

Modeling and Simulation of PWM Line Converter feeding to Vector Controlled Induction Motor Drive and 3-Level SVM based PMSM Drive

. T.Narasa Reddy¹, Dr.T.Purnachandra Rao², A.S. Reddy³, P.Sarala⁴

¹CVR College of Engineering /Department of EEE, Hyderabad (A.P), India

Email: narasaiitd@gmail.com

²NIT Warangal /Department of EEE, Warangal (A.P), India

Email: lucky200809@gmail.com

³VBIT /Department of EEE, Hyderabad (A.P), India

Email: svas_a@rediffmail.com

⁴TRK College of Engineering and Technology /Department of EEE, Hyderabad (A.P), India

Email: sarala2906@gmail.com

Abstract— The objective of this paper is to model and simulate a three-phase Voltage Source Pulse Width Modulation (PWM) Rectifier Based on Direct Current Control feeding an indirect vector controlled Induction Motor Drive (VCIM) and 3-Level SVM based PMSM Drive. Based on the mathematical model of PWM rectifier, the dual close loop engineering design with decoupled feed-forward control is applied in the three phase voltage source rectifier. The first objective is to realize unity power factor at the input ac mains and regulate output voltage. The second one is to realize that the above designed PWM rectifier will always give its objectives of stiff dc voltage and unity power factor irrespective of the load and its controlling methods. The types of loads, considered in this paper are to check the performance of the PWM rectifier with direct current control are resistive, VCIM and 3-Level SVM based PMSM Drive. The induction motor is taken with indirect vector control and PMSM is taken with 3-Level SVM based vector control so as to reflect the most practical aspect of the load for checking the viability of the rectifier design. The operation of Induction machine and PMSM is not disturbed the PWM rectifier objectives and operation of PWM rectifier is not interfered in to the independent operation of the vector controlled machine. Hence, the designed PWM rectifier is considered as capable of feeding the Common DC coupling point (dc bus).

Index Terms— Pwm rectifier, VCIM, Direct Current Control (DCC), PMSM, Indirect Vector control.

I. INTRODUCTION

THE expanding use of electric loads controlled by power electronics such as PC's, TV's, stereos, and adjustable speed drives (ASD's) has made power converters an important and unquestionable part of modern society. Nevertheless, the increasing use of power converters has also led to an increase of current harmonics drawn from the utility grid. In the last decade, major focus has been on harmonic reduction techniques and, as a result of this, several useful harmonic reduction techniques exist for the single-phase rectifier. However, finding the right solution for the three-phase rectifiers is still very difficult. This seems to be true especially for industrial ASD's where the price and reliability have the highest priorities. Even though there exist many proposals for the three-phase rectifier, many of the existing solutions may not be qualified for a grade-purpose ASD. Various methods based on the

principle of increasing the number of pulses in ac-dc converters have been reported in the literature to mitigate current harmonics [2]–[4]. These methods use two or more converters, where the harmonics generated by one converter are cancelled by another converter, by proper phase shift. The autotransformer-based configurations [5, 6, 8-10] provide the reduction in magnetic rating, as the transformer magnetic coupling transfers only a small portion of the total kilovolt-ampere of the induction motor drive. These autotransformer based schemes considerably reduce the size and weight of the transformer. Autotransformer-based 18-pulse ac-dc converters have been reported for reducing the total harmonic distortion (THD) of the ac mains current. To ensure equal power sharing between the diode bridges and to achieve good harmonic cancellation, this topology needs Interphase transformers and impedance matching inductors, resulting in increased complexity and cost. Moreover the dc-link voltage is higher, making the scheme non applicable for retrofit applications.

The solution is either only practical for low-power applications or the price and complexities are too high. Some summaries on three-phase harmonic reduction techniques can be found in [1]–[5]. So far, most customers of ASD's use the low-cost diode rectifier and accept the harmonic currents. Harmonic reduction Equipment such as an active filter or active rectifier is only used when there are severe problems with harmonic distortion. Due to the new standards, such as IEEE 519-1992 and EN 61000-3-2/EN 61000-3-12, a more general solution is desired for the ASD. Figure 1 shows a three-phase diode-rectifier working as a line side Converter, with this common DC Link, many of the Drives (like Vector Controlled IM Drive, Three-Level SVM based PMSM Drive and Static load) systems are interconnected. Due to the rectification process, the input current is highly discontinuous and contains excessive low frequency harmonics resulting in high total harmonic distortion (THD). The IEEE-519 recommended practices specify limits on the harmonics generated. Also, with this configuration, power can flow only in one direction making the PWM drive system incapable of regenerating. In order to meet clean input power requirements and allow regeneration, the diode rectifier shown in Figure 1.

can be replaced with a PWM rectifier as shown in Figure2. Such a system is currently available up to 500 kW rating from many ASD drive manufacturers. This paper is to model and simulate a three-phase Voltage Source Pulse Width Modulation (PWM) Rectifier Based on Direct Current Control feeding an indirect vector controlled Induction Motor Drive (VCIM) and 3-Level SVM based PMSM Drive. Based on the mathematical model of PWM rectifier, the dual close loop engineering design with decoupled feed-forward control is applied in the three phase voltage source rectifier. The first objective is to realize unity power factor at the input ac mains and regulate output voltage. The second one is to realize that the above designed PWM rectifier will always give its objectives of stiff dc voltage and unity power factor irrespective of the load and its controlling methods.

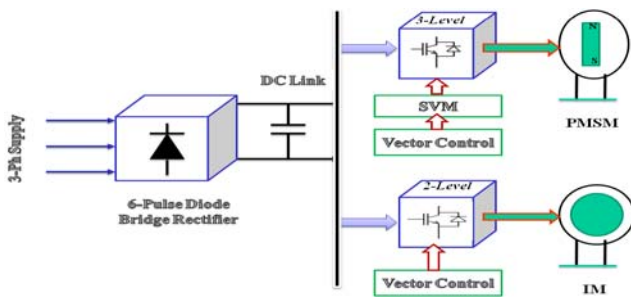


Figure1. Diode bridge rectifier feeding to different AC Drives

The use of PWM rectifier as a utility interface has many advantages such as:

- ❖ Clean input power at unity power factor to meet IEEE 519 limits.
- ❖ Power flow in both directions, hence regenerative braking is possible. This feature results in improved efficiency.
- ❖ Regulated dc-link guarantees immunity to voltage sags and other utility disturbances.

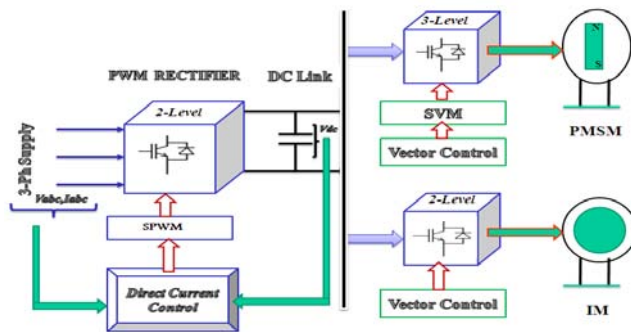


Figure2. PWM rectifier feeding to different AC Drives

II. PMSM MODELING AND CONTROL

High energy permanent magnets and high yield-strength materials like neodymium-iron-boron (NdFe) or Samarium-cobalt magnets are very suitable for high speed electrical machines [1],[5]. In a permanent magnet synchronous machine (PMSM), the dc field winding of

the rotor is replaced by a permanent magnet. The advantages are elimination of field copper loss, higher power density, lower rotor inertia, and more robust construction of the rotor. The drawbacks are loss of flexibility of field flux control and possible demagnetization. The machine has higher efficiency than an induction machine, but generally its cost is higher. The analysis of the PMSM is done in dqo axis theory. For a balanced system the 0-axis quantities are equal to zero, the dq axis equations can be written as follows:

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \quad (1)$$

$$T_e = \frac{3}{2} \left(\frac{P}{2} \right) (\lambda_d i_q - \lambda_q i_d) \quad (2)$$

$$T_e = T_L + B \omega_m + J \frac{d \omega_m}{dt} \quad (3)$$

III. THREE-LEVEL INVERTER

Figure1 shows the simplified circuit diagram of a popular three-level neutral point clamped (NPC) inverter. The inverter leg ‘a’ is composed of four IGBT switches S₁ to S₄ with four antiparallel diodes D₁ to D₄. On the DC side of the inverter, the DC bus capacitor is split into two, providing a neutral point ‘n’. When switches S₂ and S₃ are turned on, the inverter output terminal a is connected to the neutral point through one of the clamping diodes D_{n1} and D_{n2}. Ideally, the voltage across each of the DC capacitors is V_{dc}/2, which is half of the total DC-link voltage V_{dc}. With a finite value for C₁ and C₂, the capacitors can be charged or discharged by neutral current i_n, causing neutral-point voltage deviation. As indicated earlier, the neutral-point voltage V_n varies with the operating condition of the NPC inverter. If the neutral-point voltage deviates too far, an uneven voltage distribution takes place, which may lead to premature failure of the switching devices and cause an increase in the harmonic of the inverter output voltage.

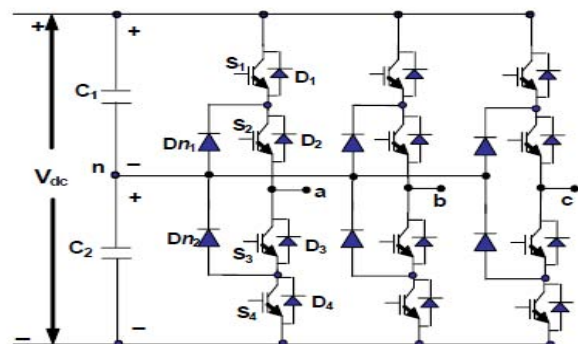


Figure3. 3-Level NPC PWM Inverter

The operating status of the switches in the NPC inverter can be represented by the switching states shown in table I. Switching state ‘P’ denotes that the upper two switches in leg ‘a’ are on and the inverter pole voltage V_a, which is ideally +V_{dc}/2, whereas ‘N’ indicates that the lower two switches conduct, leading to V_a = -V_{dc}/2. Switching state

'O' signifies that the inner two switches S_2 and S_3 are on and V_a is clamped to zero through the clamping diodes. Depending on the direction of the load current i_a , one of the two clamping diodes is turned on. For instance, a positive load current ($i_a > 0$) forces D_{n1} to turn on, and the terminal 'a' is connected to the neutral point 'n' through the conduction of D_{n1} and S_2 . The switches S_1 and S_3 operate in a complementary manner similar to switches S_2 and S_4 .

Table 1

V_{a0}	S_1	S_2	S_3	S_4	Switching State
$+V_{dc}/2$	ON	ON	OFF	OFF	P
0	OFF	ON	ON	OFF	O
$-V_{dc}/2$	OFF	OFF	ON	ON	N

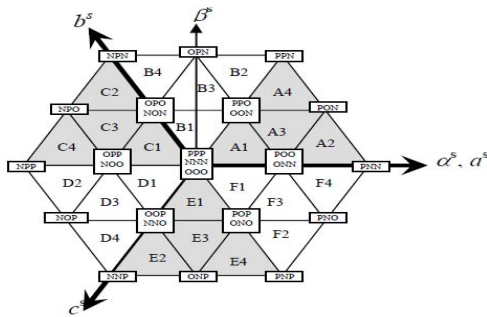


Figure 4. Switching Sectors

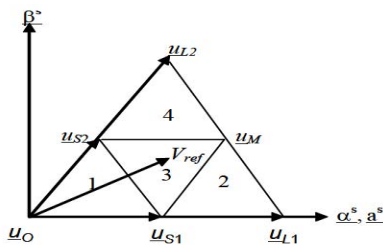


Figure 5. Reference Vector Generation

IV. PWM RECTIFIER MODELING AND DESIGN

Figure 6 shows the circuit diagram of the three phase voltage source rectifier structure. In order to set up math model, it is assumed that the AC voltage is a balanced three phase supply, the filter reactor is linear, IGBT is ideal switch and lossless [5]. Where $a u$, $b u$ and $c u$ are the phase voltages of three phase balanced voltage source, and $a i$, $b i$ and $c i$ are phase currents, v_{dc} is the DC output voltage, R and L mean resistance and inductance of filter reactor, respectively, C is smoothing capacitor across the dc bus, $L R$ is the DC side load, $r_a u$, $r_b u$, and $r_c u$, are the input voltages of rectifier, and $L i$ is load current.

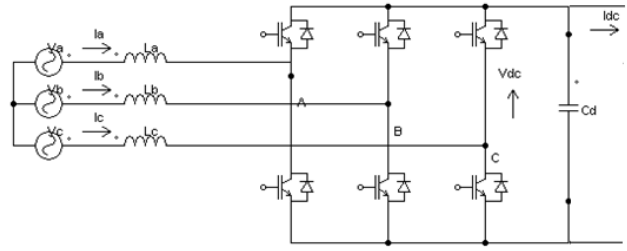


Figure 6. Three-phase Voltage source PWM rectifier

$$u_{Ld} = Ri_{Ld} + L \frac{di_{Ld}}{dt} - \omega Li_{Lq} + u_{Sd} \tag{4}$$

$$u_{Lq} = Ri_{Lq} + L \frac{di_{Lq}}{dt} + \omega Li_{Ld} + u_{Sq} \tag{5}$$

$$C \frac{du_{dc}}{dt} = (i_{Ld} S_d + i_{Lq} S_q) - i_{dc} \tag{6}$$

Where

$$S_d = S_\alpha \cos \omega t + S_\beta \sin \omega t; S_q = S_\beta \cos \omega t - S_\alpha \sin \omega t$$

V. DESIGN OF CURRENT AND VOLTAGE LOOPS

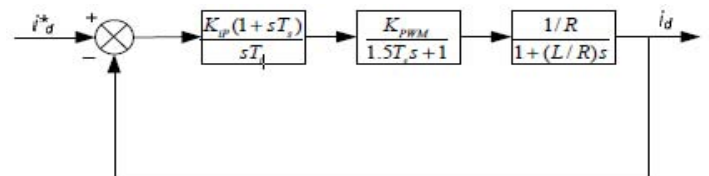


Figure 7. Inner Current Loop

When the current responses speed is concerned, the current regulator can be designed as the typical model system. For pole-zero cancellation, take $T = L/R$. The open-loop current transfer function can be expressed as

$$W_i(s) = \frac{K_{ip} K_{PWM}}{RT_i s (1.5T_s + 1)}$$

The parameters of the PI controller should be chosen as

$$K_{ip} = \frac{RT_i}{3T_s K_{pwm}}$$

$$K_{il} = \frac{K_{ip}}{T_i}$$

VI. INDUCTION MOTOR MODELING AND CONTROL

The dynamic equations of the induction motor in any reference frame can be represented by using flux linkages as variables. This involves the reduction of a number of variables in the dynamic equations. Even when the voltages and currents are discontinuous the flux linkages are continuous. The stator and rotor flux linkages in the stator reference frame are defined as

$$\left. \begin{aligned} V_{ds} &= R_s i_{ds} + p \psi_{ds} \\ V_{qs} &= R_s i_{qs} + p \psi_{qs} \\ V_{dr} &= R_r i_{dr} + \omega_r \psi_{qr} + p \psi_{dr} \\ V_{qr} &= R_r i_{qr} - \omega_r \psi_{dr} + p \psi_{qr} \end{aligned} \right\} \quad (7)$$

$$\left. \begin{aligned} \psi_{qs} &= L_s i_{qs} + L_m i_{qr}, \psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \psi_{qr} &= L_r i_{qr} + L_m i_{qs}, \psi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \psi_{qm} &= L_m (i_{qs} + i_{qr}), \psi_{dm} = L_m (i_{ds} + i_{dr}) \end{aligned} \right\} \quad (8)$$

$$T_e = \frac{3}{2} \frac{p}{L_r} \frac{L_m}{L_r} (i_{qs} \psi_{dr} - i_{ds} \psi_{qr}) \quad (9)$$

$$T_e - T_L = \frac{2}{p} J \frac{d\omega_r}{dt} \quad (10)$$

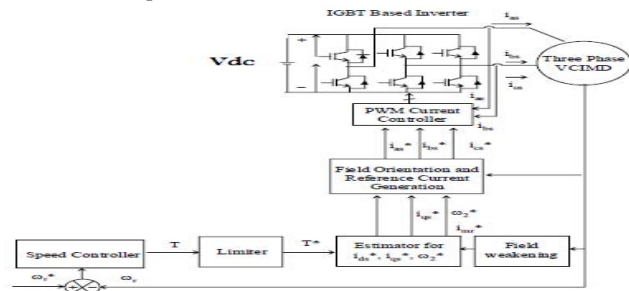


Figure 8. Induction Motor controlled by indirect vector control method

VII. SIMULATION RESULTS AND DISCUSSIONS

Various simulation tools available for simulation of power electronic and drive system. MATLAB has been chosen in this work due to its versatility. To verify the above design, the proposed Converter-Drive system is simulated in MATLAB/SIMULINK. The simulation is carried out on direct current controlled PWM rectifier with the following load conditions. Each time it is verified that the input power factor is unity and the DC voltage is stiff under all the conditions. Simulation results are presented here for different operating conditions.

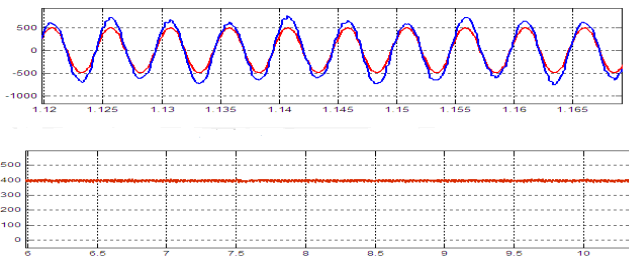


Figure9. Source voltage, source current and DC link voltage waveforms of PWM Rectifier with DCC

The Simulated Results of 3-Phase PWM Line Rectifier feeding to ASD's are shown in the Figure9. The above figure shows the source voltage and source current waveforms, These results shows that the input power factor of entire system is close to unity. The DC Link Voltage of the PWM Converter is shown in the Figure10, it is tracking the reference DC Voltage of 400v.

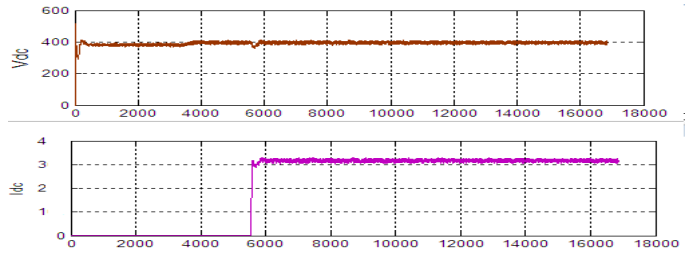


Figure10. Dynamics of DC link voltage and Current waveforms of PWM Rectifier with DCC

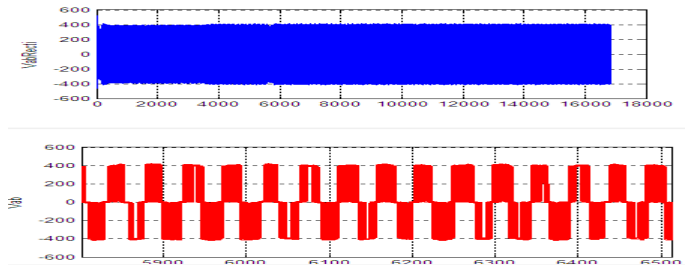


Figure11. Input voltage waveforms (at Boost Inductor) of PWM Rectifier with DCC

PWM Rectifier with VCIM

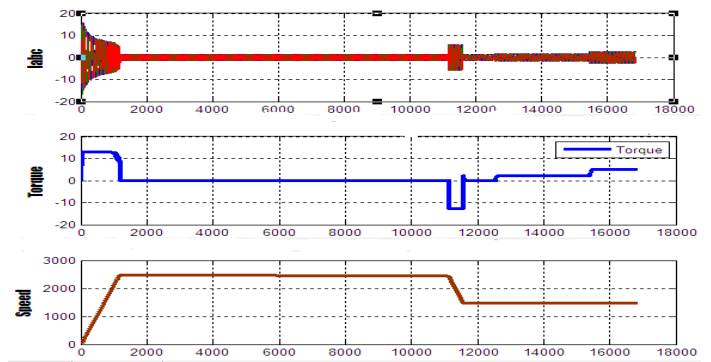


Figure12. Input current, Generated Torque and Rotor Speed waveforms of VCIM with PWM Rectifier

The dynamics source current, generated torque and rotor speed of the Indirect vector controlled Induction motor drive with pwm rectifier against step speed changes ($w=2500 \text{ rpm} \rightarrow 1500 \text{ rpm}$) and load torque ($T_L=0 \text{ N-m} \rightarrow 2 \text{ N-m} \ \& \ 2 \text{ N-m} \rightarrow 8 \text{ N-m}$) changes are shown in the Figure12. at $t=11s$, The reference speed of the drive is changed from $2500 \text{ rpm} \rightarrow 1500 \text{ rpm}$, at this instant the generated torque of the VCIM undergoes a bit dynamics and immediately after $1ms$ the generated torque is tracking its reference value (0 N-m). The Load torque (T_L) is changed from $0 \text{ N-m} \rightarrow 2 \text{ N-m} \ \& \ 2 \text{ N-m} \rightarrow 8 \text{ N-m}$ at $t=12.5s$ & $t=14s$ respectively, the moment when the load torque changes, there is no dynamics in the rotor speed of VCIM i.e the generated torque and speed are decoupled.

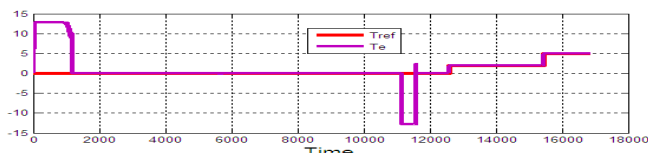


Figure 13. Reference Load Torque and Generated Torque waveforms of VCIM with PWM Rectifier

The load torque and the generated torque of the VCIM drive are shown in the Figure 13; the generated torque of the motor tracks the reference value as shown.

PWM Rectifier with 3-Level SVM based PMSM Drive

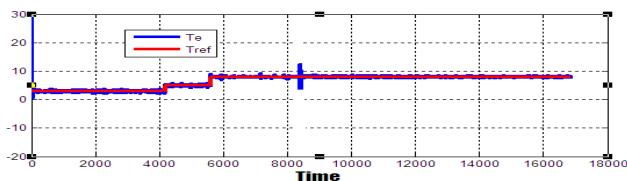


Figure 14. Reference Load Torque and Generated Torque waveforms of PMSM Drive with PWM Rectifier

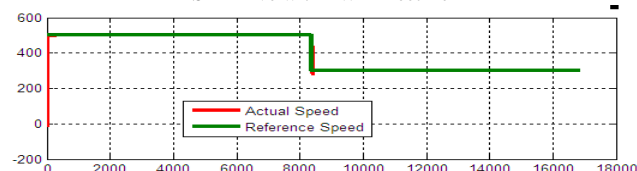


Figure 15. Reference Speed and Rotor speed waveforms of PMSM Drive with PWM Rectifier

The dynamics of electromagnetic torque developed by the 3-Level SVM based PMSM Drive against reference load torque changes are shown in the Figure 14 at $t=4s$ & $t=5s$ the TL is changed from 3 N-m \rightarrow 5 N-m & 5 N-m \rightarrow 8 N-m respectively, during these changes the generated torque of the drive is tracking the load torque. At $t=7s$ the reference speed is suddenly changed from 500 rads/sec \rightarrow 300 rads/sec, the movement when the reference speed is changed, with a bit of dynamics the rotor speed of SVM based PMSM tracks the reference speed as shown.

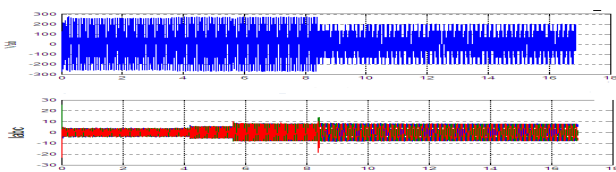


Figure 16. Input voltage and Input current waveforms of 3-Level SVM based PMSM Drive with PWM Rectifier

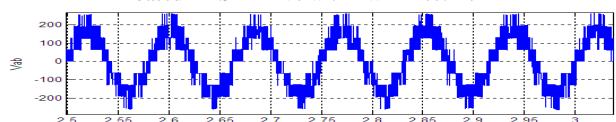


Figure 17. Enlarged 3-level Input voltage waveforms of SVM based PMSM Drive with PWM Rectifier

The input voltage and current supplied to SVM based PMSM Drive is shown in Figure 16, At $t=7s$ the reference speed is suddenly changed from 500 rads/sec \rightarrow 300 rads/sec, the movement when the reference speed is changed, then to control the motor at this reference, the

input voltage and currents drawn by the drive as to change, this changes are shown and the enlarged wave form of 3-level voltage at the input terminals of SVM based PMSM drive.

VIII. CONCLUSIONS

Interestingly, the DC bus voltage remains unchanged except with a very little dynamics. This shows that, the Direct control of the PWM rectifier, Vector control of the Induction machine and 3-Level SVM based PMSM Drive are complementary each other. The operation of the Drives will never makes the DC bus voltage to pulsate or fall. This is the most important requirement of the power system, particularly, at common coupling (AC or DC). One more important aspect of the rectifier is that it is maintaining the unity power factor even under dynamic loads and disturbances.

REFERENCES

- [1] 'IEEE recommended practices and requirements for harmonic control in electric power systems' Project IEEE 519, June 1992.
- [2] IEC Subcommittee 77A: 'Disturbance in supply systems caused by household appliance and similar electrical equipment, Part 2: Harmonics' IEC 555-2 (EN 60555-2), September 1992
- [3] Key, T.S., and Lai, J.-S.: 'Comparison of standards and power supply design options for limiting harmonic distortion in power systems', IEEE Trans. Ind. Appl., 1993, 29, (4), pp. 688–695
- [4] Rastogi, M., Naik, R., and Mohan, N.: 'A comparative evaluation of harmonic reduction techniques in three-phase utility interface of power electronic loads', IEEE Trans. Ind. Appl., 1994, 30, (5), pp. 1149–1155
- [5] Mao, H., Lee, F.C.Y., Boroyevich, D., and Hiti, S.: 'Review of high performance three-phase power-factor correction circuits', IEEE Trans. Ind. Electron., 1997, 44, (4), pp. 437–446
- [6] Kolar, J.W., and Ertl, H.: 'Status of the techniques of three-phase rectifier systems with low effects on the mains'. Proc. 21st INTELEC, Copenhagen, Denmark, 1999
- [7] Kolar, J.W., and Zach, F.C.: 'A novel three-phase utility interface minimizing line current harmonics of high-power telecommunications rectifier modules', IEEE Trans. Ind. Electron., 1999, 44, (4), pp. 456–467.
- [8] Kolar, J.W., and Zach, F.C.: 'A novel three-phase three-switch threelevel unity power factor PWM rectifier'. Proc. 28th Power Conversion Conf., Nuremberg, Germany, 1994, pp. 125–138
- [9] Kolar, J.W., Stogerer, F., Minibock, J., and Ertl, H.: 'A new concept for reconstruction of the input phase currents of a three-phase/switch/level PWM (Vienna) rectifier based on neutral point current measurement'. Proc. PESC 2000, Galway, Ireland, 2000, Vol. 1, pp. 139–146
- [10] Qiao, C., and Smedley, K.M.: 'Three-phase unity-power-factor star connected switch (VIENNA) rectifier with unified constant-frequency integration control', IEEE Trans. Power Electron., 2003, 18, (4), pp. 952–957