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New Pulsewidth Modulation Strategy of Z-Source Inverter for Minimum Inductor Current Ripple

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Abstract

The SVPWM strategy based on single phase shoot through in Z-source inverter has many advantages, such as higher equivalent operating frequency, smaller ripple of Z-source inductor current and smaller volume and weight of Z-source network. The optimal design of the inductor in Z-source inverter based on this modulation strategy is carried out in this paper. Firstly, the SVPWM strategy of Z-source inverter is achieved by modifying the traditional SVPWM strategy of Voltage-source inverter. Then the waveform and ripple expression of Z-source inductor current can be got quantitatively. The Z-source inductor is designed . At last, by experiments, it is verified that the ripple of the designed inductor current satisfies all the constraints.

Keywords: *Z-source Inverter, SVPWM, ripple of inductor Current*

1.Introduction

Due to environmental concerns, more effort is now being put into clean distributed power like geothermal,windpower,fuelcells and photovoltaic that directly uses the energy from the nature to generate electricity. As the distributed power generation is free, the major cost of generation is their installation cost. Their generation system mainly consist of inverters.The main function of inverter circuit is to convert DC input sources to AC output waveforms. Traditionally there are two types of inverters which are voltage source inverters and current source inverters. Both of these types of inverters are differentiated by their type of DC input sources. Voltage source inverters use DC voltage sources as inputs while current source inverters use DC current sources. The traditional inverters have a major setback. The major setback or problem is that the AC output can only be equal or less than the DC input values. This problem has limited the flexibility of the inverters. This means that if one wants to design a circuit that produces AC output larger than the DC input, one must design a two stage converter which is consists of boost converter and inverter. This directly affects the overall efficiency and cost of the circuit. Thus, Z-source inverters were introduced to overcome this barrier and improve the applications of inverters in electronic and electrical power fields. The main challenge faced by the Z-source inverter is system weight and volume. The capacitor value and size can be decreased by introducing new improved topologies of Z-source inverter. But this topologies cannot reduce the size of inductor. In this paper in order to reduce the inductor size a new pulse width modulation strategy is implemented. This is done by reducing the inductor current ripple.

The major advantages Of Z-Source Inverter Over traditional inverters:

(1) It can used for any type of power conversion.
(2) Can be used as both V-source as well as I-source inverters.
(3) Higher efficiency & more reliability
(4) It can Buck-boost the voltage.
(5) Self boost phenomenon can be controlled using a battery in the system.

2. Z-Source Inverter

The Z source network employs a unique impedance circuit to couple the converter main circuit to that of the power source in order to obtain the unique features that cannot be achieved using conventional VSI or CSI. The Z-source inverter (ZSI) has been reported suitable for residential PV system because of the capability of voltage boost and inversion in a single stage .The Z-source inverter has overcame the problem associated with the conventional voltage source inverter for implementing DC-AC, AC-DC, AC-AC and DC-DC power conversion. The Z-source inverter reduces harmonics, electromagnetic interference noise and low common made noise. The Z-source inverter can be used to feed the adjustable induction motor drive system and it has better performance and results as compared to the conventional VSI. This new approach has been implemented. The Z-source inverter is also implementable to grid connected PV system, which is transformer less and has low cost.

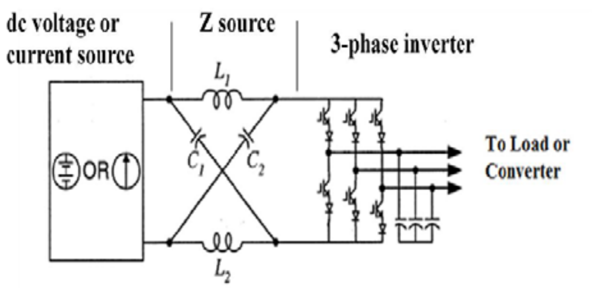

Fig. 2.1 Z-source inverter

2.1 Modes of Operation

ZSI has three modes of operation which includes;

- Mode I- the six active vectors when the dc voltage is connected across the load.
- Mode II- Two zero vectors when the load terminals are shorted through either the upper or lower three devices, respectively.
- Mode III- One more zero state (or vector) when the load terminals are shorted through both the upper and lower devices of any one of the phase leg (i.e., both devices are gated on), any two phase legs, or all three phase legs.

In mode I, the inverter bridge is operating in one of the six traditional active vectors, the equivalent circuit is as shown in figure 2.2. The inverter bridge acts as a current source viewed from the DC link. The diodes conduct and carry currents. Both the inductors have an identical current value because of the circuit symmetry. This unique feature widens the harmonic current.

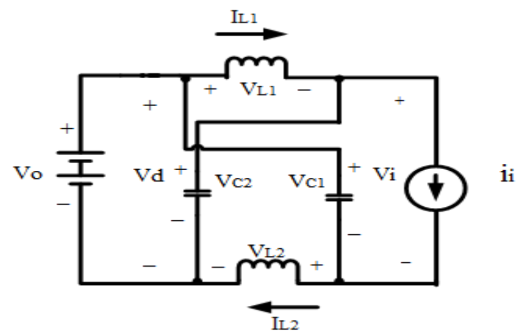

Fig. 2.2 Equivalent Circuit of the ZSI in one of the Six Active States

The equivalent circuit of the bridge in mode II is as shown in the fig 2.6. The inverter bridge is operating in one of the two traditional zero vectors and shorting through either the upper or lower three device, thus acting as an open circuit viewed from the Z-source circuit. Again, under this mode, the inductor carry current, which contributes to the line current's harmonic reduction.

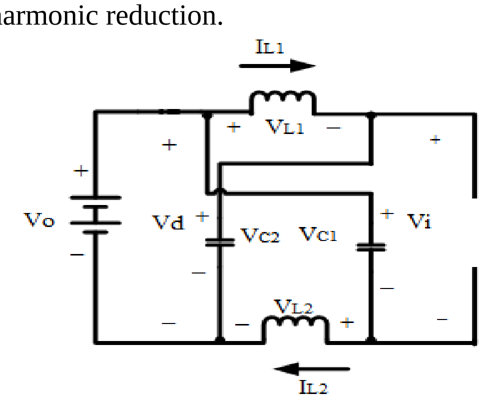

Fig. 2.3 Equivalent Circuit of the ZSI in one of the two traditional zero states.

The inverter bridge is operating in one of the seven shoot-through states. The equivalent circuit of the inverter bridge in this mode is as shown in the below figure 2.4. In this mode, separating the dc link from the ac line. This shoot-through mode to be used in every switching cycle during the traditional zero vector period generated by the PWM control. Depending on how much a voltage boost is needed, the shoot-through interval (T0) or its duty cycle (T0/T) is determined. It can be seen that the shoot-

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through interval is only a fraction of the switching cycle.

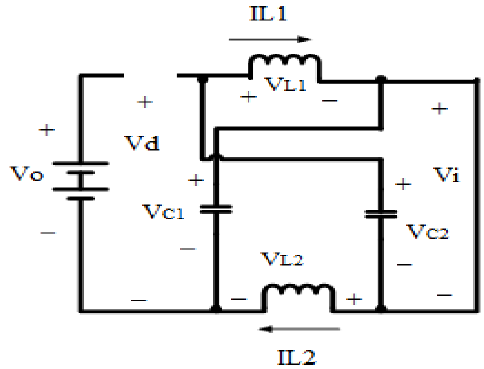

Fig.2.4 Equivalent circuit of the ZSI in the shoot-through state.

2.2 Analysis and Deaign of Impedence network

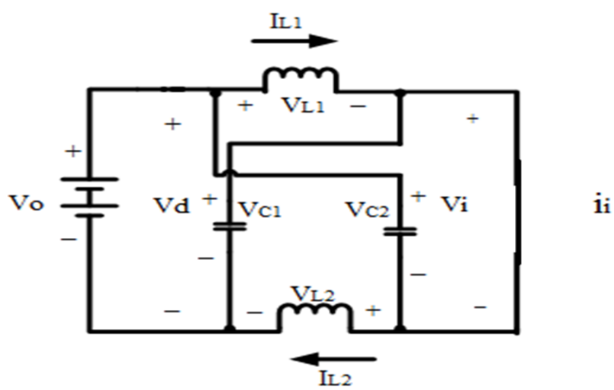

Fig 2.5 Equivalent circuit of ZSI

Assume the inductors (L1&L2) and capacitors (C1 &C2) have the same inductance and capacitance values respectively. From the above equivalent circuit:

$V_{C1} = V_{C2} = V_C$

$V_{L1} = V_{L2} = V_L$

$V_L = Vc$

$Vd = 2Vc$

$Vi = 0$

During the switching cycle T:

$V_L = Vo - Vc$

$Vd = Vo$

$Vi = Vc - V_L = Vc - (Vo - Vc)$

$Vi = 2Vc - Vo$

where, Vo is the dc source voltage and

$T = To + T1$

The average voltage of the inductors over one switching period (T) should be zero in steady state:

$V_L = V_L = To.Vc + T1(Vo-Vc)/T = 0$

$V_L = (To.Vc + Vo.T1 - Vc.T1)/T = 0$

$V_L = (To-Tc)Vc/T + (T1.Vo)/T$

$Vc/Vo = T1/T1-T0$ (2.1)

Similarly the average dc link voltage across the inverter bridge can be found as follows.

From equation (2.1):

$Vi = Vi = (To.0 + T1.(2Vc-Vo))/T$

$Vi = (2Vc.T1/T) - (T1Vo/T)$

$2Vc = Vo$ (2.2)

From equation (2.2):

$T1.Vo/(T1-To) = 2Vc.T1/(T1-To)$

$Vc = Vo.T1/(T1-To)$

The peak dc-link voltage across the inverter bridge is:

$Vi = Vc - Vl = 2Vc - Vo$

$= T/(T1-To).Vo = B.Vo$

where, $B = T/(T1-To)$

B is the boost factor

The output peak phase voltage from the inverter:

$Vac = M.vi/2$ (9)

where, M is the modulation index:

In this source $Vac = M.B.Vo/2$

In the traditional sources:

$Vac = M.Vo/2$

For Z-Source

$Vac = M.B.Vo/2$

The output voltage can be stepped up and down by choosing an appropriate buck-boost factor BB:

$BB = B.M$ (it varies from 0 to α)

The capacitor voltage can be expressed as:

$Vc1 = Vc2 = Vc = (1-To/T).Vo/(1-2To/T)$

3.Existing SVPWM Strategy

The SVPWM strategy of VSI can also be applied to ZSI through some appropriate modifications. In the traditional SVPWM, there are eight vectors, *V1-V6* are effective vectors,*V0* and *V7* are zero vectors.

If the reference vector Vr is located at Sector I, according to the SVPWM of traditional VSI, Vr can be synthesized with the boundary vectors V1,V2 and zero vectors, the three working times of them are

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displayed with Ts (switching period), θ(phase angle of Vr) ,) Vi(the peak DC link voltage).

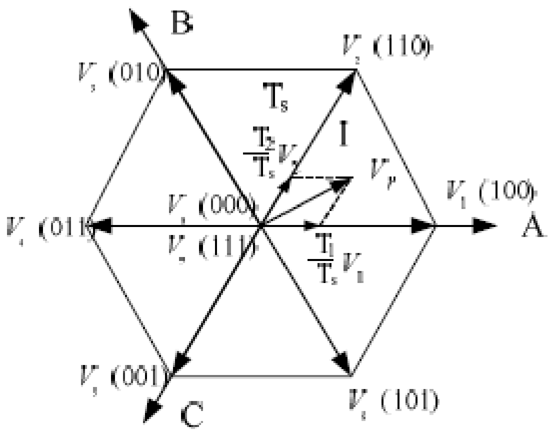

Fig. 3.1. Space Vector Sketch

$$T_1 = \sqrt{3} Vr\ Ts\ \sin\left(\frac{\pi}{3} - \theta\right) \qquad (3.1)$$

$$T_2 = \sqrt{3}\ Vr\ Ts\ \sin(\theta) \qquad (3.2)$$

To = Ts - T1 -T2

The SVPWM switching signals of traditional VSI are shown in Fig. 3.2(a). It can be applied to ZSI by appropriate modification [4]. The modified switching signals are shown in Fig. 3.3(b).

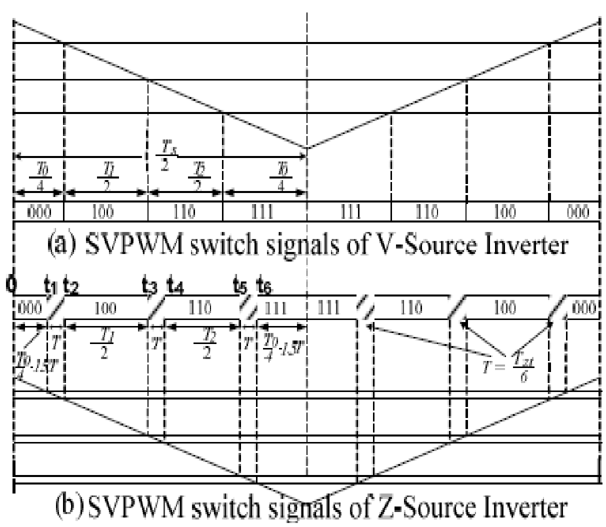

Fig. 3.2 SVPWM switching signals

For symmetry, the shoot-through time is divided into three equal parts in half switch period (each part T equals one sixth of shoot-through time in one switch period *T*),then insert them into transits between *V0* and V1, V1 and V2,V2 and V7,respectively. Ensuring that the working times of V1 and V2 after inserting shoot-through state are equal to that before inserting, working times of Vo and V7 are equal to each other,and switching moments in half switching period are calculated as (2).According to the six switching moments and the peak value of triangle carrier, the six modulation waves are achieved. As a result, the SVPWM strategy of ZSI is achieved.

4. Proposed PWM Strategy with Minimum Inductor Current Ripple

A PWM strategy with minimum inductor current ripple is proposed. For ZSI, the boost factor is determined by the total shoot-through time.therefore, the boost ability and ac output voltage of ZSI keeps the same while maintaining the same total shoot-through time. The arrangement of the shoot-through influences the inductor current obviously; thus, by careful allotment of the shoot-through time in three phase legs, the inductor current ripple can be optimized. The switching sequence of the proposed PWM strategy is shown in Fig. 4.1. The shoot-throughtime of the phases is reassigned as Ta, Tb, *Tc*, respectively,while keeping the sum of the three unchanged to get the samevoltage boost. Ta, Tb, Tc is designed according to the active state time and zero state time to minimize the inductor current ripple. The active state time, the total shoot-through time, and zero state time can be calculated instantaneously and is definite; therefore, the decreased value of inductor current in active state and zero state is also definite. The inductor current ripple is shown in Fig. 4.2.

The instantaneous value of inductor current meets the following rules:

$|i(t_2) - I_L| + |i(t_3) - I_L| = a$

$|i(t_4) - I_L| + |i(t_5) - I_L| = b$

$|i(t_1) - I_L| + |i(t_6) - I_L| = c/2$

where a, b, c is the decreased value of the inductor current in active state 1, active state 2, and zero state, respectively.

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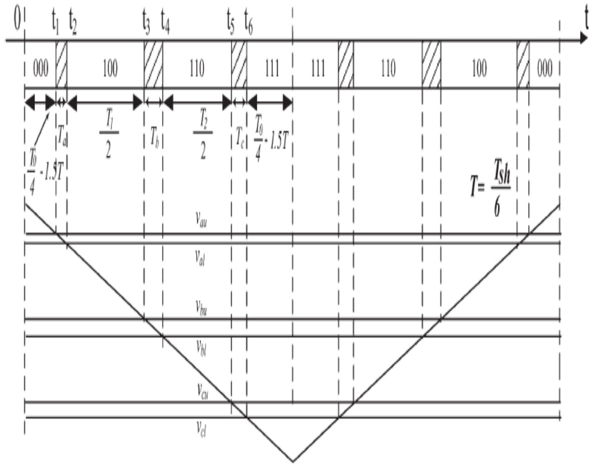

Fig4.1 Switching sequence of proposed PWM strategy

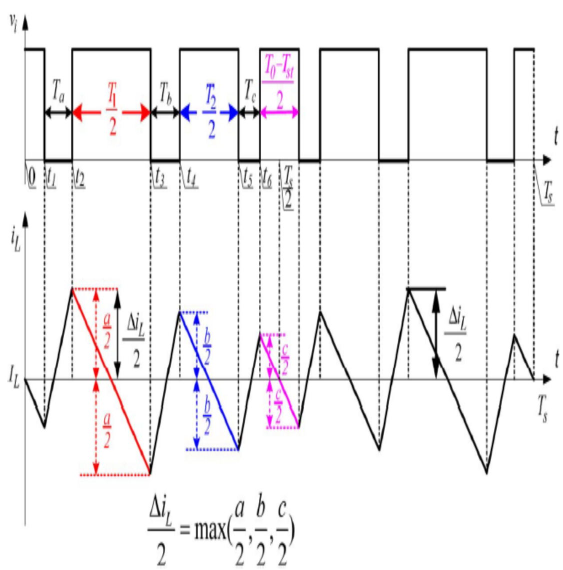

Fig4.2 Inductor current ripple with proposed PWM strategy.

The inductor current ripple can be expressed as:

$\Delta I_L = 2\max(|i(t1) - I_L|, |i(t2) - I_L|, |i(t3) - I_L|, |i(t4) - I_L|, |i(t5) - I_L|, |i(t6) - I_L|) = 2\max[(|i(t2) - I_L|, |i(t3) - I_L|, |i(t4) - I_L|, |i(t5) - I_L|, c/2]$

$\Delta I_L \geq 2\max(a/2, b/2, c/2)$

When $|i(t2) - I_L| = |i(t3) - I_L| = a/2$ &

$|i(t4) - I_L| = |i(t5) - I_L| = b/2$.

The current ripple reaches its minimum value:

$\Delta I_{L\,min} = \max(a, b, c)$

Therefore, to get the minimum inductor current ripple, the shoot-through time of the three phases *Ta*, *Tb*, *Tc* is designed to guarantee that

$i(t2) - I_L = I_L - i(t2) = a/2$

$i(t4) - I_L = I_L - i(t5) = b/2$

$\Delta I_L\_Ta = c/2 + a/2$

$\Delta I_L\_Tb = a/2 + b/2$

$\Delta I_L\_Tc = b/2 + c/2$

the shoot-through time of the three phases *Ta*, *Tb*, *Tc* can be,

$$Ta = \frac{c/2 + a/2}{(a+b+c)} \frac{Tsh}{2}$$

$$Tb = \frac{a/2 + b/2}{(a+b+c)} \frac{Tsh}{2}$$

$$Tc = \frac{a/2 + b/2}{(a+b+c)} \frac{Tsh}{2}$$

a:b:c = T1/2 :T2/2: (To-Tsh)/2

By combining the above two equations, *Ta*, *Tb*, *Tc* can be derived as,

$$Ta = \frac{Tsh}{4(Ts - Tsh)}(To+T1-Tsh) = K(To+T1-Tsh)$$

$$Tb = \frac{Tsh}{4(Ts - Tsh)}(T1+T2) = K(T1+T2)$$

$$Tc = \frac{Tsh}{4(Ts - Tsh)}(To+T2-Tsh) = K(To+T2-Tsh)$$

Where, where k is proportional to the ratio of the shoot-through time to non-shoot-through time, expressed as:

$$K = \frac{Tsh}{4(Ts - Tsh)}$$

5.Simulation and Experiment Verification

For verifying the correctness of inductor design, simulations and experiments are carried out. The working conditions are as same as that in the part of design example. The circuit parameters are shown as follows:

Z-source inductance L=1.06mH;

Z-source capacitance C=100μF;

Load resistance R=12Ω.

Vdc= 24VFigure 5.1 shows the simulation block of ZSI for proposed system and 5.2 shows the new strategy of PWM implemented in ZSI.

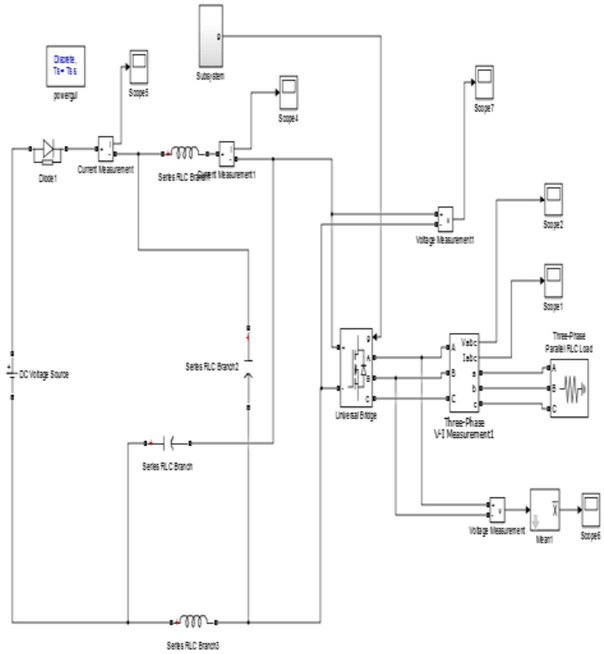

Fig 5.1 Simulation block of ZSI

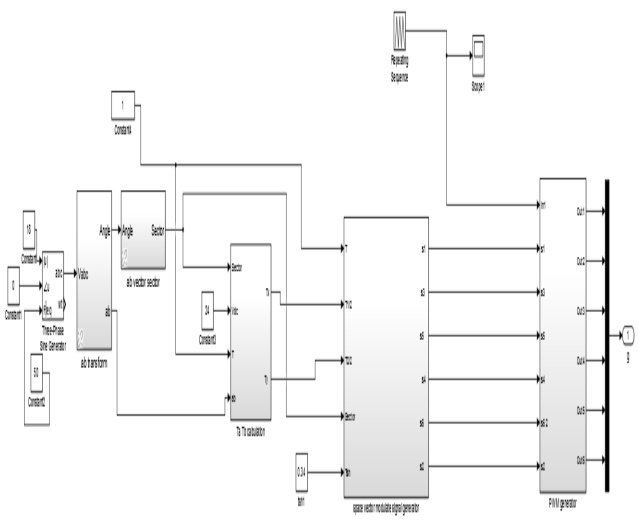

Fig 5.2 Proposed PWM technique

Outputs are displayed based on power frequency and switch frequency respectively. It can also be seen from Fig. 5.6 that there are 6 equal shoot-through states in each switching period, which is in accordance with shoot-through in SVPWM strategy. Fig.5.5 shows the simulation waveforms when the input voltage is 24V. It can be seen from Fig. 8 that the largest ripple is about 0.15A.Figure 5.3 shows the pulse generation waveform.

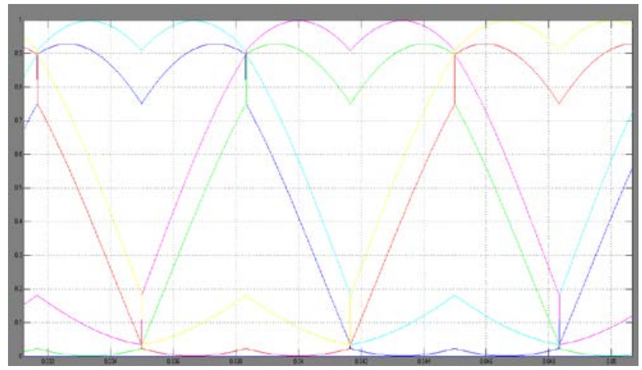

Fig 5.3 Reference waveforms

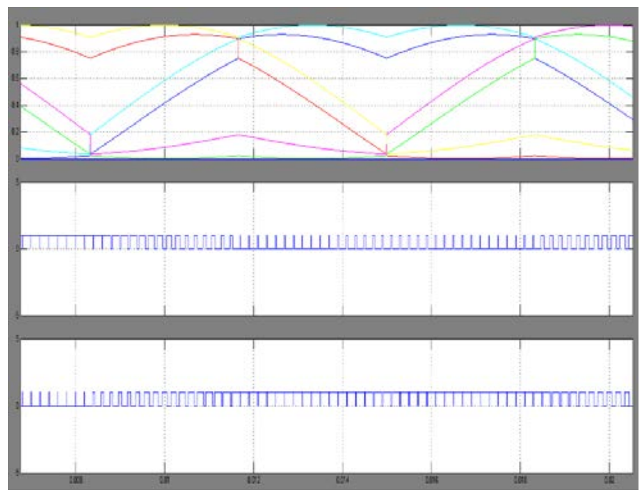

Fig 5.4 Pulse generation

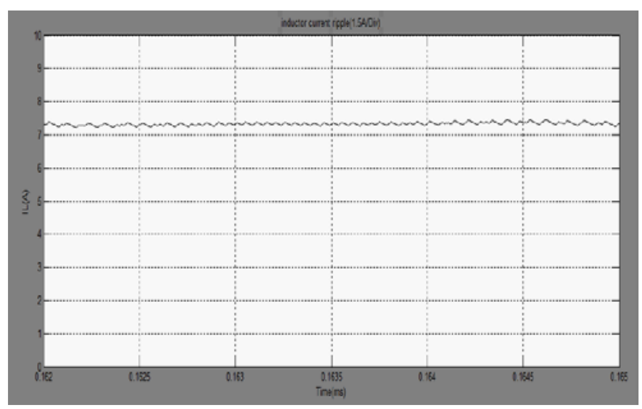

Fig 5.5 Inductor current ripple

Figure 5.1 shows the reference waveform and 5.4 shows the pulse generation.From figure 5.5 it can be understood that the current ripple is 0.15.

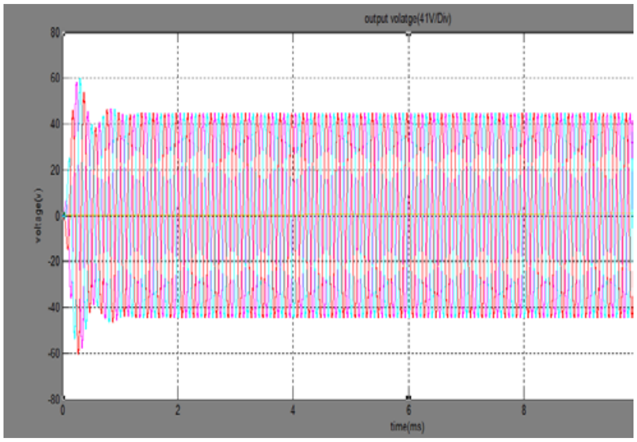

Fig 5.6 Output voltage waveform

Here an output of 41V is obtained from 24V DC source. The theoretical analysis is verified by the accordance with the simulation results. Seen from the experiment waveforms above, the experiment results are in accordance with theoretical analysis and simulation results.

6.Conclusion

In this paper, the ripple of Z-source inductor current based on shoot-through of SVPWM strategy is analyzed, and then the quantitative expression of the ripple is presented. The inductor is designed for a ZSI prototype. Experimental results show that the ripple of Z-source inductor current is inversely proportional to the inductance; the ripple decreases when the input voltage rises; the ripple reaches maximum when the reference vector is in the same phase with the six effective vectors. It is verified that the ripple of the designed inductor current satisfies the constraints, the design method proposed in this paper is feasible.

Acknowledgments

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