Analyzing and Modeling of a New Resonance Inverter for Low Power Vehicular Application

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Abstract—In this paper we proposed a novel inverter to convert a DC voltage to a desired AC voltage. This inverter is designed for variable inductive loads and low output power applications. We proposed a novel simple PWM method which enables the inverter to keep the output current at six times more than the rated output current, without reducing output voltage value. In addition, based on a simple use of resonance in the circuit, the new inverter can raise the output voltage to extremely high amplitude for a relatively short time. These characteristics make the proposed inverter useful for some industrial applications such as electrical vehicle. The new configuration of the circuit consists of a unidirectional switch, two inductors (to transfer energy), a fast diode and a capacitor. With very few elements, this system changes the input DC voltage to a desired sinusoidal AC voltage. Some advantages of this system are: number of power electronics devices is low – it only uses a simple switch; it does not need dead time, in spite of conventional inverters which need a dead time between switches to prevent from short-circuiting; volume of the circuit is very small; the total harmonic distortion (THD) is greatly reduced; and it works with high efficiency. Another advantage of this inverter is capability of the circuit in boosting or bucking the input voltage to a desirable output voltage without using any DC-DC converters. It is flexible in keeping output voltage constant when the output current is increased, and it can produce the extremely higher output voltage than input voltage. The main drawback of the method, compared with conventional voltage source inverters, is that it uses more energy storage elements in spite of its low volume of power. We used simulations to prove all these statements.

Keywords—SPWM inverter; minimizing component; single switch inverter; DC-AC converter; inverter; vehicular applications

I. INTRODUCTION

The main objective of static power converters is to produce an AC output waveform from a DC power supply. AC waveforms are required in adjustable speed drives (ASDs), uninterruptible power supplies (UPS), static VAR compensators (SVC), active filters, flexible AC transmission systems (FACTS), voltage compensators, etc. For sinusoidal AC outputs, we need to control the magnitude, frequency, and phase. Some characteristics that define the performance and efficiency of the inverter are small size, simple control system, low voltage stress, low input current ripple, simplicity of circuit, low total harmonic distortion (THD), low cost, and controllable output voltage. To achieve all these demands, for both DC-DC and DC-AC converters, several circuit topologies have been presented in literature [1-13]. Also, multilevel inverters have been proposed in recent years [14,15], but their additional components and circuit complexity, reduce both overall efficiency and reliability of the system, and may increase the cost of the power electronic interface. There are different attempts to reduce losses in switches with soft-switching method [16], but this method also adds extra components to circuit and makes it more complex.

In this paper, we proposed a novel inverter which eliminates some of the disadvantages. The novel inverter has only one switch – which reduces energy loss and costs – and has just one simple control system, which can be controlled with a simple microcontroller. Circuit is simple and its size is greatly reduced. Because of a single switch, dead time is not needed between the switches. Also, the output sinusoidal voltage is controlled easily. Finally, its total harmonic distortion is proved to be very low using simulation results. Some of disadvantages of the new inverter are discontinuities in input current and relatively high voltage stress.

This paper is organized as follows: in section II, the circuit structure is presented; in section III, modeling and numerical analysis are illustrated; in section IV, simulation results and diagrams verify our claims; finally, conclusion is in section V.

II. THE CIRCUIT STRUCTURE

A. Inverter Circuit

Circuit of the new inverter is illustrated in Fig. 1. The circuit converts a DC voltage to a desired AC output voltage and consists of five main components: two inductors for transferring energy, a simple switch, a fast diode and a capacitor. Element $R_i$ is the resistance modeled for inductor $L_i$. It has a considerable effect on system performance. The circuit is presented for inductive and resistive loads. This novel single-switch inverter and its components are considered ideally; in real exploitation, efficiency will significantly drop. Also, we supposed that input DC source does not have any resistance and it supplies current without decline in the voltage value. Diode is very fast and does not cause voltage drop.
The circuit has only two modes: when the switch is turned on and when the switch is off. These two modes are shown in Fig. 2(a) and Fig. 2(b). In these figures, the current path is drawn with bold line.

**B. Method of Gate Pulses**

In this subsection we explain our method of switching. In the simulation, gate pulses are modeled by comparing a triangular and a sinusoidal control signal as shown in Fig. 3. The gate pulse is 5 volts if (1) is applied and is 0 volts if (2) is applied.

- **Switch on** → \( V_{control} > V_{triangular} \) (1)
- **Switch off** → \( V_{control} < V_{triangular} \) (2)

In general, one of the objectives of a pulse width modulation (PWM) technique is to create a train of switching pulses with the same volt-second average as a reference-modulation signal.

The frequency of control voltage is \( f_{control} \), which can directly control the output voltage frequency, and the frequency of triangular signal is \( f_{triangular} \). The number of samples per each period can be defined as (3).

\[
\begin{align*}
{n} &= \frac{f_{triangular}}{f_{control}} \\
\end{align*}
\]

In order to get a better view of the simulation, the frequency of triangular signal is set to 1 KHz and the frequency of sinusoidal control voltage is 50 Hz. Thus, based on (4), the number of samples is 20 in each period and the frequency of gate pulse is 1 KHz, which is not a high frequency.

\[
\begin{align*}
{n} &= \frac{1KHz}{50Hz} = 20 \\
\end{align*}
\]

Although by increasing the frequency of triangular voltage, the number of samples is increased – that causes a better output voltage, lower THD and lower filter – system performance in this frequency shows a low THD value, suitable for the mentioned applications. For a better view of performance of the pulses and how they cause sinusoidal voltage in output, Fig. 4 is shown. In this figure, the three signals and the output voltage are shown at the same time. The parameters of the circuit have been adjusted to give the shown voltage. So, output voltage which is shown with black color is not the rated voltage and is drawn just to give a better view.

To adjust the amplitude of output voltage to a desired sinusoidal voltage, \( m_a \) is defined as:

\[
\begin{align*}
{m_a} &= \frac{V_{control}}{V_{triangular}} \\
\end{align*}
\]

In this circuit, \( m_a \) is set to 0.5 to get the rated voltage in output. The value of \( m_a \) can change based on user preferences. Therefore, the output voltage can be controlled by this term from zero (when \( m_a = 0 \)) to twice the rated voltage (when \( m_a = 1 \)). Fig. 5 shows two different \( m_a \)s for controlling the output voltage amplitude.

In Fig. 5(a) output voltage increases to twice the rated voltage and in Fig. 5(b) output voltage is the rated value.
III. MODELING AND NUMERICAL ANALYSIS

A. Modeling of the Proposed Structure

As mentioned in the previous section, the proposed circuit has two independent modes. Based on Fig. 2, these two modes can be shown as Fig. 6(a) and Fig. 6(b). In Fig. 6(a) switch is on and is ideally closed, so the diode can be omitted and the switch can be substituted by a wire. In this figure, the left section of the circuit – which consists of input voltage, switch and diode – is changed by a DC voltage for this mode. In second mode, the switch is off, current flows from diode and input voltage is zero, so the circuit can be modeled as Fig. 6(b).

Figure 5. Control and triangular voltages for (a) $m_a = 1$ (b) $m_a = 0.5$.

Figure 6. Shape of the circuit for the proposed system (a) in the first mode (b) in the second mode.

In the first mode of circuit operation, input voltage is $V_{dc}$, while in the second mode it is zero. These situations directly depend on the switch pulses. We define a function for gate pulses that shows the state of the switch as below:

$$
PWM(t) = \begin{cases} 
1, & \text{if } V_{\text{control}} > V_{\text{triangular}} \\
0, & \text{if } V_{\text{control}} < V_{\text{triangular}} 
\end{cases} \quad (6)
$$

Because the states of input voltage are directly based on the gate pulses, (7) is defined for input voltage as:

$$
V_{in}(t) = \begin{cases} 
V_{dc}, & PWM(t) = 1 \\
0, & PWM(t) = 0 
\end{cases} \quad (7)
$$

We can redraw the system as Fig. 7. For better view of $V_{in}(t)$, the input source voltage is shown in Fig. 8. The input DC voltage source is 12 volts. Therefore, $V_{in}(t)$ is exactly the same as Fig. 8. In this figure, the amplitude ratio – which was defined in (5) – is $m_a = 0.5$.

Evaluation of the circuit is shown in Fig. 9. Differential equations of the circuit are as follow:

KVL 1:

$$
-V_{in}(t) + R_1 I_1 + L_1 \frac{dl_1}{dt} + L_2 \frac{dl_2}{dt} = 0 \quad (8)
$$

KVL 2:

$$
-L_2 \frac{dl_2}{dt} + V_c(t) = 0 \quad (9)
$$

KVL 3:

$$
-V_c(t) + R_o I_o + L_o \frac{dl_o}{dt} = 0 \quad (10)
$$

KCL:

$$
I_1 - I_2 - I_c - I_o = 0 \quad (11)
$$

Figure 7. Circuit with the input modeled source as $V_{in}(t)$.

Figure 8. $V_{in}(t)$ for $m_a = 0.5$. 
For easier analysis and modeling, it is better to transfer all of the four equations into Laplace s-domain. In these four equations, which explain the circuit, there are four variable parameters \( I_1(s), I_2(s), I_c(s) \) and \( I_o(s) \). The equations can be rewritten as (12) in the matrix.

\[
\begin{bmatrix}
(\delta + I_1)S & L_2S & 0 & 0 \\
0 & -S L_2 & \frac{1}{\delta S} & 0 \\
0 & 0 & (R_0 + I_o)S & 0 \\
1 & -1 & -1 & -1
\end{bmatrix}
\begin{bmatrix}
V_{in}(t) + L_1(0) + L_2(0) \\
I_{L_1}(0) + \frac{V_{in}(t)}{S} \\
I_{L_2}(0) + \frac{V_{in}(t)}{S} \\
I_o(t)
\end{bmatrix}
\]

Equation \( (12) \)

These equations were solved using MATLAB. To make the analysis easier, we assume that the load is resistive and the resistance \( R_1 \) is put to zero. With these assumptions, \( R_1 \) and \( L_o \) are set to zero. The output current is obtained as:

\[
I_o(s) = \frac{L_o}{L_1CSR^3 + (R_0 + I_o)S^2 + \frac{L_2(R_0 + I_o)}{L_2}S + \frac{RR_0I_o}{L_2}}V_{in}(s). \quad (13)
\]

Regardless of \( R_1 \) value, (13) can be rewritten as:

\[
I_o(t) = \frac{1}{L_1CRD^2 + L_oD}\frac{V_{in}(t)}{L_2}. \quad (14)
\]

where D is differential operator (D = \( \frac{d}{dt} \)).

B. Examination of \( V_o(t) \)

We simulated \( V_o(t) \) in MATLAB Simulink for the following rated values: \( m_o = 0.5, f_{\text{triangular}} = 1 \text{ KHz}, f_{\text{control}} = 50 \text{ Hz} \). The result of FFT analysis for \( V_o(t) \) is illustrated in Fig. 10.

As it is known from Fig. 10, \( V_o(t) \) consists of different harmonics. As expected from Fig. 8, the biggest value is DC part, which is 6 volts. The fundamental harmony (50 Hz) is 3 volts. Harmonics less than 1 KHz are too low and can be neglected. In order to substitute \( V_o(t) \) with Fourier series, harmonics with high frequencies can be neglected because they will be removed with small filter. In fact, harmonics higher than 1 KHz will be removed by \( L_1 \) and \( C_o \). DC part is not seen in the output voltage because it penetrates from \( L_2, L_1 \) and \( R_1 \). Therefore, the output voltage can be substituted by first harmonic. Equation \( (16) \) is obtained from (14) and (15).

\[
V_o(t) = R \times I_o(t) \quad (15)
\]

Finally, the amplitude of the output voltage is:

\[
V_o\,_{\text{rms}}(t) = \frac{3}{\sqrt{2}}\sqrt{L_1CRD^2 + L_oD + \left(\frac{L_1R + L_2R}{L_2}\right)} \quad (17)
\]

The output voltage can be adjusted on the desired magnitude using (17).

IV. SIMULATION RESULTS AND DIAGRAMS

We simulated the new inverter with both PSIM and MATLAB Simulink. The result of PSIM simulation shows agreement with numerical analysis. The circuit simulated in PSIM is shown in Fig. 11.

In order to set the output voltage on 24 volts, the circuit parameters were chosen as follows, based on (17):

\[
L_1 = 1 \times 10^{-3} \text{ H}; L_2 = 3.4 \times 10^{-3} \text{ H}; C = 14 \times 10^{-3} \text{ F}; R = 24 \Omega.
\]

The output voltages and currents for a resistive load and an inductive load are shown, in Fig. 12(a) and Fig. 12(b).
Our novel inverter is simulated for rated value and as shown in Fig. 12, the effective value of the voltage and current is 24 V and 1 A, respectively. The total harmonic distortion for output voltage and current is very small and can be neglected. The output rated apparent power is 24 VA. The output voltage can be easily set on the lower or higher rated value by choosing parameters of (17) or changing the $m_a$ properly. After setting the values, the voltage value can change from zero to twice the rated voltage just by changing $m_a$. For instance, $m_a = 0$ sets output voltage to zero and $m_a = 1$ sets output voltage to twice the rated value. In the above simulation if we change $m_a$ to 1, output voltage will change to 48 volts.

The output voltage versus output current is shown in Fig. 13. The point of rated power in this inverter – when the inverter works in its rated parameters and the load is nominal – is point A, which is shown in Fig. 13.

As is obvious from Fig. 13, if the output load current increases, output voltage will significantly drop. If the load current is increased, with a simple feedback, $m_a$ will increase and will cause the output voltage to retain at the rated value. Using (5), $m_a$ will increase by raising the control signal.

Using the above explanations, when $m_a = 1$, the generated output voltage is increased to twice the voltage in Fig. 13. Therefore, generated output voltage can remain at the rated voltage value of 24 V until the voltage in the figure drops to half the rated voltage, where $m_a$ raises to 1. So, based on Fig. 13, the output current can raise up to 5.86 A without any reduction in the generated output voltage.
As seen in Fig. 14(a), the output voltage raise to about 175 volts for a short time when the inductor $L_1$ is about 900 $\mu$H. In the same way, the output voltage is increased until 160 volts when the inductor $L_2$ is 2.7 mH. This characteristic of the proposed inverter makes it suitable for vehicular application, which can raise the output voltage for a relatively short time. Fig. 14(c) also shows that the output voltage will be stable when the output load is more than 15 ohms.

V. CONCLUSION

Several attempts were made to ideally achieve a better structure of inverters with a low THD. A new inverter circuit has been introduced and simulated in this paper, which produces a sinusoidal output voltage with THD lower than 1%. The inverter is reduced in size, because of minimum number of components. It utilizes only one simple switch, which removes the problems of dead time. It does not need several individual control systems and uses only a simple control method. The output voltage can be easily controlled in amplitude and frequency. The output voltage remains constant, while the load current changes from zero to approximately 6 A, which is six times more than rated current. This structure also can produce an extremely high output voltage in the resonance frequency. All these statements were verified through simulations.

REFERENCES


