Improved Watkins-Johnson topology-based inverter with dual low-side switch and synchronous control strategy

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Abstract: The full-bridge topology is generally used in the post stage of inverter, to realize dc-ac voltage conversion. Inherent shortcomings of full-bridge such as high-side switch driving, prone to shoot-through and substantial power loss are inevitable. A topological solution is proposed in this letter, by means of improving the original coupled-inductor Watkins-Johnson topology into dual low-side switch version and conducting synchronous control. Theoretical analysis and experimental results indicate that the improved topology is capable of generating pure sinusoidal ac output. The merits include ease of driving, low power loss, nonpulsating terminal currents, immunity to shoot-through, simple control strategy and so forth.

Keywords: dual low-side switch, inverter, synchronous control, Watkins-Johnson topology

Classification: Power devices and circuits

References


1 Introduction

The full-bridge topology is generally used in the post stage of high-frequency isolated inverter for dc-ac voltage conversion, which possesses shortcomings of high-side switch driver necessity, shoot-through issue and high conduction loss [1, 2, 3, 4]. In order to solve these problems, the Watkins-Johnson (WJ) topology provides an alternative approach to realizing inverter. The WJ topology has received minimal attention since its inception, and no literature or product applies this topology to voltage inversion occasions [5].

Several papers have mentioned the WJ topology for dc-dc converter, which has referential significance. Paper [6] employed the WJ topology to dc-dc converter with small conversion ratio for automotive use, however the floating power switch is inevitable. By exchanging the source end and the load end, the inverse Watkins-Johnson (IWJ) topology is derived. It is worth noting that the IWJ topology is not able to realize dc-ac voltage inversion because the voltage conversion ratio is discontinuous [7]. The IWJ topology-based inverter is mentioned in papers [8, 9, 10], which is analogous to the Z-source converter, realizing voltage dc-dc step-up functionality in the front stage of inverter rather than dc-ac voltage inversion stage.

An improved WJ topology-based inverter (WJI) is proposed in this letter, indeed realizing the dc-ac voltage inversion stage of the inverter, with pure sinusoidal voltage output. Compared to the full-bridge topology-based inverter (FBI), the WJI possesses merits of ease of driving (dual low-side switch), low power loss (working in synchronous mode), nonpulsating terminal currents, dead-time non-necessity, and simple control strategy.

2 Topology improvement

Fig. 1(a) illustrates the original WJ converter of coupled inductor version [11]. Where, the source voltage and the load voltage are denoted as $V_s$ and $v(t)$, respectively. Two ideal switches $S_1$ and $S_2$ toggle on alternately with $DT_s$ sub-interval and $D'T_s$ sub-interval, where $D$, $D'$ and $T_s$ denote the duty cycle, the complementary of duty cycle ($D' = 1 - D$) and the switching period. The related electrical quantities are expressed as $V_{S1}$, $V_{S2}$, $I_{S1}$ and $I_{S2}$, neglecting the independent variable $t$ for convenience. Two windings marked $N_1$ and $N_2$ are incorporated into a
coupled inductor $L$, and generally the winding turns are equally distributed. The high-side or called floating switch $S_1$ is difficult to drive in practice [12], therefore it is necessary to discuss whether it can be low-side-ized.

The components are enclosed by two dashed boxes named Group A and Group B, the former includes the upper winding in series with the floating switch $S_1$, the latter consists of the filtering capacitor $C$ in parallel with the resistive load $R$. These two groups are also connected in series. Exchanging the position of series groups will not affect the voltage transfer relation between the source and the load, therefore Fig. 1(b) is obtained, with floating switch low-side-ized. Noticing that the direction of voltage and current in Group A must be kept unchanged.

### 2.1 Steady-state characteristic

The equivalent circuit during two subintervals are illustrated in Fig. 2(a) and Fig. 2(b), respectively. Upon using the small-ripple approximation in the steady state, the inductor voltage $v_L(t)$ and the capacitor current $i_C(t)$ can be expressed in (1) and (2) during the first subinterval. In which, $V$ and $I_L$ are dc components.

$$v_L(t) = V_g - v(t) \approx V_g - V \tag{1}$$
$$i_C(t) = i_L(t) - \frac{v(t)}{R} \approx I_L - \frac{V}{R} \tag{2}$$

In the same manner, during the second subinterval, one obtains

$$v_L(t) = -V_g \tag{3}$$
$$i_C(t) = -\frac{v(t)}{R} \approx -\frac{V}{R} \tag{4}$$
Upon using the principles of inductor volt-second balance and capacitor ampere-second balance, which means that both the inductor flux linkage and the capacitor charge must be reset to zero in steady state, one obtains

\[
\begin{bmatrix}
\langle v_L(t) \rangle \\
\langle i_C(t) \rangle
\end{bmatrix} = 
\begin{bmatrix}
V_g - V \\
V - V_R
\end{bmatrix}
\begin{bmatrix}
D \\
D'
\end{bmatrix} = 
\begin{bmatrix}
0 \\
0
\end{bmatrix}
\] (5)

In which \( \langle v_L(t) \rangle \) and \( \langle i_C(t) \rangle \) are average value of \( v_L(t) \) and \( i_C(t) \). Therefore, the voltage conversion ratio \( M(D) \) and the current relationship can be derived in (6) and (7), respectively.

\[
M(D) = \frac{V}{V_g} = \frac{2D - 1}{D}
\] (6)

\[
I_L = \frac{V}{DR} = \frac{1}{D}
\] (7)

### 2.2 Duty cycle range

The voltage conversion ratio of the full-bridge topology and the improved WJ topology are sketched in Fig. 3 for comparison. To step down the high-line dc voltage generated by the front stage of the inverter, \( M(D) \) should lie in the range from \(-1\) to 1.

Hence, the effective duty cycle range must satisfies (8), where \( D = 0.5 \) is a breaking point dividing the positive and the negative plane.

\[
M(D) = \begin{cases} 
-1, & D \in [-1, 0), \\
0, & D = 0.5 \\
1, & D \in (0.5, 1] \\
1/3, & D \in [1/3, 0.5] \\
\end{cases}
\] (8)

### 2.3 Control strategy

The block diagram of the closed-loop control strategy is shown in Fig. 4. In the feedback path, the potential transformer (PT) samples the output voltage with electromagnetic isolation, the I-V converter and the low-pass filter are constructed by the operational amplifier (OPAMP) for signal conditioning, and computational algorithms including RMS and duty cycle calculation are processed by the controller. \( V_{rms} \) sets the desired rms output voltage. The time-variant duty cycle \( d(t) \)
dynamically manipulates the WJI power circuit to output the rms voltage in demand.

\[ v(t) = V_g M(d(t)) = V_m \sin(\omega t + \varphi) \]  

In order to generate an ac sinusoidal voltage output, \( d(t) \) should be determined by the manner explained in (9), where, the desired peak voltage, angular frequency and sinusoidal phase are expressed as \( V_m \), \( \omega \) and \( \varphi \), respectively.

In consequence, the expression of \( d(t) \) is derived in (10). Let \( \alpha_r \) \((0 \leq \alpha_r \leq 1)\) be the attenuation ratio between \( V_m \) and \( V_g \) for convenience. The essence of control is to adjust \( \alpha_r \) dynamically on the basis of feedback network and control algorithm.

\[ d(t) = \frac{1}{2 - \alpha_r \sin(\omega t + \varphi)} \]  

In summary, the output shape is judged by (10), and the output rms voltage is regulated by the closed-loop network.

### 3 Operating principle

The operating process is divided into four states shown in Fig. 5 according to the duty cycle and the subinterval. In which states is distinguished by the current flow

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**Fig. 4.** Block diagram of control strategy.

**Fig. 5.** Operating modes.
direction when turn-on, and the voltage block direction when turn-off of the power switch. The coupled inductor can be imagined as an energy tank, which can absorb or release energy. When releasing energy, a positive current is produced, and vice versa. As for the power switch, operating in the synchronous mode is helpful to reduce the power dissipation, although the body diode is able to handle the freewheeling current in a well-designed power MOSFET. Next the situation during each state will be specifically analyzed.

3.1 State I \((D \geq 0.5, \text{subinterval 1})\)
When the duty cycle is greater than 0.5, a positive voltage is generated in the output end. Then \(Q_1\) manages the positive current, meanwhile \(Q_2\) withstands the positive voltage. The direction of the magnetomotive force (MMF) is identical to that of current.

3.2 State II \((D \geq 0.5, \text{subinterval 2})\)
During the second subinterval, the MMF must be reset down or else the flux density will increase without bound till magnetic saturation. Therefore, the source voltage forces the inductor to reset. The current non-abrupt change characteristic of the inductor renders the freewheeling current flowing through \(Q_2\) with direction from source to drain.

3.3 State III \((D < 0.5, \text{subinterval 1})\)
When the duty cycle of \(Q_1\) is less than 0.5, the positive MMF is not enough to neutralize the negative one, therefore a reverse voltage occurs at the output end.

3.4 State IV \((D < 0.5, \text{subinterval 2})\)
A relatively excessive negative MMF injects into the coupled inductor along with the turn-on interval of \(Q_2\). While \(Q_1\) must block the superposition voltage from the source, the load, and the inductor.

4 Experimental results
An experimental prototype of WJI is designed and photographed in Fig. 6.

Fig. 6. Experimental prototype.
The experiment is designed with 200 V input voltage, 110 Vrms (155.6 V peak voltage), 50 Hz sinusoidal output. The output waveforms respective with no load and 100 W resistive load are acquired and shown in Fig. 7(a) and Fig. 7(b). It can be seen from the figure that the former waveform is purer than the latter one, which shows some noise at the bottom. The quantitative analysis will be conducted later. Magnified views of Fig. 7(b) during the upward and the downward periods are shown in Fig. 7(c) and Fig. 7(d). The maximum voltage ripple is 5 V or so.

![Fig. 7. Output waveforms.](image)

The harmonics distribution and the total harmonics distortion (THD) are illustrated in Fig. 8(a) and Fig. 8(b), corresponding to Fig. 7(a) and Fig. 7(b).

It can be concluded from the figure that the THD is only 2.37% with no load, and predictably the THD will not get deteriorate so much in low power level. But the THD increases to 8.45% with 100 W load. Therefore, the improved WJ topology-based inverter can not replace the traditional full-bridge-based inverter in high power applications. The WJI is suitable for low voltage, low power and off-grid applications.
5 Conclusion

An improved Watkins-Johnson topology-based inverter is proposed in this letter, realizing dc-ac voltage inversion stage of the high-frequency isolated inverter. The WJI is composed of a coupled inductor and only two low-side power switches, which has advantages of ease of driving, low power loss, nonpulsating terminal currents, low output voltage ripple, low component consumption, dead-time non-necessity and simple control strategy. The WJI provides an alternative way for substituting the full-bridge-based inverter especially in low voltage, low power, and off-grid applications.

Fig. 8. Harmonics distribution of output voltage waveforms.