A NOVEL ALTERNATING CURRENT VOLTAGE REGULATOR BASED ON BUCK-BOOST CONVERTER

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This paper presents a novel single-phase ac voltage regulator based on buck-boost converter topology. The regulator circuit has a simple structure. It does not require a coupling transformer, uses only two bidirectional active switches and includes only one inductor and one capacitor. The proposed regulator operates through a closed loop control system, where the controller is supported by a control law depending on the instantaneous values of the regulator’s real input and the desired output voltages. The control law provides an efficient pulse width modulation (PWM) switching duty ratio for the desired output voltage when the input voltage has fast fluctuations and the output load is changed. Simulation studies have been done for the proposed ac voltage regulator in MATLAB-Simulink. The simulation results have shown that the proposed topology is capable of and efficient for both bucking and boosting the input ac voltage to generate a high quality output voltage with a low total harmonic distortion (THD) for different input voltage and load conditions.

1. INTRODUCTION

Solid-state power electronics applications have been used for voltage regulation in ac power systems for decades. Fast switching capabilities of converters based on power electronics have been efficiently used and they provide fast and high quality responses. Many ac-ac solid-state converters have been developed using different topologies. Park et al. [1] and Tsai [2] have proposed single-phase ac/dc/ac voltage regulator converters. These topologies convert ac input to dc output via a rectifier and after that the dc output generates an ac output through an inverter [2] needs also a coupling transformer at the output of the inverter. Requiring two converters (rectifier and inverter) is the main disadvantage of these ac/dc/ac voltage regulators. Dabroom [3] has presented a study based on traditional PWM ac chopping topology for resistive loads. Input single phase ac voltage is chopped to buck it at the output. No filter stage and no coupling converter is used, so the harmonic level is too high. In the studies given by [4–8] PWM ac chopping is supported with a coupling transformer to smoothen the harmonics of the chopped wave form. However, harmonic distortions cannot be reduced enough in these studies. Zhou et al. [9] have proposed a converter that uses a zero voltage/current switching technique for three-phase voltage regulation. The converter consists of one active switch, one inductor and two capacitors for each phase. Dantas et al. [10, 11] have presented a single ended primary inductor converter SEPIC based topology for single-phase regulation using four active switches, two inductors and two capacitors. Reis et al. [12] have proposed a single-phase line conditioner and Ahmed et al. [13] have presented a three-phase line conditioner for voltage regulation. Four active switches, six diodes, two inductors and three capacitors are used in the topology given in [12] and two active switches, three diodes and one RC filter are used for each phase in [13]. Ćuk converter topology is adapted for ac voltage regulation using four active switches, four diodes, two inductors and two capacitors [14]. Nan et al. [15] have given a single-phase ac voltage regulator based on the buck converter topology using two bidirectional active switches, two inductors and two capacitors.

The study is considered for resistive loads and the controller for duty ratio of switching is modelled depending on the load value. Contreras [16] has also used a buck converter based three-phase ac voltage regulator topology supported by a coupling transformer to improve the output quality. Buck-boost converter type regulator topologies have been also developed [17–21]. Khan et al. [22] and Wu et al. [23] have supported the buck-boost converter type regulators with coupling transformers. All of these given buck-boost converter type ac voltage regulators use at least seven components ( switches, diodes, passive elements such as inductor and capacitor) except transformers. The controllers for the duty ratio of switching are modelled depending on the determined load conditions.

In this paper, a novel buck-boost converter type transformerless single-phase ac voltage regulator topology is presented. The proposed topology uses only two bidirectional active switches, one inductor and one capacitor. Insulated-gate bipolar transistors (IGBTs) are used as active switches in the topology. The closed-loop proportional-integral (PI) controller is supported with a control law determined by the instantaneous real input and the desired output voltage values. Thus, the efficiency and the stability of the desired output voltage is provided for sudden surges of the input voltage and different load conditions. Simulation design is performed for the proposed topology in MATLAB-Simulink. Simulation results are given in detail to show the efficiency and the accuracy of the proposed topology on both bucking and boosting the ac input voltage to a desired output voltage with an acceptable THD ratio.

Section 2 demonstrates the circuit topology of the proposed single-phase ac voltage regulator. In section 3, the regulator circuit operation is introduced in detail. Section 4 demonstrates the simulation results of the study and section 5 gives the conclusion of the paper.

2. THE PROPOSED CIRCUIT TOPOLOGY

The circuit topology of the proposed single-phase ac voltage regulator is given in Fig. 1. In Fig. 1, $V_i(t)$, $V_o(t)$.
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voltage, the output ac current and the inductor current, respectively. \( S_1 \) and \( S_2 \) are the bidirectional active switches. The circuit operation is based on the buck-boost converter principle through controlling the \( S_1 \) switch [24]. When \( S_1 \) is turned on while \( S_2 \) is off, the input voltage supplies the inductor. During this case, the inductor is energized. When \( S_1 \) is turned off and \( S_2 \) is turned on, the energized inductor supplies the capacitor and the load connected to the output. Thus, the input voltage is bucked or boosted at the output according to the given input and output polarities [25].

![Fig. 1 – Topology of the proposed buck-boost type ac voltage regulator.](image1)

According to the switching frequency of \( S_1 \) and depending on the proper control of \( S_1 \) and \( S_2 \) mentioned above, the relationship between \( V_i(t) \) and \( V_o(t) \) can be given as

\[
V_o(t) = \frac{d}{1-d} V_i(t), \tag{1}
\]

where \( d \) indicates the duty ratio defined as the ratio of the turn on time of \( S_1 \) to the switching period of \( S_1 \)

\[
d = \frac{t_{on-S1}}{t_{on-S1} + t_{off-S1}} = \frac{t_{on-S1}}{T_{S1}}. \tag{2}
\]

Eq. (1) is valid for ideal switches of \( S_1 \) and \( S_2 \), ideal circuit components, ideally infinite switching frequency of \( S_1 \) \((f_{-S1})\) and for continuous inductor current mode.

In this study, IGBTs including antiparallel diodes are used for bidirectional active switches. Thus, the proposed ac voltage regulator demonstrated in Fig. 1 can be given by a structure using IGBTs in Fig. 2.

![Fig. 2 – Ac voltage regulator circuit using IGBTs for bidirectional active switches.](image2)

Fig. 2 – Ac voltage regulator circuit using IGBTs for bidirectional active switches.

The operation of the bidirectional active switches using IGBTs can be explained by Fig. 2. When \( V_i(t) \) is positive for the determined polarity, \( S_{1a} \) is turned on to make \( S_1 \) on. In this case, the inductor is energized by the current through the collector-emitter path of \( S_{1a} \) and the antiparallel diode of \( S_{1b} \). To make \( S_2 \) on, \( S_{2a} \) is turned on to provide a path for the current of the energized inductor when \( S_1 \) is off. So, the current of the energized inductor supplies the capacitor and the load connected to the output through the collector-emitter path of \( S_{2a} \) and the antiparallel diode of \( S_{2b} \). If \( V_i(t) \) is negative for the determined polarity, \( S_{1a} \) is turned on to make \( S_1 \) on. In this case, the inductor is energized by the current through the collector-emitter path of \( S_{1a} \) and the antiparallel diode of \( S_{1b} \). To make \( S_1 \) on, \( S_{2a} \) is turned on to provide a path for the current of the energized inductor when \( S_1 \) is off. So, the current of the energized inductor supplies the capacitor and the load connected to the output through the collector-emitter path of \( S_{2a} \) and the antiparallel diode of \( S_{2b} \). The switching pattern of the IGBTs that are parts of the bidirectional switches according to Fig. 2 is given in Fig. 3.

![Fig. 3 – Switching pattern of the IGBTs of the bidirectional switches.](image3)

3. DESCRIPTION OF THE CIRCUIT OPERATION FOR VOLTAGE REGULATION

The operation of the proposed buck-boost ac voltage regulator can be expressed through the control structure given in Fig. 4 [26]. This structure’s aim is to regulate the input ac voltage \( V_i(t) \) (pure sinusoidal or including harmonics) to a pure sinusoidal output voltage \( V_o(t) \) at the same frequency of \( V_i(t) \) with a desired magnitude.

![Fig. 4 – Control structure of the proposed ac voltage regulator.](image4)

A phase locked loop (PLL) determines the angular frequency \((w)\) of \( V_i(t) \). \( V_r \) defines the desired magnitude of \( V_o(t) \). Thus, the reference voltage waveform can be given as

\[
V_{ref}(t) = V_r \sin wt. \tag{3}
\]
The PWM generator produces the control signals of the active switches according to the obtained operation duty ratio. As seen in Fig. 4, the operation duty ratio that is transferred to PWM generator is obtained by the control law and the PI controller;

\[ d(t) = d_{CL}(t) + d_{PI}(t). \]  

(4)

The control law determines the open-loop duty ratio function that produces the output voltage \( V_{o}(t) \) according to the reference voltage \( V_{ref}(t) \) and the input voltage \( V_{i}(t) \) via (1) and can be calculated by

\[ d_{CL}(t) = \frac{V_r \sin wt}{V_r \sin wt + V_r^*}. \]  

(5)

The description of the open-loop duty ratio called as the control law is determined for a certain switching period. So, assuming that the operation duty ratio is obtained through only the control law, (5) must be discretized for the switching period and thus the control law can be modified as

\[ d_{CL}(kT_S) = \frac{V_r \sin wkT_S}{V_r \sin wkT_S + V_r^*} \quad (k = 0, 1, 2, \ldots) \]  

(6)

or simplified to

\[ d_{CL}(k) = \frac{V_r \sin wk}{V_r \sin wk + V_r^*}. \]  

(7)

Selecting a high switching frequency forces (7) to be close to (5). So, it achieves a close response to obtain the desired output voltage of the proposed voltage regulator as the switching period is significantly shorter than the circuit time constant. But as mentioned before, the determined control law for the duty ratio cannot produce the desired output because of unideal circuit components in practice and discontinuous inductor current caused by load change. So, the reference and real output voltages are compared to determine the error. As seen in Fig. 4 the determined error is applied to a controller to obtain the accurate operation duty ratio. A PI controller is used in this study. The duty ratio determined by the control law is supported by the PI controller.

The PI controller is designed through the mathematical model of the proposed voltage regulator. Figure 5 demonstrates the equivalent circuit of the buck-boost converter based single phase ac voltage regulator. The figure, \( I_L(t) \) and \( R \) indicate the capacitor current and load resistance, respectively.

The below equations are derived for mode I of Fig. 5a

\[ L \frac{dI_L(t)}{dt} = V_i(t), \]  

(8)

\[ C \frac{dV_o(t)}{dt} = -\frac{V_o(t)}{R}. \]  

(9)

For mode II, the equations of Fig. 5b are obtained as

\[ L \frac{dI_L(t)}{dt} = -V_o(t), \]  

(10)

\[ C \frac{dV_o(t)}{dt} = I_L(t) - \frac{V_o(t)}{R}. \]  

(11)

And, state-space equations can be given respectively for mode I and mode II as

\[ \frac{d}{dt} \begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -1/RC \end{bmatrix} \begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_i(t), \]  

(12)

\[ \frac{d}{dt} \begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix} \begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_i(t). \]  

(13)

Thus, the average state-space model of the proposed voltage regulator can be derived from (12) and (13) as

\[ \frac{d}{dt} \begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} 0 & (1-d)/LC \\ (1-d)/RC & -1/RC \end{bmatrix} \begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} d/L \\ 0 \end{bmatrix} V_i(t). \]  

(14)

By the help of the control structure given in Fig. 4, the closed-loop control block diagram of the system can be demonstrated in Fig. 6.

Fig. 6 – Closed-loop control block diagram of the system.

From Fig. 6, the transfer function between \( V_o(s) \) and \( d(s) \) is derived as (with index W for the working point values)

\[ \frac{V_o(s)}{d(s)} = \frac{-I_{LW} s + (V_{OW} + V_{IW})(1-d_W)}{s^2 + s \left( \frac{1}{RC} + \frac{1-d_W}{LC} \right)}. \]  

(15)

As seen in Fig. 6, the duty ratio of control law \( d_{cl}(s) \) is included into the operation duty ratio \( d(s) \). By assuming \( d_{cl}(s) \) is zero (considering there is no supporting from the control law), it is considered that,

\[ d_{PI}(s) = d(s). \]  

(16)

\( PWM_{PI}(s) \) is the transfer function of the PWM stage between \( d_{PI}(s) \) and the PI control signal \( V_c(s) \), and given as

\[ PWM_{PI}(s) = \frac{d(s)}{V_C(s)} = \frac{1}{V_{PWM}}, \]  

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where \( V_{PWM} \) is the amplitude of the ramp in the PWM conversion of the PI controller. Thus, the transfer function of the system which the transfer function of the PI controller \( G_{PI}(s) \) is designed according to is derived as, A PI controller has a dynamic behavior.

\[
\frac{V_O(s)}{V_C(s)} = \frac{1}{s^2 + \frac{1}{RC} + \frac{(1-d_W)^2}{LC}}.
\] (18)

And, it requires a response time. In this study, the proposed ac voltage regulator is also aimed to regulate the input voltages in sudden fluctuations. So, it is clear that the PI controller cannot meet the response time to clear the system fault where the error gradient and error level are too high. But the control law has a static behavior as seen from its algebraic structure. As mentioned before, the control law produces a duty ratio value close to the desired operation duty ratio simultaneously with the error change. So, the control law leads the PI controller to compensate the system from the duty ratio point obtained by the control law. Thus, the control law speeds up the system response, after than the PI controller takes over the mission from the control law to eliminate the system error.

4. SIMULATION RESULTS

A simulation prototype is implemented in MATLAB-Simulink for the proposed buck-boost converter based voltage regulator topology to show its accuracy and efficiency. Figure 7 demonstrates the simulation model of the study.

![Fig. 7 – MATLAB-Simulink simulation model for the proposed buck-boost converter type ac voltage regulator.](image)

In Fig. 7 the controlled voltage source block represents the ac input voltage. Input voltage is produced by the \( u_1 \) source in the Embedded MATLAB Function1 block. \( R_1, L_2 \) and \( C_2 \) are used to combine different load types. A 1-phase PLL block determines the frequency of the input voltage. The Embedded MATLAB Function2 block produces the control law and includes the PI controller for duty ratio and generates the control signals of the IGBTs. The IGBTs, the inductor and the capacitor are modelled with parasites. The IGBTs’ parameters are set as on-resistance \( r_m = 15 \text{m} \Omega \), forward voltage \( V_f = 1.5 \text{V} \), current 10 % fall time \( T_f = 1.5 \mu s \), and current tail time \( T_t = 3 \mu s \). The inductor’s value is 40 \text{m} \text{H} and its parasitic resistance is set as \( R_i = 10 \text{m} \Omega \). The capacitor is 100 \text{m} \text{F} and its series equivalent parasitic resistance is set as \( R_C = 25 \text{m} \Omega \). The proposed ac voltage regulator based on buck-boost converter type has been tested at different input voltages and load conditions in the given simulation model. Results for input voltage, output voltage and output current waveforms are given together.

Figure 8 demonstrates the simulation results of the proposed voltage regulator for case 1. In case 1 the input voltage’s fundamental harmonic magnitude is 100 V and includes a low order harmonic component. The desired output voltage magnitude is 70 V and the load is resistive and its value is 10 \( \Omega \). Switching frequency is selected at 50 kHz.

![Fig. 8 – Simulation results for case 1.](image)

As shown in Fig. 8 the input voltage has a non-sinusoidal waveform including harmonics with a 10 % THD. The desired output voltage magnitude value is lower than the input voltage. So the voltage regulator has been operated in buck converter mode. The ac voltage regulator has converted the ac input voltage close to an ideal sinusoidal waveform at the output, providing the desired magnitude value with a 1 % THD. As the load is resistive the output current’s THD value is the same as that of output voltage. Exemplary switching signals of the IGBTs and the inductor current for the positive half-wave and the negative half-wave for the input voltage for case 1 are shown in Fig. 9 and Fig. 10, respectively.

![Fig. 9 – Switching signals and inductor current during the positive half-wave of the input voltage for case 1.](image)

The discrete duty ratios for case 1 depending on the simple control law according to (7) and the control law supported
by the PI controller that produces the real duty ratio for the operation as a voltage regulator are interpolated in MATLAB. The interpolated duty ratios and the related input and reference voltages are shown in Fig. 11. As seen in Fig. 11, the duty ratio depending on the control law supported by the PI controller is very close to that of the simple control law. It is clear that the control law obtained by (7) improves the efficiency of the PI controller to produce the required duty ratio for voltage regulation operation in a fast and robust manner.

Fig. 11 – Duty ratios obtained by simple control law and control law supported by the PI controller for case 1.

In Fig. 12 the simulation results are given for case 2 where the input voltage’s fundamental harmonic magnitude is 80 V and includes a high order harmonic component. The desired output voltage magnitude is 60 V and the load is an inductive RL load. R is 2 Ω and L is 5 mH. Switching frequency is selected at 50 kHz.

The input voltage has a non-sinusoidal waveform including harmonics with a 6.26 % THD. The desired output voltage magnitude value is lower than the input voltage. So the voltage regulator has been operated in buck converter mode. The ac voltage regulator has produced the output voltage with the desired magnitude value with a THD of 1.72 %. The output current’s THD is lower than that of the output voltage with 0.45 %, because the inductance of the load has reduced the current harmonics too. The discrete duty ratios for case 2 depending on the simple control law according to (7) and the control law supported by the PI controller that produces the real duty ratio for voltage regulation operation are interpolated in MATLAB. The interpolated duty ratios and the related input and reference voltages are given together in Fig. 13.

Fig. 12 – Simulation results for case 2.

For case 3 the input voltage’s fundamental harmonic magnitude is 100 V and does not include a harmonic component, the desired output voltage magnitude is 150 V and the load is an inductive RL load. R is 3 Ω and L is 2 mH. Switching frequency is selected at 50 kHz. The simulation results are given in Fig. 14.

The input voltage has an ideal sinusoidal waveform. The desired output voltage magnitude value is higher than the input voltage. So the voltage regulator has been operated in boost converter mode. The output voltage meets the desired output voltage with a 1.53 % THD. The output current’s THD is 0.42 %. The discrete duty ratios for case 3 depending on the simple control law according to (7) and the control law supported by the PI controller that produces the real duty ratio for voltage regulation operation are interpolated in MATLAB. The interpolated duty ratios and the related input and reference voltages are given together in Fig. 15.

As shown in Fig. 14 the input voltage has an ideal sinusoidal wave form. The desired output voltage magnitude value is higher than the input voltage. So the voltage regulator has been operated in boost converter mode. The output voltage meets the desired output voltage with a 1.53 % THD. The output current’s THD is 0.42 %.

The simulation results are demonstrated in Fig. 16 for case 4, where input voltage’s fundamental harmonic magnitude is 75 V and includes voltage fluctuations (spikes). The desired output voltage magnitude is 100 V and the load is a capacitive RC load. R is 3 Ω and C is 2 mF. Switching frequency is selected at 50 kHz.

Figure 16 shows that the input voltage has a non-sinusoidal waveform and includes harmonics caused by spikes with an 8.44 % THD. The desired output voltage magnitude value is higher than the input voltage. So the voltage regulator has been operated in boost converter mode. The output voltage provides the desired output voltage magnitude value with a 1.08 % THD. The THD of
the output current is obtained as 1.07%. The discrete duty ratios for case 4 depending on the simple control law according to (7) and the control law supported by the PI controller that produces the real duty ratio for voltage regulation operation are interpolated in MATLAB. The interpolated duty ratios and the related input and reference voltages are given together in Fig. 17.

Fig. 17 – Duty ratios obtained by simple control law and control law supported by the PI controller for case 4.

The results show that the proposed single-phase ac voltage regulator is capable of regulating different input voltages at the output with THD ratios lower than the IEEE standard of 5% at different load conditions. From the results of the duty ratio, it is clear that the control law duty ratios are obtained close to the real operation duty ratios. So, the control law provides the PI controller to compensate the system operation efficiently. The different operation results in different conditions show that the control law based control strategy allows the proposed voltage regulator to operate in a stable manner.

5. CONCLUSION

In this paper a novel buck-boost converter type single-phase ac voltage regulator is proposed. The proposed voltage regulator is capable of regulating the input ac voltage through both bucking and boosting in a wide range with high quality without needing a coupling transformer. It has a simple structure including only two passive elements and two bidirectional active switches. The regulator circuit operation is based on the control law of duty ratio that supports the controller to improve the operation efficiency for sudden input voltage fluctuations and different load conditions. The proposed circuit topology is tested by simulation for different input voltage and load conditions. The obtained results have proved that the proposed voltage regulator is accurate and efficient in regulating the input voltage by bucking and boosting resulting in a high quality output voltage with an acceptable THD ratio.

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