Ripple reduction of DC current sources in three-level CE-CSI circuits using single core inductors

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Abstract. Current source inverter operates producing a predetermine ac current from dc current inputs. In practical, ac current waveform will have harmonic contents appeared in the frequency spectrum. Some factors may affect these harmonics contents such as voltage drops occurred in the power devices of controlled power switches, and voltage drops caused by the resistances of power inductor and conductor. The dc current sources usually generated by using power inductors connected to dc power source. Another factor that can escalate the harmonics is the current ripples of dc current sources. To regulate the dc current sources flowing in the inductor, controlled switches and current controller are required. This paper proposed a novel strategy to minimized current ripple of inductors by applying single core inductors. Some test results of computer simulation were presented in the paper.

1. Introduction

Power quality is an prominent consideration in the design of a power converter circuits such as power inverter working to convert dc power into ac power [1]-[4]. The power inverter works as power converter in many utilizations such as ac motor drive, and renewable energy conversion system. Harmonics in the ac current are the main components affecting the power quality. The harmonics content will enhance the power losses in the circuits, consequently, the system could experience unwanted overheating condition. It causes torque ripple in the ac motor drive application [5]-[9]. In the renewable energy conversion system, injection harmonics into the power system will decrease the power quality [10]-[13].

A current source inverter works producing a controllable ac current from one or some dc input currents [14]-[18]. The dc input currents usually obtain using power inductor and dc power source [19]-[22]. The ac output voltage of a current source inverter hinges on the output current and load condition. To make a pure sinusoidal ac current and output voltage waveforms, a capacitor filter is installed across power load. The harmonic components will flow through filter capacitor. Furthermore, to ensure current path, overlap-time is added in the gating signals of inverter power switches. It functions also to prevent voltage spikes in the inverter circuits caused by possible open circuit condition of power inductor [23], [24].

In a current source inverter, the power inductors are required to generate dc input currents of inverter circuits. Some issues are introduced by the power inductors such as power losses caused by the inductor core and conductor wire. Applying superconductor for power inductor is a good solution in minimizing...
the power losses. However, economical aspect is the main constraint of superconductor application. Minimizing the power inductor size could be another alternative solution to reduce the power losses and cost of inverter [25], [26]. However, ripple of the dc current sources generated by the power inductor will introduce more harmonic distortion to the ac output current waveform. Hence, minimizing inductor size, current ripple and harmonic contents are important strategies and steps in the development of current source inverter circuits [27].

This paper presents application of single core power inductor to minimize ripples of dc current in inverter circuits. The proposed circuit needs only one dc current sensor and single power switch to control two different currents flowing through inductors. Some computer simulation test were conducted to tempt the accomplishment of the proposed strategy. Furthermore, experimental verification of inverter prototype was carried out in laboratory. The test results confirmed the features of proposed dc current source circuits in minimizing dc current ripple and harmonics contents of inverter output current.

2. Proposed System
Figure 1 presents the circuit of three-level CE-CSI previously developed by author. This inverter works generating a three-level ac current from two dc input currents. In this circuits, all power MOSFET switches are configured at common-emitter connection. Figure 2 shows the inverter circuits including dc current source generation as discussed in [30]. Two power inductors $L_1$ and $L_2$ are used to generate dc current sources from dc power source, $V_{dc}$. Magnitude of dc current sources was controlled by power switch $Q_c$. The power diode $D_f$ function as free-wheeling diode, to keep current path of dc current sources. In this circuits, even 100 mH power inductors were applied, large dc current ripples were still remain.

Another circuit configuration was presented in [27], in which each inductor current was controlled independently by using controlled switch. Two power switches and two current sensors were required to control two dc inductor currents. For higher number of dc current sources, more complex dc current generators are mandatory. This could make the overall inverter circuits more complex and expensive. This can be a problem in practical manner.
To reduce ripple of dc current sources, Figure 3 shows the proposed dc current generation in this paper. Two power inductors $L_1$ and $L_2$ with a single core were used. It was basically like a transformer with the same turn number $N_1$ and $N_2$, and with opposite polarity as shown in the figure. The inductors $L_1$ and $L_2$ are the leakage inductance of inductor system. $L_m$ is the magnetizing inductance of the two inductors that can be calculated as follow:

$$L_m \cong \mu_r L_1$$

The $\phi_{l1}$ and $\phi_{l2}$ are the fluxes which cause the leakage inductances.

The purpose of positioning opposite wiring of inductor is to add up the magnetic flux as $\phi$ in the power inductors caused by current $i_1$ and $i_2$ as shown in Figure 4. In this circuits a single dc current sensor was needed to sense and control the current flowing through the power inductor. The control signals was implemented by controlled switch $Q_c$ connected with dc power source. To further reduce the current ripple, a grounded carrier PI current controller was proposed and implemented to the inverter circuits as depicted in Figure 5.

| Test Parameters | DC power source voltage | 48 V |
|-----------------|-------------------------|------|
| Switching frequency | 22 kHz |
| Output frequency | 50 Hz |
| Power load | 4Ω, 5 mH |
| Capacitor filter | 10 µF |
| PI controller constants | $K_p=100$, $T=0.01$ s |

3. Test Results and Analysis

To explore the performance of the proposed circuits, some examinations were carried out for both conventional and the proposed circuit. The test parameters were set the same as tabulated in Table 1. The main different is the inductor configuration only.
3.1. Test Results of Conventional Circuits

Inverter circuit configuration of Figure. 2 was tested using computer simulation. The dc inductor size was 100 mH with 0.1 Ω copper resistance in series. Fig 6 shows the simulation results depicting the three-level PWM current, load current and inductor current $I_{L1}$ and $I_{L2}$.

**Figure 6**  PWM current, load current and inductor current waveforms of conventional circuit

**Figure 7**  Enlarged inductor current of conventional circuits

**Figure 8**  Enlarged starting waveform of inductor currents of conventional circuit
The enlarged waveform of inductor currents are shown in Figure. 7. Measured current ripple of these inductor currents was 10.43%. Figure. 8 shows the transient current waveform of $I_{L1}$ and $I_{L2}$ during inverter starting. The current reached stable condition for 5.34 ms. Furthermore Figure. 9 presents the harmonic contents of the PWM current. Because of single phase configuration, the triple harmonics were still appear of which the 3rd component was 1.3%.

![Figure 9 FFT of PWM current of conventional circuit](image)

**3.2. Test Results of Proposed Circuits**

To investigate the merits of the proposed circuits, the inverter as shown in Figure. 3 was also tested in computer simulation. The leakage inductance of single core inductors labeled as $L_1$ and $L_2$ were set as 10 mH, where the magnetizing inductance $L_m$ was set at 100 mH.

![Figure 10 PWM current, load current and inductor current waveforms of proposed circuit](image)

![Figure 11 Enlarged inductor currents of proposed circuit](image)
Figure 10 presents the waveform of PWM current, load current and inductor currents of the inverter circuit. The enlarged waveform of inductor currents was shown in Figure 11. The ripple value of this currents was 5.37%. It was almost 50% reduced compared to the conventional circuits as shown in Figure 12. Moreover, Fig. 13 shows the transient current of $I_{L1}$ and $I_{L2}$ during start-up of inverter.

The measured settling time of this current was 0.428 ms. It was much faster than the conventional circuits of which its settling time was 5.34 ms. Figure 14 is the harmonics profile of the PWM current waveform. As one see all low harmonic components were less than 1%. The highest magnitude was the 3rd order with magnitude 0.8%. It was also smaller than the conventional one.

![DC current Ripple (%)](image1)

Figure 12 Ripple comparison

![Enlarged starting waveform of inductor currents of proposed circuit](image2)

Figure 13 Enlarged starting waveform of inductor currents of proposed circuit

![FFT of PWM current of proposed circuit](image3)

Figure 14 FFT of PWM current of proposed circuit
4. Conclusion
Application of single core inductors to reduce current ripple in a three-level CE-CSI was proposed and presented in this paper. The dc input current ripple will add more harmonic distortion to the ac output current of inverter circuit. The proposed method use the magnetizing inductance of power inductor to store energy and minimize the current ripple. Moreover, a simple dc current source generator circuits also can be applied with only a single sensor and a single control power switch. Computer simulation test results confirmed that the circuits was able to lower the current ripple and transient time of dc input current.

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