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A New Single Phase Inverter Based on Buck Converter

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Abstract

In this paper, a new single phase inverter is proposed. The proposed inverter topology is obtained through modifying the well-known DC-DC buck converter to produce sine wave alternative voltage at the output. Thus, the peak value of the alternative output voltage can be provided lower than the input direct voltage value. The inverter is designed for producing alternative voltage at the output in the frequency range of 0-50 Hz. PI feedback controller is used for the control of the inverter operation. A simulation study is done for the proposed inverter and its operation in MATLAB-Simulink in order to prove its accuracy on different operation conditions. The results demonstrate that the proposed inverter can accurately produce nearly sine wave alternative voltage in various frequencies with low THD values on different operation conditions.

Keywords: single phase inverter, buck converter, THD, harmonics

1. INTRODUCTION

The inverters are the solid-state power electronics converters that produce alternative voltage from direct voltage and they can find wide application areas in the application such as asynchronous motor control, renewable energy sources, uninterruptible power supplies and power systems [1, 2]. The produced output voltage of the inverter must be as possible as close to sine wave

including low total harmonic distortion (THD) to provide voltage quality [3]. According to the international standards, THD values of the alternative voltages have to be less than 5% [4].

The most traditional inverters are pulse width modulation (PWM) inverters and they are widely used in industrial applications [5]. In general, the output voltage wave forms of PWM inverters are far from sine wave because of the natural

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technique of PWM technique. However, there are many techniques to reduce the THD levels of the PWM based inverters such as sine-triangle wave comparison method [6] and selective harmonic elimination method (SHEM) [7]. In order to close the output voltage wave form to sine wave, pulse amplitude modulation (PAM) inverters are developed as an alternative instead of PWM inverters [8]. In PAM inverters, various voltage steps are produced through series connected more than one inverters or cascade connected capacitor sets. Although the PAM inverters are better than PWM inverters in terms of producing high quality output voltage, it is clear that the PAM inverters require more components, so, more physical area and cost. The main advantage of the PWM and PAM inverters is the simple controllability because the output voltage wave forms are not dependent of the load.

In recent years, switch mode inverters derived from the DC-DC converters are increasingly researched. There many topologies for boost [9], buck-boost [10] and Ćuk [11] inverters in the literature and they are successfully studied. Switch mode operation structure and naturally consisting low pass filter of these inverters provide producing closely to sine wave output voltage with low THD levels according to the PWM and PAM inverters. On the other hand, the output voltages of these inverters strictly depend on the load. So, difficult feedback control according to the PWM and PAM inverters is required for these switch mode inverters. Buck converter based single phase inverters are also studied well in the literature. Different type topologies and control techniques for the buck inverters are proposed [12-16]. In these studies, the aim of developing various topologies is enhancing the output voltage quality while reducing the number of circuit elements.

In this study, a new type buck converter based single phase inverter is proposed. The proposed inverter topology has reduced number of elements with 8 active switches, 1 inductor and 1 capacitor. The proposed inverter is controlled by a PI feedback controller. The study is tested as simulation for different test cases on MATLAB-Simulink.

2. THE PROPOSED INVERTER

In this section, the proposed single phase buck converter topology, operation procedure, dynamic analysis and control structure are given.

2.1. The Inverter Topology

The general representation of the proposed buck inverter circuit topology can be shown in Fig. 1 [17]. E , $V_i(t)$, $V_s(t)$, $V_o(t)$, L and C define the direct voltage source, inverter input voltage, input voltage of S_5 switch, inverter output voltage, the inductor and the capacitor, respectively in Fig. 1. The direct voltage source can produce a time-variant voltage, but in this paper the direct voltage source is considered as a battery. So, the input voltage of the inverter can be given as,

$$V_i(t) = E \quad (1)$$

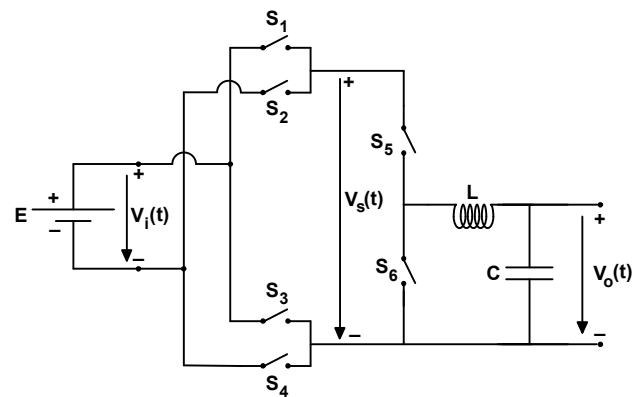


Figure 1. General representation of the inverter circuit topology

In Fig. 1, S_1 , S_2 , S_3 , S_4 switches are unidirectional switches and S_5 , S_6 switches are bidirectional active switches. The proposed inverter circuit using MOSFETs for the mentioned switches is shown in Fig. 2.

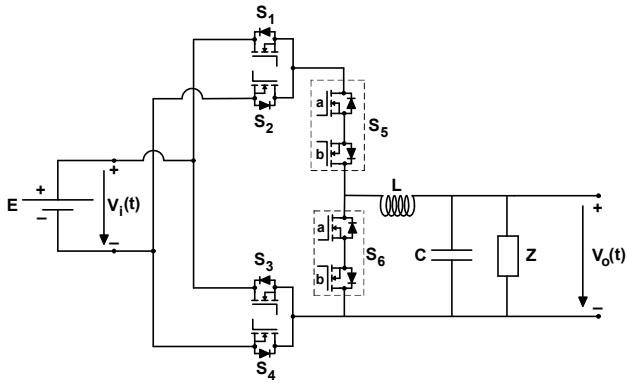


Figure 2. Proposed inverter circuit with MOSFETs

Z defines the load at the output of the inverter in Fig. 2 and it can be ohmic, inductive or capacitive.

2.2. The Procedure of the Inverter Operation

The procedure of the inverter operation can be given by the general topology shown in Fig. 1. The main energy transfer operation is based on the well-known DC-DC buck converter. As similar to the DC-DC buck converter, PWM duty ratio of S_5 switch (d) determines the relationship between the amplitudes of input and output voltages. When S_5 is turned on, S_6 is turned off. During this PWM on stage, $V_s(t)$ supplies the inductor, the capacitor and the load. So, the inductor and the capacitor are energized. S_6 is turned on and S_5 is turned off during PWM off stage. In this stage, the previously energized inductor and capacitor supply the load. Thus, the inverter output voltage is obtained lower than the input voltage depending on the S_5 switch's PWM duty ratio.

S_1, S_2, S_3, S_4 switches determines the polarity of $V_s(t)$ in order to produce alternative voltage at the inverter output. When S_1, S_4 are turned on and S_2, S_3 are turned off, $V_s(t)$ becomes equal to $V_i(t)$ with the same polarity. So, the inverter output voltage $V_o(t)$ can be produced as positive in the determined output polarity in Fig. 1. When S_2, S_3 are turned on and S_1, S_4 are turned off, $V_s(t)$ becomes equal to $V_i(t)$ but with the reverse polarity. So, the inverter output voltage $V_o(t)$ can

be produced as negative in the determined output polarity in Fig. 1. Thus, in both positive and negative output voltage producing stages depending on the control of S_1, S_2, S_3, S_4 switches, ideally sine wave can be obtained through determining the PWM duty ratio of S_5 switch continually.

S_5 and S_6 bidirectional switches are built by two back to back MOSFETs as seen in Fig. 2. In positive half-wave output voltage producing stage, S_{5a} is turned on and S_{5b} is turned off to make S_5 turned on. In negative half-wave output voltage producing stage, S_{5b} is turned on and S_{5a} is turned off to make S_5 turned on. In positive half-wave output voltage producing stage, S_{6b} is turned on and S_{6a} is turned off to make S_6 turned on. In negative half-wave output voltage producing stage, S_{6a} is turned on and S_{6b} is turned off to make S_6 turned on. In both positive and negative half-wave output voltage producing stages, both S_{5a} and S_{5b} switches are turned off to make S_5 turned off. Similarly, both S_{6a} and S_{6b} switches are turned off to make S_6 turned off.

2.3. The Dynamic Analysis of the Inverter

In this section, dynamic analysis of the proposed inverter given in Fig. 2 is done in order to obtain small-signal transfer function of the inverter to be used in the feedback controller design. In the dynamic analysis of Fig. 2, all of the elements are considered as ideal and the load is considered as pure ohmic as R .

The dynamic equations of positive half-wave output voltage producing stage can be derived from Fig. 3. Fig. 3(a) represents the equivalent circuit during on stage of S_5 (S_6 is turned off) and Fig. 3(b) represents the equivalent circuit during off stage of S_5 (S_6 is turned on).

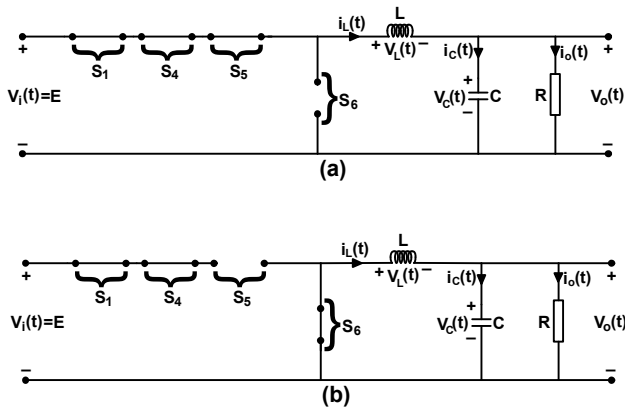


Figure 3. Equivalent circuit of the inverter during producing positive half-wave output voltage (a) On mode – S_5 is on, S_6 is off, (b) Off mode – S_6 is on, S_5 is off

Stage 1 (on state): From Fig. 3(a), the state equations for the inductor current and the output voltage can be derived as below,

$$\frac{di_L(t)}{dt} = -\frac{1}{L}V_o(t) + \frac{1}{L}V_i(t) \quad (2)$$

$$\frac{dV_o(t)}{dt} = \frac{1}{C}i_L(t) - \frac{1}{RC}V_o(t) \quad (3)$$

Stage 2 (off state): From Fig. 3(b), the state equations for the inductor current and the output voltage can be derived as below,

$$\frac{di_L(t)}{dt} = -\frac{1}{L}V_o(t) \quad (4)$$

$$\frac{dV_o(t)}{dt} = \frac{1}{C}i_L(t) - \frac{1}{RC}V_o(t) \quad (5)$$

The state-space equation for on state (stage 1) can be derived from Eq. (2) and (3) as,

$$\begin{bmatrix} \dot{i}_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_i(t) \quad (6)$$

The state-space equation for off state (stage 2) can be derived from Eq. (4) and (5) as,

$$\begin{bmatrix} \dot{i}_L(t) \\ V_o(t) \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_o(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_i(t) \quad (7)$$

During negative half-wave producing operation of the inverter, just only, S_2 and S_3 replaces instead of S_1 and S_4 switches in Fig. 3. And so, $V_i(t)$ and the other voltage/current representations change their polarities/directions. In this case, the state-space equations are the same as obtained in Eq. (6) and (7).

By using the state-space equations derived by Eq. (6) and (7), linearized small-signal transfer function between the PWM duty ratio of S_5 switch d and the inverter output voltage $V_o(t)$ can be derived as,

$$G_s(s) = \frac{\hat{V}_o(s)}{d(s)} = \frac{\bar{V}_i}{LC} \frac{1}{s^2 + \frac{s}{RC} + \frac{1}{LC}} \quad (8)$$

In Eq. (8), \bar{V}_i defines the input voltage value at the operation point.

2.4. The Control Structure of the Inverter

The control structure of the inverter can be represented by Fig. 4.

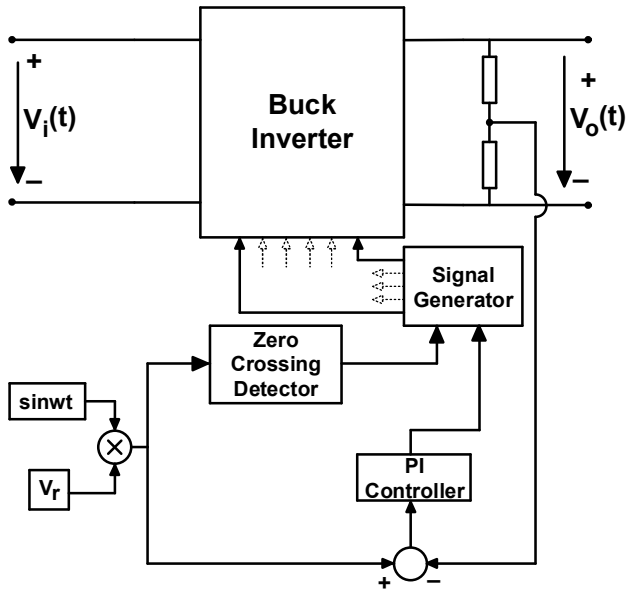


Figure 4. General inverter control structure

V_r represents the peak value of the reference output voltage that is lower than the inverter input voltage $V_i(t)$ in Fig. 4. From the figure, reference output voltage can be defined as below,

$$V_{ref}(\omega t) = V_r \sin \omega t \quad (9)$$

In Eq. (9), ω represents the angular frequency. So, the desired output voltage frequency is determined by ω . Thus, Eq. (9) determines both the desired frequency and amplitude of the inverter output voltage together. The signal generator generates the control signal of all of the active switches. The zero crossing detector detects the zero crossing points of the reference output voltage and determines the alternation of it. When the zero crossing detector determines the reference output voltage in positive half-wave, signal generator generates on signal for S_1, S_4 switches and generates off signal for S_2, S_3 switches. When the zero crossing detector determines the reference output voltage in negative half-wave, signal generator generates off signal for S_1, S_4 switches and generates on signal for S_2, S_3 switches.

The PI feedback controller compensates the error between reference and actual output voltages and eliminates the error. Thus, it provides to obtain desired duty ratio of S_5 switch (d) to produce the

reference voltage at the output of the inverter. The control block diagram of the closed loop inverter operation system can be given in Fig. 5.

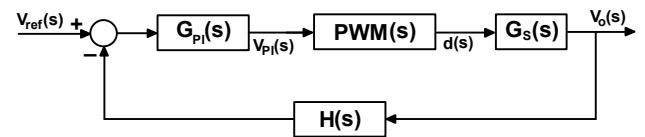


Figure 5. Control block diagram of the inverter

In Fig. 5, $G_{PI}(s)$, $PWM(s)$ and $H(s)$ define the transfer functions of PI controller, measurement stage and PWM stage of duty, respectively. $G_{PI}(s)$ is described as,

$$G_{PI}(s) = K_p + K_i / s \quad (10)$$

3. THE SIMULATION RESULTS

In order to prove the accuracy of the proposed inverter and its control, a simulation study is done in MATLAB-Simulink. Switching frequency of S_5 switch is selected as $f_s = 20kHz$. The study is tested on three different cases.

Test case 1: In case 1, inverter input voltage is selected as 75V. The amplitude and the frequency of the desired sine wave inverter output voltage are determined as 30V and 50Hz, respectively. A pure ohmic load with the value of 3Ω is connected to the inverter output. The obtained voltage and current wave forms of the inverter output for case 1 are given in Fig. 6.

As seen from Fig. 6, the desired output voltage is obtained at the output of the inverter closely to sine wave with the determined amplitude and frequency. THD value of the output voltage is measured as $THD_V=1.547$. As the load is pure ohmic, THD value of the output current is measured identical to THD_V as $THD_I=THD_V=1.547$.

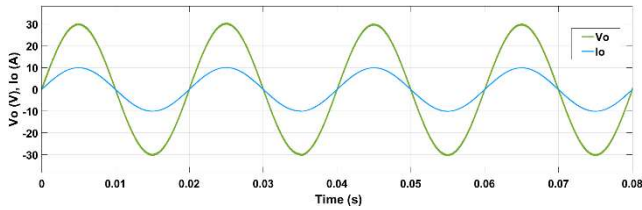


Figure 6. Inverter output wave forms for case 1

Test case 2: In case 2, inverter input voltage is selected as 90V. The amplitude and the frequency of the desired sine wave inverter output voltage are determined as 50V and 30Hz, respectively. An inductive load with the resistor value of 7Ω and the inductor value of 4.7mH is connected to the inverter output. The obtained voltage and current wave forms of the inverter output for case 2 are given in Fig. 7.

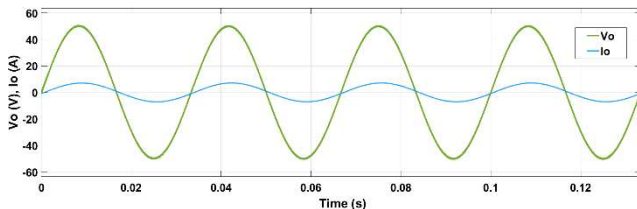


Figure 7. Inverter output wave forms for case 2

As seen from Fig. 7, the desired output voltage is obtained at the output of the inverter closely to sine wave with the determined amplitude and frequency. THD value of the output voltage is measured as $THD_V=1.763$. THD value of the output current is measured as $THD_I=0.459$. It is clear that the inductive characteristic of the load reduces the high order harmonics of the output current.

Test case 3: In case 3, inverter input voltage is selected as 110V. The amplitude and the frequency of the desired sine wave inverter output voltage are determined as 90V and 10Hz, respectively. A capacitive load with the resistor value of 5Ω and the capacitor value of 10mF is connected to the inverter output. The obtained voltage and current wave forms of the inverter output for case 3 are given in Fig. 8.

As seen from Fig. 8, the desired output voltage is obtained at the output of the inverter closely to sine wave with the determined amplitude and frequency. THD value of the output voltage is measured as $THD_V=1.665$. THD value of the output current is measured as $THD_I=3.452$. It is

clear that the capacitive characteristic of the load increases the high order harmonics of the output current.

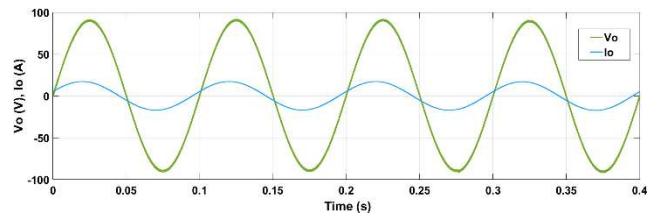


Figure 8. Inverter output wave forms for case 3

The simulation results show that the proposed inverter can produce close to sine wave output voltage with low THD values in various frequencies on different input and output operation conditions.

4. CONCLUSION

This study presents a novel single phase inverter based on buck converter. The inverter can produce alternative voltage at the output in the frequency range of 0-50 Hz close to sine wave. The simulation results on MATLAB-Simulink prove that the proposed inverter can successfully produce close to sine wave inverter output voltage in various frequencies with low THD values less than 5% on different operation conditions. The comprehensive experimental design study of the proposed inverter is still being proceeded on a supported research project given in the acknowledgements.

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