s	10000 Hz

(b) Induction Motor Parameters

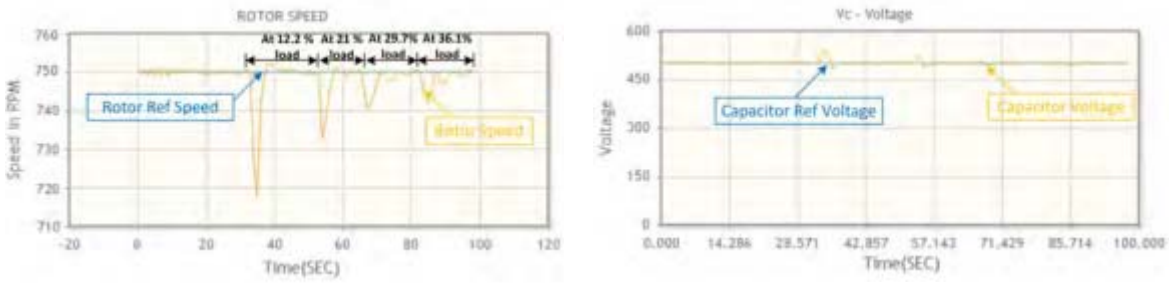
Parameters	Value
Output Power	3.2 kW
Line Voltage	400 V
Frequency	50 Hz
No of Ploes P	4
Speed	1440 r.p.m
Stator Resistance, R_s	2.125 Ohm
Rator Resistance, R_r	2.05 Ohm
Statot Inductance, L_s	2 mH
Rator Inductance, L_r	2 mH
Mutual Inductance, L_m	6.4 mH
Inertia, J	0.015 kg.m^2

5. SIMULATION AND HARDWARE IMPLEMENTATION

5.1. Simulation Studies

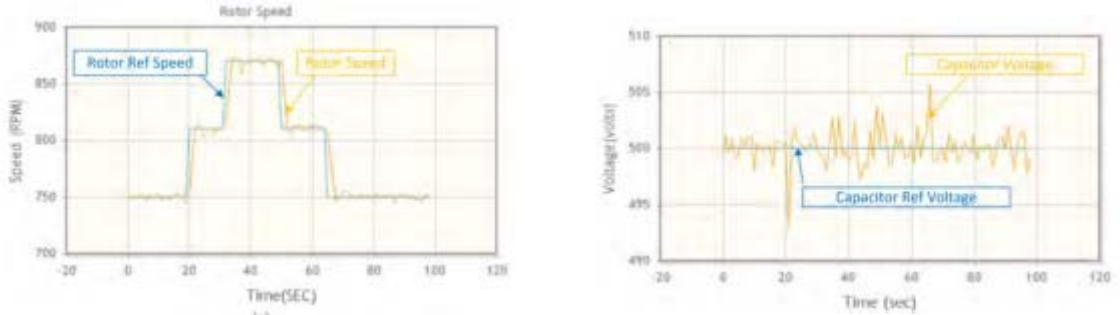
The dynamic performance of the ZSI with DC link voltage through capacitor voltage control technique has been simulated using MATLAB / Simulink (11.B) tool, for circuit parameters of ZSI in table. 1(a) and 3-phase induction motor parameters in table 1b used as the load.

Figure 6(a) shows the ZSI fed induction motor response during the different operation modes. The acceleration mode with the rated torque during the time interval 0-0.5 sec, the steady state operation mode with the rated torque and the rated speed 1400 rpm during the time interval 0.5-1 sec, the deceleration transient mode from the 1400 rpm speed to 1000 rpm speed with the rated torque during time interval 1-1.2 sec and step change 1000 rpm from 1400rpm at 1.6 sec. Figure 6.b shows reference 950 V, capacitor voltage (V_c = (V_{dp} + V_{in})=2 = (950+500)/2 = 725 V) and the actual ZSI DC-link voltages is controlled to 950 V.



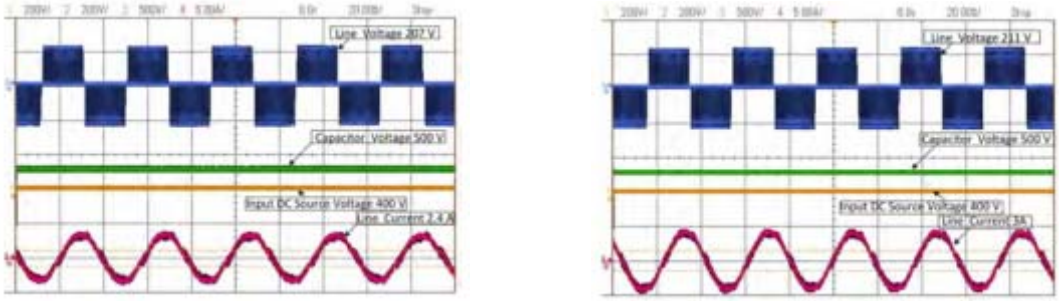
(a) Induction Motor Rotor Speed Response (b) Capacitor Voltage Response

Figure 7. Response of ZSI Fed Induction Motor Drive with Load Changes



(a) Induction Motor Rotor Speed Response (b) Capacitor Voltage Response

Figure 8. Response of ZSI Fed Induction Motor Drive with Speed Changes



(a) ZSI Response at 25% Load (b) ZSI Response at 30% Load

Figure 9. ZSI Response at Different Loads

5.2. Hardware Studies

This section explains the hardware implementation of the ZSI fed induction motor drive for voltage sag control. The ZSI fed induction motor is controlled by programming IFOC algorithm with DSVPWM technique on a TMS320F28335 Texas Instruments microcontroller. The input voltage 'V_{in}', motor line currents 'i_a' and 'i_b' and the rotor speed 'ωr' are sensed and given as analog inputs to the microcontroller shown in Figure 5(a). The CCS5.4 software with GUI composer by Texas Instruments provides integrated environment for development of target application. The IFOC with DSVPWM algorithm is programmed using CCS5.4 software and loaded into the microcontroller. The microcontroller executes the algorithm using the analog inputs to generate gating pulses for the inverter switches with required modulation and shoot-through time for speed, DC link and capacitor voltage control.

(a) (b)

Figure 10. Experimental Setup

5.2.1. ZSI fed Induction Motor Drive with DSVPWM Technique

The ZSI is connected to a 400V DC source. The DC link voltage reference has been set to 600V so the capacitor voltage reference indirectly set to 500V (V_c = (V_{dc} + V_{in})/2 = (600 + 400)/2 = 500V). The two cases studied in ZSI drive are studied here for evaluation.

Case1: The ZSI fed drive, under constant speed reference, varying load torque, not only maintains the speed but also compensates the capacitor voltage control to 500V. Figures 7(a) and 7(b) shows the rotor speed N_r and capacitor voltage V_c response.

Case2: The speed reference of ZSI fed drive is changed in four steps from 750rpm - 810rpm - 870rpm - 810rpm - 750rpm under loading condition. The motor speed N_r and the capacitor voltage V_c are seen following the speed reference and 500V V_{cref} respectively. Figures 8(a) and 8(b) shows the rotor speed N_r and capacitor voltage V_c response.

The Figures 9(a) and 9(b) show the input, capacitor voltage, line voltage and line current under loaded condition. The ZSI fed induction motor drive experimental setup is shown in Figure 10.

6. CONCLUSION

The digital implementation of proposed DSVPWM technique is successfully accomplished for induction motor drive fed through Z-source inverter. It ease in implementation and effectiveness is proved by simulation and experimentally. It has been established here that the Z-source inverter topology with appropriate PWM technique gives better result for EV / induction motor drive than the traditional inverter based drive.

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