Australasian Universities Power Engineering Conference (AUPEC 2004)
26-29 September 2004, Brisbane, Australia

A LOW COST PORTABLE CAR HEATER BASED ON A NOVEL CURRENT-FED PUSH-PULL INVERTER

Aiguo Patrick Hu   Ping Si

Department of Electrical and Computer Engineering
The University of Auckland, New Zealand

Abstract

Current-fed resonant converters have been widely used in large induction heating systems due to their low power losses and low EMI (Electromagnetic Interference). However, because of the bulky magnetic components and complicated control circuits employed, conventional current-fed inverters can hardly satisfy low power heating applications where the cost and size are of major concerns. This paper proposes a novel low cost push-pull current-fed inverter that is suitable for a portable car heater or other similar applications. The inverter integrates the dc inductor and the splitting transformer used in a conventional push-push inverter into one magnetic component using two drum cores wound with two identical windings. Furthermore, it does not require any additional controllers, thus the cost, weight, and physical size of the inverter are significantly reduced, making it ideal for portable car heater applications. The operation of the proposed inverter has been analysed in detail, and both simulation and practical experimental results have demonstrated that the proposed inverter works very well in generating the high frequency current required for an induction car heater or other low power heating devices.

1. Introduction

It is desirable for a car traveler to have a portable heater to warm up their food or drinks during a long journey. Professional truck or taxi drivers may also find such a portable car heater useful. The heater for this types of applications should be very small, efficient and easily plugged into the lighter socket of a car to get power. Although joule element type heaters may be used for this purpose, their heating transfer efficiency is very low and they have safety concerns due to exposed heating elements. Moreover, conventional inverters employed in conventional induction heating systems are too costly and bulky to be used in practical portable car heater applications [1].

This paper proposes a novel current-fed push-pull inverter which is suitable for a car heater or other similar applications. The size and cost of the proposed inverter are significantly reduced by integrating the bulky reactive components used in conventional push-pull current-fed resonant inverters. Also, the complicated control circuitry of switching devices is eliminated so as to reduce the cost and improve the reliability of the inverter.

2. Proposed Inverter

The general structure of the proposed novel current-fed push-pull inverter is shown in Fig. 1. Its basic topology is similar to a conventional push-pull inverter [2-3], but an integrated magnetic component is used to replace the independent dc inductor and splitting transformer employed in a conventional push-pull inverter as shown in Fig. 2. Another outstanding feature of this proposed inverter is that no additional controller is required, only a resistor and a zener diode are needed to undertake the gate control of each semiconductor switch as shown in Fig. 1.

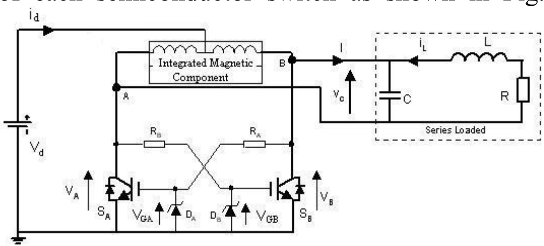

Fig. 1: Proposed novel current-fed push-pull inverter

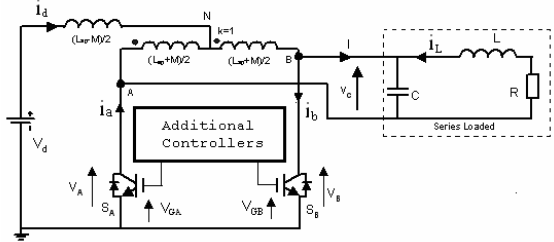

Fig. 2: Conventional current-fed push-pull inverter

Instead of using IGBTs (Insulated Gate Bipolar Transistors), or MOSFETs (Metal Oxide Silicon Field Effect Transistors) as semiconductor switches, cheap BJTs (Bipolar Junction Transistors) can also be employed in the proposed inverter with a slight modification of the base control circuit. Due to the elimination of additional controllers, the new inverter needs no extra dc power supply and feedback circuits, thus the whole control circuit can be greatly simplified with reduced element count and improved reliability.

As will be discussed further later, the proposed converter can start up automatically without any additional circuity. Also, similar to other conventional current-fed resonant converters [4], it can maintain resonant operation with ZVS (Zero Voltage Switching) under steady state operating conditions, thus high power efficiency and low EMI (Electro-magnetic Interference) is assured.

3. Integrated Magnetic Component

Since the magnetic components employed in conventional inverters are very heavy and bulky, integrating them is a very important design goal. Based on the fact that a phase splitting transformer with two partially coupled windings (coupling coefficient $k<1$) is equivalent to a transformer with two fully coupled windings and a leakage inductance, as shown in Fig 3, the bulky dc inductor and phase splitting transformer employed in conventional inverters can be integrated into one in principle [5]. Based on this theory, a new integrated component is proposed by having two identical windings on two drum cores, as shown in Fig. 4. Therefore, if each winding has an inductance L_{sp} and the mutual inductance between them is M (see Fig. 3 (a)), then, this integrated component will be equivalent to a transformer which has two fully coupled windings with an inductance $(L_{sp}+M)/2$ at each side, plus a single winding (dc inductor) with an inductance of $(L_{sp}-M)/2$ connected to the middle point of those two fully coupled windings, as shown in Fig. 3 (c).

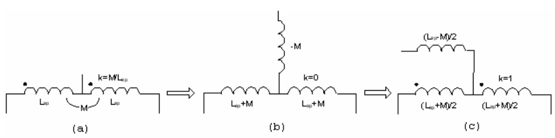

Fig. 3: Equivalent circuits of a phase splitting transformer

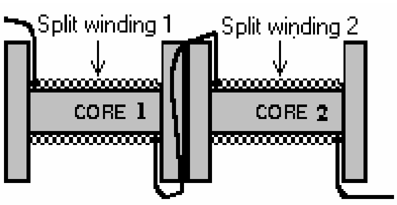

Fig. 4: Two identical splitting windings on two identical drum cores

In a conventional current-fed resonant converter, the dc inductor keeps the input current flowing into the inverting network approximately constant under steady operating conditions, even though a dc voltage source is actually used in practical circuit. This essentially forms a dc current source to drive the parallel resonant tank comprising the inductance L, its tuning capacitor C, and the equivalent load which can be treated as being in series with the inductor for induction heating applications. Since the larger dc inductance, the smaller the DC current ripple, the two windings on the drum cores are normally designed to be loosely coupled ($k<0.7$) so as to maintain a large equivalent inductance and minimised DC ripple.

4. Self-sustained Operations without External Controllers

Apart from integrating the magnetic components, another key feature of the proposed inverter is the elimination of any external controllers required by conventional converters. As can be seen from Fig. 1, in the proposed inverter, both the power and signals needed for the gate drives are obtained directly from the voltages across the main switching devices without any external controller and auxiliary power supplies. Moreover, an advantageous feature of the proposed current-fed push-pull inverter is that it can start up automatically. Due to the existence of actual parameter differences and external disturbances, the voltages across the active switches cannot be exactly the same in a practical circuit. The lower voltage, say V_A, will provide a lower gate drive voltage V_{GB} in the other leg. Consequently, S_B will turn off resulting in a higher voltage drop $V_{B,}$ which will further increase the gate drive voltage V_{GA} and decrease the voltage V_A. This positive feedback will quickly (typically within several ms) lead to complete resonant operation with ZVS (Zero Voltage Switching).

5. Steady State Analyses

Although the dc inductor and the phase splitting transformer of the proposed converter is integrated into one component physically, its equivalent circuit topology remains the same as that of the conventional push-pull converter shown in Fig. 2 The difference is that the equivalent dc inductance is changed to (Lsp-M)/2, and the inductance of each fully coupled windings is (Lsp+M)/2 at each side.

Under steady state conditions, if the harmonics are ignored and ZVS (Zero Voltage Switching) operation is achieved, the resonant voltage v_c (shown in Fig. 1) is approximately a sinusoidal waveform. The voltage at the central point of the equivalent splitting transformer is half of the voltage across the off side switch. Due to the fact that the average voltage across the DC inductor is always zero under the steady state conditions, the average voltage of at the central point of the splitting transformer (V_N) would always be equal to the dc input voltage V_d [6], which is illustrated in Fig. 5.

From this relationship, the rms and the peak value of the resonant voltage v_c can be obtained as:

$$V_c = \frac{\pi V_d}{\sqrt{2}} \qquad \hat{V}_c = \pi V \tag{1}$$

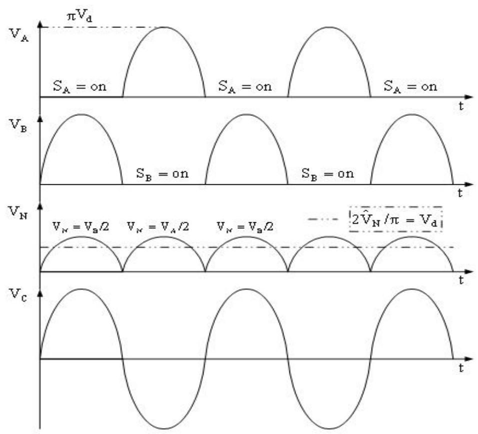

Fig. 5: AC and DC voltage balance of current-fed resonant converter at ZVS condition

Furthermore, assuming ZVS condition is accurately achieved, the input dc current i_d can be analysed using a model as shown in Fig. 6.

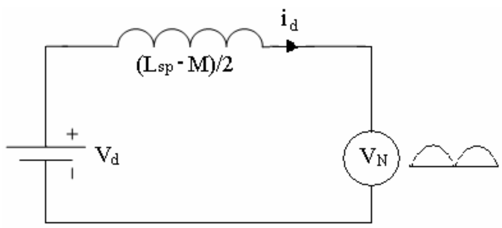

Fig. 6: Model for dc input current i_d analysis

For this model, a first order differential equation can be set up as:

$$\frac{\left(L_{sp} - M\right)}{2}\frac{di_d}{dt} = V_d - \frac{\pi V_d}{2}\left|\sin(\omega t)\right| \tag{2}$$

Considering the fact that average value of current i_d is I_{DC}, the complete solution of the above equation can be obtained as:

$$i_d = \frac{2V_d}{L_{sp} - M}t + \frac{\pi V_d}{\omega(L_{sp} - M)}\left(\cos(\omega t) - 1\right) + I_{DC} \tag{3}$$

This equation can be further simplified into the following equation using Fourier analysis method:

$$i_d \approx I_{DC} + \frac{2V_d}{3\omega(L_{sp} - M)}\sin(2\omega t) \tag{4}$$

where ω is the angular oscillation frequency $(\omega = 1/\sqrt{LC})$.

Equation (4) shows that the current i_d consists of a dc component I_{DC}, and also an ac component whose amplitude is $2V_d/(3\omega(L_{sp}-M))$. The frequency of this ac component doubles that of the ac oscillatory frequency in the resonant tank. From this equation it can be seen that a large mutual inductance M will also result in a large ac component. When the two winding are completely coupled, M and Lsp would be equal so that the ac current would be infinite. Consequently the circuit would be physically unworkable. This explains why the two windings of an integrated magnetic component have to to be loosely coupled in design, providing the windings are wound and connected in the same direction as shown by the dots in Fig. 2.

The current flowing through the windings at each side of the integrated component can be analysed using the following model as shown in Fig. 7:

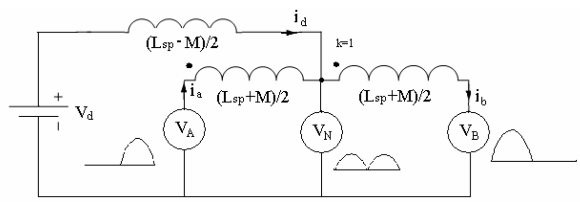

Fig. 7: Model for winding current i_a analysis

For this model, a differential equation group can be obtained as:

$$\begin{cases} \frac{L_{sp}+M}{2}\left(\frac{di_a}{dt}+\frac{di_b}{dt}\right) = -\frac{\pi V_d}{2}\sin(\omega t) & 0 \le \omega t \le \pi \\ -i_a + i_b = \frac{2V_d}{L_{sp}-M}t + \frac{\pi V_d}{\omega(L_{sp}-M)}(\cos(\omega t)-1) + I_{DC} & 0 \le \omega t \le \pi \\ \frac{L_{sp}+M}{2}\left(\frac{di_a}{dt}+\frac{di_b}{dt}\right) = \pi V_d \sin(\omega t - \pi) - \frac{\pi V_d}{2}\sin(\omega t - \pi) & \pi \le \omega t \le 2\pi \\ -i_a + i_b = \frac{2V_d}{L_{sp}-M}\left(t - \frac{\pi}{\omega}\right) + \frac{\pi V_d}{\omega(L_{sp}-M)}(\cos(\omega t - \pi)-1) + I_{DC} & \pi \le \omega t \le 2\pi \end{cases} \tag{5}$$

Considering the condition of the average value of $i_a = -I_{DC}/2$ and $i(t)|_{t=(\pi/\omega)-} = i(t)|_{t=(\pi/\omega)+}$, the complete solution of i_a is:

$$i_a = \begin{cases} -\frac{V_d}{(L_{sp}-M)}t - \frac{\pi V_d M}{\omega(L_{sp}^2 - M^2)}\cos\omega t - \frac{I_{DC}}{2} + \frac{\pi V_d}{2\omega(L_{sp}-M)} & 0 \le t \le \frac{\pi}{\omega} \\ -\frac{V_d}{(L_{sp}-M)}t + \frac{\pi V_d L}{\omega(L_{sp}^2 - M^2)}\cos\omega t - \frac{I_{DC}}{2} + \frac{3\pi V_d}{2\omega(L_{sp}-M)} & \frac{\pi}{\omega} \le t \le \frac{2\pi}{\omega} \end{cases} \tag{6}$$

which can be further simplified using Fourier analysis method into:

$$i_a \approx -\frac{I_{DC}}{2} + \frac{\pi V_d}{2\omega(L_{sp}+M)}\cos(\omega t) - \frac{V_d}{3\omega(L_{sp}-M)}\sin(2\omega t) \qquad (7)$$

Equation (7) shows that the current flowing through one side of the windings consists of a dc component $I_{DC}/2$, a fundamental component with an amplitude of $\pi V_d/(2\omega(Lsp+M))$ and a second harmonic component with an amplitude of $V_d/(3\omega(Lsp-M))$. It should be noted that when mutual inductance M increases, the amplitude of the second order harmonic also increase. However, the amplitude of the fundamental component will decrease. This phenomenon can be illustrated by plotting Equation (7) using MATLAB as shown in Fig. 8. This plot shows that when M=0.7, the waveform of the winding current is approaching the second harmonic component. However, when M=0.35, the waveform is changed to be similar to that of the fundamental component.

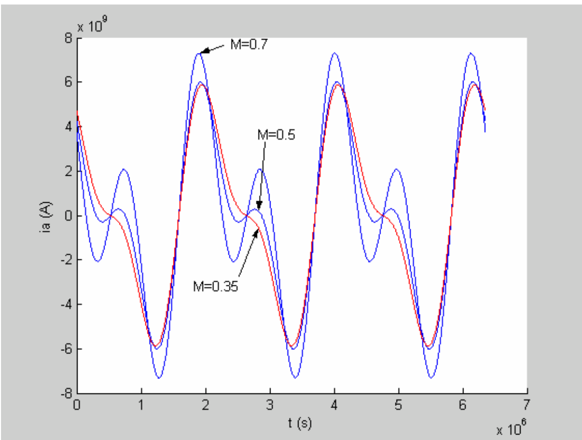

Fig. 8: Waveform of the current i_a under M=0.7, M=0.5 and M=0.35

6. Simulation Results

To prove the circuit design and the steady state analyse, the proposed converter as shown in Fig. 1 is simulated using a PSpice package. Fig. 9 shows the simulation results of switch voltages v_A, v_B, and gate driving voltages V_{GA},V_{GB}. It can be seen that the voltage waveform across each switch is consistent with what is shown in Fig. 5. In addition, the peak value of the voltage v_A and v_B is about 38V, being very close to the result obtained from equation (1), which should be 12π when the DC input voltage is 12V from most car batteries. The gate drive voltages V_{GA} and V_{GB} are nearly in square waveform with a magnitude of 5V, resulting from a 5V zener used at the gate of each IGBT or MOSFET switch. When BJTs are used, zener diodes become unnecessary but the base current has to be design carefully.

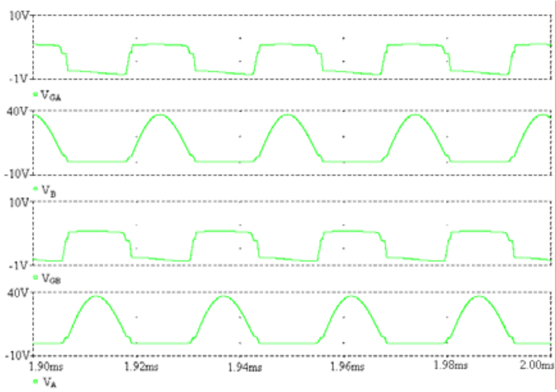

Fig. 9: Simulation results of gate drive voltages and the voltages across the switches

Fig. 10 shows the simulation results of the current flowing through the resonant inductor i_L and the dc current i_d supplied by the power source. It can be clearly seen that the frequency of the ac component of the current i_d doubles that of the ac current flowing through the resonant inductor i_L. This is consistent with what has been predicted from equation (4).

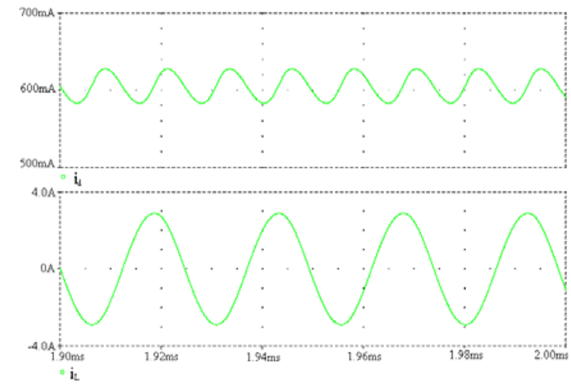

Fig. 10: The dc current supplied by the power source (i_d) and the current flowing through the resonant inductor (i_L)

7. Experimental Results and Discussion

A prototype converter with an integrated magnetic component as shown in Fig. 1 has been built and tested in the laboratory. The main parameters used include L=10μH, C=3.2μF for the resonant circuit; and equivalent Lsp=1.0mH and M=0.5mH (corresponding to k=0.5) for the integrated magnetic component. Two 4.7Vzener diodes and two 55V/16A/5.3mΩ MOSFETs were used. Fig. 11 shows the measured waveforms of the resonant voltage v_C (Channel 1) and current i_L (Channel 2). It can be seen that a high frequency resonant current at about 28kHz in a beautiful sinusoidal waveform has been generated. The peak value of the current is about 20A which is high enough for most car heating applications. It has been tested and proven that a metal can can be heated up very quickly with an electric power output of about 50-100W.

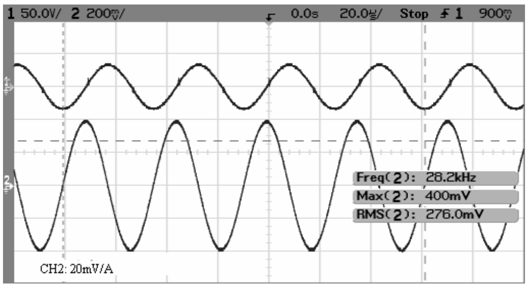

Fig. 11: Experimental results of track voltage and current (Channel 1: v_c 50V/div, Channel 2: i_L 10A/div, 20us/div)

Fig. 12 shows the waveforms of the gate drive signal V_{GA} (Channel 1), and the switching voltage v_A (Channel 2) over switch S_A. It can be seen that the switching occurs approximately at zero voltage crossing points as designed. And from the waveform of V_{GA}, it can be observed that the gate drive signal is slightly in trapezoid shaped waveform in practice due to the effect of the gate input capacitor and the miller effect of practical MOSFETs. Unlike normal converters with external controllers, a very unique feature of the proposed inverter is that a higher operating frequency or voltage level makes the resonant voltage rise more rapidly, thus improves the gate signals. Consequently, it would be easy to increase the frequency and the maximum power level (which related to the maximum voltage) of the inverter. It should be noted in stead of using 12V or 24V batteries, 42 voltage would be the new standard for the next generation cars power supplies. To eliminate the acoustic noise, operating frequency was chosen to be over 20kHz in the lab experiments. By taking the induction heating element (material, size, shape, etc) into consideration, more research is needed to investigate the optimal frequency to be used for car heater applications.

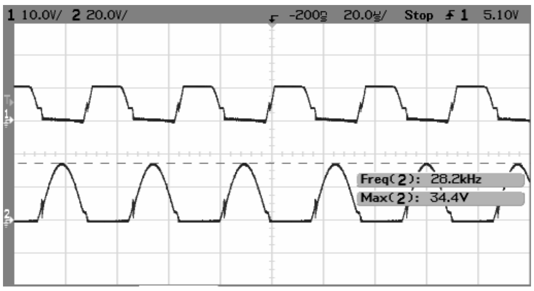

Fig. 12: Experimental results of the gate drive voltage and the resonant voltage across the switch

8. Conclusion

This paper has proposed a novel current-fed push-pull inverter which provides a low cost solution for portable car heater applications. Two improvements have been made to reduce the size, weight and cost of the inverter. One is integrating the bulky reactive elements into a small and light magnetic component. Another is inventing a novel self sustained gate drive circuit to control the switching devices without using any external controllers. Mathematical analysis, PSpice simulation, as well as experimental results have demonstrated that the proposed inverter functions very well in generating high frequency currents required for car heater or other similar low power heating applications.

9. References

[1] Fairchild Semiconductor, "Induction Heating System Topology Review", AN9012, July 2000.

[2] Green, A. W.: "Modelling a push-pull parallel resonant convertor using generallsed state-space averaging", IEE Proceedings-B, Vol. 140, No. 6, 1993.

[3] Gulko, M. and Yaakov, S. B.: "Current-sourcing push-pull parallel-resonance inverter (CS-PPRI): theory and application as a fluorescent lamp driver", IEEE Transactions on Industrial Electronics, Vol. 41, No. 3, 1994.

[4] Rashid, M. H.: "Power electronics: circuits, devices, and applications", Englewood Cliffs, N.J.: Prentice Hall, 2nd Edition, 1988.

[5] Hu, A. P. and Liu, S. R.: "Integrating the magnetic components used in a push-pull current-fed resonant converter", Applications of Electromagnetic Phenomena in Electrical and Mechanical Systems, 3rd Japan, Australia and New Zealand Joint Seminar, Auckland, 22-23 Jan, 2004.

[6] Hu, A. P.: "Selected resonant converters for IPT power supplies", PhD thesis, Department of Electrical and Computer Engineering, University of Auckland, Oct 2001.