

A NINE-SWITCH AC/AC CONVERTER WITH REDUCED SWITCHING FREQUENCY

M.Saida Rao

Post-Graduate Student

Department of Electrical and Electronics Engineering
Vignan Institute of Technology and Science, Vignan Hills
Deshmukhi Village, Pochampally Mandal, Nalgonda District-508284

L Bhanu Ganesh

Assistant Professor

Department of Electrical and Electronics Engineering
Vignan Institute of Technology and Science, Vignan Hills
Deshmukhi Village, Pochampally Mandal, Nalgonda District-508284

Abstract—This paper proposes a novel three-phase nine-switch ac/ac converter topology. 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; its modulation schemes are discussed. Simulated semiconductor loss analysis and comparison with the back-to-back two-level voltage source converter are presented. Finally, experimental results from a 5-kVA prototype system are provided to verify the validity of the proposed topology.

Key words—AC/AC converter, pulse width modulation (PWM), reduced switch count topology.

I. INTRODUCTION

THREE-PHASE ac/dc/ac and ac/ac converters with variable frequency (VF) and variable voltage operation have found wide applications in the industry. The most popular configuration uses 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 [1]. 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 [2].

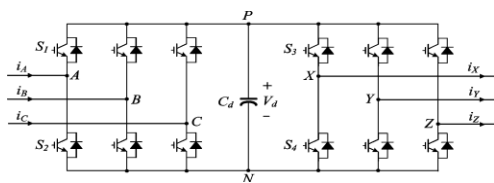


Fig. 1. B2B 2L-VSC

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 first approach reported in [3]–[5] puts two dc capacitors in cascade and takes their midpoint as one of the input–output terminals, whereby an entire phase leg for the rectifier and/or inverter can be saved. It is also possible to reduce the total number of switches, as the second approach suggests [6], [7], by sharing one of the three phase legs between the rectifier and inverter with proper control. In addition, combined use of dc midpoint connection and phase leg sharing has been proposed in [8], where only four legs are needed to perform three-phase ac to ac conversion with bidirectional power flow and power factor control. Although all the earlier references achieve the goal of reducing the number of switches and thus reducing the cost, they unexceptionally have limits or involve complex control due to their unbalanced topological structure. For unidirectional applications, diodes can be used in place of active switches in the rectifier part, such as the VIENNA rectifier [9], three-phase three-switch buck-type

rectifier [10], and three-phase three-switch two-level rectifier. These converters may also be regarded as topologies with a saved number of switches, despite their employment of a large number of diodes.

Unlike VSCs that inevitably require the dc-link stage, the matrix converter 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. However, the conventional matrix converter (CMC) normally requires 18 active switches and its switching scheme is complex. The high semiconductor cost and complex control have made this topology less attractive. Similar to the situation of VSCs, efforts to reduce the number of active switches for a matrix converter have been made in recent publications where a couple of topological variants such as the sparse matrix converter (SMC) were proposed. The SMC provides equivalent functionality to the CMC. It employs 15 switches with the semiconductor cost still higher than that of the B2B 2L-VSC.

In this paper, a novel one-stage three-phase ac/ac converter topology is proposed. Different from all other existing topologies, this converter has only three legs with only nine active switches for bidirectional ac/ac power conversion.

II. NINE-SWITCH CONVERTER TOPOLOGY

Fig. 2 shows the proposed three-phase nine-switch converter topology. 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.

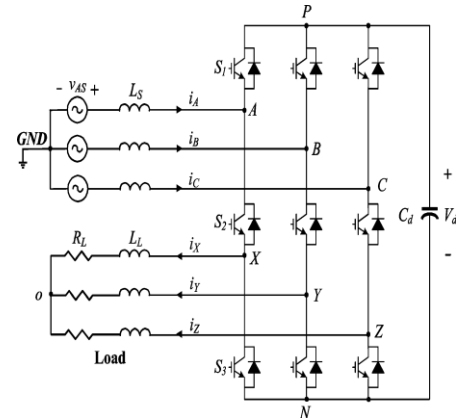


Fig. 2. Proposed nine-switch ac/ac converter with a quasi-dc link.

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.

III. MODULATION SCHEMES

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. 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.

TABLE I
SWITCHING STATES AND
CONVERTER LEG VOLTAGES

(a) 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

(b) Proposed nine-switch converter					
Switching State	S_1	S_2	S_3	v_{AN}	v_{XN}
1	On	On	Off	V_d	V_d
2	Off	On	On	0	0
3	On	Off	On	V_d	0

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. The principles of these methods can all be applied to the nine-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 v_c . 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.

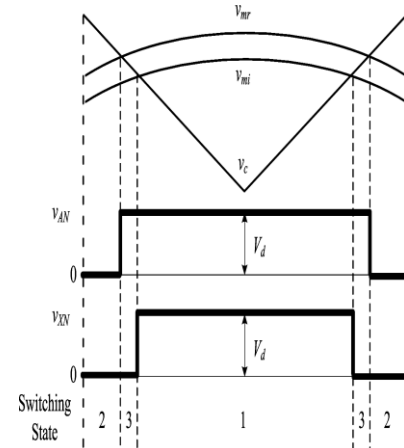


Fig. 3. PWM waveform generation, where switching state 4 of the B2B 2L-VSC is eliminated.

B. Modulation Scheme for CF-Mode Operation

Taking SPWM as an example, Fig. 4 illustrates the modified scheme for CF-mode operation, where mr and mi are the rectifier and inverter modulation indexes (defined as the peak-to-peak magnitude of the sinusoid divided by the peak-to-peak magnitude of the carrier), respectively. 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. 4, both the rectifier and inverter's modulation indexes can simultaneously reach a maximum of unity.

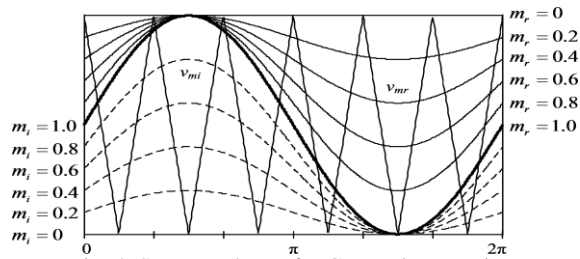


Fig. 4. SPWM scheme for CF-mode operation.

C. Modulation Scheme for VF-Mode Operation

Fig. 5 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 rectifier's. 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.

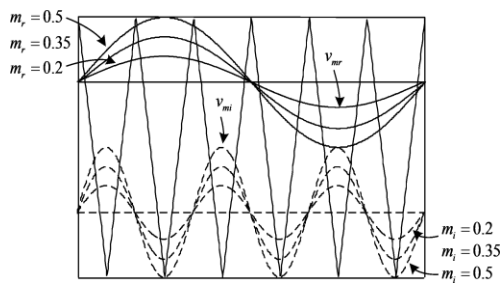


Fig. 5. SPWM scheme for VF-mode operation

It should be pointed out that although the added dc offsets guarantee that the instant value of v_{mr} is always higher than that of v_{mi} , they are of zero sequence in the three phases and have no 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 V_{XY} will be higher than that of the rectifier input voltage V_{AB} .

IV. SIMULATION ANALYSIS

The performance of the proposed nine-switch converter topology is simulated with the Matlab/Simulink software. In the simulation, the utility supply is rated at 208 V and 60 Hz with a source inductance of $L_s = 2.5$ mH. The converter is rated at 5 kVA and is driving a three-phase RL load of $RL = 8\Omega$ and $LL = 2.5$ mH. The dc capacitor Cd is $2350 \mu\text{F}$. SVPWM method is used to modulate the converter for its superior performance over SPWM and higher dc voltage utilization. The rectifier is controlled by a vector control scheme with unity power factor operation. The inverter output voltage is not detected, and therefore is not tightly controlled. The switching frequency of both rectifier and inverter is 3240 Hz. Both CF and VF modes of operation are investigated.

A. CF-Mode Operation

Fig. 6(a) & (b) shows the simulation circuit & waveform of the rectifier input voltage V_{AB} and its harmonic spectrum with the converter operating in the CF mode. The modulation indexes for the rectifier m_r and inverter m_i are both set at 0.9 and the dc voltage is maintained at 320 V. The frequency of the dominant switching harmonics is centered around 3240 Hz, which is the carrier frequency and also the switching frequency of the converter. The low-order harmonics are negligibly small.

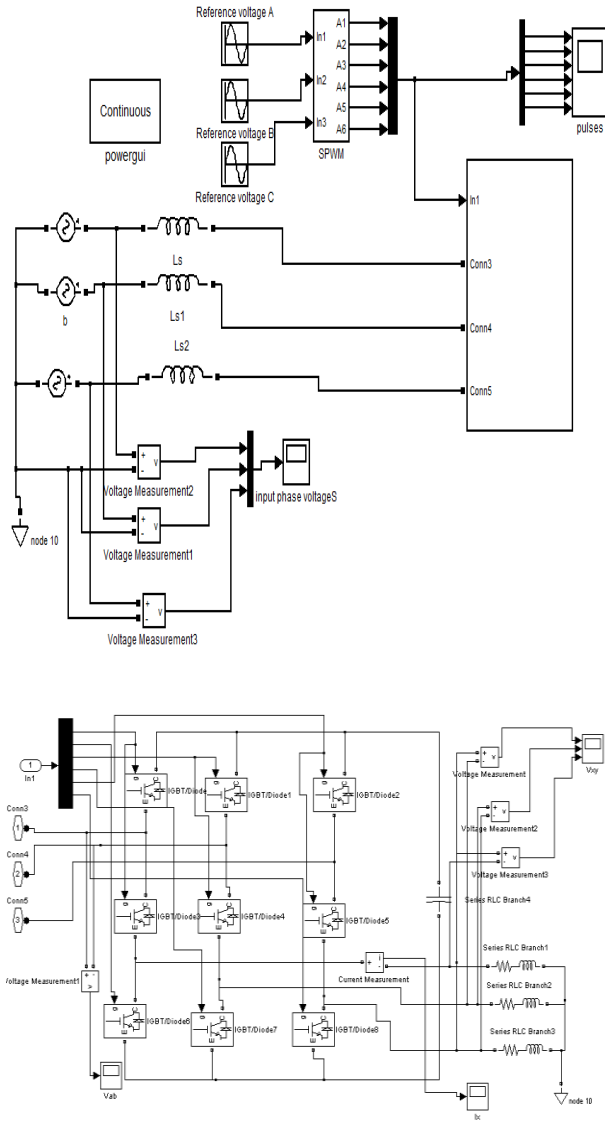
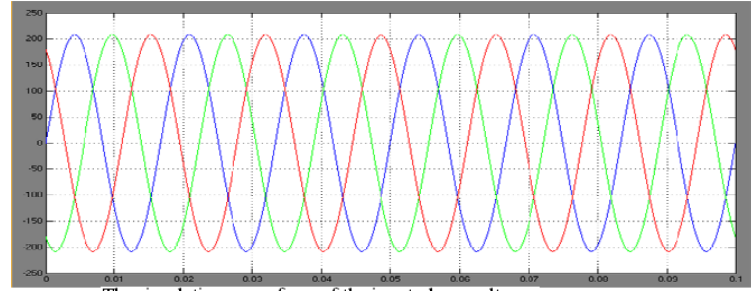
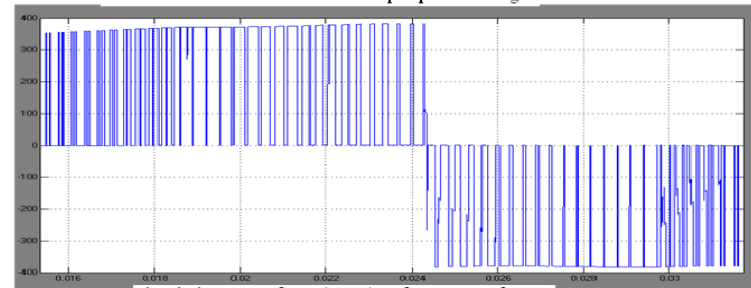


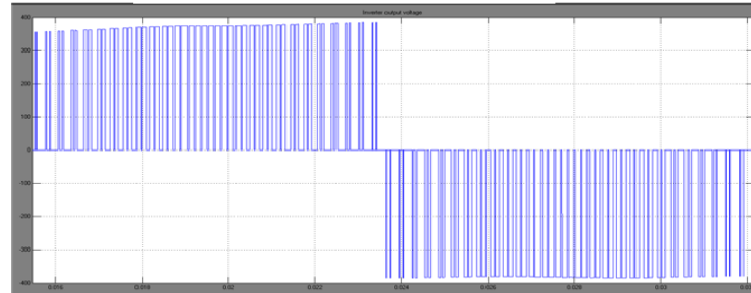
Fig.6 (a). Simulation Circuit & Sub-Circuit



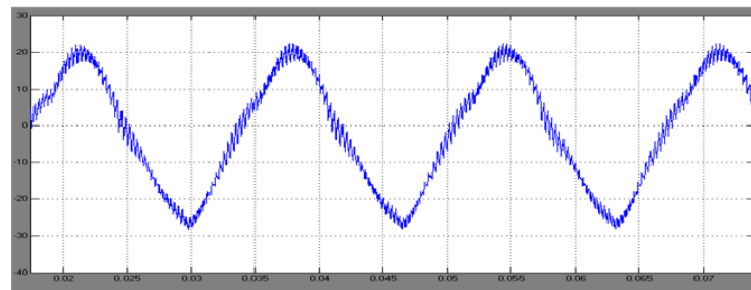
The simulation wave form of the input phase voltages



Simulation wave form (VAB) at frequency of 60Hz



Simulation wave form (Vxy) at frequency of 60Hz



Simulation wave form Ix(A) at frequency of 60HZ

F
i
g

B. VF-Mode Operation

Fig. 7 (a) & (b) shows the simulation circuit & simulated rectifier input and inverter output Waveforms when the converter operates in the VF mode. The rectifier operates at 60 Hz while the

inverter operates at 30 Hz. The modulation indexes for the rectifier and inverter are both 0.45. The figure illustrates that the rectifier and the inverter can operate independently with different fundamental frequencies.

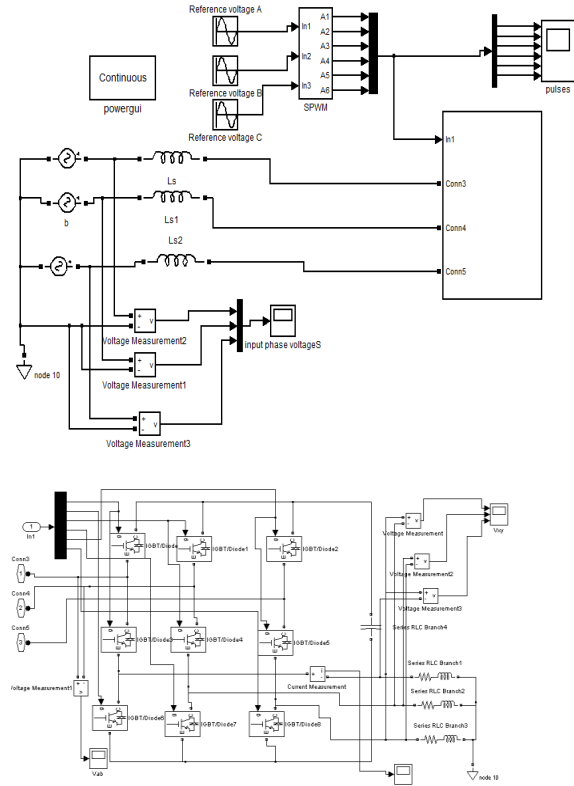
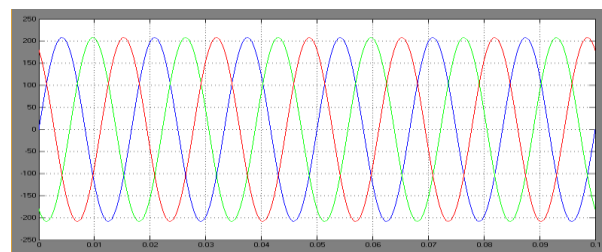


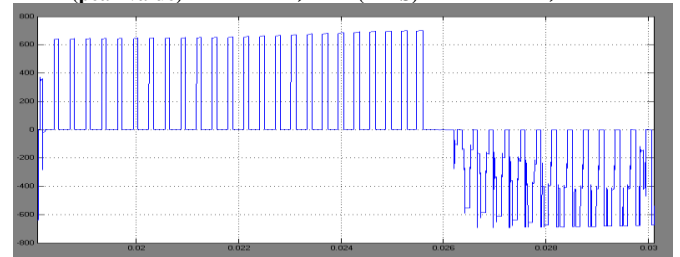
Fig.7(a): Simulation Circuit & Sub-Circuit



The simulation wave form of the input phase voltages

Rectifier input voltage (VF mode)

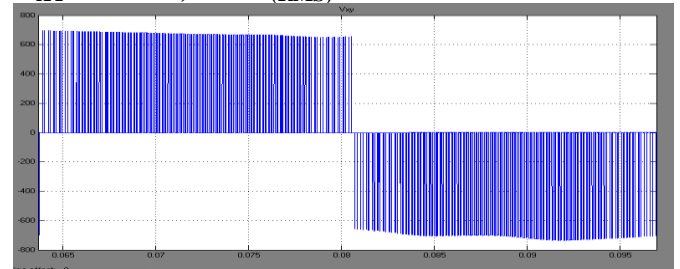
$V_{AB}(\text{peak value})=691.8V, V_{AB(RMS)}=489.17V,$



Simulation wave form (VAB), at frequency of 30HZ

Inverter output voltage waveform (VF-mode operation).

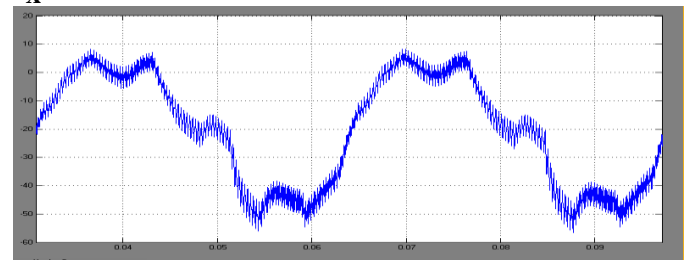
$V_{XY}=691.8V, V_{XY(RMS)}=489.17V$



Simulation wave form (Vxy), at frequency of 30HZ

Inverter output current (VF mode)

$I_X=9.236A$



Simulation wave form Ix (A), at frequency of 30HZ

Fig 7 (b): Simulation waveforms at frequency 30Hz

V. 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 and the matrix converter that uses 18, 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 VF operations were developed. Simulation results including a semiconductor loss analysis and comparison were provided, which reveal that 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.

REFERENCES

1. B. Wu, *High-power Converters and AC Drives*. Piscataway, NJ: IEEE/Wiley, 2006.
2. B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of three-phase improved power quality AC-DC converters," *IEEE Trans. Ind. Electron.*, vol. 51, no. 3, pp. 641-660, Jun. 2004.
3. F. Blaabjerg, S. Freysson, H. H. Hansen, and S. Hansen, "A new optimized space-vector modulation strategy for a component-minimized voltage source inverter," *IEEE Trans. Power Electron.*, vol. 12, no. 4, pp. 704-714, Jul. 1997.
4. R. L. A. Ribeiro, C. B. Jacobina, E. R. C. da Silva, and A. M. N. Lima, "AC/AC converter with four switch three phase structures," in *Proc. IEEE PESC*, 1996, vol. 1, pp. 134-139.
5. K. Gi-Taek and T. A. Lipo, "VSI-PWM rectifier/inverter system with a reduced switch count," *IEEE Trans. Ind. Appl.*, vol. 32, no. 6, pp. 1331-1337, Nov./Dec. 1996.
6. A. Bouscayrol, B. Francois, P. Delarue, and J. Niiranen, "Control implementation of a five-leg AC-AC converter to supply a three-phase induction machine," *IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 107-115, Jan. 2005.
7. C. B. Jacobina, I. S. de Freitas, E. R. C. da Silva, A. M. N. Lima, and R. L. A. Ribeiro, "Reduced switch count DC-link AC-AC five-leg converter," *IEEE Trans. Power Electron.*, vol. 21, no. 5, pp. 1301-1310, Sep. 2006.
8. C. B. Jacobina, I. S. de Freitas, and A. M. N. Lima, "DC-link three-phase to three-phase four-leg converters," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 1953-1961, Aug. 2007.
9. J. Minibock and J. W. Kolar, "Novel concept for mains voltage proportional input current shaping of a VIENNA rectifier eliminating controller multipliers," *IEEE Trans. Ind. Electron.*, vol. 52, no. 1, pp. 162-170, Feb. 2005.
10. T. Nussbaumer, M. Baumann, and J. W. Kolar, "Comprehensive design of a three-phase three-switch buck-type PWM rectifier," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 551-562, Mar. 2007.