A New Transformerless Single-Phase Buck-Boost AC Voltage Regulator

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***Abstract*—Voltage regulation is one of the important goals for electrical sources and consumers. In this paper a new transformerless single-phase AC voltage regulator based on buck-boost converter topology is presented. The regulator circuit has a simple structure using only two bidirectional active switches, one inductor and one capacitor. A closed loop control system is implemented for the proposed regulator operation. A control law depending on the instantaneous values of the regulator's real input and desired output voltage is obtained and supports the PI controller. The control law allows the controller to obtain efficient pulse width modulation (PWM) switching duty ratio for the desired output voltage when the input voltage has surges or fluctuations and the output load is changed. An experimental laboratory setup has been implemented for the proposed AC voltage regulator. The obtained results demonstrate that the proposed topology is capable of and efficient for both bucking and boosting the input AC voltage to a high quality output voltage with a low total harmonic distortion (THD) for different input voltage and load conditions.**

***Index Terms*—AC voltage regulator, buck-boost converter, PWM, THD.**

I. Introduction

Electrical power quality is a main purpose for consumers in power systems. Power quality strictly depends on the supply voltage characteristics [1]. A supply voltage, should have a desired magnitude and ideally not include harmonics. In practice, voltage magnitudes of the supply nodes are forced to change due to loading of the power lines. On the other hand, nonlinear loads, system faults and transient dynamics cause harmonic distortions and surges in voltage waveforms [2].

Increasing development of the solid-state power electronics switches leads the researchers to this area for voltage regulation solutions. Fast switching capabilities of power electronics based converters 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. [3] and Tsai [4] have proposed single-phase AC/DC/AC voltage regulator converters. These topologies convert AC input to DC output via a rectifier and after that DC output generates AC output through an inverter. The structure in [4] 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 [5] 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 transformer are used, so harmonic level is too high. In the studies given by [6]-[10] PWM AC chopping is supported with a coupling transformer to snub the harmonics of the chopped wave form. However, harmonic distortions cannot be reduced enough in these studies. Zhou et al. [11] have proposed a converter that uses a zero voltage/current switching technique for three-phase voltage regulation. The converter consists one active switch, one inductor and two capacitors for each phase. Dantas et al. [12]-[13] have presented single ended primary inductor converter based topology for single-phase regulation using four active switches, two inductors and two capacitors. Reis et al. [14] have proposed a single-phase line conditioner and Ahmed et al. [15] 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 [14], while two active switches, three diodes and one RC filter are used for each phase in [15]. Ćuk converter topology is adapted for AC voltage regulation using four active switches, four diodes, two inductors, and two capacitors [16]. Nan et al. [17] have given a single-phase AC voltage regulator based on the buck converter topology which uses 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 [18] 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 [19]-[23]. Khan et al. [24] and Wu et al. [25] 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. And controllers for 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. High speed MOSFETs are used as active switches in the topology. The closed-loop PI controller is supported with a control law determined by the instantaneous real input and desired output voltages values. Thus, the efficiency and the stability of the desired output voltage is provided for sudden surges of the input voltage and different

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load conditions. An experimental laboratory setup is performed for the proposed topology. Detailed experimental results are given to show the efficiency and the accuracy of the proposed topology on both bucking and boosting the AC input voltage for a desired output voltage with an acceptable THD ratio.

II. The Proposed Circuit Topology

The circuit topology of the proposed single-phase AC voltage regulator is given in Fig. 1. In Fig. 1, $V_i(t)$, $V_o(t)$ $I_o(t)$ and $I_L(t)$ represent the input AC voltage, the output AC 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 by controlling the S_1 switch [26]. When S_1 is turned on while S_2 is off, 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 [27].

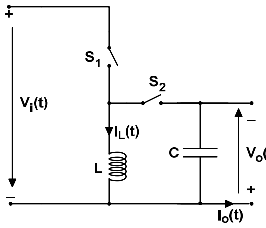

Figure 1. Topology of the proposed buck-boost type AC voltage regulator

According to the switching frequency of S_1 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

$$d = \frac{t_{on-S_1}}{t_{on-S_1} + t_{off-S_1}} = \frac{t_{on-S_1}}{T_{S_1}} \tag{2}$$

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

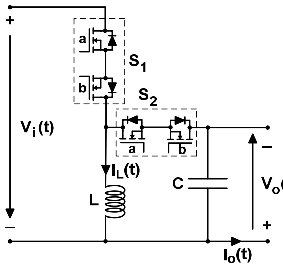

Figure 2. AC voltage regulator circuit using MOSFETs for bidirectional active switches

In this study, high speed MOSFETs 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 which uses MOSFETs according to Fig. 2.

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

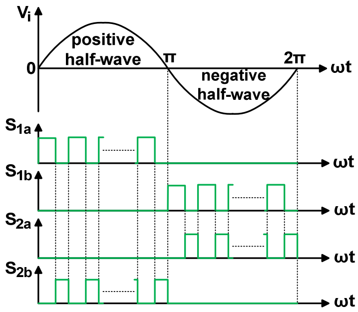

Figure 3. Switching pattern of the MOSFETs of the bidirectional switches

III. 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 [28]. 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.

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

$$V_{ref}(t) = V_r \sin \omega t \tag{3}$$

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;

$$d(t) = d_{CL}(t) + d_{PI}(t) \tag{4}$$

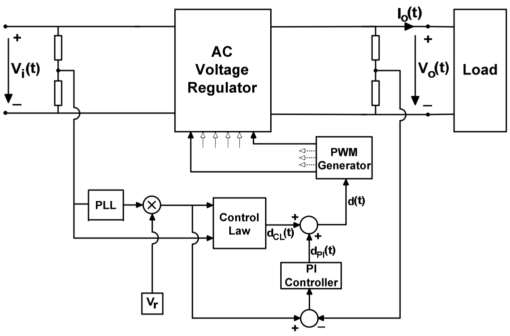

Figure 4. Control structure of the proposed AC voltage regulator

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

$$d_{CL}(t) = \frac{V_r \sin \omega t}{V_r \sin \omega t + V_i(t)} \tag{5}$$

The description of the open-loop duty ratio called as the control law is determined for a certain switching period (T_{S_1}). This means that (5) is defined as constant during each switching period time. So, assuming that the operation duty ratio is obtained through only the control law, (5) must be sampled for the switching period and thus the control law can be modified as

$$d_{CL}(kT_{S_1}) = \frac{V_r \sin \omega k T_{S_1}}{V_r \sin \omega k T_{S_1} + V_i(kT_{S_1})} \qquad (k = 0, 1, 2, \ldots) \tag{6}$$

or simplified to

$$d_{CL}(k) = \frac{V_r \sin \omega k}{V_r \sin \omega k + V_i(k)} \tag{7}$$

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. Thus, obtaining the accurate operation duty ratio is achieved.

The PI controller is designed through the mathematical model of the proposed voltage regulator. Fig. 5 demonstrates the equivalent circuit of the buck-boost converter based single phase AC voltage regulator. In the figure, $I_C(t)$, R, r_L and r_{on} indicate the capacitor current, load resistance, parasitic resistance of the inductor and the total turn on resistance of the active switches, respectively.

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

$$L\frac{dI_L(t)}{dt} = -I_L(t)(r_L + r_{on}) + V_i(t) \tag{8}$$

$$C\frac{dV_o(t)}{dt} = \frac{V_o(t)}{R} \tag{9}$$

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

$$L\frac{dI_L(t)}{dt} = -I_L(t)(r_L + r_{on}) - V_o(t) \tag{10}$$

$$C\frac{dV_o(t)}{dt} = -I_L(t) + \frac{V_o(t)}{R} \tag{11}$$

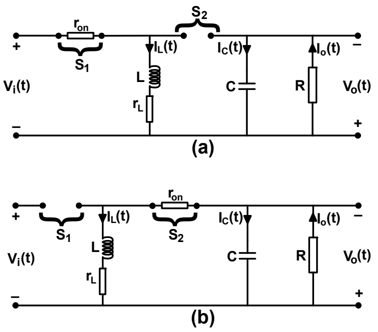

Figure 5. Equivalent circuit of the proposed single phase AC voltage regulator: (a) S_1 is on and S_2 is off (mode I), (b) S_1 is off and S_2 is on (mode II)

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

$$\frac{d}{dt}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} -(r_L + r_{on})/L & 0 \\ 0 & 1/RC \end{bmatrix}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_i(t) \tag{12}$$

$$\frac{d}{dt}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} -(r_L + r_{on})/L & -1/L \\ -1/C & 1/RC \end{bmatrix}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_i(t) \tag{13}$$

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

$$\frac{d}{dt}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} -(r_L + r_{on})/L & -(1-d)/L \\ -(1-d)/C & 1/RC \end{bmatrix}\begin{bmatrix} I_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} d/L \\ 0 \end{bmatrix} V_i(t) \tag{14}$$

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.

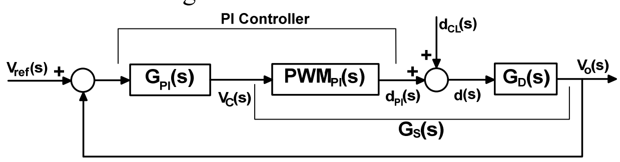

Figure 6. Closed-loop control block diagram of the system

From Fig. 6, the transfer function between $V_o(s)$ and $d(s)$ is derived as

$$G_D(s) = \frac{V_o(s)}{d(s)} = \frac{-V_i(s)(1-d)}{s^2 LC(r_L + r_{on}) - s\frac{L}{R}(r_L + r_{on}) - (1-d)^2} \tag{15}$$

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,

$$d_{PI}(s) = d(s) \tag{16}$$

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

$$PWM_{PI}(s) = \frac{d(s)}{V_C(s)} = \frac{1}{V_{PWM}} \tag{17}$$

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,

$$G_S(s)=\frac{V_o(s)}{V_C(s)}=\frac{-V_i(s)}{V_{PWM}}\frac{(1-d)}{s^2LC(r_L+r_{on})-s\dfrac{L}{R}(r_L+r_{on})-(1-d)^2} \tag{18}$$

PI controller has a dynamic behavior and it requires a response time. In this study, the proposed AC voltage regulator is also aimed to regulate the input voltage 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.

IV. EXPERIMENTAL RESULTS

An experimental laboratory setup is implemented for the proposed buck-boost converter based voltage regulator topology to show its accuracy and efficiency. Fig. 7 shows the hardware implementation of the experimental laboratory setup. The inductor's value is selected enough smaller with the value of 56 µH to minimize the phase shift. The capacitor is selected enough smaller with the value of 180 µF to enable the output voltage to be changed quickly where the output resistances values are high. The PI controller is designed as digital and it is executed in the microcontroller. The discrete PI controller coefficients are obtained through the discrete transfer function of the controller that is transformed from the s-domain transfer function of the controller given in (18). The discrete proportional and integral coefficients of the controller are obtained as $K_P=0.00275$ and $K_I=0.01324$, respectively.

Figure 7. Experimental laboratory setup for the proposed AC voltage regulator based on buck-boost converter topology

The proposed single-phase AC voltage regulator based on the buck-boost converter has been tested at different input voltage and load conditions through the given experimental laboratory setup. Results for both input voltage, output voltage and output current waveforms are given together. THD ratios for both input voltage, output voltage and output current waveforms are calculated in MATLAB through the digital values of the waveforms obtained from the oscilloscope.

Fig. 8 demonstrates the experimental results of the proposed voltage regulator operation for case 1. In case 1 input voltage is obtained from the 50 Hz network and has 80 V magnitude. The desired output voltage magnitude is 60 V. The load is resistive and its value is 10 Ω. Switching frequency is selected as 50 kHz.

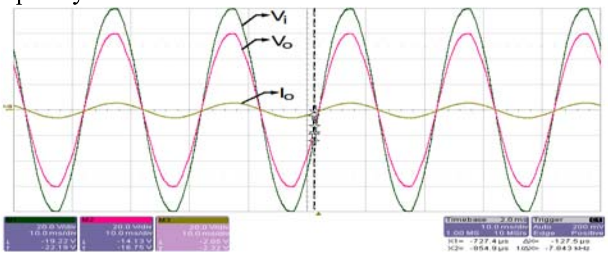

Figure 8. Experimental results for case 1

As shown in Fig. 8 the input voltage has a nearly ideal sinusoidal waveform including harmonics with 0.11% 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 (close to ideal) sinusoidal AC input voltage to an output voltage with the desired magnitude value and a THD of 0.97%. It is clear that THD value of the output voltage is higher than THD value of the nearly sinusoidal input voltage, as the input voltage is distorted by switching. This situation is the nature of all solid-state converters. But it is obvious from the results that the output voltage of the proposed voltage regulator has a negligible THD value with high quality. As the load is resistive, the output current's THD value obtained is the same as that of the output voltage. Fig. 9 and Fig. 10 show the inductor currents and the control signals of the MOSFETs for case 1 when the input voltage is positive and negative, respectively.

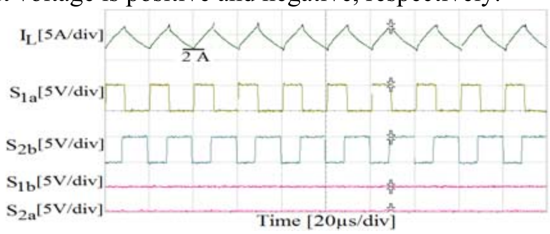

Figure 9. Switching signals and inductor current measurements during positive half-wave of the input voltage for case 1

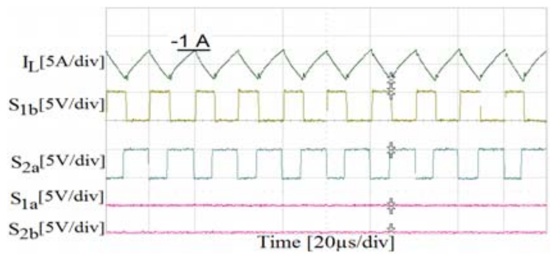

Figure 10. Switching signals and inductor current measurements during negative half-wave of the input voltage for case 1

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 which produces the real duty ratio for the voltage regulation operation are transferred from the microcontroller to the PC and are plotted in MATLAB. The plotted duty ratios and the related input and reference voltages are given together 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.

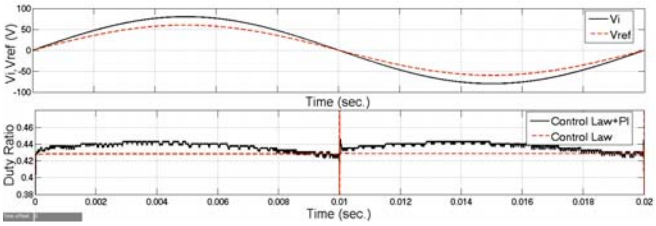

Figure 11. Duty ratios obtained by simple control law and control law supported by the PI controller for case 1

In Fig. 12 the experimental results are given for case 2 where the input voltage is obtained from the 50 Hz network and has 50 V magnitude, the desired output voltage magnitude is 75 V and the load is a serial inductive RL load where R=10 Ω and L=35 mH. Switching frequency is selected as 50 kHz.

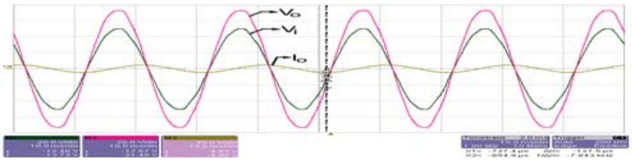

Figure 12. Experimental results for case 2

The input voltage has a nearly ideal sinusoidal waveform including harmonics with a 0.11% 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 AC voltage regulator has produced an output voltage with the desired magnitude value with a 1.28% THD. The output current's THD obtained is lower than the output voltage's as 0.53%, because the inductance of the load has effected to snub the current harmonics. 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 which produces the real duty ratio for the voltage regulation operation are transferred from the microcontroller to the PC and are plotted in MATLAB. The plotted duty ratios and the related input and reference voltages are given together in Fig. 13.

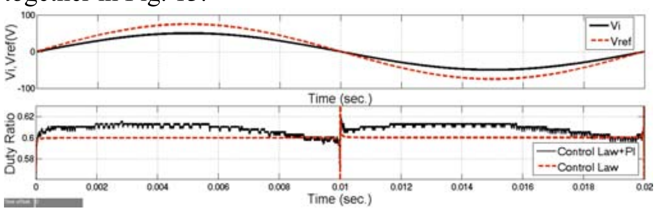

Figure 13. Duty ratios obtained by simple control law and control law supported by the PI controller for case 2

For case 3 the input voltage is obtained through an inverter, its fundamental harmonic magnitude is 65 V with 50 Hz and includes harmonic components. The desired output voltage magnitude is 45 V and the load is a serial inductive RL load where R=3 Ω and L=12 mH. Switching frequency is selected as 50 kHz. The experimental results are given in Fig. 14.

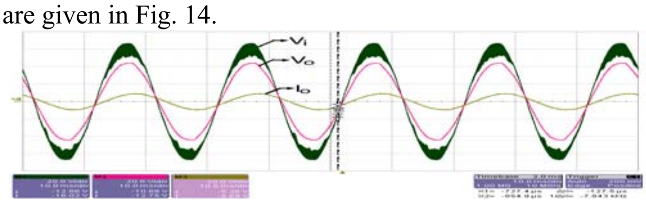

Figure 14. Experimental results for case 3

As shown in Fig. 14, the input voltage has a non-sinusoidal waveform including harmonics with a 7.43% 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 output voltage meets the desired output voltage with a 2.01% THD. The output current's THD is 0.88%. 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 which produces the real duty ratio for the voltage regulation operation are transferred from the microcontroller to the PC and are plotted in MATLAB. The plotted duty ratios and the related input and reference voltages are given together in Fig. 15.

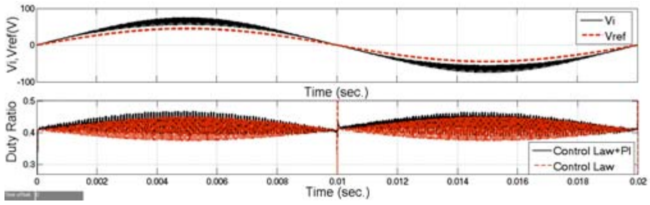

Figure 15. Duty ratios obtained by simple control law and control law supported by the PI controller for case 3

The experimental results are demonstrated in Fig. 16 for case 4 where the input voltage is obtained through an inverter, its fundamental harmonic magnitude is 35 V with 50 Hz and includes harmonic components. The desired output voltage magnitude is 70 V and the load is a serial capacitive RC load where R=5 Ω and C=14 μF. The switching frequency is selected as 50 kHz.

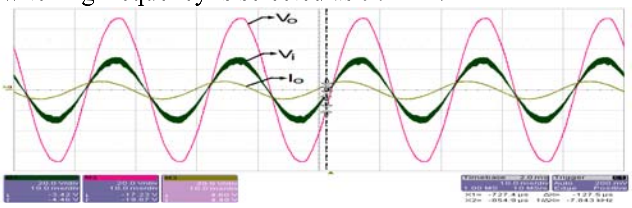

Figure 16. Experimental results for case 4

Fig. 16 shows that the input voltage has a non-sinusoidal waveform including harmonics with a 7.45% 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 2.27% THD. The THD of the output current is obtained as 1.35%. 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 which produces the real duty ratio for the voltage regulation operation are transferred from the microcontroller to the PC and are plotted in MATLAB. The plotted duty ratios and the related input and reference voltages are given together in Fig. 17.

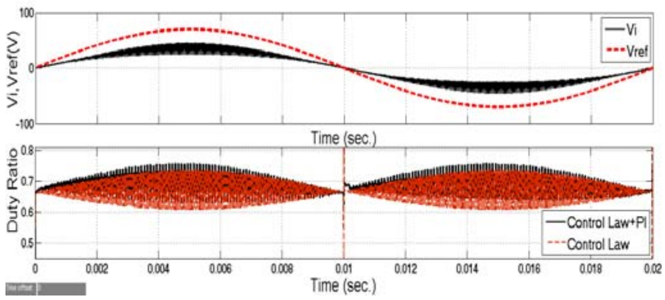

Figure 17. Duty ratios obtained by simple control law and control law supported by the PI controller for case 4

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 ratios depending on the simple control law and the real operation duty ratios, 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.

V. Conclusions

This paper proposes a novel transformerless single-phase AC voltage regulator based on buck-boost converter topology. The proposed voltage regulator circuit is efficient on regulating the input AC voltage in a wide range with high quality where the desired output voltage is lower or higher than the input. The regulator structure is simple and includes only two bidirectional active switches and two passive elements. Closed loop regulator circuit operation is based on a control law for the duty ratio that supports the controller to improve the operation efficiency for different input voltage and load conditions. The proposed regulator circuit is tested experimentally for different system conditions. The obtained experimental results have shown that the proposed AC voltage regulator is accurate and efficient on regulating the input voltage by bucking and boosting to an output voltage of high quality with an acceptable THD ratio.

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