International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 10, October - 2013

Implementation of Three Phase Three Leg AC/AC Converter Drives for BLDC Motor

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Abstract*—This paper presents the implementation of a novel three phase three leg AC/AC converter for BLDC motors. Since the number of switches required in this converter is only nine which is much less than that of the number of switches required in other direct AC/AC converter, the gate drivers used in this converter is reduced drastically which in turn reduces the cost and the losses of the drives used for motors by more than thirty percent. Apart from those only six pulses is required to drive the circuit with the help of space vector modulation (SVPWM) which is used to control the input current and hence unity power factor is maintained even for BLDC motors. The duty cycle calculation for the input current control of BLDC motor is also shown. Simulation results show the effectiveness and efficiency of the proposed technique.*

Keywords—AC/AC Converter; BLDC motor drives; Space Vector Modulation.

1. Introduction

The three-phase ac–ac power conversion can be achieved with the full-bridge configuration in which twelve semiconductor switches (six legs) are employed [1]; such a topology requires a relatively large number of power switches. In general, the use of too many power switches increases the cost and at the same time it reduces the reliability of the power conversion system. Thus, the study of topologies with a reduced number of power switches constitutes an important topic in power electronics [2].

Three-phase ac-dc-ac and ac-ac converters with variable frequency (VF) and variable voltage operation have been found wide applications in the industry. The most popular configuration uses the voltage source inverter (VSI) with a diode rectifier as the front end for adjustable speed drives (ASDs), uninterruptible power supplies (UPS), and other industrial applications [3]. This configuration features low cost and reliable operation due to the use of a diode rectifier, but it generates highly distorted input line currents and does not have regenerative or dynamic braking capability. These problems can be mitigated by using a back-to-back two-level voltage source converter (B2B 2L-VSC), shown in Fig. 1, where a pulse width modulation (PWM) voltage source rectifier is used to replace the diode rectifier [4][5]. Unlike VSCs that inevitably require the dc-link stage, the matrix converter [6] presents a radical change in topology and directly converts a fixed ac input voltage to an adjustable ac output voltage. It features sinusoidal input–output, controllable power factor, and is capable of bidirectional energy transfer from the supply to the load or vice versa. Since there is no dc-link circuit, the dc capacitor in the VSC is not necessary here, leading to cost reduction as well as improved reliability and longevity.

There are several reasons why AC/AC converters remain very attractive for some applications and a very promising technology that contribute to the development of power electronics. Few of these are [7]:

- Energy storage elements like inductors and capacitors are absent.
- The bidirectional power flow capability and input displacement factor control of these converters make them an ideal solution for same application.
- Large Power Density factors are achievable.

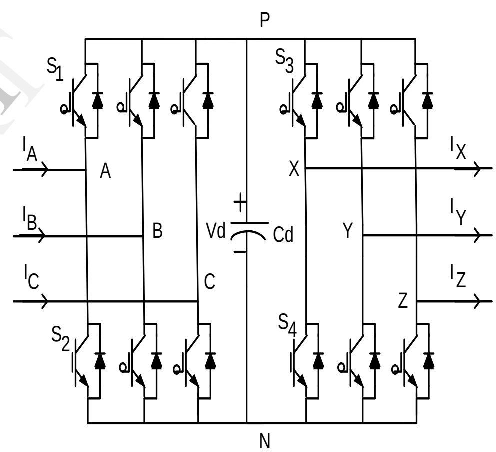

Fig. 1. Back-to-Back Two Level Voltage Source Converter

2. Three Phase Three Leg AC/AC Converter

Fig. 2 shows the proposed three-phase nine-switch converter topology [8]. This converter has only three legs with three switches installed on each of them. The novelty herein is that the middle switch in each individual leg is shared by both the rectifier and the inverter, thereby reducing the switch count by 33% and 50% in comparison to the B2B 2L-VSC and CMC, respectively. The input power is delivered to the output partially through the middle three switches and partially through a quasi-dc-link circuit. For the convenience of discussion, we can consider that the rectifier of the nine-switch converter is composed of the top three and middle three switches, whereas the inverter consists of the middle three and bottom three switches.

The converter has two modes of operation: 1) constant frequency (CF) mode, where the output frequency of the inverter is constant and also the same as that of the utility supply, while the inverter output voltage is adjustable; and

2) VF mode, where both magnitude and frequency of the inverter output voltage are adjustable. The CF-mode operation is particularly suitable for applications in UPS, whereas the VF mode can be applied to variable-speed drives.

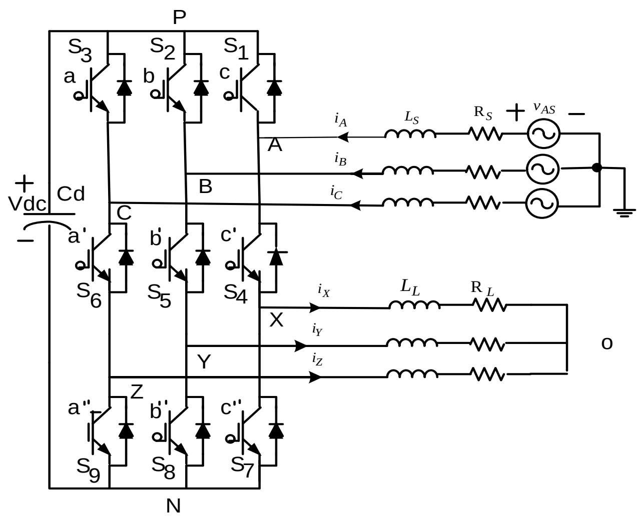

Fig. 2. Proposed Nine Switch AC/AC Converter with a Quasi DC-Link

3. Modulation Schemes

3.1 Switching Constraint

The reduction of the number of switches in the proposed converter topology imposes certain switching constraints for the switching pattern design [8]. In the B2B 2L-VSC shown in Fig. 1, the rectifier leg voltage v_{AN} , which is the voltage at node *A* with respect to the negative dc bus *N*, can be controlled by switches *S*1 and *S*2 in the rectifier, whereas the inverter leg voltage v_{XN} can be controlled by *S*3 and *S*4 in the inverter. This means that the rectifier and inverter leg voltages can be controlled independently. The B2B 2L-VSC has four switching states per phase, as defined in Table I.

For the nine-switch topology, the control of the input and output voltages has to be accomplished through the three switches on each leg. Because the middle switches are shared by the rectifier and inverter, the proposed converter has only three switching states per phase, as listed in Table I. It can be observed that switching state 4 for the B2B 2L-VSC does not exist in the nine-switch converter, which implies that the inverter leg voltage v_{XN} cannot be higher than the rectifier leg voltage v_{AN} at any instant. This is, in fact, the main constraint for the switching scheme design of the nine-switch converter. Carrier-based continuous PWM schemes for modulating the 2L-VSC, such as sinusoidal PWM (SPWM), space vector PWM (SVPWM), and third-harmonic injection PWM (THIPWM), are well established in the literature [9]. The principles of these methods can all be applied to the nine-

TABLE 1: SWITCHING STATES OF BACK-TO-BACK CONVERTER

Back-to-back converter						
Switching State	S_1	S_2	S_3	S_4	V_{AN}	V_{XN}
1	On	Off	On	Off	V_d	V_d
2	Off	On	Off	On	0	0
3	On	Off	Off	On	V_d	0
4	Off	On	On	Off	0	V_d

TABLE 2: SWITCHING STATES OF PROPOSED CONVERTER

Proposed nine switch converter					
Switching State	S_1	S_4	S_7	V_{AN}	V_{XN}
1	On	Off	On	V_d	V_d
2	Off	On	Off	0	0
3	On	Off	Off	V_d	0

switch converter but a little modification would be necessary, because when designing the switching pattern for the nine-switch converter, the switching constraint discussed earlier must be satisfied. Fig. 3 illustrates the generalized carrier-based modulation scheme in a single switching period for the nine-switch converter. The rectifier modulating wave v_{mr} and the inverter modulating wave v_{mi} are arranged such that v_{mr} is not lower than v_{mi} at any instant of time. These two modulating waveforms are compared with a common triangular carrier *vc* . The generated rectifier and inverter leg voltages v_{AN} and v_{XN} are also shown in the figure. This arrangement guarantees that switch state 4 in the B2B 2L-VSC is eliminated here for the nine-switch converter.

3.2 Space Vector Pulse Width Modulation(SVPWM) for input current control and output voltage control

The rectifier stage is similar to the traditional one except that all the six switches are bidirectional. The purpose of the rectifier stage is to generate sinusoidal input currents a well as to maintain the positive dc-link output voltage.

The space vector of the rectifier stage is composed of six active current vectors with fixed directions and two zero vectors, as shown in Fig. 3(a) [10]. The reference current vector is generated from two active current vectors. For example, in sector 1, the reference current vector I_{ref} is synthesized from two vectors I_{ab} and I_{ac}. Current vectors I_{ab} and I_{ac} represent the connection of the input phase *a* to the positive pole and the input phases *b* and *c* to the negative pole of dc-link bus, respectively. For the sake of explaining the indirect SVPWM method in MC without missing the generality of the analysis, it is assumed that the rectifier stage operates in sector 1 and the reference output voltage vector V_{ref} is located in sector 1 at the inverter stage, as shown in Fig. 3(a) and (b), respectively. The duty cycles $d\gamma$ and $d\delta$ for the active vectors in the rectifier stage are given by [10]

$$d_\gamma = m_1 \sin\left(\pi/3 - \theta_{in}\right) \tag{1}$$

$$d_\delta = m_1 \sin\left(\theta_{in}\right) \tag{2}$$

Where m_1 is the rectifier stage modulation index and θ_{in} is the angle between the reference vector I_{ref} and the right neighbor

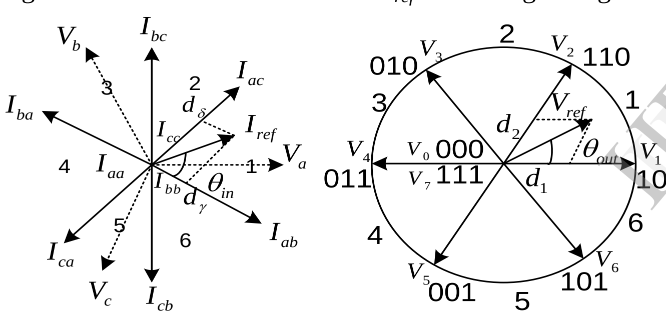

Fig. 3. Space Vector Diagram of (a) Rectifier stage and (b) Inverter Stage

active current vector I_{ab}. In the modulation of the rectifier stage, the zero vectors are not considered, and the modulation index is unity. Hence, the switching sequence only consists of the two active current vectors I_{ab} and I_{ac}, whose duty cycles are given by:

$$d_{ab} = \frac{d_\gamma}{d_\delta + d_\gamma} \tag{3}$$

$$d_{ac} = \frac{d_\delta}{d_\delta + d_\gamma} \tag{4}$$

By utilizing the same approach, the duty cycles and the switching states for all sectors can be obtained. Table I summarizes the sectors and the switching states at the rectifier stage corresponding to the phase of the input voltage. Space vector modulation techniques are widely used in inverter control because they reduce the harmonic components of output voltages easily. Given a sampled reference vector V_{ref} and angle θ_{out} in sector 1, as shown in Fig. 4(b), the duty cycles of two active vectors V_1 and V_2 and zero vectors V_0 and V_7 are

$$d_1 = \sqrt{3}\frac{\left|V_{ref}\right|}{\bar{V}_{dc}} \sin\left(\pi/3 - \theta_{out}\right) \tag{5}$$

$$d_2 = \sqrt{3}\frac{\left|V_{ref}\right|}{\bar{V}_{dc}} \sin\left(\theta_{out}\right) \tag{6}$$

$$d_0 = d_7 = 0.5(1 - d_1 - d_2) \tag{7}$$

where θ_{out} is the angle of reference output voltage vector V_{ref} and d_1, d_2, d_0, and d_7 are the duty cycles of output voltage space vectors V_1, V_2, V_0, and V_7, respectively.

To obtain balanced input currents and output voltages in the same sampling period, the PWM pattern should produce all combinations of the rectifier and the inverter switching states. As there are two switching states for the rectifier stage, the switching states at the inverter stage should be divided into two groups, as shown in Fig. 4. As shown in Fig. 4, the inverter switching frequency is twice the rectifier switching frequency, where T_s is the sampling period. The duty cycles of active vectors and zero vectors of the output voltage space vectors in d_{ab} and d_{ac} are calculated by:

$$\begin{aligned} d_{0ab} &= d_0.d_{ab} \qquad d_{7ab} = d_7.d_{ab} \\ d_{1ab} &= d_1.d_{ab} \qquad d_{2ab} = d_2.d_{ab} \end{aligned} \tag{8}$$

$$\begin{aligned} d_{0ac} &= d_0.d_{ac} \qquad d_{7ac} = d_7.d_{ac} \\ d_{1ac} &= d_1.d_{ac} \qquad d_{2ac} = d_2.d_{ac} \end{aligned} \tag{9}$$

The voltage transfer ratio of MC is defined as follows:

$$m = \frac{\left|V_{ref}\right|}{V_1} \tag{10}$$

According to (5)–(7), the voltage transfer ratio *m* should be smaller than 0.866 in orders to maintain all duty cycles positive.

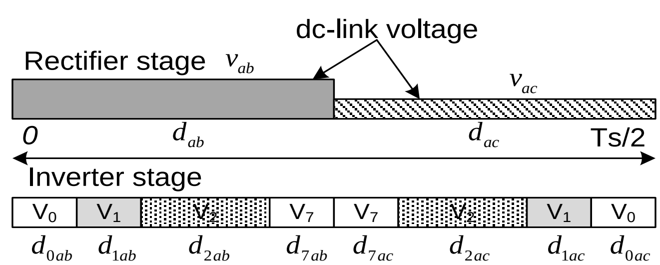

Fig. 4. Synthesis of switching states for rectifier and inverter stages in MC

4. Modelling of BLDC Motor

4.1 Voltage Controller

The BLDC Motor requires a power electronic drive circuit and a commutation system for its operation [12]. The Fig.5 describes the functional units present in the drive circuit and the associated commutation controller for the BLDC Motor. A 4-pole BLDC motor is driven by the inverter for 1200 commutation. The rotor position can be sensed by a hall-effect sensor or slotted optical disk, providing three square wave signals with phase shift of 1200. These signals are decoded by a combinational logic to provide the firing signals for 1200 conduction on each of the three phases. The inverter voltage for the motor is filtered by the filter circuit provided, which minimizes the high frequency switching voltage ripple component. The LC filter for the proposed work is connected

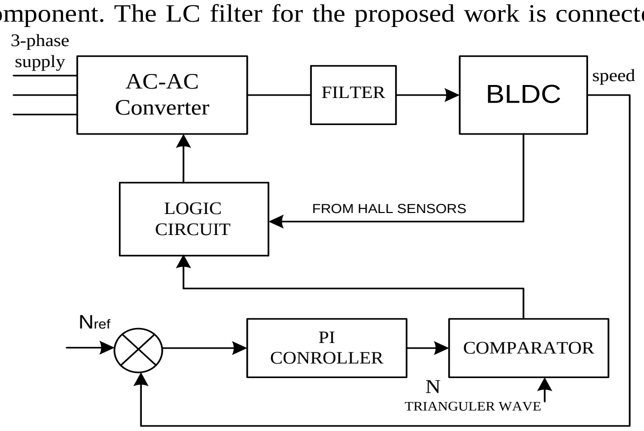

Fig. 5. Voltage Controller for BLDC Motor With Filter

in the interface of the drive and the motor. The LC filter in this system acts as a low pass filtering circuit which offer high impedance to high frequency component of the voltage and very minimum impedance to the power frequency voltage components and thereby minimizes harmonics in the supply voltage to the motor and the series inductance opposes the sudden changes in the current due to electronic commutation and thereby reduces the torque ripple.

4.2 Current Controller

Fig.4 shows the simple block diagram of the proposed method. The current controller block is shown in the Fig.6. The operation of the system is as follows: as the motor is of The brushless dc type, the waveforms of the armature currents are quasi square. These currents are sensed through current sensors, and converted to voltage signals. These signals are then rectified, and a dc component, with the value of the ceiling of the currents, I_{max} is obtained as shown in Fig.5 this dc signal is compared with a desired reference I_{ref} , and from this comparison, and error signal I_{ref} is obtained. This error is then passed through a PI control to generate the PWM for all the six valves of the inverter, which are sequentially activated by the shaft position sensor. The torque is directly commanded by I_{ref}. The larger the reference I_{ref}, the higher the torque produced. The strategy becomes simple, because the control only needs to be in command of one dc current instead of three alternating waveforms. Another advantage of this strategy is that the modulation of the currents can be done using one of the simplest control strategies available: the "Triangular carrier modulation strategy" which offers the following additional advantages: 1) the switching frequency becomes defined by the triangular carrier Fig.7. Stator and Rotor's MMF during step change from motor to brake operation. 2) The ability to follow the template with the proposed method becomes quite accurate when triangular carrier is used 3) the hardware implementation is very simple.

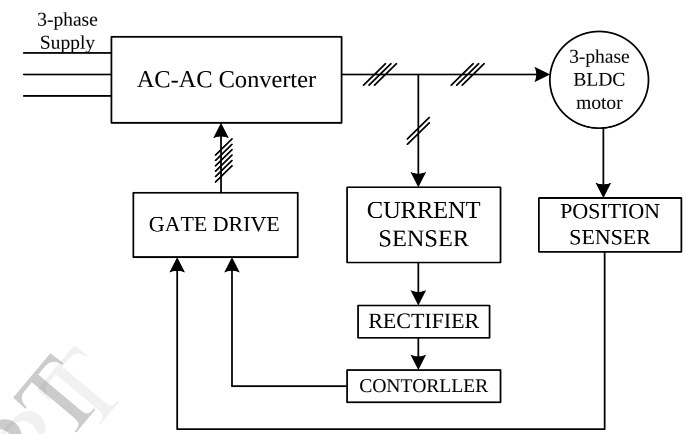

Fig. 6. Current Controller of BLDC Motor

The control strategy also allows regenerative braking, which is very important in many applications, like electric vehicles, where energy can be returned to the battery pack. To brake the motor (regenerative braking) the stator magnetic field is reversed. This action is accomplished through the inversion of the signals given by the position sensor. The position sensor discriminates six positions each 360^{o} electric degrees. During motor operation, the rotor moves clockwise. When the brake signal is applied, the stator field is reversed 180^{o} electric degrees. This action produces an instantaneous change in the direction of the torque, making a fast reduction of the speed of the machine, which begins to return its energy to the dc link. The same strategy can be used for reversal of rotation of the machine.

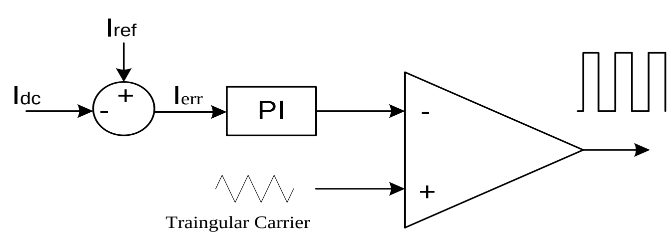

Fig.7. Current Controller Block

ISSN: 2278-0181
Vol. 2 Issue 10, October - 2013

The tuning of the current controller starts with the determination of the amplitude and frequency of the triangular carrier, and the gains of the PI control. To get a PWM signal operating at the carrier frequency, the control should be adjusted to keep the reference current moving around the reference.

5. Proposed Technique

The duty cycles for the rectifier stage and the inverter stage are calculated using the equations (1) to (10) according to the switching restrictions explained in section III. Thus the six pulses (P_1 to P_6)are obtained with the help of space vector modulation as explained in above section and the combination of these pulses are applied to the nine switches of the proposed converter as shown in Table 3. And the same combination of pulses are applied to the AC-AC converters as shown in the fig. 5 and fig. 6 in BLDC modeling for the operation of BLDC motor at unity power factor.

TABLE 3: COMBINATION OF PULSES APPLIED TO VARIOUS SWITCHES

Pulse	Switches	
P_1	S_4	
P_2	S_1	S_7
P_3	S_5	
P_4	S_2	S_8
P_5	S_6	
P_6	S_3	S_9

6. Simulation Results

Simulations are carried out for a three phase RL load using MATLAB software. The simulation parameters are as follows:

1) Power Supply (Phase peak Voltage) is 230V/50Hz.
2) BLDC Motor with circuit parameters R=0.2Ω, L=8.5mH.
3) Output frequency f_{out}=50Hz.
4) All switches in the converter are ideal.
5) Switching Frequency used=6 KHz.
6) Modulation Index m_r=0.9 and m_i=0.9.

Fig. 8 shows the input voltage applied to the proposed converter and the input current obtained at the converter side. As shown in the result the input current reaches to the steady state after few cycles because of the transients obtained. Fig. 9 shows the Three Phase Output Line Voltages of the converter which is fed to the BLDC Motor and acts as input voltage source for the same. In Fig. 10 the variation of stator current is shown which changes in accordance with the reference rotor speed and reaches to the steady state at 0.5 sec i.e. only after when the actual rotor speed of the motor comes to steady state as shown in Fig. 11. Now the variation of actual electromagnetic torque and the reference torque is shown in Fig. 12 which is varying according to the speed variation and load demand. Fig. 14 shows the input power factor which is settled to unity after transient period while the Fig. 13 shows the fictitious dc voltage obtained at the converter side.

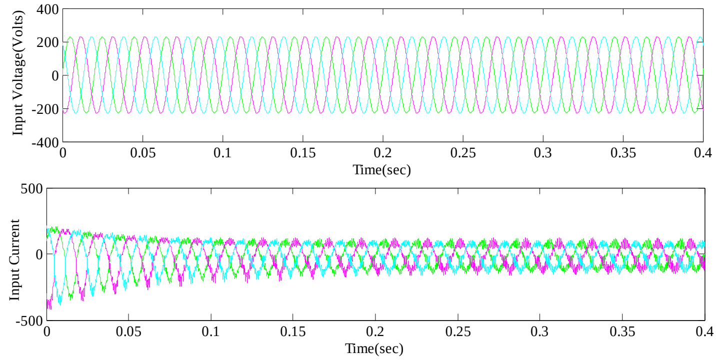

Fig. 8. Three Phase Input Voltage and Input Current at the Converter Side

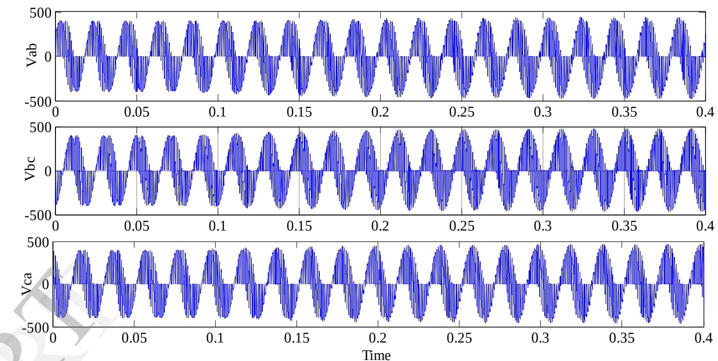

Fig. 9. Three Phase Output Voltages of the Converter fed to the BLDC motor

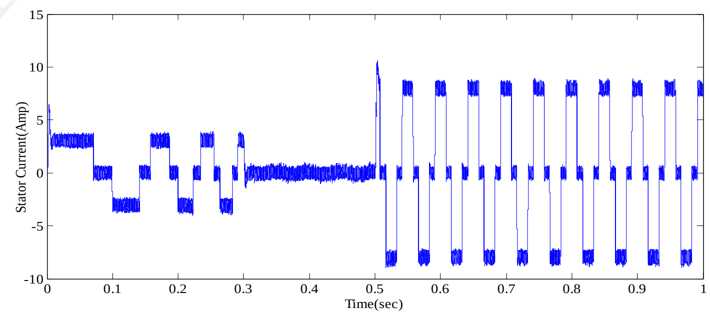

Fig. 10. Stator Current

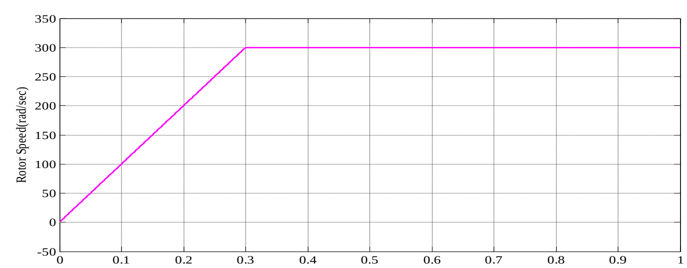

Fig. 11 Rotor Speed Variation of BLDC Motor

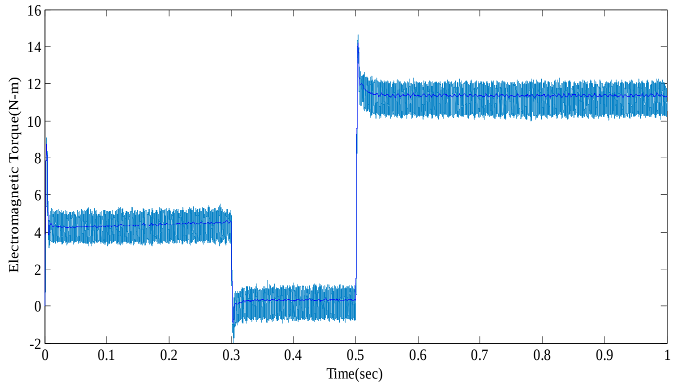

Fig. 12. Electromagnetic Torque Variation of BLDC Motor

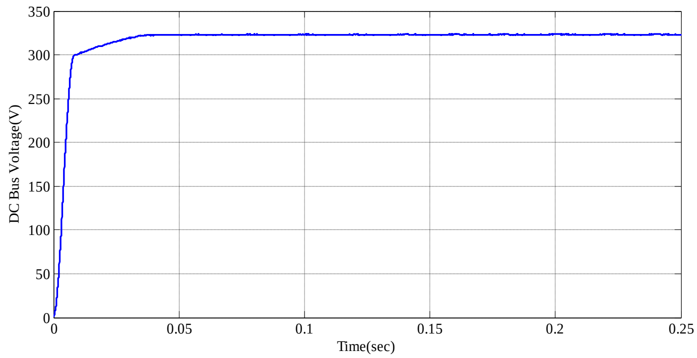

Fig. 13. DC Bus Voltage

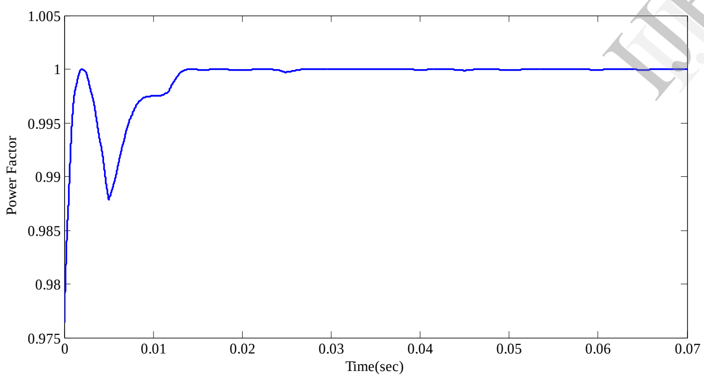

Fig. 14. Input Power Factor

7. Conclusion

In this paper, the effectiveness of the proposed technique for BLDC motor has been clearly justified. For controlling the input current and to increase the input power factor, space vector modulation technique is used which is clearly shown in the results. It has also been shown that how the only six pulses can be used to control the nine switches of the proposed converter whose duty cycle calculation is also shown in this paper. The advantages of this strategy are a) very simple control scheme; b) phase currents are kept balanced; c) current is controlled through a quasi dc component, and hence phase over currents are eliminated. So, this technique provides the desired result which can be used in various direct AC-AC conversion applications with minimum number of gate driver circuits as the number of pulses used is only six as compared to other AC/AC converters.

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