New Three Phase Bidirectional Switch Based AC Voltage Controller Topologies

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Abstract—**A new family of three-phase AC voltage controllers has been presented in this paper. The proposed converters consisting of two three-phase modified bidirectional switches have supply and load side neutral connections either directly or indirectly which may be the requirements of three phase AC-AC switched mode voltage controllers in certain applications. Steady state analysis and simulation results are presented in this paper using the Boost topology as an example. Performance of the circuit has been found satisfactory with duty cycle variation. Because the proposed converters employ only two active devices, they can reduce cost and complexity with simple control and improve system reliability.**

Keywords—ac voltage controller; boost converter; pulse width modulation; power quality; switched mode power supply;

I. Introduction

Power utilities deliver AC power at a fixed voltage and frequency. Due to the nature of industrial, commercial, and domestic application requirements of electricity with variable amplitude and/or frequency power conversion is necessary in order to guarantee quality and energy efficient operation of equipment and appliances [1], [2]. The conversion of power may include AC-DC (rectifier), DC-DC (chopper), DC-AC (inverter), and AC-AC at the same (ac voltage controller) or different frequencies (matrix and cycloconverter) [1]-[3]. The AC-AC voltage converter, also known as AC voltage controller, is a kind of power converter that converts a constant voltage and constant frequency AC input supply to a variable voltage AC output delivered to a load through the use of power semiconductor devices. They can be used in light illumination control, industrial heating, power condition and flow control in flexible AC transmission systems, line/bus voltage control for variations in input voltage and load, soft start of AC motors (without v/f control) and their speed control by voltage variation only [4]-[13]. Comprehensive review on single and three phase AC voltage controllers are presented in [14]-[17]. AC voltage converters based on transformers are large and heavy, have sluggish response, include harmonics and need a great number of switches for better regulation [18]. Thyristor based converter topologies give rise to power quality problems and associated effects in supply/load side, machines, transformers, and cables and adversely affect the voltage at the end of common coupling [18], [19]. Bulky and large filters are required for reduction of harmonics and improvement of power factor at input side. The progress in power semiconductor devices and their use as high-power, low-loss and high frequency switching devices with high frequency control results in a variety of AC voltage controller topologies with fewer number of switches, reduction of overall circuit size and volume and improvement of power quality and transient response [20]-[28]. One of the early works available on direct multiple pulse width modulated (MPWM) three-phase AC voltage controller topology was by Mozdzer et al. in [20], where a three-phase AC load is supplied by using six switches, each one was composed of a pair of back to back connected npn transistors and a diode in series with each transistor, counting the total amount of transistors to 12 and also 12 number of diodes. P. D. Ziogas et al. in the 90's, suggested further improvement of AC voltage controller using six switches [21]. Another modification on AC voltage controller was cited by D. Vincenti et al. [22]. This modification substituted the three freewheeling switches in [21] with a unilateral controlled switch and a diode-bridge. As a result the number of switching devices was reduced to four. In [23], S. Srinivasan et. al presented a group of three-phase switch mode AC-AC voltage converters with six AC bi-directional switches, namely – Buck, Boost, Buck-Boost and Ĉuk. In [24], F. Z. Peng et al. replaced the three main switches and the three freewheeling switches used in the AC voltage controllers presented in [23] by two three-phase semi bi-directional switches suggested by D. Vincenti et al. in [22]. Similar two semi bi-directional switch based three-phase Z-source AC voltage converter was proposed by X.P. Fang et. al [25]. The semi bidirectional switch based three phase AC voltage converters of [24], [25] require opening of neutral connection of source and load. They have the disadvantage that if the loads are not balanced, then there will be unbalanced currents which will change phase voltages due to absence of load and source neutral. This shortcoming was overcome in three phase rectifiers [26] and voltage controllers [27], [28] having modular structure in which the converter works on per phase basis. A new true three-phase AC bi-directional switch has been developed consisting of a unidirectional switch included in two three-phase diode bridges. This three-phase AC bi-directional switch allows modular operation even if the converter neutrals (supply and load side) are not connected. As a result three phase output voltages remain same in case of load unbalance.

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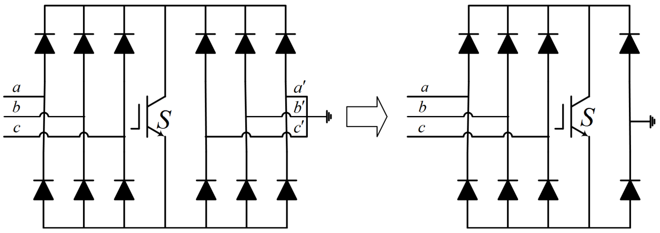

Fig. 1. Three-phase modified bidirectional switch obtained from three phase true bidirectional switch.

In certain applications, it may be necessary to use supply and load neutral points. Investigation has been made to obtain such topologies and in this paper a new group of three phase AC voltage controller topologies has been proposed using two modified three-phase AC bi-directional switches with neutral and less number of diodes. The modified bidirectional switch has been derived from the true three-phase bi-directional switch as shown in Fig. 1. This offers the proposed converters to have supply and load side neutral connections intact with even less utilization of semiconductor devices. Because the proposed converters have neutral connections and employ only two active devices, they can be less costly and can reduce complexity with simple control and enhance reliability of the system.

II. New Three Phase AC-AC Converter Topologies

Using the novel three-phase modified bi-directional switch with neutral new three-phase switch mode AC voltage controllers, namely - Buck, Boost, Buck-Boost, Ĉuk and SEPIC converters, are presented as shown in Figs. 2 - 6 respectively. The proposed converters have only two bidirectional switches - one act as the main switch and the other operates as freewheeling path across the load. Both supply and load sides are connected with neutral either directly or indirectly through the switches. Due to less number of active devices, control becomes easier. Easy control, decreased number of switches and the associated gate drive circuits, availability of source and load side neutral connections make the topologies potential candidates for AC-AC voltage control applications.

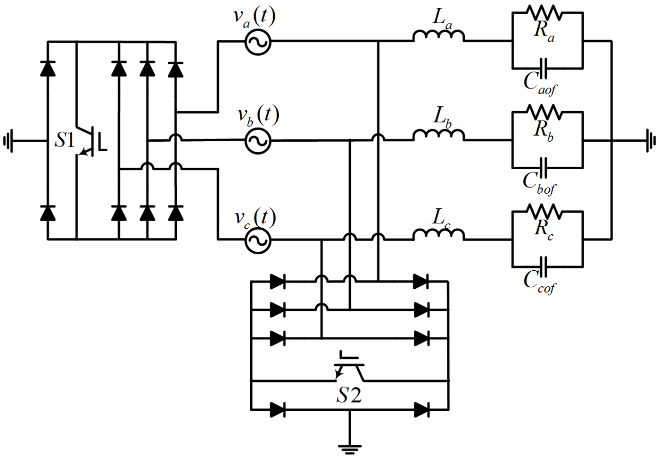

Fig. 2. Three-phase modified Buck AC voltage controller based on two three-phase bi-directional switches with neutral.

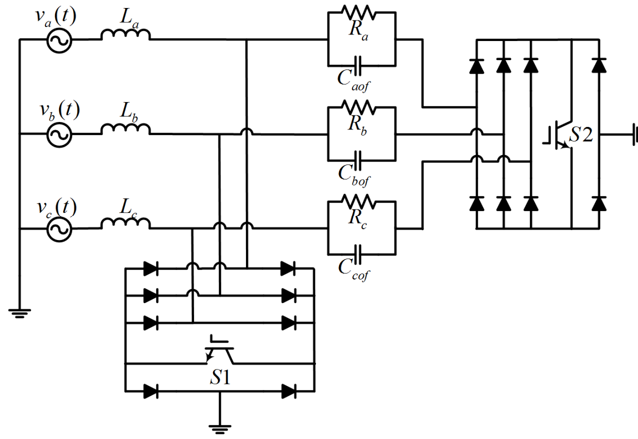

Fig. 3. Three-phase modified Boost AC voltage controller based on two three-phase bi-directional switches with neutral.

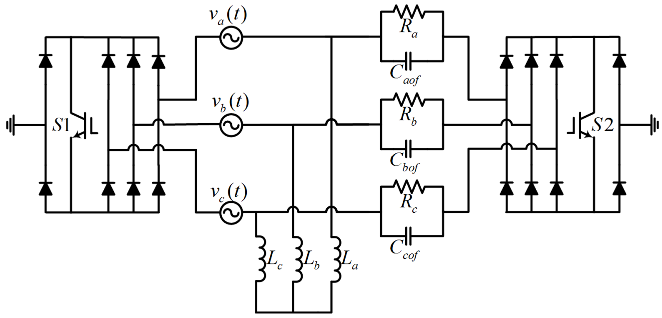

Fig. 4. Three-phase modified Buck-Boost AC voltage controller based on two three-phase bi-directional switches with neutral.

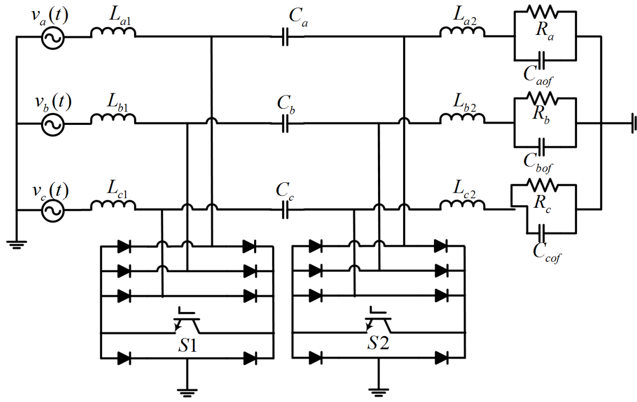

Fig. 5. Three-phase modified Ĉuk AC voltage controller based on two three-phase bi-directional switches with neutral.

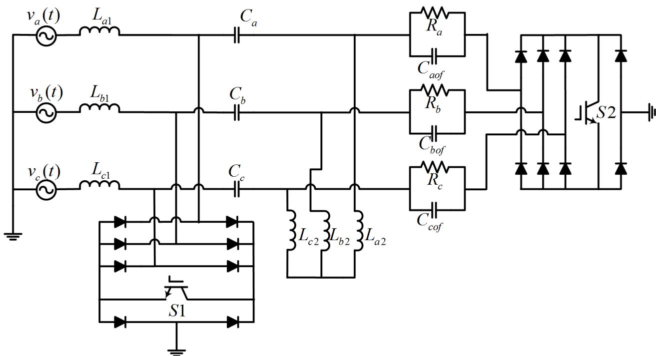

Fig. 6. Three-phase modified SEPIC AC voltage controller based on two three-phase bi-directional switches with neutral.

III. Analysis of Boost AC-AC Converter: An Example

To justify the new three-phase modified AC voltage controller topologies of Figs. 2-6, the three-phase Boost AC voltage controller is analyzed in this paper. Boost converters permits the output voltage to be higher than the input voltage depending on the duty-ratio of the gate signal. As given in Fig. 3, the proposed three-phase Boost AC-AC voltage converter have two three-phase modified bi-directional switches *S1* and *S2* with neutral each consist of a unidirectional switch and 8 number of diodes, three boost inductors L_a, L_b, L_c, output filter capacitors $C_{aof}, C_{bof}, C_{cof}$ and load resistances R_a, R_b, R_c. Here the sources have neutral connection and the loads are placed individually in each phase and connected to neutral through the bidirectional switch $S2$. The two switches act on alternate switching intervals by high frequency pulses at each gate. As the switching frequency is much higher than the AC line frequency of the supply, in a switching period, line frequency variables, such as, input voltage can be considered as constant. Then two equivalent circuits of the two states can be obtained, as shown in Figs. 7 and 8. Suppose the line-frequency input and output voltages of the balanced three-phase Boost AC voltage controller with resistive load are defined as,

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V_m \begin{bmatrix} sin(\omega t) \\ sin\left(\omega t - 120^o\right) \\ sin\left(\omega t + 120^o\right) \end{bmatrix} \text{ and}$$
$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = V_{om} \begin{bmatrix} sin(\omega t) \\ sin\left(\omega t - 120^o\right) \\ sin\left(\omega t + 120^o\right) \end{bmatrix} \text{ respectively.} \tag{1}$$

In state 1, both in +ve and -ve half cycles of the supply voltage, turning the switch *S1* ON while *S2* is turned OFF during the time DT_S, take apart the input stage from the output. Input provides energy to the boost inductors. Here D is the duty ratio of switch *S1* and T_S is the switching period. Voltage across the inductor can be expressed as,

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{2}$$

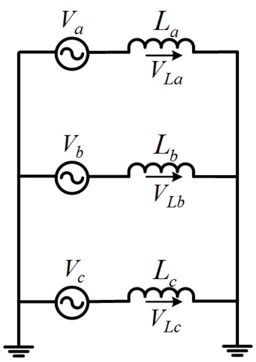

Fig. 7. State 1: switch S1 is ON and S2 is OFF.

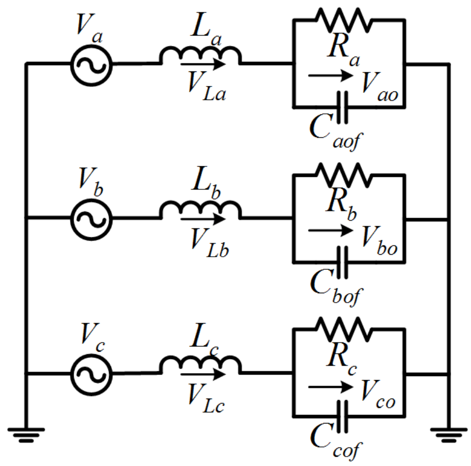

Fig. 8. State 2: switch S1 is OFF and S2 is ON.

In state 2, when the switch *S1* is OFF and *S2* turns ON during the time $(1-D)T_S$, the load gets energy from the supply and the boost inductors. Voltage across the inductor can be expressed as,

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \tag{3}$$

In the generalized switching cycle, the inductor volt-second is,

$$\int_t^{t+Ts} \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} dt = \int_t^{t+DTs} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} dt + \int_{t+DTs}^{t+Ts} \left(\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \right) dt \tag{4}$$

In AC-AC switching converters, in steady state, total volt-second of an inductor over one line frequency AC-cycle should be equal to zero. From volt-second balance,

$$\sum_{i=1}^{n} \int_{t_i}^{t_i+Ts} \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} dt = 0 \tag{5}$$

Which implies,

$$\sum_{i=1}^{n} \int_{t_i}^{t_i+DTs} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} dt + \sum_{i=1}^{n} \int_{t_i+DTs}^{t_i+Ts} \left(\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \right) dt = 0 \tag{6}$$

Where, $n = \dfrac{AC\ line\ Period, T_l}{Switching\ Period, T_s} = \dfrac{Switching\ frequency, f_s}{AC\ line\ frequency, f_l}$

From equation (6) it is possible to get equation (7),

$$\sum_{i=1}^{n} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} DTs + \sum_{i=1}^{n} \left(\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \right) (1-D)Ts = 0 \tag{7}$$

Simplifying we get,

$$\sum_{i=1}^{n}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} D + \sum_{i=1}^{n}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}(1-D) - \sum_{i=1}^{n}\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix}(1-D) = 0 \tag{8}$$

This can be written as,

$$\sum_{i=1}^{n}\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \frac{1}{(1-D)}\sum_{i=1}^{n}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{9}$$

with $T_s \rightarrow 0$ or $n \rightarrow \infty$, we can write

$$\sum_{i=1}^{n}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V_m \begin{bmatrix} sin(\omega t) \\ sin(\omega t - 120^o) \\ sin(\omega t + 120^o) \end{bmatrix} \tag{10}$$

$$\sum_{i=1}^{n}\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = V_{om} \begin{bmatrix} sin(\omega t) \\ sin(\omega t - 120^o) \\ sin(\omega t + 120^o) \end{bmatrix} \tag{11}$$

Thus bearing in mind that the switching period is extremely small compared to the supply line period, the voltage gain expression of the proposed three phase Boost AC voltage controller can be expressed as,

$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \frac{1}{(1-D)}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{12}$$

The above input/output relationship indicates that ideally the instantaneous output voltages of the Boost AC voltage controller will be greater than the input voltages. The output voltage can be controlled by duty cycle variation. In practice, switching loss, inductor/capacitor non-idealities, diode/switch conduction losses will cause deviation of ideal gain relationship, which eventually will not allow the circuit to work at high efficiencies at all duty cycles. Almost ideal gain characteristics will be followed near high efficiency operation. A similar analysis applies to other AC-AC converters.

IV. Simulation Results

The proposed three-phase Boost AC voltage controller has been simulated using the application software PSIM version 9.0. The input is a balanced three-phase AC source with peak voltage amplitude of 300V at supply frequency of 50 Hz. The two bi-directional switches are operated in complement by high frequency pulses of 10 KHz. Each Boost inductances has been selected as 7mH, filter capacitances at output are 1μF each and load resistances of 100Ω each. Fig. 9 illustrates the sample three-phase input and output voltages and input currents waveforms of the proposed Boost AC voltage controller with resistive load in open loop control. The wave shapes in the Fig. depicts that the proposed circuit can maintain good power quality by keeping the input currents almost sinusoidal and in phase with input voltage.

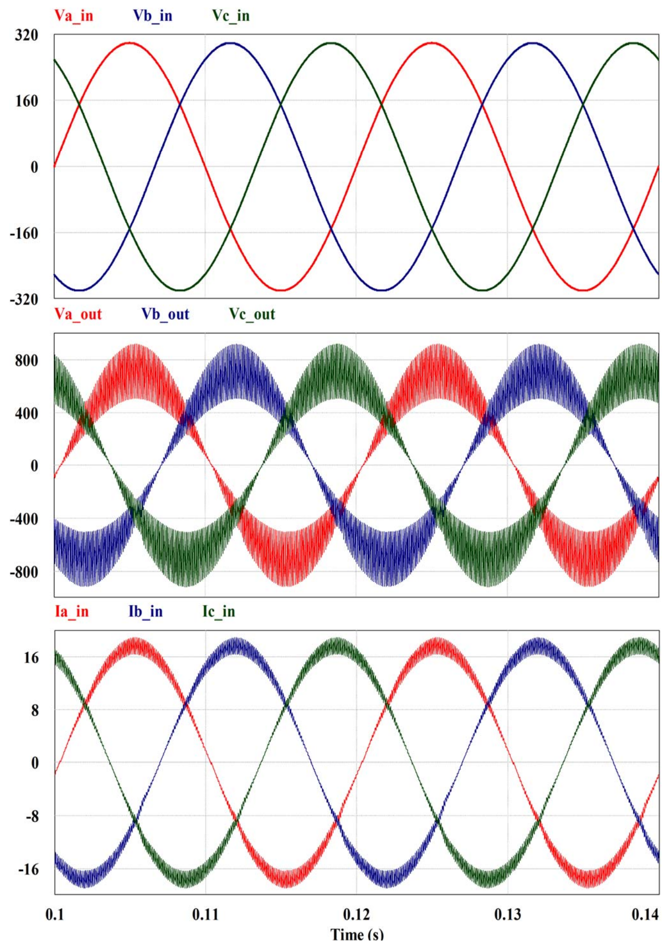

Fig. 9. Typical input and output voltages and input current wave shapes of three-phase modified Boost AC voltage controller at duty cycle D=0.6.

A. *Power Quality with Variation of Duty Cycle*

In open loop condition by varying the duty-ratio of the gate signals of the two bi-directional switches the performance of the proposed three-phase Boost AC voltage controller has been measured in terms of power quality indices such as efficiency(Eff(%)), input power factor (PF), percent Total Harmonic Distortion (THD (%)) of input current, and voltage gain (Vgain). The outcomes of this observation are given in Table I and in Figs. 10 - 13.

TABLE I. PERFORMANCE OF BOOST AC VOLTAGE CONTROLLER UNDER DUTY CYCLE VARIATIONS

Duty Cycle, *D*	Eff (%)	PF	THD (%)	Vgain
0.2	99.94	1.00	5.86	1.24
0.3	99.61	1.00	6.21	1.41
0.4	99.31	1.00	6.50	1.64
0.5	98.46	1.00	5.34	1.95
0.6	97.67	0.99	4.43	2.39
0.7	95.01	0.98	2.89	3.09
0.8	90.12	0.91	1.67	4.05

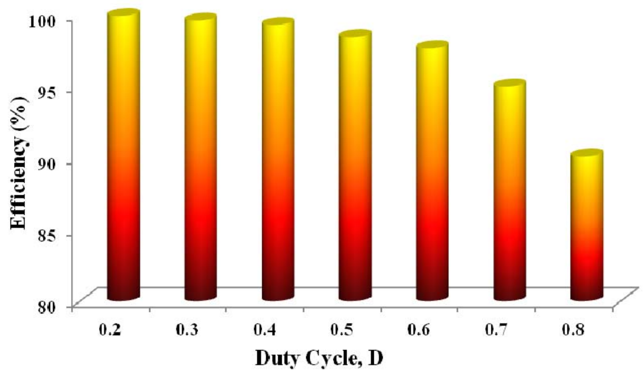

Fig. 10. Performance of three-phase Boost AC voltage controller in terms of efficiency (%) under duty cycle variation.

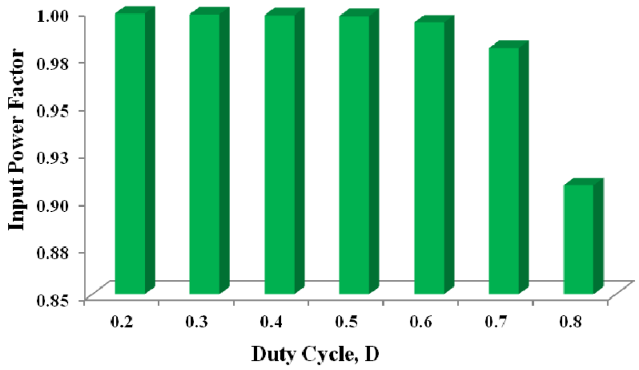

Fig. 11. Performance of three-phase Boost AC voltage controller in terms of input power factor under duty cycle variation.

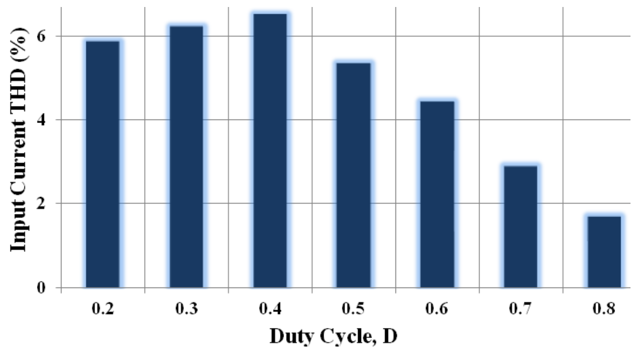

Fig. 12. Performance of three-phase Boost AC voltage controller in terms of input current THD (%) under duty cycle variation.

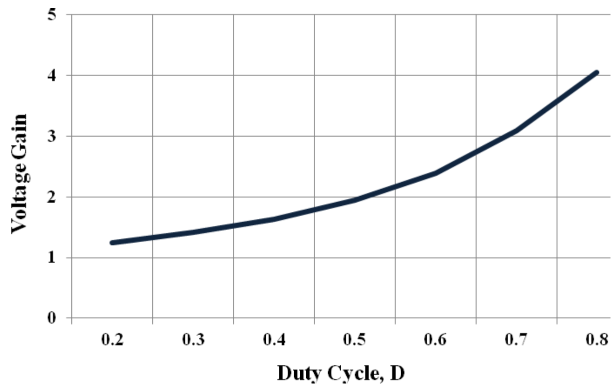

Fig. 13. Performance of three-phase Boost AC voltage controller in terms of voltage gain under duty cycle variation.

In open loop condition with duty-cycle variation the proposed modified Boost AC voltage converter circuit gives high efficiency of more than 90%. The input power factor is almost unity all over the range of duty cycle. The maximum value of input current THD is below 7% at 40% duty-ratio. With duty-cycle variation the voltage at output is always found higher than the input voltage as expected.

V. CONCLUSION

A novel design of three-phase modified bi-directional switch with neutral has been proposed in this research. The modified bi-directional switch consists of a unidirectional controlled switch enclosed by a three-phase diode bridge the three legs of which are connected to three individual phases and an additional leg of two diodes connected to the source/load side neutral. Based on two new three-phase modified bi-directional switches a new family of three-phase AC voltage controller topologies has been proposed. The proposed converters have supply and load side neutral connections intact and contain less number of diodes. Current ratings of the unidirectional controlled switches (such as IGBTs) used in the proposed converters can be less compare to those employed in the AC voltage controllers having modular structure in which the converters work on per phase basis. Thus overall switching and conduction losses reduce significantly and efficiency of the converters increases. The modified bidirectional switch based converters also give design advantages like simple control, reliable operation, reduction in cost and complexity. The three-phase Boost AC voltage controller circuit has been investigated as an example. Reasonable performance of the converter in terms of power quality has been observed with duty cycle variation. The research outcome is expected to result in a family of simple, cheap, less weight and compact with better power quality AC voltage controller topologies suitable for AC-AC applications. Experimental verification will be conducted in future both in open and closed control to justify the validation of the proposed converter.

REFERENCES

[1] F.L. Luo, Y. Hong, Renewable Energy Systems: Advanced Conversion Technologies and Applications, CRC Press, Taylor & Francis Group, Sep. 2012.
[2] R.W. Erickson, D. Maksimović, Fundamentals of Power Electronics, Springer (India) Pvt. Ltd., New Delhi, 2006.
[3] B.K. Bose, Power Electronics and Motor Drives: Advances and Trends, Elsevier, New Delhi, 2011.
[4] H. Sarnago, A. Mediano, and O. Lucia, "High efficiency ac–ac power electronic converter applied to domestic induction heating," *IEEE Transactions on Power Electronics*, vol. 27, no. 8, pp. 3676-3684, Aug. 2012.
[5] J. C. R. Caro, F. M. David, J. M. R. Arredondo, and A. M. Bakir, "Two-switch three-phase ac-link dynamic voltage restorer," *Power Electronics, IET*, vol. :5, no. 9, pp. 1754 - 1763, Nov. 2012.
[6] M. R. Hajimoradi, E. Karimi, H. Mokhtari, and A. Yazdian, "Performance improvement of a double stage switch mode ac voltage regulator," in *Proc. Power Electronics and Drive Systems Technology (PEDSTC)*, 2012, pp. 181 – 186.
[7] T. Soeiro, C. A. Petry, C. S. Fagundes, and I. Barbi, "Direct ac-ac converters using commercial power modules applied to voltage restorers," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 278-288, Jan. 2011.

[8] L. Lei, Y. Jundong, and Z. Qinglong, "Novel family of single-stage three-level ac choppers," *IEEE Transactions on Power Electronics*, vol. 26, no. 2, pp. 504-511, 2011.

[9] S. Subramanian, and M. K. Mishra, "Interphase ac–ac topology for voltage sag supporter," *IEEE Transactions on Power Electronics*, vol. 25, no. 2, pp. 514-518, Feb. 2010.

[10] K. Basu, and N. Mohan, "A power electronic transformer for three phase pwm ac/ac drive with loss less commutation and common-mode voltage suppression," in *Proc. 36th Annual Conference on IEEE Industrial Electronics Society, IECON* 2010, pp. 315-320.

[11] J. C. R. Caro; J. M. Ramirez; and F. Z. Peng, "Simple topologies for AC-link flexible AC transmission systems," in *Proc. 2009 IEEE Bucharest Power Tech Conference*, 28 Jun.-2 Jul. 2009, pp. 1-8.

[12] F. M. David, S. Bhattacharya, and S. Venkataramanan; "A comparative evaluation of series power-flow controllers using dc- and ac-link converters"; *IEEE Transactions on Power Delivery*, vol. 23, no. 2, pp. 985 – 996, Apr. 2008.

[13] A. Prasai, J. Sastry, and D. Divan, "Dynamic Var/Harmonic Compensation with Inverter-Less Active Filters," in *Proc. IEEE Industry Applications Society Annual Meeting, 2008. IAS '08*, pp. 1 – 6.

[14] J. C. R. Caro, F. M. David, J. M. G. Lopez, J. M. R. Arredondo, A. G. Rodriguez, N. S. Cabrera, M. G. Garcia, and H. C. Villegas, "A review of ac choppers," in *Proc 20th International Conference on Electronics, Communications and Computer (CONIELECOMP)*, Feb. 2010, pp. 252 - 259.

[15] J. W. Kolar, M. Hartmann, and T. Friedli, "Three-Phase PFC Rectifier and AC-AC Converter Systems," *Tutorial at the 26th Annual IEEE Applied Power Electronics Conference and Exposition (APEC 2011)*, Ft. Worth, TX, USA, 6-10 Mar. 2011.

[16] J. W. Kolar, T. Friedli, J. Rodriguez, and P.W. Wheeler, "Review of three-phase pwm ac–ac converter topologies," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 11, pp. 4988-5006, Nov. 2011.

[17] J. W. Kolar, T. Friedli, F. Krismer, and S. D. Round, "The essence of three-phase ac/ac converter systems," in *Proc. of the 13th Power Electronics and Motion Control Conference,* Sep. 2008, pp. 27 - 42.

[18] P. C. Sen, *Modern Power Electronics*, S. Chand & Company Ltd., New Delhi, 2004.

[19] A. Eberhard, *Power Quality*, ISBN 978-953-307-180-0, In Tech, Rijeka, Croatia, Mar. 2011.

[20] A. Mozdzer and B.K. Bose, "Three-phase ac power control using power transistors," IEEE Transactions on Industry Applications, vol. IA-12, no. 5, pp. 499–505, Sept. 1976.

[21] P.D. Ziogas, D. Vincenti, and G. Joos, "A practical pwm ac controller topology," in IEEE Industry Applications Society Annual Meeting, Oct. 1992, vol. 1, pp. 880–887.

[22] D. Vincenti, H. Jin, and P.D. Ziogas, "Design and implementation of a 25-kva three-phase pwm ac line conditioner," IEEE Transactions on Power Electronics, vol. 9, no. 4, pp. 384–389, July 1994.

[23] S. Srinivasan, and G. Venkataramanan, "Comparative evaluation of pwm ac-ac converters," in *Proc of the 26th Annual IEEE Power Electronics Specialists Conference*, 18-22 Jun. 1995, vol. 1, pp. 18 - 22.

[24] F. Z. Peng, L. Chen, and F. Zhang, "Simple topologies of pwm ac-ac converters," *IEEE Power Electronics Letters*, vol. 1, no. 1, pp. 10 – 13, Mar. 2003.

[25] X. P. Fang, "Three-phase z-source ac-ac converter" in *Proc. of the Power Electronics and Motion Control Conference, EPE-PEMC*, 2006, pp. 621-624.

[26] M. M. S. Khan, M. S. Arifin, M. H. Rahaman, I. Amin, M.R.T. Hossain, A.H. Abedin, M.A. Choudhury, and M.N. Uddin, "Input switched high performance three phase buck-boost controlled rectifier," in *Proc. 2013 IEEE International Conference on Industrial Technology (ICIT)*, 25-28 Feb. 2013, Cape Town, Western Cape, South Africa, pp. 557 – 562.

[27] M. R. T. Hossain, A. H. Abedin, M. A. Choudhury, and M. N. Uddin, "True three-phase bidirectional switch based ac-ac buck-boost converter topology," in *Proc.2013 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT 2013)*, 3-5 Dec. 2013, Amman, Jordan, pp. 1-6.

[28] M.R.T. Hossain, M.A. Choudhury, and M.N. Uddin, "A three-phase boost ac-ac voltage converter," in Proc. 2014 IEEE Industry Applications Society Annual Meeting, 5-9 Oct. 2014, Vancouver, BC, Canada, pp. 1 - 8.