Asian Power Electronics Journal, Vol. 8, No. 2, Nov 2014

A Simple Transformerless Buck-Boost Switching Voltage Regulator

H. Prasad [1] T. Maity [2] V. K. Singh [3]

Abstract–This paper proposes a single phase ac-ac transformerless voltage regulator based on a simple ac-ac converter. The converter is analysed through state space averaging technique followed by small signal analysis. The proposed system employs a pulse width modulation (PWM) ac-ac converter along with feed-forward and PID closed loop control and uses power semiconductor device IGBT as bi-directional switch. This circuit can easily maintain constant voltage at the output to the end user and power quality problems both steady and dynamic in nature are arrested by this technique. The controller is designed based on its stability analysis. The system is verified with simulation and experimental results.

Keywords–Buck-boost, Pulse width modulation, PID, Sag, Surge, IGBT

I. INTRODUCTION

Traditional ac voltage regulators [1]-[3] are made with tap changer transformers. To obtain variable ac voltage from a constant ac voltage source, PWM single phase ac-ac choppers [4]-[6] have been widely used in ac power control applications such as light dimming, heater control, and ac motor speed control. There are different types of power quality problems exist in transmission and distribution system like transients, voltage sags, surges, harmonics and impulses. Because the power electronics technology has played a role in different areas in which technology can be manipulated into several forms. Again, the traditional single phase ac-ac converters are implemented by anti-parallel ac thyristor pairs or traic, employing phase angle or integral cycle control methods to obtain the desired output ac voltage. But, these techniques are having disadvantages like low power factor, high total harmonic distortion (THD) in the source current and poor power transfer efficiency. The proposed circuit is to design a transformerless voltage regulator having fast dynamic response and a good percentage of the voltage regulation. A single phase ac-ac voltage regulator is operating with a simple "feed-forward" design and PID closed loop control. The proposed circuit is to design a transformerless voltage regulator having fast dynamic response and a good percentage of the voltage regulation.

They have advantages like the better power factor, efficiency, and low harmonic contain in transmission line, easy control, smaller size and lower cost. It is a single stage ac-ac power conversion topology.

The paper first received 9 Feb. 2014 and in revised form 8Oct.2014.
Digital Ref: APEJ-2014-02-0433

[1] Department of Mining Machinery Engineering, Indian School of Mines, Dhanbad-826004, India, E-mail: hpshukla271@gmail.com
[2] Department of Mining Machinery Engineering, Indian School of Mines, Dhanbad-826004, India, E-mail: tanmoy_maity@yahoo.com
[3] Department of Electrical Engineering, Indian School of Mines, Dhanbad-826004, India, E-mail: singhvipingcet@gmail.com

Small Signal analysis is used to approximate the behaviour of nonlinear devices with linear equations. State space averaging is a powerful tool for analysis of pulse width modulated converters. Small signal analysis is used for the analysis of dynamic model of buck-boost circuit [7]-[10].

One of the main requirements is to study stability [11]-[15] of the system. In this paper, the stability analysis of the buck-boost converter in s domain is investigated by using the transfer function through different approach.

In this paper, the single phase ac-ac power converter is presented with a different kind of topology. The converter system is employing a feed-forward controller and PID controller which runs as an ac regulator under wide input variable condition. The high frequency switching of two set of bi-directional switch through proper duty ratio control can provide variable output voltage in buck-boost mode. Feed-forward control technique can eliminate the effect of the disturbance on the process output.

II. ANALYSIS OF THE CONVERTER

The topology of the buck-boost converter is a cascade connection of inductance and capacitance (Fig. 1). The main application of this circuit is in single phase ac chopper power supply, where a negative polarity output may be desired with respect to the common terminals of the input voltage. The output voltage can be controlled by changing the duty ratio. This output voltage may be higher or lower than input voltage, depending on the duty ratio. The circuit contains two bi-directional switches i.e. *S1* and *S2* with the inductor, capacitor and load. Switches *S1* and *S2* turn on alternately i.e. when S1 turns ON at that time *S2* turns OFF and vice versa. When S1 is closed and *S2* is open, source energy is dumped into inductor. That means source power does not transferred into load. When *S2* is closed and *S1* is open, the stored energy inductor is transfer through *L-S2-* load. If both switches are open, then no power is transferred to be source to the load. When duty ratio is less than 0.5, it operates in buck mode and when duty ratio is larger than 0.5, it operates in boost mode.

The relationship between input and output voltage is

$$Vo/Vi = -D/(1-D) \qquad (1)$$

where V_o is the output voltage, V_i is the input voltage and D is duty ratio. The negative sign indicates the output phase is out of phase with the input. The open loop buck boost characteristic is shown in Fig. 2.

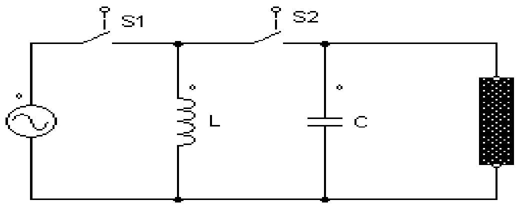


Fig. 1: Topology of the ac-ac converter

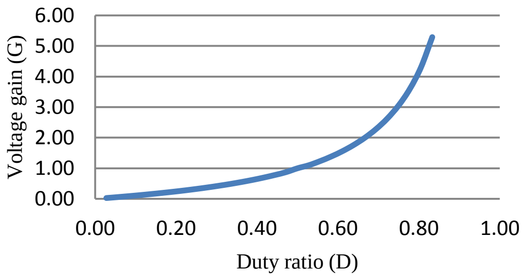


Fig. 2: Open loop characteristics of the converter

III. Small Signal Analysis

Small signal modeling is a common analysis which is used to approximate the behaviour of nonlinear devices with linear equations. Since most of the systems are non-linear in nature, hence we require linearization. The assumptions made for the purpose are: Inductors, capacitors, and resistors are linear, time invariant, and frequency independent, all semiconductor switches, i.e. the IGBT and diode are ideal switch. The converter time constant of the circuit is much larger than one switching time period.

Now, assuming input voltage - v_i, output voltage - v_o, voltage across inductors - v_L, voltage across capacitors - v_C, current through inductors - i_L, output current-i_o, and input current -i_i .

Also, order of the system = 2, states of the system- $X = \begin{bmatrix} i_L \\ v_C \end{bmatrix}$, inputs of the system- $u = \begin{bmatrix} v_i \\ i_o \end{bmatrix}$, output of the system- $y = \begin{bmatrix} v_o \\ i_i \end{bmatrix}$.

Now, when S1 is closed and S2 is open i.e. during [*DT*], where *D* and *T* are the duty cycle and time period respectively, the Fig. 3(a) gives the state equation as

$$\begin{bmatrix} \dot{i_L} \\ \dot{V_C} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} 1/L & 0 \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V_i \\ i_o \end{bmatrix} \tag{2}$$

When *S2* is closed and *S1* is open, i.e. during [(*1-D*) *T*], the state equation is derived as from Fig. 3(b)

$$\begin{bmatrix} \dot{i_L} \\ \dot{V_C} \end{bmatrix} = \begin{bmatrix} 0 & 1/L \\ -1/C & 0 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V_i \\ i_o \end{bmatrix} \tag{3}$$

We take signals as a sum of steady state value and small signal value. In the other words, we apply perturbations to the quantities as follows-

$v_i = V_i + \widehat{v_i}$, $i_i = I_i + \widehat{i_i}$, $i_L = I_L + \widehat{i_L}$, $v_C = V_C + \widehat{v_C}$, $v_o = V_o + \widehat{v_o}$, $i_o = I_o + \widehat{i_o}$, $d = D + \hat{d}$ *where* $\widehat{v_i}$, $\widehat{i_i}$, $\widehat{i_L}$, $\widehat{v_C}$, $\widehat{v_o}$, $\widehat{i_o}$, $\hat{d}$ are small signal value and steady state value V_i, I_i, I_L, V_C, V_o I_o, D.

After application of perturbation, we apply state space averaging method to obtain the average model as

$$\dot{\hat{x}} = \bar{A}.\hat{x} + \bar{B}.\hat{u} + [(A_1 - A_2).X + (B_1 - B_2).U].\hat{d} \tag{4}$$

where
$\bar{A} = A_1.D + A_2.(1-D)$ and $\bar{B} = B_1.D + B_2.(1-D)$

where, *A1* and *A2* are System matrix and *B1* and *B2* are input matrix.

Similarly, small signal output equation will be as follows-

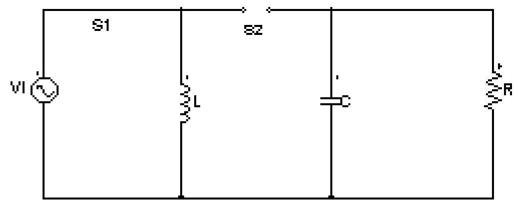
$$\hat{y} = \bar{C}\hat{x} + \bar{D}.\hat{u} + [(C_1 - C_2).X + (D_1 - D_2).U].\hat{d} \tag{5}$$

Then, the state space averaging equation is derived as

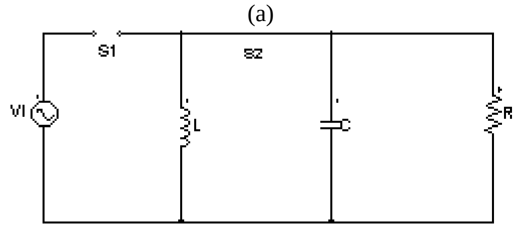
$$\begin{bmatrix} \widehat{i_L} \\ \widehat{v_C} \end{bmatrix} = \begin{bmatrix} 0 & -(D-1)/L \\ (D-1)/L & 0 \end{bmatrix} \begin{bmatrix} \widehat{i_L} \\ \widehat{v_C} \end{bmatrix} + \begin{bmatrix} D/L & 0 & (v_i - v_C)/L \\ 0 & -1/C & i_L/C \end{bmatrix} \begin{bmatrix} \widehat{v_i} \\ \widehat{i_L} \\ \hat{d} \end{bmatrix} \tag{6}$$

The output equation is derived as

$$\begin{bmatrix} \widehat{v_o} \\ \widehat{i_i} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ D & 0 \end{bmatrix} \begin{bmatrix} \widehat{i_L} \\ \widehat{v_C} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & i_L \end{bmatrix} \begin{bmatrix} \widehat{v_i} \\ \widehat{i_o} \\ \hat{d} \end{bmatrix} \tag{7}$$



(a)



(b)

Fig. 3: Equivalent circuit (a) when *S1* is on and *S2* is off (b) when *S2* is on and *S1* is off

IV. Stability Analysis

Transfer function is derived for the converter considering its operating value D = 0.667, input Voltage = 200V, voltage across C = 400V, L = 0.8mH, C = 20 µF.

$$G(s) = \frac{2.5\times10^5 s + 3.918\times10^7}{s^2 + 6.523\times10^4} \tag{8}$$

It is clear from pole-zero map of the above transfer function that poles are located on imaginary axes. The pole location of the system in Fig. 4 shows that the system is marginally stable.

Now, the closed loop transfer function with unity feedback is given as-

$$G(s) = \frac{2.5\times10^5 S+3.918\times10^7}{S^2+2.5\times10^5 S+3.924\times10^7} \quad (9)$$

It is clear from unity feedback system pole-zero plot shown in Fig. 5 that poles are located in left half of the s-plane. The close loop transfer function goes on stable.

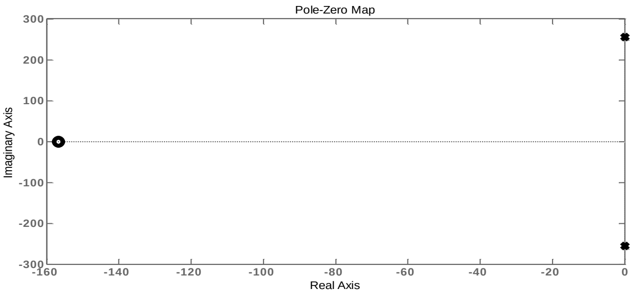


Fig. 4: Pole-zero map of open loop control system

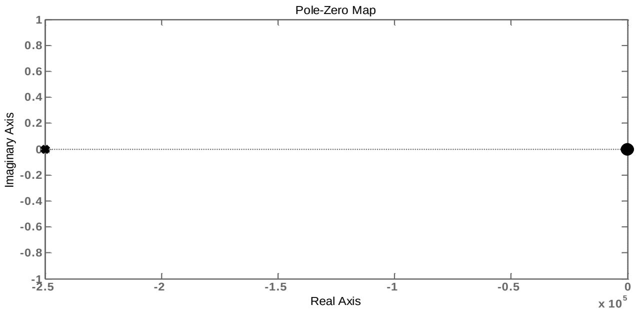


Fig. 5: Pole- zero Map of unity feedback system

V. PROPOSED VOLTAGE REGULATOR

As the closed loop system with unity feedback is stable system, it needs to design a controller which improves the stability of the previous systems and provide a stable output voltage. So, a PID controller is used to get the desired output, which includes various methods to get appropriate design parameters of the PID controller. This is further verified by direct tuning method and 'sisotool' in MATLAB. So the controller provided control transfer function with unity feedback is given by:

$$G_{CV}(S) = 0.1\frac{(1+2.4\,S)}{S} \quad (10)$$

After the application of controller, the poles of the system is shifted to left side of the s-plane and also the system looks highly stable by its step response as indicated in Fig. 6. The schematic diagram of the system is presented in Fig. 7.

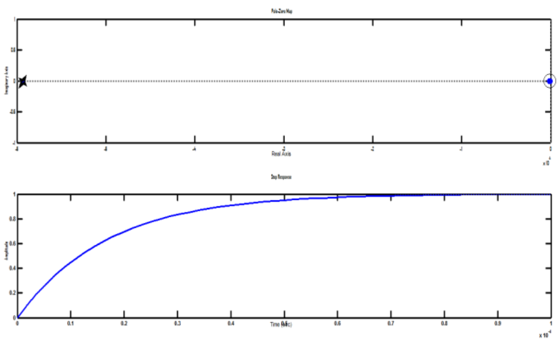


Fig. 6: Pole- zero Map and Step response of unity feedback system with controller provided

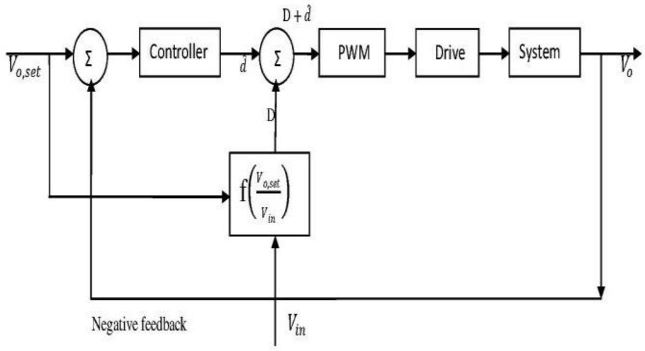


Fig. 7: Proposed closed loop system

VI. RESULTS AND DISCUSSION

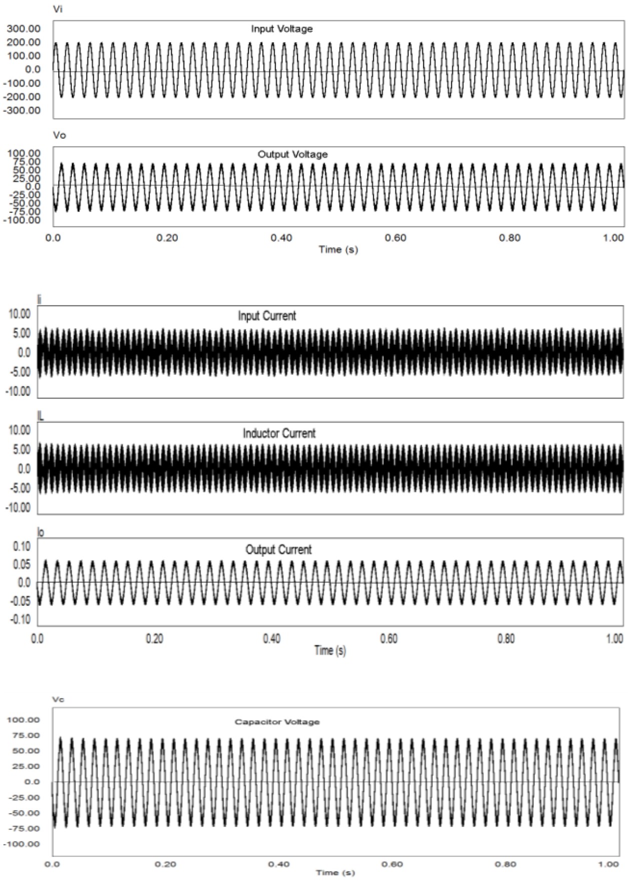
In order to verify the proposed single phase ac-ac converter in open loop, the PSIM simulation software is used. The components are chosen for simulation are L = 0.8mH, C = 20 µF, and Resistive load = 1200ohm. The bidirectional switches are designed with two IGBTs connected back to back in series. The switching frequency was set to 5 KHz and input sinusoidal voltage is selected as 200V peak. When D = 0.25, the input voltage is buck to 46 V_{rms} from 141 V_{rms} at the output and when D = 0.67, the output voltage is boosted to 283 V_{rms} from 141 V_{rms} input voltage. The buck and boost operation is clear from the waveform shown in Fig 8(a) and 8(b). The output voltage waveform is out of phase with the input voltage. Because of that, the voltage stress across switch is more equal to sum of the input and output peak voltages. The switching stress is therefore increased during boost condition.

The proposed single phase closed loop ac-ac regulator has the buck-boost capability i.e. it can operate in buck or boost mode depending upon desired output voltage and this overcome the problem of voltage sag or voltage surge in power system. Simulation result is carried out based on the proposed control system. The feed-forward system automatically selects the value of gain and accordingly the desired output voltage. A set of results shown in Table I prove its capability of buck, boost and regulation.

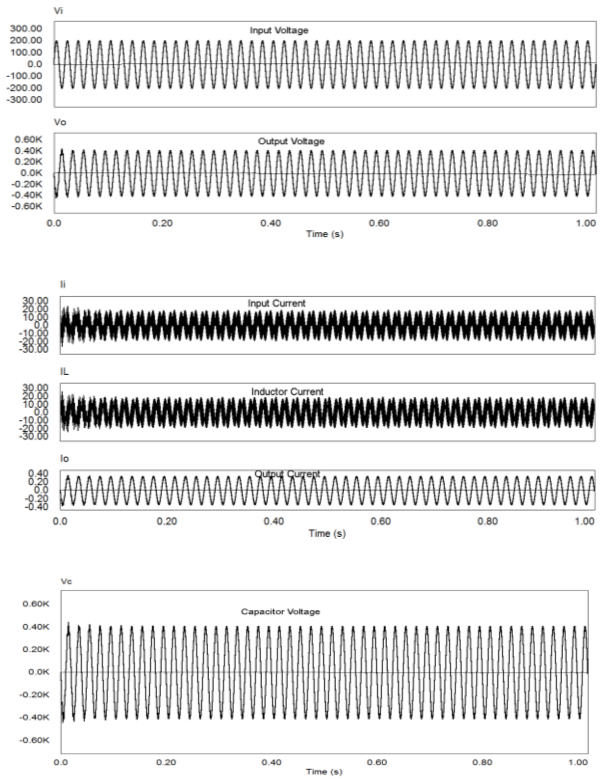
To check its dynamic response, input voltage is varied suddenly. First a voltage surge is applied at steady running condition from 170V to 280V rms and then voltage sag is applied over the steady voltage from 200V to 140V rms.

The input and output voltage waveforms are recorded in Fig. 9 and Fig. 10 respectively for sag and surge conditions and it shows a steady value except some small transient during change over instant in both the cases.

The laboratory based experimental setup is also done for analysis, the control is implemented with microcontroller and it will provide to voltage regulation as a viable solution. The experimental waveform of output voltage is shown in Fig. 11.



(a)



(b)

Fig. 8: Waveforms for Input voltage (V), Output voltage (V), Input current (A), Inductor current (A), Output current (A) and Capacitor voltage (V) under open loop condition of the converter at (a) Buck mode with D= 0.25 (b) Boost mode with D=0.67

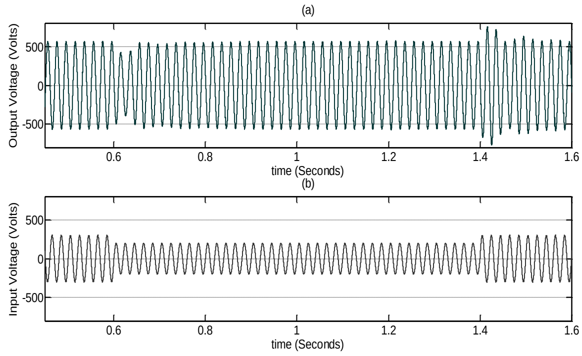


Fig. 9: Waveforms with PID Controller during input voltage Sag condition .(a) Output Voltage. (b) Input Voltage.

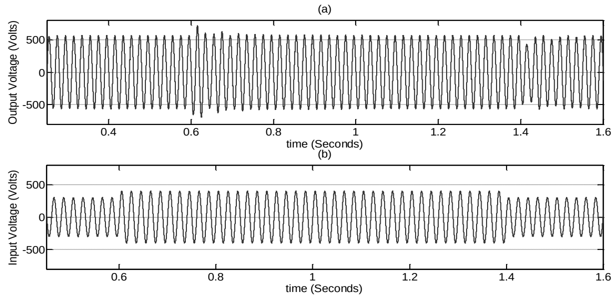


Fig. 10: Waveforms with PID Controller during input voltage Surge condition .(a) Output Voltage. (b) Input Voltage.

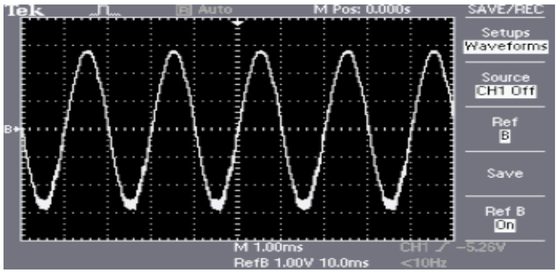


Fig. 11: Experimental waveform of output voltage

Table 1: Simulation and experimental results showing buck-boost and regulation (Output set value = 200V)

Input Voltage (Vrms)	Simulation Output Voltage (Vrms)	Experimental Output Voltage (Vrms)
230V	210.60V	205.60V
220V	210.0V	203.50V
200V	208.10V	203.0V
184V	207.20V	200.80V
170V	200.30V	197.60V
163V	199.20V	196.0V
150V	198.75V	194.80V

VII. CONCLUSION

In this paper, a novel simple single phase ac-ac buck-boost converter with closed loop feed-forward control and PID control are proposed. With a simple technique single phase AC-AC converter can keep the output voltage steady by operating at buck-boost mode. The proposed topology has the capability to overcome the voltage sag or voltage surge in transmission line and distributed power system. This work shows that ac-ac converter performs well during the voltage fluctuation. The operating principle, steady-state and transient analysis of the system were presented. To verify the proposed system, the simulation and laboratory based experiments are carried out. The fast response will allow rural power consumers, to better withstand variable voltage conditions and can provide reliable and quality power supply. The proposed circuit is simple, robust and low cost. It has only drawbacks like inverted phase at the output and maximum voltage stress across switches.

REFERENCES

[1] Zbigniew Fedyczak, Ryszard Strzelecki, Grzegorz Benysek, "Single phase PWM ac-ac semiconductor transformer topologies and applications", *IEEE Power Electron. Specialists Conf. (PESC)*, vol.2, 2002, pp. 1048-1053.

[2] Fang Zheng Peng, Lihua Chen, Fan Zhang, "Simple topologies of PWM AC-AC converters," *IEEE Power Electron. Letter*, vol. 1, March 2003, pp. 10-13.

[3] Minh khai Nguyen, Young-Gook Jung, Young-Cheol Lim, "Single phase AC-AC converter based on quasi-z-source topology" *IEEE Trans. Power Electron*., vol. 25, no. 8, August 2010, pp. 2200-2210.

[4] N. Vazquez, A. Velazquez, C. Hernandez, "AC voltage regulator based on the AC-AC Buck-Boost converter" *IEEE Conf. Ind. Electron. (ICIE)*, 2007, pp. 533-537.

[5] Num-Sup, Choi Yulong, "Current programmed control of three Phase PWM AC-AC Buck-boost converter" *IEEE Conf. on Electrical Machines and System (ICEMS)*, vol. 2, 2005, pp. 1146-1151.

[6] S. Sonar, T. Maity, M. Minu, "Single phase transformerless wide range ac boost voltage regulator based on z-source network" Elsevier, *Electrical Power and Energy System*, vol. 47, 2013, pp. 193-197.

[7] Angelo Brambilla, Giancarlo Storti Gajani, "Synchronization and small signal analysis of nonlinear periodic circuits" *IEEE Trans. on Circuits and Systems*, vol. 55, no. 4, May 2008, pp. 1064-1073.

[8] A.F. Witulski, "Buck converter small signal models and dynamics comparison of quasi-resonant and pulse width modulated switches" IEEE Trans. on Power Electron. , vol. 6, no. 4, 1991, 727-738.

[9] Yanyan Jin, JianpingXu, Guohua Zhou, "Small Signal modelling and analysis of improved digital peak current control of boost converter" *IEEE Conf. on Power Electronics and Motion Control*, 2009, pp.326-330.

[10] Paolo Mattavelli, Giorgio Spiazzi, "Small Signal analysis of DC-DC converters with sliding mode control" *IEEE Trans. on Power Electro.*, vol. 12, no. 1, Jan. 1997, pp. 96-102.

[11] Fu-Sheng Tsai, "Small Signal and transient analysis of a zero-voltage switched, phase controlled PWM converter using averaged switch model" *IEEE Trans. on Ind. Appl.*, vol. 29, no. 3, 1993, pp. 493-499.

[12] Jaw-Kuen Shiau, Chun-Jen Cheng, "Stability analysis of a non-inverting Synchronous Buck-Boost power converter for a solar power management system" *IEEE Conf. on Sustainable Energy Technologies (ICSET)*, 2008, pp. 263-268.

[13] H.M. Mahery, S. Torabzad, M. Sabahi, E. Babaei, "Modeling and stability analysis of buck-boost dc-dc converter based on Z transform" *IEEE Conf. on Power Electronics (ICPE)*, 2012, pp. 1-6.

[14] Xiaoho Hu, P.K.T. Mok, "Analysis and design of three state controlled transition mode for a buck-boost converter with efficiency and stability enhancement" *IEEE Conf. on Circuits and Systems (ICCS)*, 2013, pp. 697-700.

[15] A.H. Abedin, A. Kabir, E. Ahmad, D. Rahman, M.A. Choudhury, "A single phase Buck-Boost AC-AC converter with low input current THD and high input power factor" *IEEE Conf. Electrical Machines and Power Electronics(ICEMPE)*, 2011, pp. 175-179.

BIOGRAPHIES

Hanuman Prasad, born in 1984, received the Graduation in Electrical Engineering from U.P. Technical University, Lucknow and Master Degree in Power Electronics & Drives from National Institute of Technology, Kurukshetra, India in 2007 and 2011 respectively. Currently, he is pursuing PhD from Indian School of Mines Dhanbad India.

Tanmoy Maity, born in 1969, received Graduation and Master Degree in Electrical Engineering from Calcutta University and PhD from Bengal Engineering & Science University, Shibpur. He has six years industrial and more than fifteen years academic experience. He is currently working as faculty in Indian School of Mines, Dhanbad, India.

Vipin Kumar Singh, born in 1992, received the Graduation in Electrical and Electronics Engineering from G.B. Technical University, Lucknow. Currently, he is pursuing Master degree in Power System Engineering from Indian School of Mines, Dhanbad, India.