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Carrier Based Sinusodial PWM Scheme for the Nine-Switch Converter

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***Abstract:** To reduce the device count and minimize the dc capacitor filter CBSPWM proposed in the thesis as compared to back to back converter. It converts fixed ac input voltage to an adjustable ac output voltage. It is capable of bi-directional energy transfer for the supply to the load or vice versa. This converter features sinusoidal inputs and outputs, unity input power factor, and more importantly, low manufacturing cost due to its reduced number of active switches. The operating principle of the converter is elaborated and its modulation schemes are discussed. Finally, experimental results for back to back converter and CBSPWM are provided to verify the validity of the proposed topology using MATLAB/SIMULINK.*
***Index Terms:** AC/AC converter, pulse width modulation (PWM), reduced switch count topology.*

I. INTRODUCTION

Universal ac-dc-ac converter uses diode for the grid side rectifying, the energy transfer is not reversible, hence it can not meet the needs for fast start-up, braking and frequently reversible operation. The back-to-back connected PWM converter system shown in Fig.1 is one of the latest high-quality energy feedback technology with many advantages, it has bi-directional energy flow ability, and can achieve four-quadrant operation by simply controlling the switch devices according to certain on-off rules, it has not only very fast motor dynamic response, but also very small grid side harmonic contents and very high power factor[1-2].Generally the configuration which features low cost and reliable operation is 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 [2].

The B2B 2L-VSC requires a relatively high number (12) of active switches such as insulated gate bipolar transistors (IGBTs). It also needs a dc-link capacitor that is responsible for a limited lifespan and increased cost. To reduce the device count and minimize/eliminate the dc-capacitor filter, various converter topologies have been proposed in the literature. The matrix converter has been already- compared with the back-to-back converter obtaining some important but not conclusive results. The comparison is extremely difficult due to the high number of system parameters (i.e. input filter and load parameters, switching frequency, output frequency, modulation strategies, etc.) and to the inherent differences between the two converter topologies, such as the maximum voltage transfer ratio. The switching frequencies of the two converters are related to the adopted modulation strategies and should be Chosen with care in order to make a fair comparison furthermore both converters need an input filter for reducing the input current hamonics, and the filter parameters are strictly- related to the switching frequency. The recent progress in power semiconductor device technology followed by advancements in power electronic control methods; variable frequency inverter-fed ac drives are being adopted for a wide variety of applications. Recently there has been growing interest in low cost ac drives to meet the needs for reducing cost. Improvements in power semiconductor switch technology have significantly reduced the cost and size of such drives and improved waveform quality. Little change, however, has been made to the basic structure of the conventional ac-ac converter, while significant advances have been made in soft switching techniques and control strategies

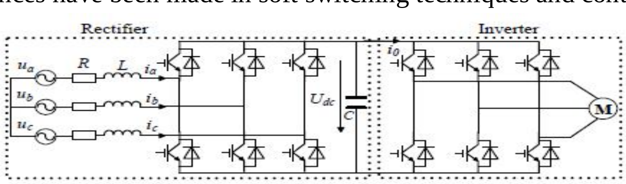

Fig (1): Representation of Back to Back converter

Pulse width modulation (PWM) control strategies development concerns the development of techniques to reduce the total harmonic distortion (THD) of the current. It is generally recognized that increasing the switching frequency of the PWM pattern reduces the

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lower-frequency harmonics by moving the switching frequency carrier harmonic and associated sideband harmonics further away from the fundamental frequency component. The most widely used PWM schemes for multilevel inverters are the carrier-based sine-triangle PWM (SPWM) technique.

The SPWM schemes are more flexible and simpler to implement, but the maximum peak of the fundamental component in the output voltage is limited to 50% of the DC link voltage, and the extension of the SPWM schemes into the over-modulation range is difficult. The basic principle of the SPWM used in two level inverters is explained here. The reference signal (V_r) which generally is sinusoidal is compared with the high frequency triangle wave (V_c) of constant amplitude. When $V_r > V_C$, the PWM output will be high (state +1), and output will be low (state -1) for $V_r < V_C$.

In general, the modulation index is defined as the ratio of the magnitude of the reference signal to that of the magnitude of the carrier signal. The modulation index is m = V_r / V_c

Where V_r is the magnitude of the sinusoidal reference signal waveform

V_c is the magnitude of the triangular carrier signal

By varying V_r and keeping V_c constant, the modulation index can be changed. By changing the modulation index, the amplitude of the fundamental component of the output can be varied. For three phase inverters, the same carrier signal V_c is used for all the three phases and three reference signals which are phase displaced by 2Π/3 radians are used for each of the phases.

II. SIMULATED FORM OF BACK TO BACK CONVERTER

The below fig (2) shows the simulated form of back to back converter

The IGBT specifications of the back to back converter can be given as

1) Resistance Ron= 0.01 ohms
2) Inductance Lon= 1e-6 H
3) Forward Voltage Vf = 1V
4) Current fall time Tf = 1e-6 s
5) Current tail time Tt = 2e-6
6) Snubber Capacitance Cs =0.01e-6

A. Switching Constraint

The reduction of the number of switches in the proposed converter topology imposes certain switching constraints for the switching pattern design. In the B2B 2L-VSC shown in Fig. 2, the rectifier leg voltage *vAN* , 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 *vXN* 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.

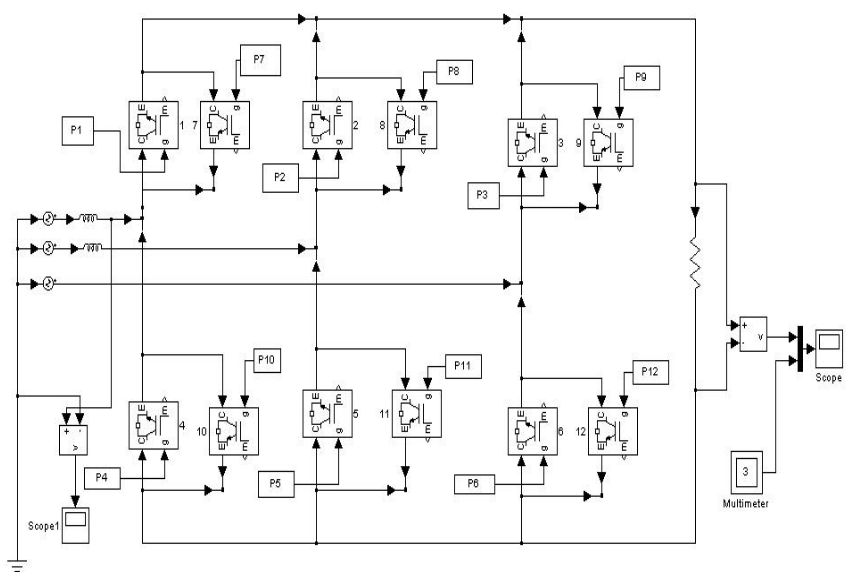

Fig (2) Simulated Form of Back to Back Converter

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Table I Switching State of Back to Back Converte

Switching State	S1	S2	S3	S4	Van	Vxn
1	On	Off	On	Off	Vd	Vd
2	Off	On	Off	On	0	0
3	On	Off	Off	On	Vd	0
4	Off	On	On	Off	0	Vd

The above Switching table shows when the switch is entering and leaving which desired the output voltage as shown in fig (3)

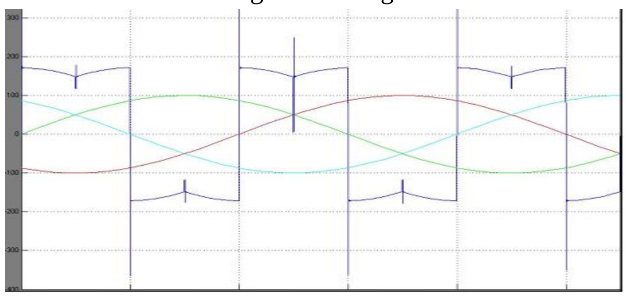

Fig (3) Output Wave Form of Back to Back Converter

III. SIMULATED FORM OF CBSPWM

The Carrier Based Sinusoidal Pulse Width Modulation (CBSPWM) scheme is shown in below fig (4) with simulated. The IGBT specifications of the proposed technique can be given as

1) Internal resistance Ron=1e-3 ohm
2) Snubber Resistance Rs =1e-5
3) Snubber Capacitance Cs =inf
4) Source inductance of Ls = 2.5 mH.
5) RL = 8ohm.
6) LL = 2.5 mH.

In which the novelty in this is 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 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. 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

Table II Switching State Of CBSPWM

Switching State	S1	S2	S3	Van	Vxn
1	On	On	Off	Vd	Vd
2	Off	On	On	0	0
3	On	Off	On	Vd	0

It can be observed from table I and table II that switching state 4 for the B2B 2L-VSC does not exist in the nine-switch converter, which implies that the inverter leg voltage *vXN* cannot be higher than the rectifier leg voltage *vAN* at any instant. This is, in fact, the main constraint for the switching scheme design of the nine-switch converter which is shown in fig (4) 2L-VSC is eliminated.

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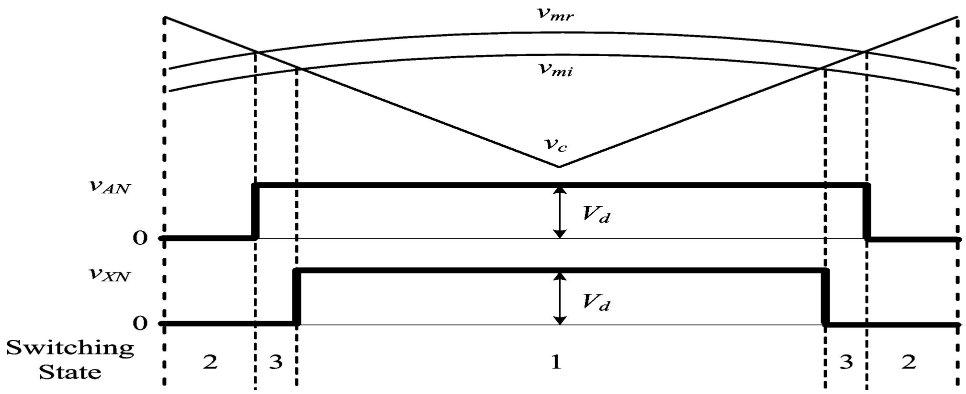

Fig (4) PWM waveform generation, where switching state 4 of the B2B

Fig. 4 illustrates the generalized carrier-based modulation scheme in a single switching period for the nine-switch converter. The rectifier modulating wave *vmr* and the inverter modulating wave *vmi* are arranged such that *vmr* is not lower than *vmi* at any instant of time. These two modulating waveforms are compared with a common triangular carrier *vc* . The generated rectifier and inverter leg voltages *vAN* and *vXN* 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.

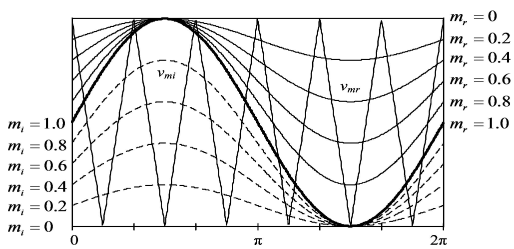

Fig (5) SPWM scheme for CF-mode operation

A. Modulation Scheme for CF-Mode Operation

Taking SPWM as an example, Fig. 5 illustrates the modified scheme for CF-mode operation, where *mr* and *mi* are the rectifier and inverter modulation indexes The difference between this scheme and the traditional SPWM for 2L-VSC is that here the modulating waves of the rectifier (solid line) and the inverter (dashed line) are placed in a single dc plane and compared to a common triangular carrier wave. The gate signals are generated at the waveforms' intersections with the carrier. To prevent the modulating waves from intersecting each other, the rectifier's modulating waves are lifted to the top of the dc plane whereas the inverters are pushed to the bottom by adding proper dc offsets. In this way, the switching constraint of the nine-switch converter can be satisfied. In practice, the rectifier side modulation can be synchronized to the grid via a phase-locked loop (PLL). The freedoms of choosing its modulation index *mr* and firing angle *α* between the modulating wave and the grid can be employed to control
the dc voltage and the input power factor. The inverter-side modulation index *mi* can be freely selected to adjust the output magnitude. If the inverter's modulating wave is set in phase with the rectifier's, as in the case shown in Fig. 5, both the rectifier and inverter's modulation indexes can simultaneously reach a maximum of unity.

B. Modulation Scheme for VF-Mode Operation

Fig. 6 shows the SPWM modulation scheme for the VF mode of operation. In this case, the inverter's modulation index and phase angle can both be adjusted independently from the rectifiers. In order to satisfy the switching constraint discussed earlier, the sum of the two modulation indexes *mr* and *mi* of the rectifier and inverter must not exceed 1. For matching the input and output ratings, we limit both of their maximums to 0.5. It can be observed from the figure that both the rectifier and inverter's modulating waves can only be adjusted within half of the carrier's magnitude (which represents the dc voltage); therefore, the dc voltage *vd* of the converter is twice as high as the rated dc voltage of a B2B 2L-VSC with the same ac ratings.

This is different from the situation of the CF mode with identical input and output phases, in which the dc voltage of the converter can be tightly controlled and maintained at around its rated value. It should be pointed out that although the added dc offsets guarantee that the instant value of *vmr* is always higher than that of *vmi*, they are of zero sequence in the three phases and have no

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effect on the input/output ac magnitudes. In fact, if the inverter's modulation index is selected to be higher than the rectifier's, e.g., *mi* = 0.5 and *mr* = 0.2, the fundamental component of the inverter output voltage *vXY* will be higher than that of the rectifier input voltage *vAB* .

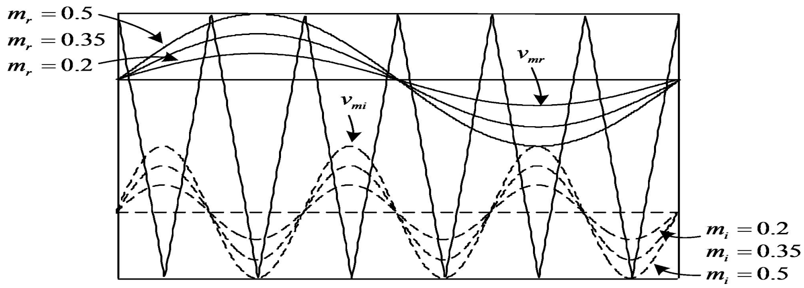

Fig (6) SPWM scheme for VF-mode operation

IV. SIMULATION ANALYSIS

In the simulation, the utility supply is rated at 208 V and 60 Hz with a source inductance of *Ls* = 2.5 mH. The converter driving a three-phase *RL* load of *RL* = 8Ω and *LL* = 2.5 mH, dc capacitor*Cd* is 2350 μF.

A. Proposed Technique with out applying SPWM

The V-I and voltage characteristics of Proposed circuit with out applying spwm is shown in below fig (7) and fig(8)

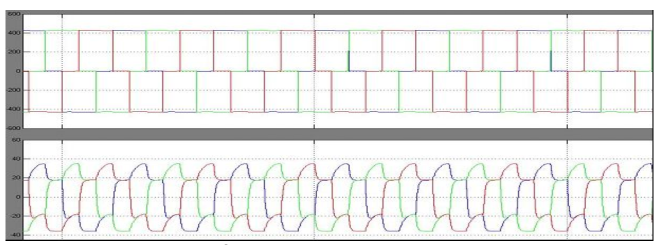

Fig (7) V-I characteristics of proposed technique with out applying SPWM

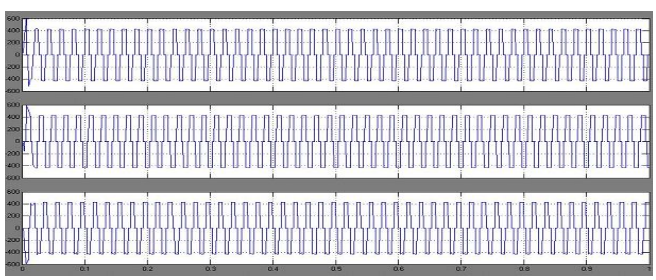

Fig (8) Voltage Characteristics of proposed technique with out applying SPWM

B.Proposed Technique applying SPWM (Constant Frequency)

The Simulated representation of SPWM for nine switch converter of CF mode with rectifier input voltage and inverter output voltage is shown in below fig (9) and fig (10). The specifications are given below

1) Constant Frequency

a) The modulation indexes for the rectifier mr and inverter mi are both set at 0.9

b) The frequency of the dominant switching harmonics is centered around 3240 Hz

c) which is the carrier frequency and also the switching frequency of the converter.

d) The low-order harmonics are negligibly small.

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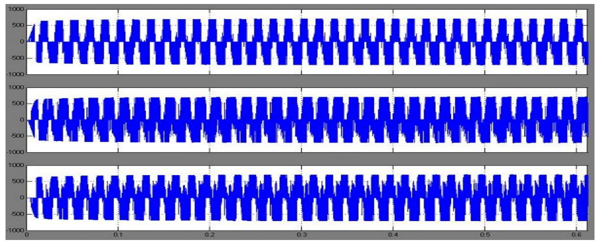

Fig (9) Rectifier Side Input Voltage Wave form

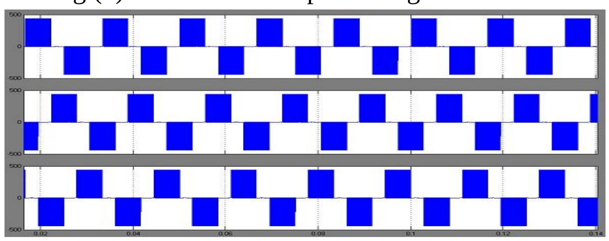

Fig (10) Inverter Side Output Voltage Form

C. Proposed Technique applying SPWM (Variable Frequency)

The Simulated representation of SPWM for nine switch converter of VF mode with rectifier input, inverter output voltages and currents is shown in below fig 11(a), 11(b) and fig 12 (a), 12 (b). The specifications are given below

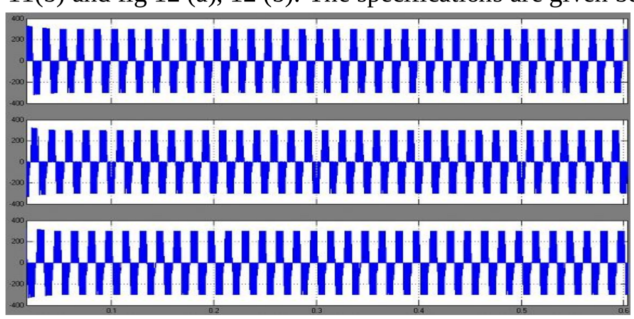

Fig 11(a) Rectifier Input Voltage for VF Mode

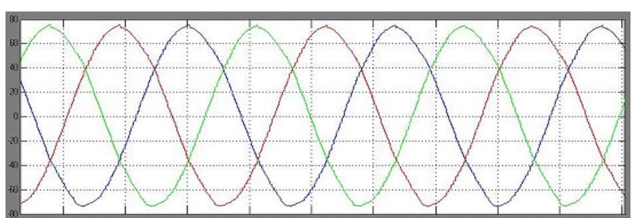

Fig 11(b) Rectifier Input Current for VF Mode

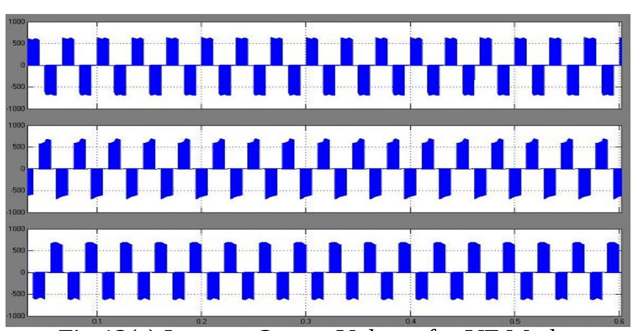

Fig 12(a) Inverter Output Voltage for VF Mode

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D. Variable Frequency:

1) The rectifier operates at 60 Hz while the inverter operates at 30 Hz.
2) The modulation indexes for the rectifier mr and inverter mi are both set at 0.45.
3) The low-order harmonics are negligibly small.

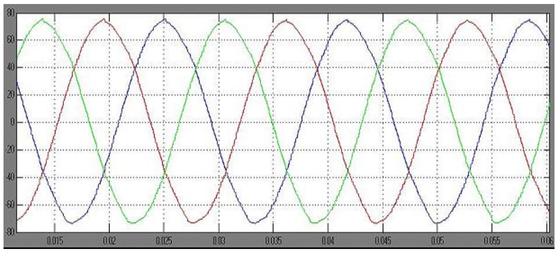

Fig 12(a) Inverter Output Current for VF Mode

The rated DC Voltage of the nine switch converter is shown in below fig (13)

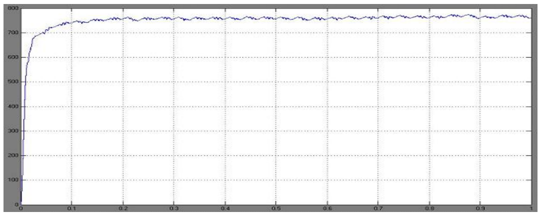

Fig (13) Rated DC voltage

Table III RATED SYSTEM PARAMETERS

	Nine-Switch (CF)	Nine-Switch (VF)	B2B 2L-VSC
Rated Dc Voltage	380V	760V	320V
Rated IGBT Voltage	600V	1200V	600V

V. SIMULATED SPWM FOR NINE-SWITCH CONVERTER WITH MOTOR

A motor connected to the circuit and the values of the supply voltage, source inductance *Ls* , dc capacitor *Cd* , and *RL* load parameters are the same as those given in the simulation.

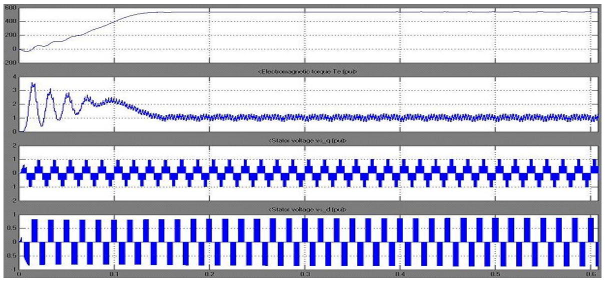

Fig (14) SPWM for nine switch converter with motor

A. Unity Power Factor Operation

The input power factor of the converter can be leading, lagging, or unity. Fig. 15 (a), (b) shows the measured supply phase voltage and line current of the converter with unity power factor operation. During the test, the dc voltage was maintained at 380 V by the rectifier, and the converter modulation index was mr = mi =0.9. It should be noted that the control of the rectifier and inverter is decoupled, and therefore, the inverter operation will not affect the operation of the rectifier. T

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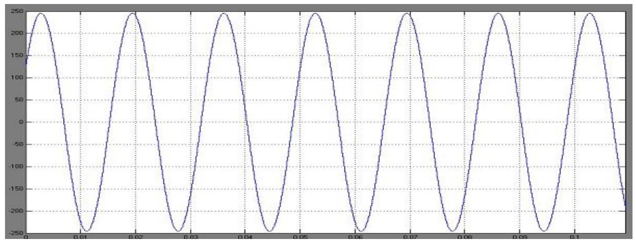


Fig 15(a) Unity input power operation of the rectifier voltage

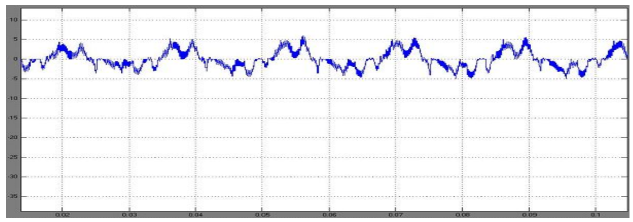
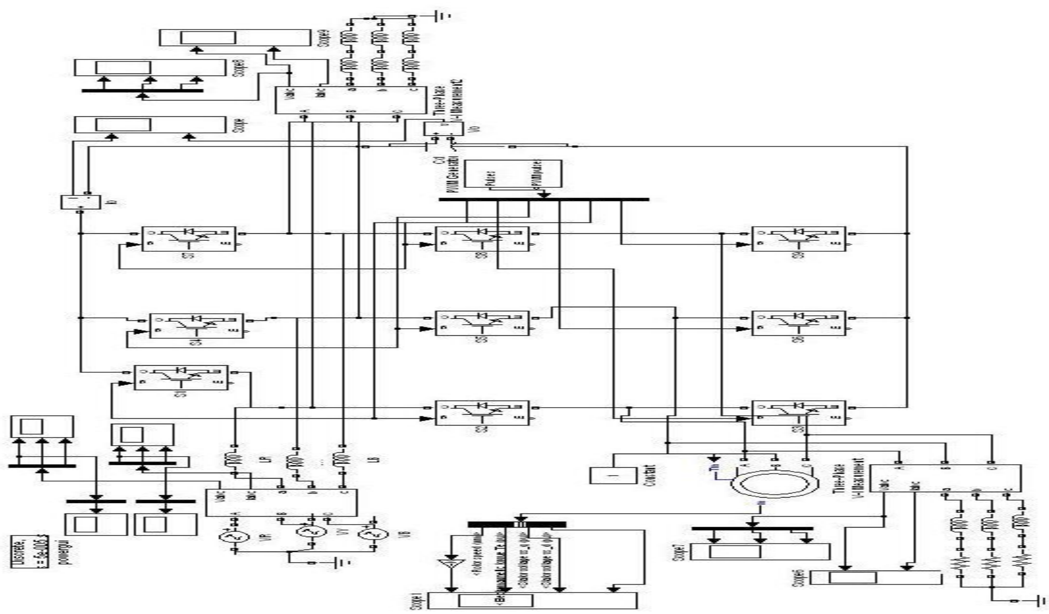


Fig 15(b) Unity input power operation of the rectifier current

B. Total Circuit



VI. CONCLUSION

A novel nine-switch PWM ac/ac converter topology was proposed in this paper. The topology uses only nine IGBT devices for ac to ac conversion through a quasi dc-link circuit. Compared with the conventional back-to-back PWM VSC using 12 switches, the number of switches in the proposed converter is reduced by 33% and 50%, respectively. The proposed converter features sinusoidal inputs and outputs, unity input power factor, and low manufacturing cost. The operating principle of the converter was elaborated, and modulation schemes for constant and variable frequency operations were developed. The proposed converter, while working in CF mode, has an overall higher efficiency than the B2B 2L-VSC at the expense of uneven loss distribution. However, the VF-mode version requires IGBT devices with higher ratings and dissipates significantly higher losses, and thus, is not as attractive as its counterpart.

In this thesis the proposed topology that is carrier based sinusoidal pwm for the nine switch converter simulated using Matlab/Simulink. In overview, this thesis consists of back to back converter, carrier based for the nine switch converter without pwm, carrier based sinusoidal pwm for the nine switch converter with constant frequency, carrier based sinusoidal pwm for the nine

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switch converter with variable frequency, and carrier based sinusoidal pwm for the nine switch converter with motor. The basic circuit representation using Matlab with voltage, current as well as THD wave forms are analyzed.

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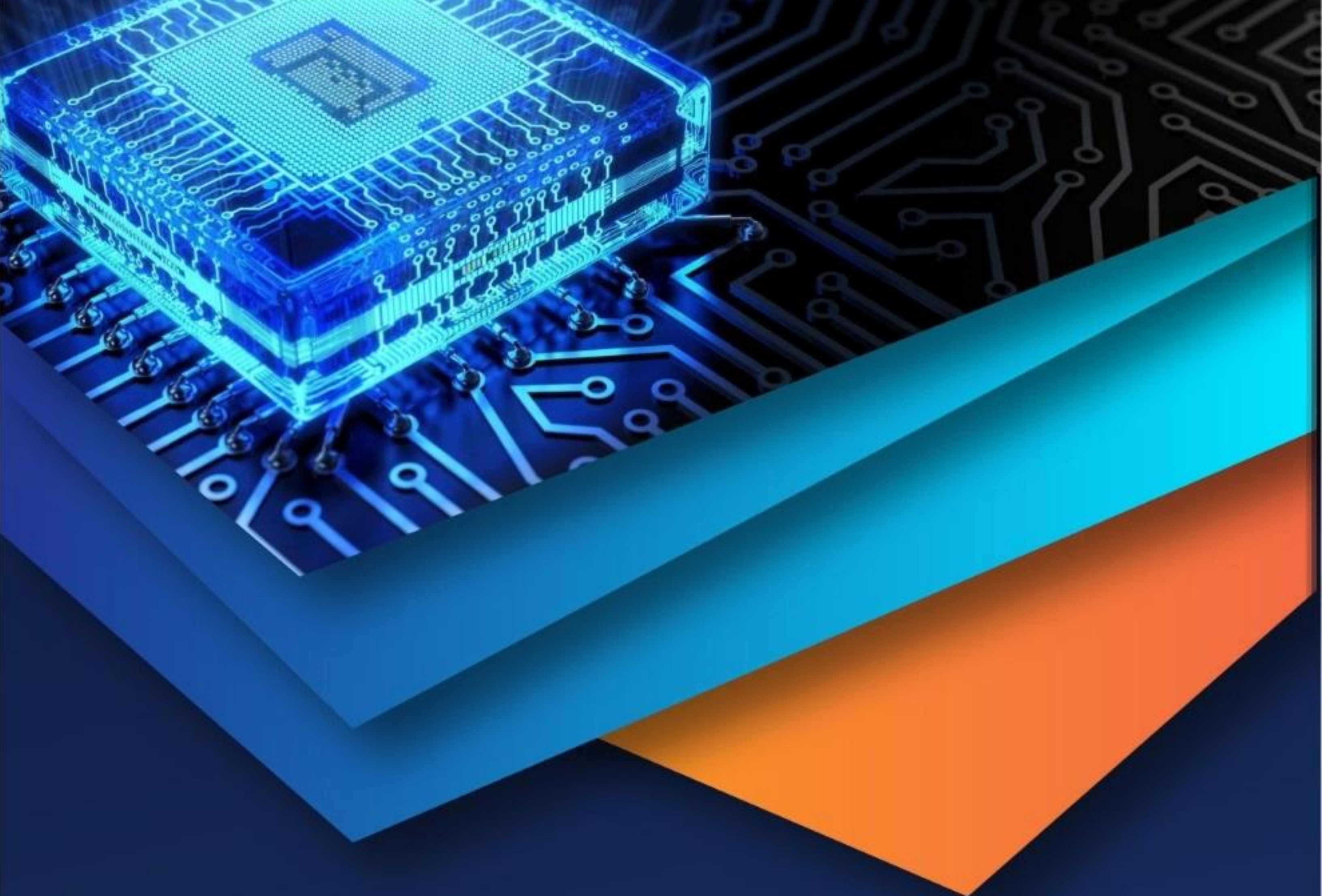

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