

DC/DC Boost Converter Functionality in a Three-phase Indirect Matrix Converter

Goh Teck Chiang* and Jun-ichi Itoh*

*Nagaoka University of Technology, Niigata, Japan

Abstract-

An indirect matrix converter connected with two input power sources is proposed; a gasoline generator as the main AC power supply and batteries as the secondary power source. The indirect matrix converter is small in size because of having a DC link part without an electrolytic capacitor. The DC link part is utilized by connection with a boost up chopper with batteries as a secondary input power source. Furthermore, the chopper connects to the neutral point of the motor and utilizes the leakage inductance of the motor as a reactor component. The proposed technique successfully further reduce the size of the converter by removing the boost reactor in the boost converter stage. The proposed converter is simulated and experimentally validated using a 750 W prototype and an induction motor driven with V/f control. The total harmonic distortion (THD) of the input and output currents are 4 and 3.7%, respectively, and the efficiency is 96%.

Index Term-

Three-phase AC/AC converter, Neutral point of a motor, Zero vector switching, Boost-up chopper, Leakage inductance

*Nagaoka University of Technology, Nagaoka, Japan

Telephone: +81-258-47-9563

FAX: +81-258-47-9563

E-mail: tcgoh@stn.nagaokaut.ac.jp (Goh Teck Chiang)

itoh@vos.nagaokaut.ac.jp (Jun-ichi Itoh)

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INTRODUCTION

Environmental responsibility has become a significant concern for communities, so that the development of renewable power sources, such as wind turbines and low-carbon-emission hybrid electric vehicles (HEVs) is progressing rapidly. One of the most common applied converters in hybrid systems is the AC/DC/AC converter, because it has the ability of connection to two different power sources. The generator mainly supplies constant power to the load and a battery is used as an alternate power source to drive an electric motor and also to absorb the power fluctuation during periods of high peak energy demand.

Figure 1 shows a conventional AC/DC/AC power converter, which typically consists of a pulse width modulation (PWM) rectifier, a DC link capacitor and a PWM inverter, also known as a back-to-back (BTB) system [1-3]. The PWM rectifier is often used to reduce the harmonic currents in a generator and control the DC link voltage [4-7]. In order to obtain high performance under an adjustable speed drive system, a constant DC link voltage is required in a BTB system, because the voltage fluctuation of the DC link part will cause an output voltage error. A typical method for reduction of the voltage fluctuation is to place a large electrolytic capacitor into the DC link part as a filtering device between the rectifier and the inverter. However, a large electrolytic capacitor is bulky.

Another approach is to reduce the capacity of the electrolytic capacitor by application of a high speed DC voltage controller to the rectifier control [8]. However, the control response is limited by the delay of the voltage detection and digital controller; therefore, the electrolytic capacitor is still required. In addition, the capacitance is not reduced since the DC link capacitor is dominated by the capacitor current. As a result, a large amount of space is required for the capacitor installation in a practical device. In addition, electrolytic capacitors are not suitable for high temperature applications, such as in HEVs. Overall, these disadvantages of the electrolytic capacitor affect the reliability of the converter.

For the secondary input power source, a boost converter which consists of a boost reactor and a switching leg (IGBT) is connected with batteries to the DC link part of the BTB system. Boost converter will control the battery current and the battery power will be used as a secondary power to drive the electric motor.

In this paper, a new circuit topology is presented, which is composed of an indirect matrix converter and a DC/DC boost converter that connects to the neutral point of a motor. An indirect matrix converter (IMC) has high efficiency and is easily configured in comparison to matrix converters [9-14]. In addition, this converter does not require a DC link electrolytic capacitor to filter the DC ripple voltage. It uses a direct conversion technique where the frequency of the DC link voltage contains a ripple with six times of the input frequency. However, the output voltage transfer ratio is limited by this direct conversion technique which is similar to the matrix converter, where output voltage = 0.866 of the input voltage [15].

Nevertheless, an appropriate control over the inverter is also proposed, so that it is possible to connect a DC chopper to the neutral point of the motor and to operate as a DC/DC converter [16]. This DC/DC converter with a battery is performed as a secondary power source of the IMC to drive the electric motor. The proposed circuit utilizes the neutral point of a motor in the boost converter, because the leakage inductance of the motor can be used as a reactor. Generally, the leakage inductance is around 10% of the rating impedance in an induction motor. For the proposed DC converter, around 3% of the reactor is enough to use as a boost reactor component. Please note that the synchronous reactance in a permanent motor is higher than the leakage inductance of an induction motor.

By removing the electrolytic capacitor and the boost-up reactor, the remaining part of the proposed circuit is constructed only of silicon components, namely insulated gate bipolar transistors (IGBTs) and diodes. As a result, the proposed circuit is high efficiency and high reliability. Simulation and experimental results clearly demonstrate that the circuit is capable of providing sinusoidal waveforms for the input and output, and high efficiency and a high power factor can be achieved.

PROPOSED CIRCUIT TOPOLOGY

Figure 2 shows the proposed circuit configuration. The indirect matrix converter can be simply divided into primary and secondary stages. The primary stage for the AC power source consists of twelve units of reverse blocking IGBTs [17], also known as a current source rectifier, where bidirectional power flow is possible in this circuit structure. A LC filter is required at the input of the primary stage to smooth the input current. The secondary stage for the motor consists of six IGBT units, which is similar to a standard voltage source inverter. The advantage of this converter over a BTB is that the primary side does not contain switching loss because zero current switching can be applied. The switching timing of the primary side is during the zero-current period of the DC link when the secondary stage output zero voltage. Therefore, high efficiency is achievable in this converter [12].

The other reason to use the indirect matrix converter is that the indirect matrix converter has a DC link part which is difference to the conventional matrix converter. The DC link part is utilized by adding a

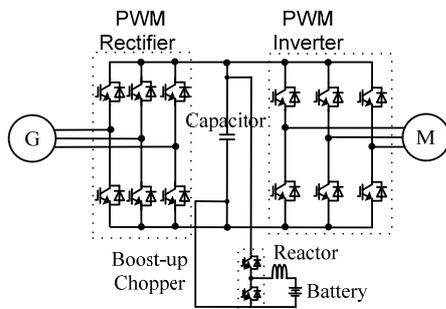


Fig. 1. Back-to-back converter.

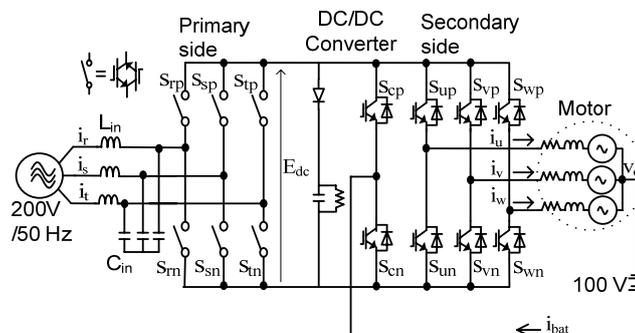


Fig. 2. Proposed circuit topology.

boost converter to the indirect matrix converter. The boost converter connects to the battery and the other terminal of the battery is then connected to the neutral point of the motor.

A snubber circuit is also included in the DC link part to absorb the voltage overshoot from reactive elements in the circuit [18]. It is used to prevent damage to the switching devices in the secondary side due to a sudden large voltage. It should be noted that the capacity of the snubber capacitor is smaller than the DC link capacitor in a BTB system, because the ripple current of the DC link part does not flow in the snubber capacitor.

The chopper circuit is connected in the DC link and batteries are connected to the neutral point of the motor. The leakage inductance of the motor is used as a boost up reactor in the proposed circuit. As a result, the proposed converter does not require bulky passive components.

CONTROL STRATEGY

Figure 3(a) shows a control block diagram of the proposed circuit. The primary side, the DC chopper and the secondary side are individually controlled by their own commands. A carrier comparison method is used as the PWM modulation, according to the control strategy [19]. The relationship between the output and input voltages is obtained by (1). The secondary side operates as a four-phase voltage source inverter by addition of the DC chopper as the fourth leg,

$$\begin{bmatrix} v_u \\ v_v \\ v_w \\ v_{bat} \end{bmatrix} = \begin{bmatrix} s_{up} & s_{un} \\ s_{vp} & s_{vn} \\ s_{wp} & s_{wn} \\ s_{cp} & s_{cn} \end{bmatrix} \begin{bmatrix} s_{rp} & s_{sp} & s_{tp} \\ s_{rn} & s_{sn} & s_{tn} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \quad (1)$$

where s_{xy} represents the switching function of the switches. When s_{xy} is turned on, $s_{xy} = 1$ and when s_{xy} is turned off, $s_{xy} = 0$.

A. Primary side control

The primary side controller is designed with a current-type PWM rectifier command. It uses a pulse pattern conversion to convert the PWM pulses of the voltage source type into the PWM pulse of the current source type by a simple logic selector. It uses a single leg modulation where the switching period can be reduced from $2\pi/3$ to $\pi/3$, where the $2\pi/3$ is the switching period of the conventional two-phase modulation [17]. That is, the leg with the maximum input phase voltage will always be turned ON, and the other two legs will be always turned OFF as shown in Figure 3(b). When the maximum input phase voltage is changing, (for example, from +R-phase to -S-phase), the related max phase voltage leg and the mid phase voltage leg will be switched at zero current until the relevant switch that contains the mid phase voltage becomes the maximum input phase voltage. From this direct conversion technique, a DC link voltage that contains a ripple with 6 times of the input frequency will be formed [17].

B. Secondary side control

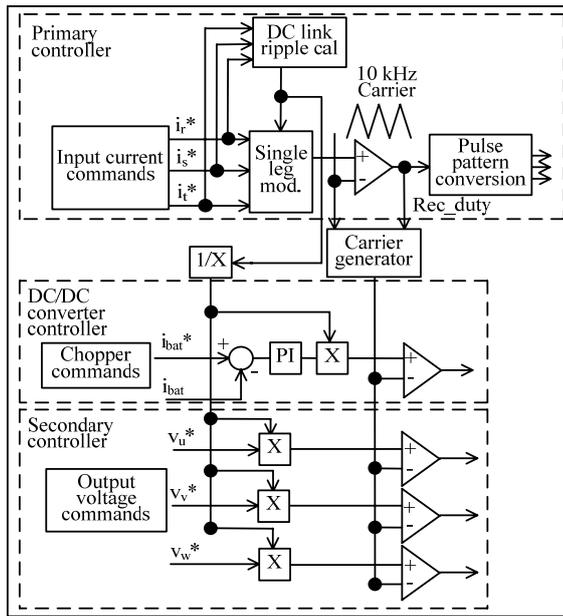


Fig. 3(a). Control block diagram.

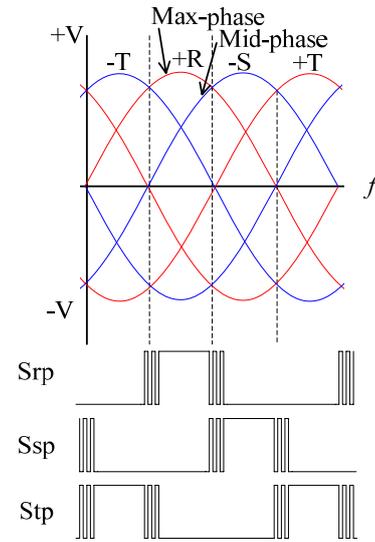


Fig. 3(b). Primary side switching pattern.

A conventional controller method for a voltage source type inverter is applied to the DC chopper and the inverter with a lean controlled carrier modulation. The carrier modulation forms a new carrier where the peak position of the triangular carrier is controlled by the duty ratio of the rectifier side pulse. This rectifier pulse is used to control the switching timing of the primary stage and the zero vector of the secondary stage. From the control, zero current switching is achieved in the primary stage where the dc link current becomes zero at the peak of every carrier. This new carrier is then used in the secondary side and the DC chopper side as a normal PWM comparison method, also referred to as an inverter carrier.

The boost converter is not a stand-alone circuit in the proposed circuit. Operation is strongly dependent on the secondary side of the indirect matrix converter. Zero vector outputs on the secondary side are the key factor to link the boost converter to the indirect matrix converter. The zero vector controls the amplitude of the output voltage. There are two functions of the zero vector output to the secondary side. The first is to implement zero current switching on the primary side, so that switching losses do not occur at the primary side. The second function involves operation of the boost converter, which will be described in a later chapter.

Figure 4 shows an example of the relationship between the normal carrier applied to the primary side and the new inverter carrier applied to the secondary side. The inverter commands are given by the voltage controller as described in Chapter IV. It is noted that the DC chopper is controlled as the fourth leg of the inverter, so that the DC chopper command is compared by the same carrier with the inverter voltage commands. There are two methods to generate an inverter carrier; Figure 4(a) represents the symmetrical type, which has approximately double the switching frequency of the rectifier switching frequency, and Figure 4(b) shows the asymmetrical type, which has the same switching frequency as the

rectifier switching frequency [18].

In Figure 4(a), the bottom peak position of the triangular carrier is controlled by the duty ratio of the rectifier pulse, as shown in the upper part of the figure. The chopper commands, along with the inverter output voltage commands, are compared with this new inverter carrier to obtain the desired switching patterns. The zero vector periods are shown in the lower part of Figure 4(a). The switching pulses of the secondary side attain the zero vectors for every carrier cycle. The primary side arms switch at every zero vector period.

In Figure 4, z_{v_u} and z_{v_l} represent the zero vector periods of the inverter, where $z_{v_u} = S_{up}=S_{vp}=S_{wp}=1$ (upper arm zero vector) and $z_{v_l} = S_{up}=S_{vp}=S_{wp}=0$ (lower arm zero vector ($S_{un}=S_{vn}=S_{wn}=1$)). The upper arm of the chopper (S_{cp}) switches ON at every zero vector period of z_{v_u} . On the other hand, the lower arm of the chopper (S_{cn}) will switch ON at every zero vector periods of z_{v_l} . During these zero vector periods, the boost converter is operated in the on-state, and the battery current through the leakage inductance of the motor increases. During the non-zero vector periods, also known as the Off-state operation, the battery current is released into the capacitor in the LC filter at the power source. The operation state in the figure is referred to the boost converter operation.

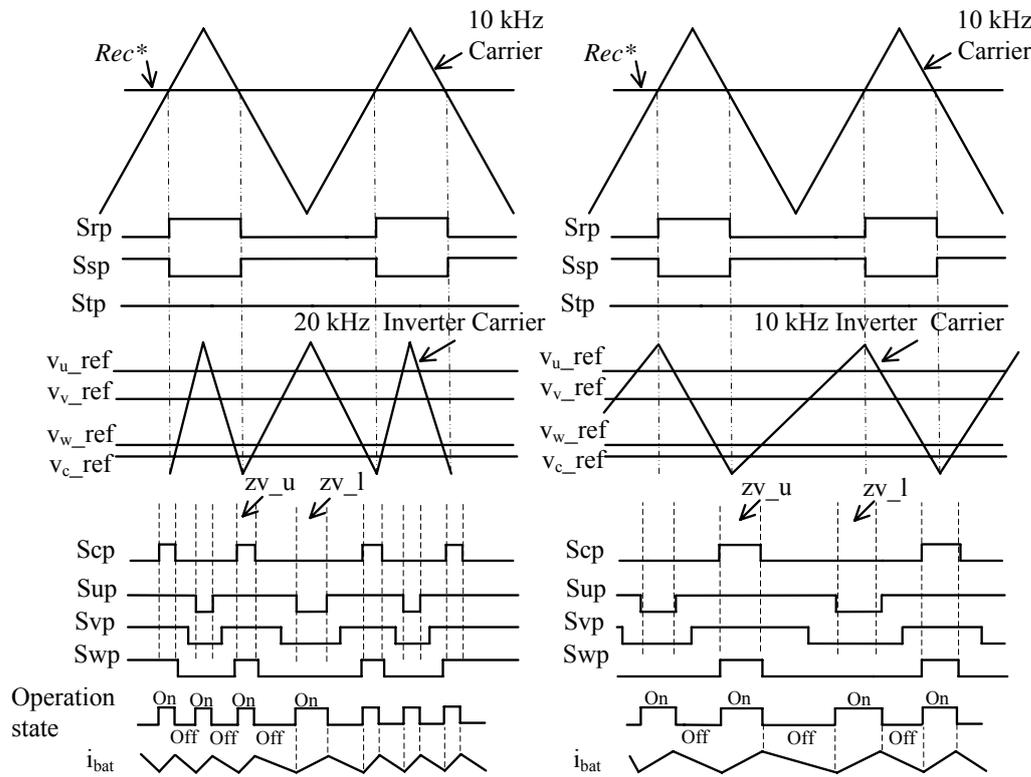
When the switching frequency of the rectifier is 10 kHz, the control method applied in Figure 4(a) generates a new symmetrical carrier that has a frequency of approximately 20 kHz. This is approximately twice the primary side switching frequency. Alternatively, according to Figure 4(b), an inverter carrier can be formed based on the duty of the rectifier command, which is asymmetrical with a frequency of 10 kHz.

By comparing the symmetrical and asymmetrical inverter carriers in Figure 4, it should be noted that the zero current switching in the rectifier is not affected by the inverter carrier, because both carriers are formed following the rectifier duty. Since every carrier time is longer in the asymmetrical inverter carrier, the sequence of the zero vector periods becomes slower; therefore, the boost converter will achieve better efficiency, but the current ripple in the battery will be increased. Further, the asymmetrical method can achieve better total harmonics distortion (THD) values for the output because the dead time effect is smaller due to the lower switching frequency.

The other disadvantage of the asymmetrical inverter carrier is the detection of the load current. Usually, the average value of the load current appears at the peak of the symmetrical inverter carrier, so that it can be easily detected using the symmetrical inverter carrier. However, for the asymmetrical carrier, the average current point does not agree with the peak of the asymmetrical carrier; therefore, in order to detect the average current, a low-pass-filter is required. Consequently, control performance will be decreased.

UTILIZATION OF THE NEUTRAL POINT OF THE MOTOR

The voltage commands of the secondary stage are decided by the battery current command and the



(a). Symmetrical inverter carrier.

(b). Asymmetrical inverter carrier.

Fig. 4. Relationship between the zero vectors and boost converter operation.

output voltage commands for the three-phase load. A three-phase inverter has eight output voltage space vectors, including two zero vectors. The importance of the zero vectors explains the behavior of the boost converter along with the neutral point of the motor. The boost converter will operate at every zero vector of the secondary side of the converter. On the other hands, the output voltage for the three-phase load is controlled by other voltage vectors as shown in [16].

Figure 5 illustrates the output current flow diagram of the secondary side under the normal operation and Figure 6 shows the zero-phase sequence equivalent circuit where the battery is operating at discharge mode. In Figure 5, the secondary side functions as a conventional three-phase inverter with a motor; it controls the motor speed and torque. Zero-phase sequence is happening at every zero vector periods of the secondary side. The current at the neutral point of the motor is zero and a positive or negative battery current can be controlled as shown in Figure 6. Note that the polarity of the battery voltage can be connected in facing the neutral point of the motor or in a reverse way [16]. C_{in} represents the capacitors from the LC filter; since two switches in the primary side will always be turned ON, the capacitors C_{in} can be considered in the DC link voltage. On the other hand, for the zero-phase sequence, the motor line voltage can be considered as zero, so that the motor can be considered as a leakage inductance. In addition, the secondary side of the converter can be considered as a single leg topology. The battery

current first goes into the secondary side and flows out through the neutral line and charges or discharges the battery. The battery current can be controlled by the PI controller.

The zero vectors are two particular vectors that generate zero line voltage to the motor. The neutral point voltage v_o of the motor, based on the neutral point of the DC link part, is obtained by (2)

$$\begin{cases} v_o = \frac{E_{dc}}{2} & \text{When all upper arms are ON} \\ v_o = \frac{-E_{dc}}{2} & \text{When all lower arms are ON} \end{cases} \quad (2)$$

where E_{dc} is the DC link voltage and v_o is the voltage of the neutral point of the motor, based on the neutral point of the DC link part.

A high DC link voltage is mandatory in order to control the zero vectors; therefore, the relationship between the DC link voltage (E_{dc}), the inverter line voltage (v_{inv}) and the battery voltage (V_{bat}) will be discussed. The inverter output voltage, v_u , v_v , and v_w , with respect to the neutral point voltage of the DC link, is expressed as

$$\begin{cases} v_u = a \frac{E_{dc}}{2} \sin \omega t + v_o \\ v_v = a \frac{E_{dc}}{2} \sin(\omega t - \frac{2\pi}{3}) + v_o \\ v_w = a \frac{E_{dc}}{2} \sin(\omega t - \frac{4\pi}{3}) + v_o \end{cases} \quad (3)$$

where a is the modulation index of the motor phase voltage, $0 < a < 1$, v_o is the neutral point voltage of the motor (during zero phase sequence), and ω is the inverter output angular frequency.

The inverter line voltage is then given by (u-v phase)

$$v_{uv} = a \frac{\sqrt{3}}{2} E_{dc} \sin(\omega t + \frac{\pi}{6}). \quad (4)$$

Eq. (5) shows the relationship for an inverter to obtain the maximum output line voltage V_{inv} (RMS) under the maximum reference magnitude of a three phase modulation.

$$E_{dc} \geq 2 \frac{\sqrt{2}}{\sqrt{3}} V_{inv}. \quad (5)$$

The maximum line voltage between the inverter leg and chopper leg can be obtained as, (RMS)

$$v_{ux} = \frac{\sqrt{2}}{\sqrt{3}} V_{inv} + V_{bat}. \quad (6)$$

Because v_{ux} must be smaller than E_{dc} , the inverter voltage and battery voltage are constrained by Eq. (7)

$$E_{dc} > \frac{\sqrt{2}}{\sqrt{3}} V_{inv} + V_{bat}. \quad (7)$$

As a result, the DC link voltage of the proposed circuit must satisfy both requirements as shown by Eq.

(8), which can be referring to Figure 6.

$$E_{dc} \geq \begin{cases} 2 \frac{\sqrt{2}}{\sqrt{3}} V_{inv} & \text{When } \frac{\sqrt{2} V_{inv}}{\sqrt{3}} \geq V_{bat} \\ \frac{\sqrt{2}}{\sqrt{3}} V_{inv} + V_{bat} & \text{When } \frac{\sqrt{2} V_{inv}}{\sqrt{3}} < V_{bat} \end{cases} \quad (8)$$

Note that in Eq. (8), the V_{bat} can always be neutralized with half of the E_{dc} under the two conditions. That is, the V_{bat} must be always smaller than half of the E_{dc} , since the E_{dc} is always known as the 0.866 of the input phase voltage, as shown in Eq. (9).

$$\frac{\sqrt{2}}{2} V_{in} 0.866 > V_{bat} \quad (9)$$

Furthermore, a new expression of the secondary side current is given as follows, assuming that the leakage impedance is even during the zero-phase sequence equivalent circuit.

$$\begin{cases} i_u = i_a + \frac{i_{bat}}{3} \\ i_v = i_b + \frac{i_{bat}}{3} \\ i_w = i_c + \frac{i_{bat}}{3} \end{cases} \quad (10)$$

where i_u , i_v , and i_w are the inverter current, i_a , i_b , and i_c are the positive-phase inverter current and i_{bat} is the battery current.

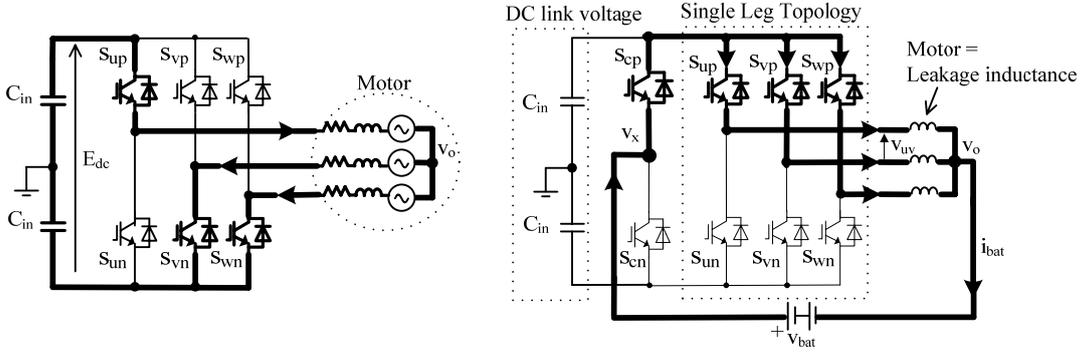


Fig. 5. Secondary side current flow diagram (Normal operation). Fig. 6. Zero phase sequence equivalent circuit.

SIMULATION RESULTS

Table I shows the simulation parameters for both results. The proposed circuit was simulated under two conditions of battery discharge and charge by using a circuit simulator (PSIM, Powersim Technologies Inc.). An ACR (Automatic current regulator) controller controls the battery current to a desired positive or negative value. An ideal battery current i_{bat} is purposely adjusted at a specific time of 38 ms to confirm the proposed circuit performance. The motor model, which consists of three sets of voltage sources as

back-electromotive forces and leakage inductances, is used in the simulation. The asymmetrical inverter carrier was used in the simulation.

Figure 7 shows the battery discharge mode, with the battery current controlled from 0.5 to 2 A. The two waveforms show the input power supply voltages v_r , v_s , and v_t , the input currents i_r , i_s , and i_t , and the output line voltages ($v_{uv(LPF)}$, $v_{vw(LPF)}$, and $v_{wu(LPF)}$) through a low pass filter, which has a cut-off frequency of 1 kHz, to observe the low frequency components, the output currents i_u , i_v , and i_w , and the battery current i_{bat} . The results show that the THD of both the input and output currents are less than 4%. It should be noted that at 20 ms, the input current magnitude decreases due to the increment of i_{bat} , which indicates that the increase of the battery power leads to a decrease in generator power.

On the other hand, Figure 8 shows the ACR (Automatic current regulator) controls the battery current from 0.5 to -2 A. The battery is charged from a generator under this condition. The results are also show that when in the charging mode, both the input and output currents have good sinusoidal waveforms. At 20 ms, as the i_{bat} decreases, the input current is forced to increase, because higher power is required to charge the battery. These two waveforms provide evidence of good power management between the generator and the battery.

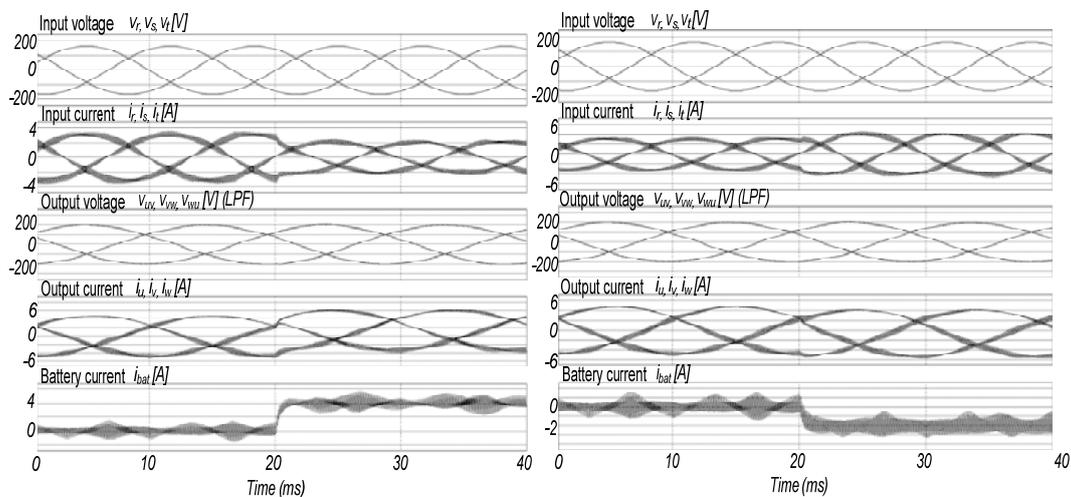


Fig. 7. Simulation results (Battery = Discharge mode).

Fig. 8. Simulation results (Battery = Charge mode).

TABLE I

SIMULATION PARAMETERS

Input voltage	200 V	DC source	100 V
Input frequency	50 Hz	Output voltage	173 V
Carrier frequency	10 kHz	Output frequency	35 Hz
Inverter frequency	10 kHz	Leakage inductance	5 mH

TABLE II
EXPERIMENTAL PARAMETERS

Input voltage	200 V	Inductor	1.7 mH
Input frequency	50 Hz	Capacitor	2.5 μ F
Carrier frequency	10 kHz	DC source	100 V
Output frequency	30 Hz	LC Filter Cut-off frequency	2.4 kHz

TABLE III
MOTOR PARAMETERS (FUJI: MLH6085M)

Motor Power	750 W	Rated current	3.6 A
Poles	4/ 50 Hz	Rated voltage	200 V
RPM	1420	Leakage inductance	4.42 mH

EXPERIMENTAL RESULTS

A 750 W prototype was built and tested using two operation modes, the same as those described in the simulation section. Mode I is battery discharge under motoring operation and Mode II is battery charge under motoring operation. Both conditions were verified using the parameters shown in Table II. The controller used the asymmetrical format to generate the 10 kHz inverter carrier. Table III shows the specification data for the motor. Note that this is conventional motor with no particular settings required for the neutral point connection.

Fundamental Operations

Figures 9 and 10 show the Mode I and Mode II operations, respectively. In Figure 9, the DC power supply is set to 100 V and the battery current is controlled to 2 A. Similarly, in Figure 10, the battery current is controlled to -2 A. Good sinusoidal waveforms were achieved for the input and output current of both operation modes. Figure 11 shows the input power factor of the discharge and charge modes. Both modes achieved input power factors of more than 98%, which can be considered as a unity power factor. The input power factor decreases during the discharge mode, because the input current becomes smaller

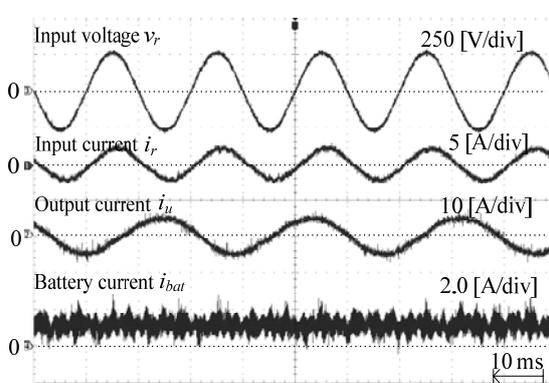


Fig. 9. Experimental results (Mode I = Battery discharge).

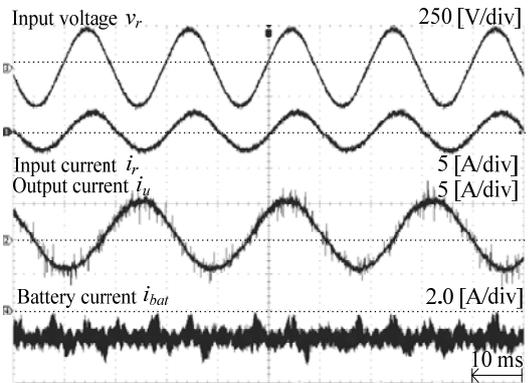


Fig. 10. Experimental results (Mode II = Battery charge).

in comparison with the charge mode.

Figure 12 shows the input current THD and the output current THD for both modes. The input current THD obtained during the charge mode is 3.6%, and that during the discharge mode is 4.0%. The lowest output current THD obtained during the charge mode is 3.0% and that during the discharge mode is 3.7%.

Figure 13 shows the picture of the prototype. All switching units are mounted on top of a heat sink. The top of the picture shows the primary side switching units. GDU boards are placed on top of the primary side switching units. The picture also shows that the switching units for the secondary side and the boost converter are based on a single module IGBT unit.

Motor Performance Analysis

Figure 14 demonstrates motor related experimental results in order to confirm the motor performance for the proposed circuit. This figure shows the torque impact characteristic of the tested motor. The output frequency is 30 Hz, and the step increase of torque is 100%. The battery power is set at 200 W, and the input power is closely to 50 W when the torque is 0%. The input current i_r shows a bad quality of waveform due to the low input power since battery power is supplying the induction motor. When the torque increases to 100%, the battery power maintains at 200W, subsequently the input power provides the additional required power to keep the motor speed. The RPM waveform demonstrates a good control of speed and the output current shows a corresponding sinusoidal waveform.

Efficiency and Loss Analysis

The loss analysis of the proposed circuit is now discussed, which is carried out using a circuit simulator (PSIM, *Powersim Technologies Inc.*) and Dynamic Link Library (DLL) files [20]. The analysis was conducted for two categories, by application of the symmetrical and asymmetrical inverter carriers. Figures 15, 16, 17 and 18 show the loss analysis results simulated under the parameters as shown in Table I and Table IV shows the devices parameter. Note that in the loss analysis, the primary side is assumed to use RB-IGBT. The output power is 750 W and the input power ratio is 9:1 in Figs. 15 and 16. The input power ratio is referring between the generator power and battery power respectively. A ratio of 9:1 means that the total input power supplied from the generator power is 90% and the remaining 10% is supplied from the battery power.

Figure 15 shows details of the switching losses when the symmetrical inverter carrier is applied. Zero current switching is implemented on the primary side, and therefore conduction loss occurs only in that side. The total loss for the discharge mode is approximately 27 W, and that for the charge mode is approximately 29 W. The analysis verifies that the converter can achieve an efficiency of 96.4%. A conventional back to back converter may achieve an efficiency of approximately 93% [21].

Two reasons are found for the higher losses in the secondary side. The first is that the switching frequency in the secondary side is 20 kHz when using the symmetric method, as discussed in chapter III.

The second reason is that the inverter current contains the battery current during the zero phase sequence. The higher switching frequency and larger battery current resulted in increased losses.

Figure 16 shows the results of the asymmetric inverter carrier loss analysis, which was simulated under

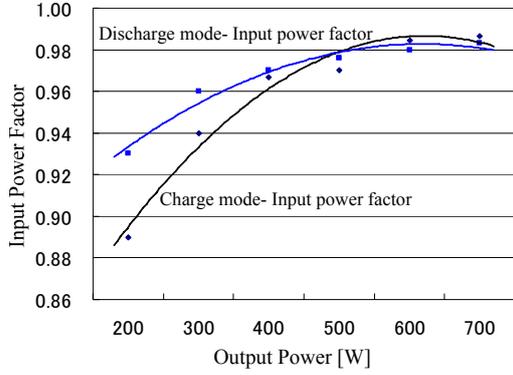


Fig. 11. Input power factor.

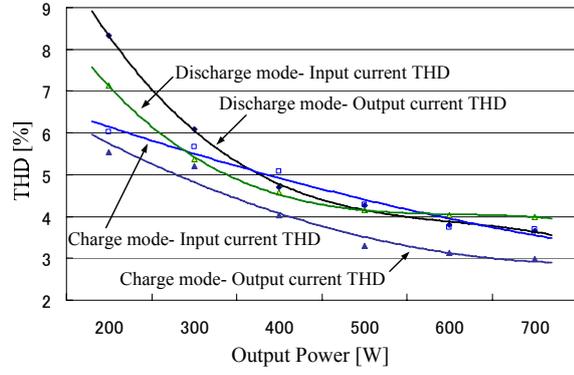


Fig. 12. Input and output current THD values

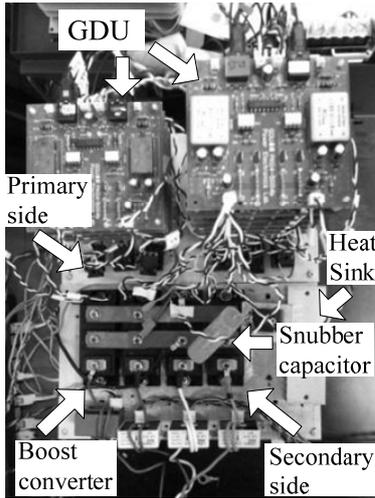


Fig. 13. Picture of the prototype

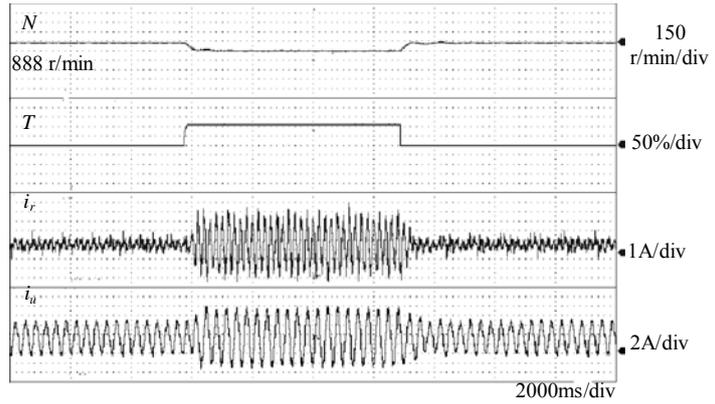


Fig. 14. Torque impact characteristic of the proposed circuit.

TABLE IV
DEVICE PARAMETERS

	Primary side	Secondary side	Chopper
Devices model	1MBH30D-060 (Fuji Electric)	2MBI50N-060 (Fuji Electric)	2MBI50N-060 (Fuji Electric)
Collector-Emitter voltage	600 V	600 V	600 V
Gate-Emitter voltage	± 20 V	± 20 V	± 20 V
Collector current	30 A	50 A	50 A
Turn-on time (Typ.)	0.16 μ s	0.6 μ s	0.6 μ s
Turn-off time (Typ.)	0.30 μ s	0.6 μ s	0.6 μ s
Reverse recovery time	300 ns	300 ns	300 ns

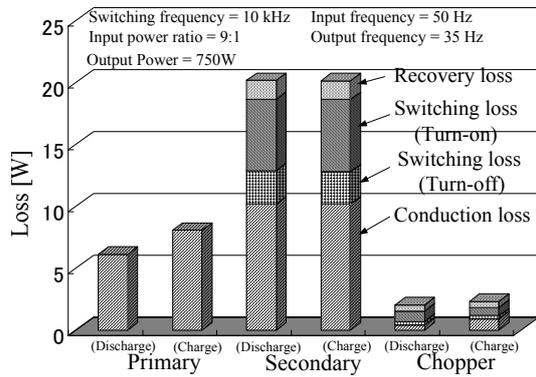


Fig. 15. Loss analysis – Switching device losses (Symmetric method).

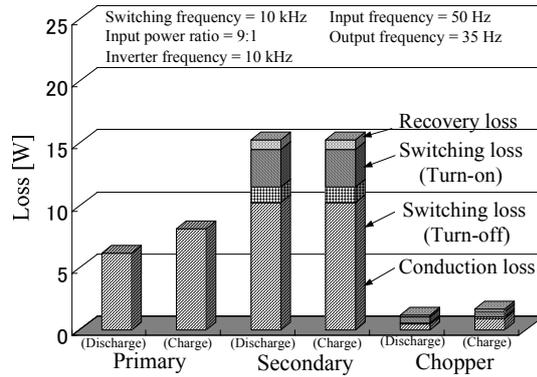


Fig. 16. Loss analysis – Switching device losses (Asymmetric method).

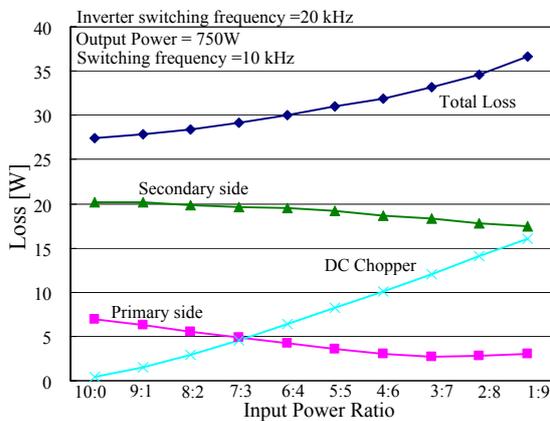


Fig. 17. Loss analysis – Changes in input ratio (Symmetric method).

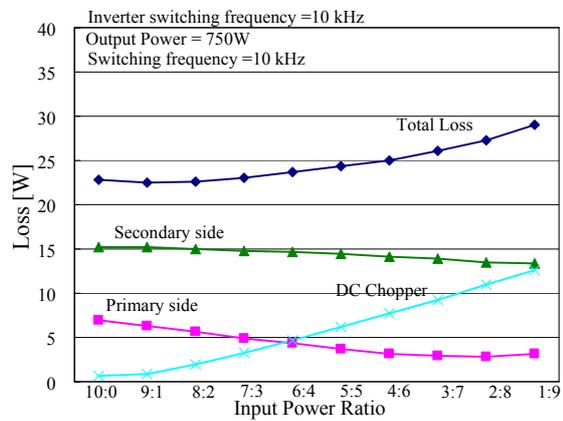


Fig. 18. Loss analysis – Changes in input power ratio (Asymmetric method).

the same conditions as those for Figure 15. The loss in the secondary side decreases approximately 20% and the loss in the chopper decreases by approximately 25%. The total loss for the discharge mode is 23 W and that for the charge mode is 25 W. An efficiency of 96.9% can be achieved, which is an improvement of approximately 0.5%.

Furthermore, in comparison the proposed circuit with the typical indirect matrix converter; provided the energy flow is from AC to AC only, the efficiency is almost equivalent for the proposed circuit. But for DC to AC, the motor loss will affect the efficiency, where a special type of motor with a connectable neutral point is required in order to reduce the copper loss in the motor.

Figures 17 and 18 show the calculations of loss analysis by powering with various input power ratios from 10:0 to 1:9, which represent the ratio of the generator power to battery power. In this case, the losses in chopper gradually increase as the battery power is going larger. The losses in primary side decrease accordingly to the input power.

For the symmetric method in Figure 17, it is obvious that the loss in the DC chopper increases sharply

as the battery current increases. However, the loss in the primary side does not reach zero, but drops to a constant 4 W from 7 W.

On the other hand, as the generator power is less than 225 W, the loss in the secondary side starts to decrease. This is because the output voltage is directly dependent on the input voltage in the indirect matrix converter. As the input voltage decreases, the magnitude of the output voltage also decreases. However in the proposed circuit, the boost converter maintains the DC link voltage even if the generator power drops; therefore, the output side can maintain its power.

Figure 18 shows the same analysis with the second condition, where the asymmetric format is applied. As expected, the loss in the primary side remains unchanged; however, the loss in the secondary side is reduced approximately 18% compared to that for the symmetric format in Fig. 17. When the battery is at full power, the loss reduces approximately 25%. This comparison shows that the proposed converter can achieve better efficiency by applying the asymmetric method and the performance of the boost converter is not limited by the change of carrier.

CONCLUSION

A new control method is proposed by utilizing the neutral point of a motor and connection to an indirect matrix converter for motor drive applications. Control over the inverter zero vector periods allows an additional chopper leg to perform as a boost converter with connection to the neutral point of a motor. Simulation and experimental results demonstrated good sinusoidal waveforms and confirmed the validity of the proposed method. From the loss analysis of the proposed circuit, an efficiency of 96% was estimated. EMC behavior of the circuit will be subjected for further investigation.

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