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AN IMPROVED HIGH PERFORMANCE THREE PHASE AC-DC BOOST CONVERTER WITH INPUT POWER FACTOR CORRECTION

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Abstract

A three-phase 3-level unidirectional AC/DC converter is proposed to achieve almost unity power factor and reduction of harmonics distortion. A power factor corrector using the hysteresis current control technique is presented to improve the power quality at the rectifier side. A high-power-factor rectifier based on a neutral point switch clamped scheme is presented. A control scheme for the proposed rectifier is propounded to draw a sinusoidal line current with nearly unity power factor, achieve balanced neutral point voltage and regulate the DC bus voltage. A hysteresis current control scheme is used to track the line current in phase with the mains voltage. The line current command is derived from a voltage controller and a phase-locked loop circuit. A capacitor voltage compensator is employed in the proposed control algorithm to achieve the balanced neutral point voltage. The effectiveness and validity of the proposed control strategy is verified through computer simulation results. The simulation result reveals that the proposed control technique offers considerable improvement in Power factor and reduction in total harmonic distortion.

1. Introduction

In the present scenario, there have been lots of developments in the field of power electronics by shaping the utility-supplied voltages by means of power semiconductor devices. Often electronic equipment is supplied by 50/60 Hz utility power and more than 50% of power is processed through some kind of power converters. Conventionally, most of the power conversion equipment employs diode rectifiers or thyristor rectifiers to convert AC voltage to DC voltage before processing it. Phase-controlled rectifiers are widely utilized in the front-end converter for both uncontrollable and controllable DC-bus voltage in industrial and commercial applications. Low power factor and non-sinusoidal line currents are drawn from the AC source owing to large electrolytic capacitor used on the DC link. Power pollution owing to the use of power converters results in serious power-quality problems in transmission and distribution systems. Thus, international standards such as IEC 1000-3-2 are defined [1] to restrict the harmonic contents on the AC-source current. Power pollutants such as reactive power and current harmonics result in line voltage distortion, heating of the transformer core and electrical machines and increased losses in the transmission and distribution line.

In the single-phase voltage-doubler boost rectifiers with one, two, three or four switches were used to achieve power factor correction and DC-bus voltage regulation [2]. The DC bus voltage is twice the peak voltage mains. Switched mode rectifiers with three or four rectifier legs can achieve high-power factor and low current harmonics in the three-phase three-wire or four-wire systems. Six or eight power switches are used in the three-leg or four-leg converter [3–7] to generate bipolar PWM waveforms on the AC terminal. If the bidirectional power flow is not necessary in the application system, switched-mode rectifiers are not a good choice for the large number of power switches. Multilevel rectifiers and inverters have been proposed [8–12] for high-power and medium-voltage applications because they provide advantages such as the low voltage rating of power semiconductors and low voltage harmonics.

Power factor corrected (PFC) converters are an important area of study and research in the Power Electronics field. The proposed AC-DC converters provide stable DC voltage at the output with high input power factor. This ability makes PFC converters are extremely attractive choice for offline power supplies and other AC-DC for power conversion applications because of increasing concerns about various power quality regulations and standards. These converters cater to the unique requirements of a large number of applications. Because of the standards and the problems related to the distorted line current, power supply manufacturers most probably have to equip their products with power factor correction (PFC) circuits.

2. AC-DC Conversion

AC to DC rectifiers usually interface with the mains. These devices convert the sinusoidal line voltage to a dc voltage. It is a well-known fact that the input current of a SMPS tends to have a non-sinusoidal, distorted waveform. The distorted line current of a power converter is composed of the line frequency component and higher frequency harmonic components of the current. It should be noted that only the line frequency component of the current is carrying power when voltage is sinusoidal. As use of energy is growing, the requirements for the quality of the supplied electrical energy are becoming stricter. This means that power electronic converters are used to convert the input voltage to a precisely regulated dc voltage.

2.1 Circuit Configuration and Operating Principle

Conventional 3-level AC-DC converters are based on neutral-point clamped, flying capacitor and series connections of H-bridge topologies. A three-level neutral-point diode-clamped converter needs four active switches and two clamping diodes in each converter leg to achieve power factor correction. A three-level converter with flying capacitor topology needs four active switches and one flying capacitor to draw a sinusoidal line current from the utility system.

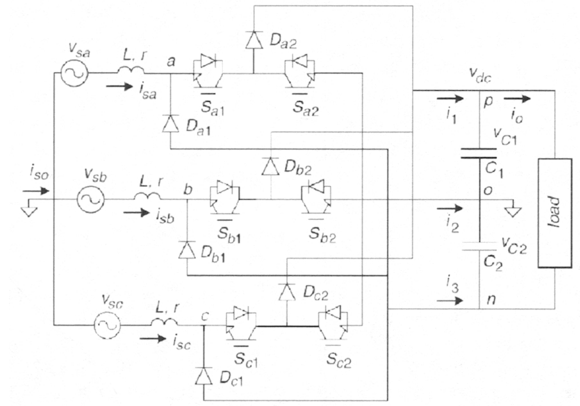

Fig. 1. Three-Phase Circuit Configuration

Fig. 1 shows the proposed three-phase unidirectional power flow rectifier to draw a sinusoidal line current with almost unity power factor and maintain the DC-bus voltage constant. There are a boost inductor L, two power diodes Da_1 and Da_2, two DC-bus capacitors C1 andC2, and two active switches Sa_1 and Sa_2 in the proposed converter. The voltage stress of switch Sa_2 and diode Da_2 is equal to half the DC-bus voltage and the voltage stress of switch Sa_1 and diode Da_1 is equal to the DC-bus voltage. No clamping capacitor or diode is needed in the proposed Single-phase converter. A unipolar PWM voltage waveform is generated on the voltage V_{ao}.

2.2 Principle of Operation

There are two independent active switches in the proposed converter leg. Unipolar PWM voltage waveforms can be generated on the AC terminal to neutral-point voltages. The following assumptions are made in the proposed converter.

1. The power switches are ideal.
2. The supply voltage is constant during one switching period.
3. $S_{xy} = 1$ (or 0) if active switch S_{xy} is turned on (or off), $x = a \sim c, y = 1 \sim 2$.
4. The capacitor voltages on the DC side are equal ($V_{c1}=V_{c2}=V_{dc}/2$).

2.2.1 Operating State 1

Fig. 2 shows the equivalent circuit of the first operating state. In this state, positive line current flows through the body diode of active switch Sa1 and diode Da2 to charge capacitor C1. The AC-side voltage v_{ao} equals vdc/2.

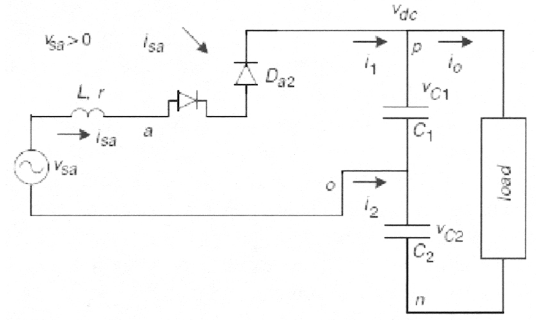

Fig. 2. Equivalent Circuit for operating state 1

$$v_{ao} = v_{dc}/2 \qquad (1)$$

The line current i_{sa} is linearly decreasing in this state because the boost inductor voltage is negative.

$$v_L = v_{Sa} - v_{dc}/2 < 0 \qquad (2)$$

2.2.2 Operating State 2

The line current flows through the body diode of active switch S_{a1} and active switch S_{a2}. The AC-side voltage v_{ao} equals 0.

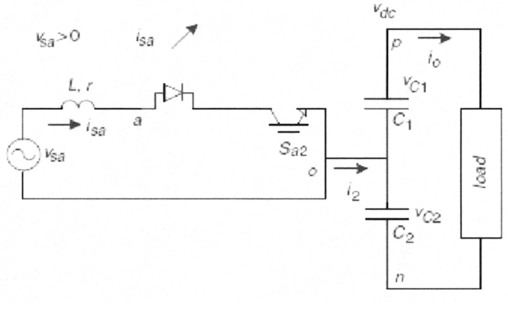

Fig. 3. Equivalent Circuit for operating state 2

The boost inductor voltage equals v_{sa}. The line current i_{sa} is linearly increasing if the mains voltage v_{sa} is positive.

2.2.3 Operating State 3

The equivalent circuit of the third operating state is shown in Fig. 4.The negative line current flows through switch Sa1 and the body diode of switch Sa2 to obtain AC-side voltage v_{ao}=0.

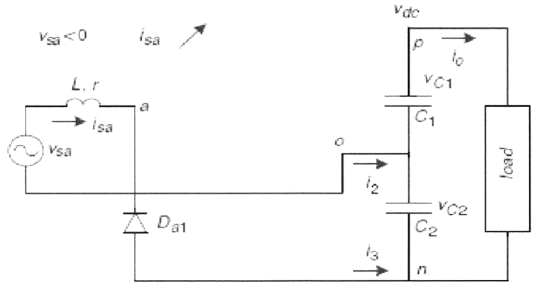

Fig. 4. Equivalent Circuit for operating state 3

The line current is linearly decreasing because, $v_L = v_S < 0$.

2.2.4 Operating State 4

The equivalent circuit of the fourth operating state is given in Fig. 5.

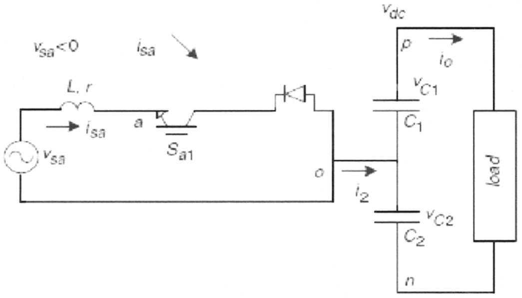

Fig. 5 Equivalent Circuit for operating state 4

The line current flows through capacitor C2 and Da1 to generate AC terminal voltage v_{ao}=v_{C2}.The negative line current will charge capacitor C2. The boost inductor voltage equals $v_{Sa} + v_{c2} > 0$ such that the line current is linearly increasing. In the state 4 only one diode Da1 is conducting as shown in Figure 5.

Based on this analysis of four operating states in each converter leg, two operating states can be selected in each half cycle of mains voltage to control the line current with almost unity power factor. During the positive line current the states 1 and 2 are used to generate high voltage level (v_{dc}/2) and low voltage level (0) on the voltage v_{ao}. During the negative line current the states 3 and 4 are selected to generate voltage levels 0 (high voltage level) and -v_{dc}/2 (low voltage level) on the AC terminal voltage respectively.

During each half cycle of mains voltage, the high voltage level on the AC side is used to decrease the line current and a low voltage level is adopted to increase line current. The same analysis of phase-b and phase-c can be achieved according to the same analysis.

2.2.5 Equivalent Circuit

The system behavior of the proposed AC/DC converter can be expressed as,

$$\frac{d}{dt}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \\ v_{c1} \\ v_{c2} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 & 0 & 0 & 0 \\ 0 & \frac{-r}{L} & 0 & 0 & 0 \\ 0 & 0 & \frac{-r}{L} & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{Rc_1} & \frac{-1}{Rc_1} \\ 0 & 0 & 0 & \frac{-1}{Rc_2} & \frac{-1}{Rc_2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \\ v_{c1} \\ v_{c2} \end{bmatrix} + \begin{bmatrix} \frac{v_{sa} - v_{ao}}{L} \\ \frac{v_{sb} - v_{bo}}{L} \\ \frac{v_{sc} - v_{co}}{L} \\ \frac{i_1}{c_1} \\ -\frac{i_3}{c_2} \end{bmatrix} \quad \text{-(3)}$$

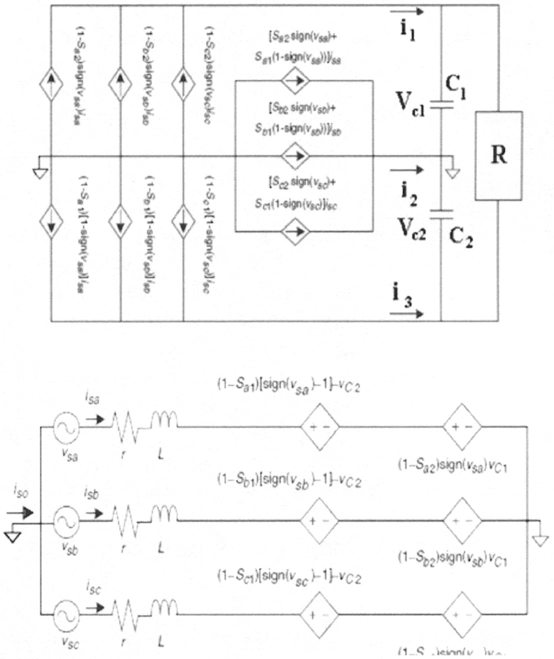

Fig. 6 Equivalent circuit for proposed AC-DC Converter

where v_{ao},v_{bo} and v_{co} are AC terminal to neutral-point voltages and i_1 and i_3 are DC-side currents.

Based on the on and off states of the active switches in the proposed converter the DC-side currents and AC terminal voltages can be expressed as,

$$v_{ao} = (1-S_{a2})\text{sign}(v_{sa})v_{c1} - (1-S_{a1})[1-\text{sign}(v_{sa})]v_{c2} \quad -(4)$$
$$v_{bo} = (1-S_{b2})\text{sign}(v_{sb})v_{c1} - (1-S_{b1})[1-\text{sign}(v_{sb})]v_{c2} \quad -(5)$$
$$v_{co} = (1-S_{c2})\text{sign}(v_{sc})v_{c1} - (1-S_{c1})[1-\text{sign}(v_{sc})]v_{c2} \quad -(6)$$

The DC Side currents i_1 and i_3 are,

$$i_1 = (1-S_{a2})\text{sign}(v_{sa})i_{sa} + (1-S_{b2})\text{sign}(v_{sb}) i_{sb} + (1-S_{c2})\text{sign}(v_{sc})i_{sc} \quad -(7)$$

$$i_3 = (1-S_{a1})[1-\text{sign}(v_{sa})]i_{sa} + (1-S_{b1})[1-\text{sign}(v_{sb})] i_{sb} + (1-S_{c1})[1-\text{sign}(v_{sc})]\, i_{sc} \quad -(8)$$

where,

$$\text{sign}(v_{sx}) = \begin{cases} 1, v_{sx} > 0 \\ 0, v_{sx} < 0 \end{cases}, x = a,b,c$$

a ,b and c are the legs of the three phase ac-dc converter.
Based on (3)–(8) the system equations of the proposed converter can be rewritten as,

$$\begin{bmatrix} \frac{di_{sa}}{dt} \\ \frac{di_{sb}}{dt} \\ \frac{di_{sc}}{dt} \\ \frac{dv_{c1}}{dt} \\ \frac{dv_{c2}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 & 0 & -\frac{1-S_{a2}}{L}\text{sign}(v_{sa}) & \frac{1-S_{a1}}{L}[1-\text{sign}(v_{sa})] \\ 0 & \frac{-r}{L} & 0 & -\frac{1-S_{b2}}{L}\text{sign}(v_{sb}) & \frac{1-S_{b1}}{L}[1-\text{sign}(v_{sb})] \\ 0 & 0 & \frac{-r}{L} & -\frac{1-S_{c2}}{L}\text{sign}(v_{sc}) & \frac{1-S_{c1}}{L}[1-\text{sign}(v_{sc})] \\ \frac{1-S_{a2}}{C_1}.\text{sign}(v_{sa}) & \frac{1-S_{b2}}{C_1}.\text{sign}(v_{sb}) & \frac{1-S_{c2}}{C_1}.\text{sign}(v_{sc}) & -\frac{1}{R_{C1}} & -\frac{1}{R_{C1}} \\ -\frac{1-S_{a1}}{C_2}[1-\text{sign}(v_{sa})] & -\frac{1-S_{b1}}{C_2}[1-\text{sign}(v_{sb})] & -\frac{1-S_{c1}}{C_2}[1-\text{sign}(v_{sc})] & -\frac{1}{R_{C2}} & -\frac{1}{R_{C2}} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \\ v_{c1} \\ v_{c2} \end{bmatrix} + \begin{bmatrix} \frac{v_{sa}}{L} \\ \frac{v_{sb}}{L} \\ \frac{v_{sc}}{L} \\ 0 \\ 0 \end{bmatrix} -(9)$$

3. Control Scheme

The objective of the control scheme of the boost converters is to regulate the power flow ensuring tight output voltage regulation as well as unity input power factor. The control structure shown in Fig. 7 is the most extensively used control scheme for these converters and essentially similar control philosophy is applied to all the other topologies of boost converter. Proportional integral voltage controller and hysteresis based current controller are used in the proposed control scheme.

Two control loops are used in the proposed three phase high power factor AC-DC converter to achieve unity power are,

1. Hysteresis Band PWM current control
2. Proportional integral Voltage control.

The main functions of the proposed control scheme are,

1. Power-factor correction.
2. Current-harmonic reduction.
3. DC-link voltage regulation.
4. Neutral point Voltage Compensation

The internal high-bandwidth current control system is designed to achieve a short settling time and the outer low-bandwidth voltage control system is designed to be somewhat slower to maintain the DC bus voltage constant. Fig. 7 shows the Control scheme for proposed converter.

In the inner loop a carrier based current controller is used to track the reference line current and in the outer loop control a classical proportional-integral controller was used to balance the AC-side input power and DC-side output power so that the DC-side capacitor voltage can be a constant value. If the DC-side voltage is lower than the reference voltage, the output value of the PI controller will increase the amplitude of the line current command to increase the input AC power for compensation of DC-bus voltage drop. If the DC-bus voltage is higher than the reference voltage, the output value of PI controller will decrease the input AC power for compensation the DC side voltage

3.1 Proportional Integral Voltage Controller

To achieve the power balance between the AC-source side and DC-load side of the AC/DC converter, a proportional integral voltage controller is used to obtain the amplitude of the line current commands. The proportional plus integral (PI) is probably the most commonly used controller in the industry that arguably the PI controller is the simplest practical controller that provides integral action which required in many process control applications for asymptotic tracking of set point commands .

The amplitude of line current command is expressed as,

$$I_S = K_P \Delta v_{dc} + K_i \int \Delta v_{dc} dt \quad -(10)$$

Where K_p and K_i are proportional and integral gains respectively $\Delta v_{dc} = v^*_{dc} - v_{dc}$ is the DC-bus voltage error, v^*dc is the voltage command and v_{dc} is the measured DC-side voltage. The parameters of voltage controller can be selected from the given system transfer function and the designed damping factor and natural angular frequency of the voltage response. The voltage error between the voltage command and the measured DC-bus voltage can be reduced by adjusting the amplitude of the line currents. To achieve unity power factor at the input side of the converter, a phase-locked loop circuit generates three unit sinusoidal waves with 120° phase shift.

These balanced sinusoidal waves are synchronized to three phase source voltages and expressed as,

$$\begin{vmatrix} i_{sa}(t) \\ i_{sb}(t) \\ i_{sc}(t) \end{vmatrix} = I_s \begin{vmatrix} e_a(t) \\ e_b(t) \\ e_c(t) \end{vmatrix} = \begin{vmatrix} I_s \sin \omega t \\ I_s \sin(\omega t - 2\pi/3) \\ I_s \sin(\omega t + 2\pi/3) \end{vmatrix} \quad -(11)$$

3.2 Hysteresis Band PWM Control

Hysteresis control shown in Fig.8 is also called tolerance-band or dead-band control. This controller type recognizes that voltage source converters can only have seven different output voltages. This leads naturally to a limit-cycle oscillation in the line current vector, which by the controller is kept inside a small area of some shape in the current vector space.

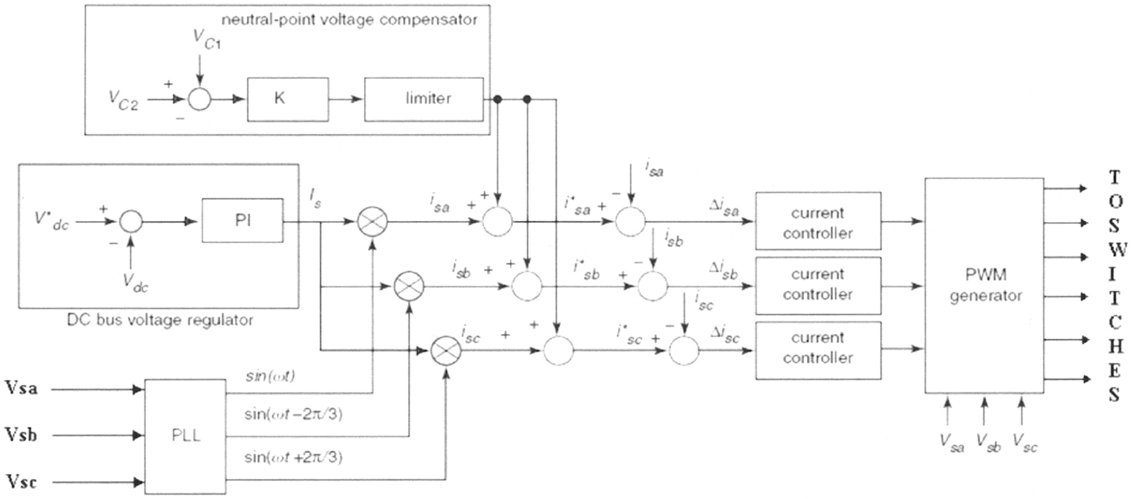

Fig. 7. Control Scheme for Proposed Converter.

The advantage is a known deviation from the current reference, but the switching pattern is more or less random, making it hard to predict converter losses.

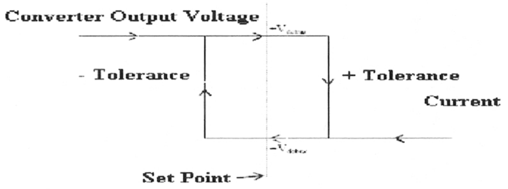

Fig. 8.Hysteresis Band

3.3 Neutral point voltage compensation

In the proposed control scheme, a neutral-point voltage compensator is used to balance the neutral-point voltage. To balance the neutral-point voltage under load variation a voltage compensator is used in the control scheme to compensate the neutral-point voltage. This additional current for neutral-point balance is given as,

$$I_{npc} = K(Vc_2 - Vc_1) \qquad -(12)$$

where v_{c1} and v_{c2} are average voltages across capacitors C1and C2, respectively, and K is a small gain of the neutral point voltage compensator. To avoid a large DC term in the line current command due to unbalance neutral-point voltage, a limiter can be placed after the neutral-point voltage compensator. The resultant line-current commands are illustrated as,

$$= \begin{vmatrix} I_s \sin(\omega t) + I_{npc} \\ I_s \sin(\omega t - 2\pi /3) + I_{npc} \\ I_s \sin(\omega t + 2\pi /3) + I_{npc} \end{vmatrix} \qquad -(13)$$

3.4 PWM Technique

A hysteresis based PWM technique is and used to generate appropriate switching signals for the power switches.Hysteresis current comparators track the input-current references and the PWM generator obtains the switching signals for the power switches. The line-current errors between the measured line currents and the current commands are sent to the hysteresis comparators to generate the proper PWM signals for active switches.

Fig. 9 shows the source voltage, line current, PWM signals and AC-side voltage for each converter leg where *x* =a, b, c.

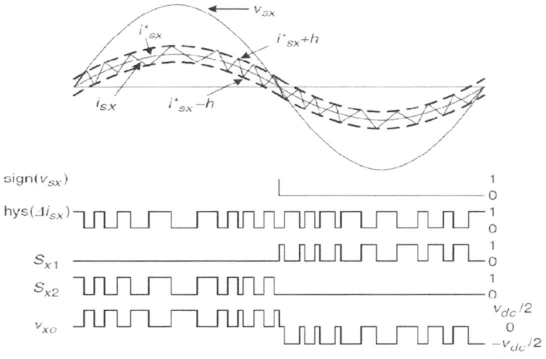

Fig. 9. PWM Generation

Based on the operation states explained earlier there are three voltage levels $v_{dc}/2$, 0 and $-v_{dc}/2$ generated in each converter leg. During the positive half cycle, high voltage levels $v_{dc}/2$ and low voltage level 0 are generated on the AC terminal to neutral-point voltage. During the negative half cycle, high voltage level 0and low voltage level $-v_{dc}/2$ are generated on the AC side to control the line current. The high voltage level is adopted to decrease the line current and low voltage level is used to increase the line current.

Fig. 10 shows the relationship between the measured phase voltage, hysteresis current comparator and the PWM signals for active switches in each converter leg.

The PWM signals of active power switch at the converter leg A can be expressed as,

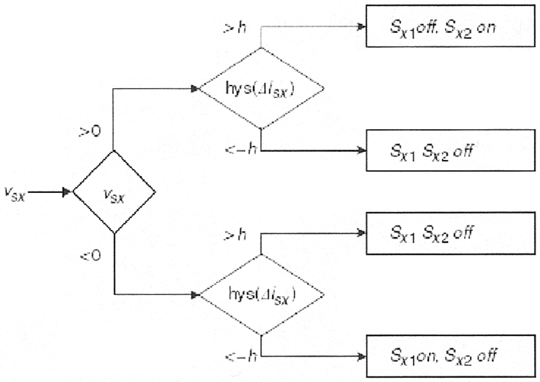

Fig. 10 Control Strategy for each Converter Leg

$$S_{a1} = \overline{\mathrm{Sign}(v_{sa})}\ .\ \overline{\mathrm{hys}(\Delta i_{sa})}$$

$$S_{a2} = \overline{\mathrm{Sign}(v_{sa})}\ .\ \overline{\mathrm{hys}(\Delta i_{sa})}$$

The PWM signals of active power switch at the converter leg B can be expressed as,

$$S_{b1} = \overline{\mathrm{Sign}(v_{sb})}\ .\ \overline{\mathrm{hys}(\Delta i_{sb})} \qquad S_{b2} = \overline{\mathrm{Sign}(v_{sb})}\ .\ \overline{\mathrm{hys}(\Delta i_{sb})}$$

The PWM signals of active power switch at the converter leg C can be expressed as,

$$S_{c1} = \overline{\mathrm{Sign}(v_{sc})}\ .\ \overline{\mathrm{hys}(\Delta i_{sc})} \qquad S_{c2} = \overline{\mathrm{Sign}(v_{sc})}\ .\ \overline{\mathrm{hys}(\Delta i_{sc})}$$

where,

$$\mathrm{hys}(\Delta i_{sx}) = \begin{cases} 1, \text{if } \Delta i_{sx} > h \\ 0, \text{if } \Delta i_{sx} < -h \end{cases}$$

$$\mathrm{Sign}(v_{sx}) = \begin{cases} 1, \text{if } v_{sx} > 0 \\ 0, \text{if } v_{sx} < 0 \end{cases}$$

$\Delta i_{sx} = i^{*}_{sx} - i_{sx}$ gives the difference between actual and reference current.

where i_{sx} is the actual current

i^{*}_{sx} is the reference current

$\overline{\mathrm{Sign}(v_{sa})} = 1 - \mathrm{Sign}(v_{sa})$ x= a, b, c, where a,b and c are converter legs.

4. Simulation Results

Three-phase unidirectional AC/DC converter with power factor correction was verified through simulation. A computer software package based on MATLAB simulated the system behaviour.

Input voltage	220 r.m.s
Source inductance	3mH
Output capacitance	2200μF
Output voltage	400V DC
Switching frequency	7.5 kHz
Line current T.H.D	<5%
Frequency	50HZ

The Various Simulated Waveforms of three phase AC-DC converter for full load are shown below

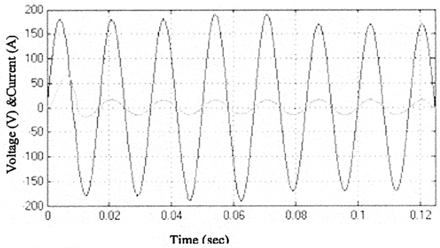

Fig. 11. Simulation output of Line Voltage and Line Current at Converter Leg A

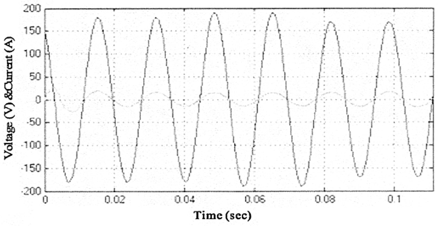

Fig. 12 Simulation output of Line Voltage and Line Current at Converter Leg B

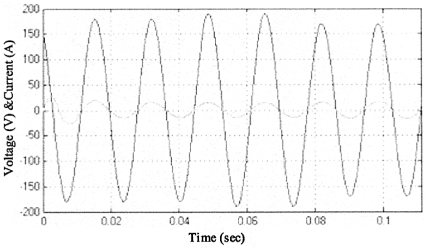

Fig. 13. Simulation output of Line Voltage and Line Current at Converter Leg C

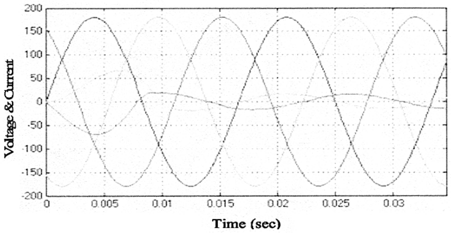

Fig. 14. Simulation output of Three Phase Line Voltage and Line Current

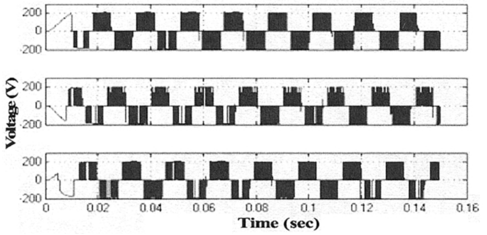

Figure . 15 Simulation output of Phase Voltages

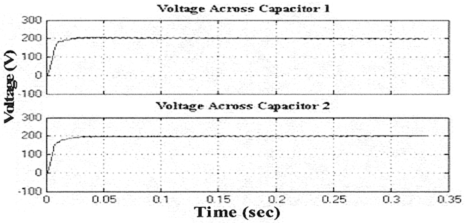

Fig.16. Simulation output of Capacitor Voltage Vc1 and Vc2

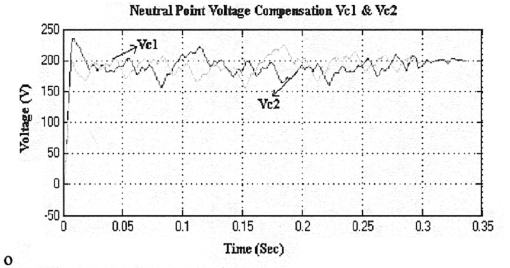

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Fig.17. Neutral Point Voltage Compensation under load Variation

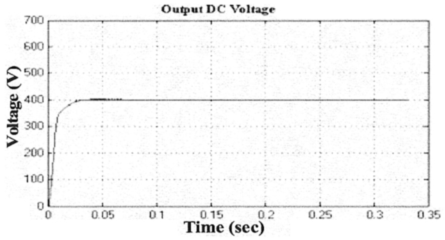

Fig. 18 Simulation output of DC output Voltage at Full Load.

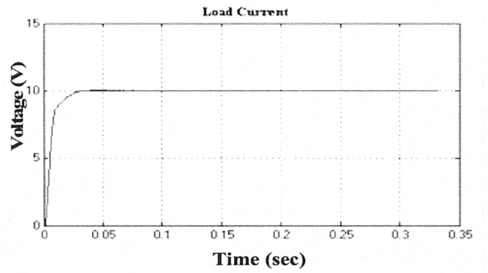

Fig. 19 Simulation output of Load Current

TABLE 1

PERFORMANCE COMPARISON BY VARYING SUPPLY VOLTAGE
AT CONSTANT LOAD OF 40 OHMS

VS (V)	Pin (W)	Pout (W)	THD	Power Factor
180	4323.52	3998.00	0.05126	0.999
170	4089.20	4000.00	0.05357	0.999
160	4109.39	4006.99	0.05867	0.998
190	4069.29	3998.40	0.04404	0.999
200	4052.30	3995.60	0.02894	0.997

TABLE 2

PERFORMANCE COMPARISON BY VARYING LOAD
FOR CONSTANT SUPPLY VOLTAGE OF 180 V

R ohm	Pin (W)	Pout (W)	THD	Power Factor
40	4071.67	3992.00	0.04632	0.999
50	3276.03	3202.40	0.05236	0.999
60	2754.38	2670.62	0.10460	0.999
90	2004.54	1777.15	0.4083	0.999
100	1902.27	1600.00	0.4553	0.999

Table 1 and Table 2 shows the performance comparisons of the three phase AC-DC converter by varying the supply voltage and load respectively. It's assumed that the power factor is closer to unity and total harmonic distortion is also reduced (less than 5%) irrespective of the load and line voltage variations

5. Conclusions

The control scheme for the proposed three phase AC-DC converter has been discussed. The PI controller is used to regulate the DC link voltage in the outer control loop to maintain the DC bus voltage constant. The output signal of the DC-link voltage controller is multiplied by a unit sinusoidal wave in phase with supply voltage to obtain the reference line current. The current error between the reference line current and measured line current is given to the current controller in the inner control loop to track the reference line current. The simulated results are discussed above

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