Analysis of an Over Modulation Control in an Indirect Matrix Converter

Goh Teck Chiang*, Jun-ichi Itoh*

*Nagaoka University of Technology

This paper discusses the control of over modulation for an indirect matrix converter and analysis the results from the experimental and converter losses. Indirect matrix converter has disadvantage at the output voltage transfer ratio which is limited by the ratio of 0.866 multiply with the input voltage. When this converter is running at high frequency in motor drive, the limited output voltage results high output current and motor loss will be increased. The over modulation improves the voltage transfer ratio by transforming the output voltage from sinusoidal waveforms into square waveforms and obtain a high efficiency at the same time.

(Keywords: Indirect Matrix Converter, Over modulation, Square wave inverter)

1. Introduction

Recently, the developments of energy saving converters are studied and researched intensively due to the global warming issue. Especially in the field of transportation, three phase converters are used many in the motor drive applications, such as Hybrid Electric Vehicle (HEV) or electric train. One of the AC/DC/AC converters known as Indirect Matrix Converter (IMC) have been demonstrated and presented actively [1]-[2]. The size of this converter is smaller because the passive component, electrolytic capacitors are not required and high efficiency can be achieved. However, the application of this converter is constrained by the limited output voltage, where the output voltage = 0.866 of the input voltage, which is similar to the matrix converter. When driving a motor with variable frequency technique with matrix converters, the motor capability will be degraded by approximately 15%. In order to overcome the problem, one of the methods is to apply the over modulation technique [3]-[5].

This paper proposes an over modulation control method that can improve the output voltage ratio of an indirect matrix converter. Since the indirect matrix converter can be divided into two stages; the secondary stage which is similar to a voltage source inverter, can be easily applied with a single pulse modulation. This modulation will transform the output voltage into square wave from sinusoidal waveform (PWM) and also increase the amplitude of the output voltage. However, under the square wave operation there will be no zero vectors in the secondary side and therefore the primary side cannot switch at zero current. Therefore, switching loss will be occurring in the primary side.

This paper also analyses about the losses of the converter by comparing with two over modulation methods. One is without zero current switching (ZCS) in the primary side and the second is with ZCS in the primary side. The second method forces the output voltage reference at the secondary side to reduce and produce zero vector periods for ZCS. This will restricted the output voltage transfer ratio of the converter but note that the purpose is to compare and analysis about the losses and efficiency with the first control method. The validity of the proposed method is then confirmed in the simulation results and experimental results.

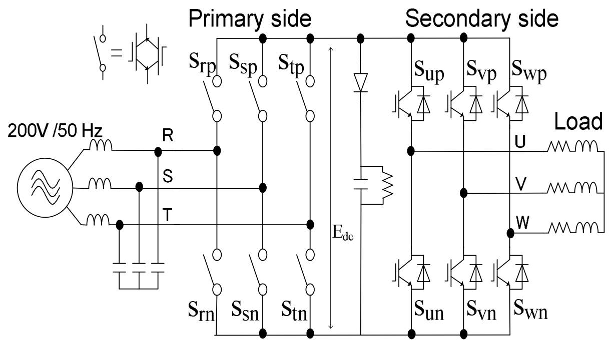

Fig.1 Indirect Matrix Converter circuit topology.

2. Circuit Configuration

Fig.1 shows the indirect matrix converter circuit topology. The primary side is similar to the input side of a matrix converter which is formed by 6 units of bidirectional RB-IGBTs. A stable DC link voltage will be established at the snubber circuit before the secondary side. The snubber circuit is used for protection purpose to absorb over voltage from the secondary side and therefore a film capacitor is enough. The secondary side is similar to a typical voltage source inverter that is form by 6 units of IGBTs.

In the proposed control, since the secondary side is the same as a voltage source inverter, the single pulse modulation can be easily applied. The input voltage of the secondary side is from the DC link voltage; where the DC link voltage is 270 V which is formed by the 3-phase 200 V input voltage, and therefore no extra control is required in the primary side since a sufficient DC link voltage is formed. A transition control that is based on the *V/f* conversion is applied in the secondary side. This transition control is a non-linear control of the output voltage [6], which is a proportional compensation to the amplitude of the output voltage command.

3. Proposed Control Method

Fig. 2 shows the proposed control block diagram that is fundamental from the ref. [7]. The primary control uses a single leg modulation to obtain a series of switching patterns; then these switching patterns are converted to current source switching patterns by using the pulse pattern conversion. The rec_duty command is used as a referral to generate a new carrier for the secondary side. Two types of carrier can be generated known as the symmetrical and the asymmetrical [8].

A transition control is included in the secondary side based on the *V/f* conversion. Practically, under the *V/f* constant condition, IMC can operate up to 42 Hz due to the $0.866v_{in}$ limitation with a 2 phase modulation in secondary side. Therefore, the transition control will start the transformation from 40 Hz to 50 Hz which is transforming from PWM to single pulse modulation. The amplitude of the Vq* will be expended in the over modulation range according to the frequency. Then, the output voltage command will be calculated from the dq conversion. A limiter is included to control the amplitude of the output voltage reference after the dq conversion. At 50 Hz, a complete square wave voltage reference switches at 120 degrees of each phase will be formed.

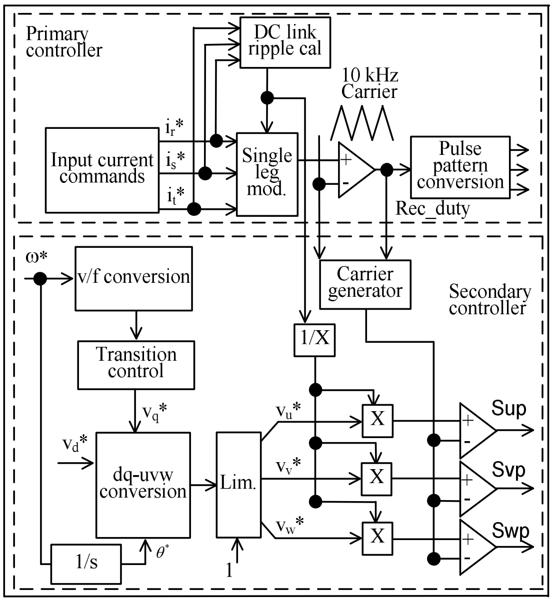

Fig.2. Proposed control block diagram.

Zero vector periods do not exist when the output voltage is in the shape of square wave. That is, the zero current switching cannot be applied in the primary side and dead time is required to protect the switches. However, by applying deadtime in the primary side will cause the DC link voltage distorted.

4. Simulation results

Fig. 3 illustrates the simulation results of the proposed control method by using circuit simulator (PSIM, Powersim Technologies Inc.). Note that low-pass filters are inserted in the input current i_r and the output line-line voltage v_{uv} in order to observe the low frequency component waveforms. The transition control is programmed to start at output frequency 40 Hz and completed by 50 Hz, which is referring to the Fig. 4, the over modulation starts at 0.8s and stop at about 1s. During the transition process, there is no surge voltage found in either the input side or the output side. The input current i_r is keeping a nearly sinusoidal waveform through out the process, and the output current i_u can keep a sinusoidal waveform and transformed into a six-step waveform when the output voltage command becomes a square wave.

Simulation parameters are shown in Table 1. Before the transition control begins (PWM), at 40 Hz, the input current i_r is about 3.25 A, the output current i_u is 3.78 A and the output line-line voltage v_{uv} is about 170 V. After completing the transition, at 50Hz, the input current i_r is about 4.34 A, the output current i_u is 4.38 A that is nearly equal to the input current and the output line-line voltage v_{uv} is 198 V. Note that this is an ideal

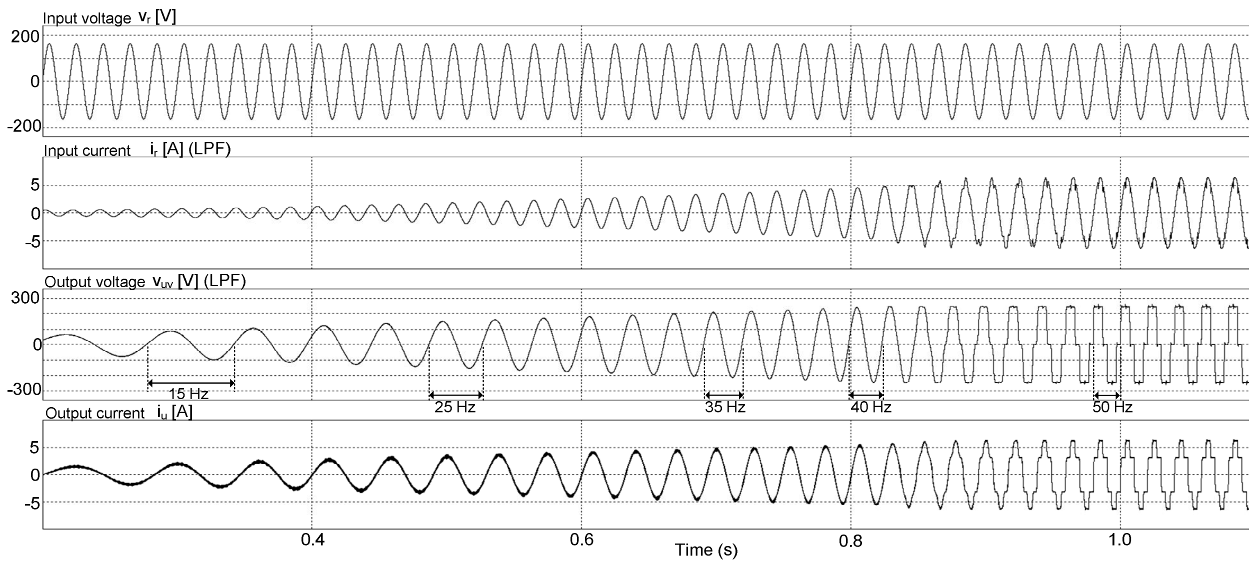

Fig.3 Simulation results (From PWM to single pulse modulation)

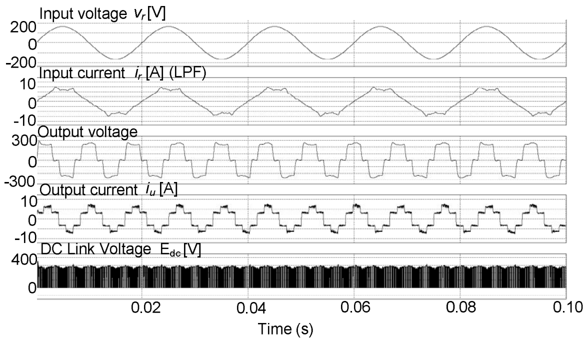

Fig.4 Square wave operation simulation results.

Table 1 Simulation Parameters

Input voltage	200V
Input frequency	50 Hz
Output frequency	50 Hz (Fig. 3)/ 120 Hz (Fig. 4)
Output voltage (RMS)	189 V
Output power	1500 W

condition, dead time effect is not being considered.

Fig. 4 shows another simulation results where the dead time is adding into the switches of primary side. Note that the Edc voltage is distorted due to the dead time effect in the primary side. During the deadtime, since the secondary side switches at 120 degree per phase and therefore output current is free wheeling within the secondary side. The output line-line voltage v_{uv} is 189V.

5. Loss Analysis

This section will discuss about the losses in the converter. The comparison will be among the following, PWM, single pulse modulation without zero current switching (ZCS) and single pulse modulation with ZCS. Note that the switching devices in the primary side are assumed to be RB-IGBTs in the simulation analysis. The simulation condition does not consider about the dead time, LC filter loss and snubber loss.

Fig. 5(a) shows the comparison between PWM and single pulse without ZCS. For the PWM, zero current switching can be applied in the primary side, and therefore the switching loss is zero. However, for the single pulse modulation, the switching loss is moved from secondary side into the primary side. The square wave operation in the secondary side switches at 120 degrees for each phase per time, the switching loss is reduced close to zero. In PWM, the loss for primary side is 12 W and for secondary side is 17 W. As for the single pulse modulation, the loss in primary side is 18 W and the secondary side is 10 W.

Fig. 5(b) shows the comparison between single pulse without ZCS and single pulse with ZCS. In order to obtain zero vector periods in the secondary side, the limiter reduces the output voltage reference to the peak of the carrier at 0.95 (peak =1). Zero vector periods will be occurring when the carrier is larger than the v_{out}* and zero current switching can be applied. The drawback is the amplitude of the output voltage will be reduced, which will affect the voltage transfer ratio. However, the purpose of this comparison is to prove that the losses of these two methods are about the same, even the zero current switching

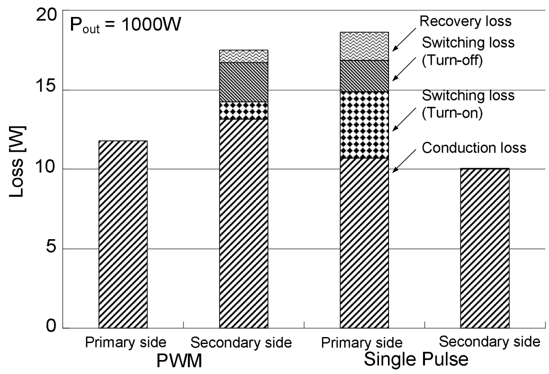

Fig. 5(a) Losses comparison among PWM and single pulse mod.

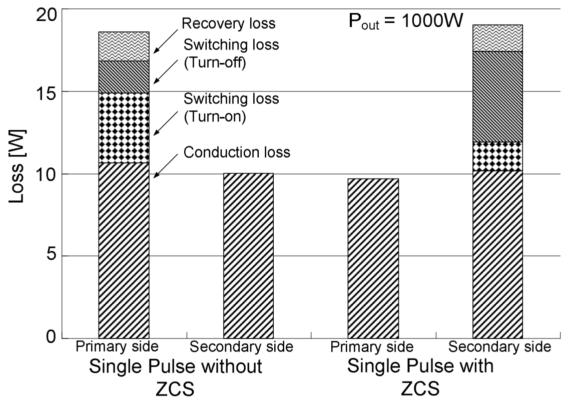

Fig .5(b) Losses comparison – single pulse without ZCS and with ZCS

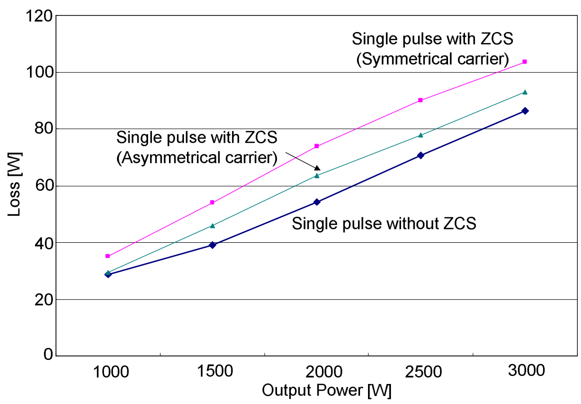

Fig. 6 Estimated efficiency in terms of various output powers.

cannot be applied in the primary side. For the single pulse with ZCS, the loss in the primary side is 10 W, and the secondary side is 19 W, where the total losses are about the same to the single pulse without ZCS; 28 W for a 1 kW system.

Fig. 6 shows the estimated efficiency in regards to various output powers. Since the method with ZCS results the switching loss occur in the secondary side, the asymmetrical carrier can reduced the switching loss by half and increase the total efficiency by 5 %. From the graph, we can understand that the efficiency is about the same even the ZCS does not apply in the primary side. We can conclude that in single pulse modulation, ZCS is not an element will affect the overall efficiency.

6. Experimental results

The experimental parameters are the same with the simulation condition. Fig. 7 demonstrates the experimental data of the single pulse modulation. The input current i_r is about 4.04 A, the output current i_u is 4.08 and the output line-line voltage v_{uv} is 183V. The input current is near to a sinusoidal waveform and the output current shows a six-step square waveform. The voltage transfer ratio is improved from 0.866 to 0.92.

Fig. 8 shows the input current harmonic analysis of the proposed control method. The input current THD is 6.14% and the 3rd harmonic component is less than 1% as shown in Fig. 8. Fig. 9 shows the effciency chart where the frequency is varying according to the modulation index. The condition was tested under a *V/f* constant situation, where modulation index 1.0 = 50 Hz. The data shows the modulation index from 0.5 to 1.0, where at 1.0 the output command is a square waveform. The efficiency can achieve 93.5 % in the process. Please note that in the experimental, the primary side is connected with dual IGBTs at per switching unit instead of RB-IGBT.

Fig. 10 shows the efficiency comparison between simulation analysis and the experimental data. The two lines in the top shows the simulation data. The line in top shows the efficiency excluding the LC filter loss. The line in the second shows the efficiency including the LC filter loss. The LC filter loss is considered at about 0.6 % of the total efficiency. The last line shows the experimental data. The maximum efficinecy of the proposed converter is about 93.5 % which can be confirmed from the comparison between the simulation analysis and the experimental test.

7. Conclusion

This paper proposed a single pulse modulation for an indirect matrix converter. The voltage transfer ratio can be improved from 0.866 to 0.92 with confirmation in simulation analysis and experimental results. This paper also shows that without applying the zero current switching in the primary side, this converter still can achieve high efficiency at 93.5 %.

This study was supported by Industrial Technology Grant Program in 2009 from New Energy and Industrial Technology Development Organization (NEDO) of Japan.

References

1. J.W Kolar, Schafmeister. F, Round. S.D, and Ertl. H "Novel Three Phase AC/DC/AC Sparse Matrix Converter", *IEEE Trans Power Electronics*, Vol 22, pp. 1649-1661, Sept 2007.
2. J.W. Kolar, Friendi. T, Heldwein M.L, and Giezendanner. F, "A High Efficiency Indirect Matrix Converter Utilizing RB-IGBTs", in *Power Electronics Specialist Conference*, pp1-7, 18-22 June 2006.
3. Thuta.S, Mohapatra. K.K, and Ned Mohan, "Matrix Converter Over-Modulation Using Carrier-based Control: Maximizing the Voltage Transfer Ratio", in *Power Electronics Specialist Conference,* pp. 1727-1733,
4. Tamai. Y, Ohguchi. H, Sato. I, Odaka. A, Mine. H, and Itoh. J, "A Novel Control Strategy for Matrix Converters in Over-Modulation Range", in *Power Conversion Conference*, Nagoya Japan, pp. 1049-1055, April 2007.
5. Bingsen. W, and Venkataramanan. G, "Six Step Modulation of Matrix Converter with Increased Voltage Transfer Ratio", in *Power Electronics Specialist Conference,* pp. 18-22, June 2006.
6. Itoh. J and Ohtani. N, "Square Wave Operation for a Single-Phase PFC Three-Phase Motor Drive System without a Reactor", in *International Conference on Electrical Machines and Systems,* Session LS3F-3, Nov 2009.
7. Itoh. J, Sato. I, Odaka. A, Ohguchi. H, Kodatchi. H, and Eguchi. N, "A Novel Approach to Practical Matrix Converter Motor Drive System with RB-IGBT", in *Power Electronics Specialist Conference*, Vol 3, pp. 2380-2385, June 2004.
8. Teck Goh and Itoh. J, "A Three-Port Interface Converter by Using an Indirect Matrix Converter with the Neutral Point of the Motor", in *Energy Conversion Congress Expo*, San Jose, pp. 3282- 3289, Sept 2009

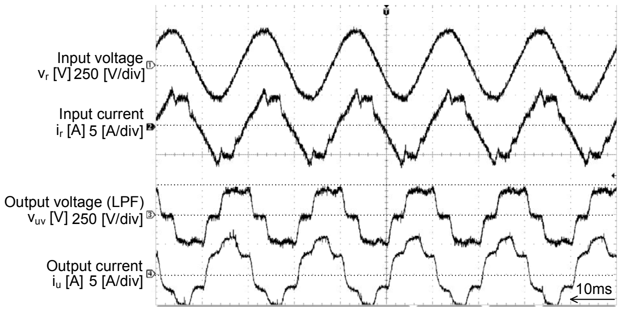

Fig.7 Single pulse modulation experimental results.

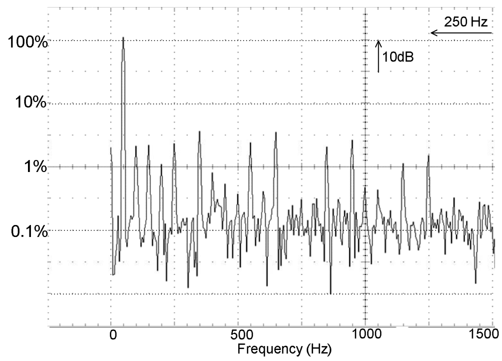

Fig.8 Input current harmonic analysis.

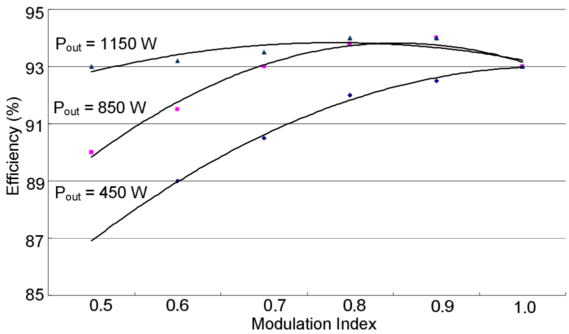

Fig.9 Experimental efficiency chart (PWM to single pulse mod).

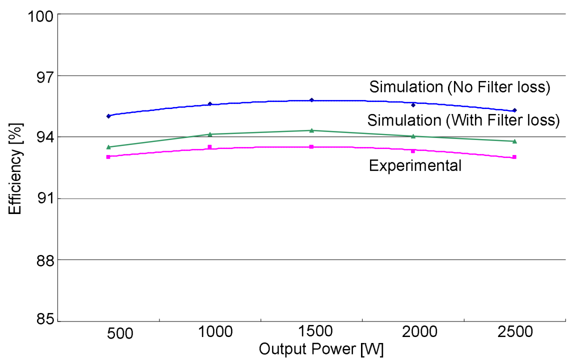

Fig.10 Efficiency comparison - simulation analysis and experimental.