Evaluation of a Three-port Indirect Matrix Converter connected to the Neutral Point of Motor

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Abstract – This paper proposes using an indirect matrix converter as a main circuit and connected with two input power sources, where main power source is an AC generator and secondary power source is DC battery. The proposed circuit utilizes the neutral point of the motor and it is connected to the battery. Leakage inductance from the motor is used as a boost-up reactor. The size of the proposed circuit is successfully reduced because it does not require an electrolytic capacitor and a boost-up reactor. An additional DC chopper controls over zero vectors allows the control of the battery current along the neutral line of the load. The proposed converter has been validated experimentally using an induction motor driven with v/f control.

1. Introduction

During recent years communities have shown a great concern on environmental responsibility. The development of renewable power energy sector such as wind power generation and HEV (Hybrid Electric Vehicle) is growing rapidly. One most common applied converter is AC/DC/AC converter because two different power sources can be applied. Battery can be put into a good uses to reduce gasoline consumption and hence reduces emission. A typical traction system is subjected to dynamic loads as the energy converter needs to deliver sufficient energy at any time. In order to response to high peak energy demands the control over energy reservoirs are often found important [1]. An electronic motor in fact can be improved with a combination of a gasoline motor and battery in many ways.

Fig.1 shows a conventional AC/DC/AC power system typically consists of a PWM rectifier, a DC link capacitor and an inverter. A PWM rectifier is often used for reducing harmonic currents produced by electronic devices [2-3]. The AC power generated by the generator is provided to the rectifier, which provides a rectified signal to the DC link. The inverter uses the rectified signal provided to the DC link to generate the desired AC power to the load. The quality of the AC power generated by the inverter is related to the quality of the DC power provided to the DC link. The overall performance of the system can be improved by reducing fluctuations in current on the DC link, commonly referred to as ripple. A typical method of reducing ripple on the DC link is to provide an electrolytic capacitor as a filtering device between the rectifier and the inverter. However, a large capacitance electrolytic capacitor has a relatively limited operating lifetime [4]. Because of its electrolytic characteristics, other components such as resistors are required for voltage balancing purpose. Thus, the breakdown of the capacitor will release electric charges that will damage other components as well.

For the secondary power source, an additional boost-up chopper consists of batteries and a boost-up reactor is designed and connected to the DC link section. This small circuit tends to increase battery voltage, however problem is there is a voltage imbalance between the high side and the low side of DC link voltage [5]. Further, its operation is heavily depends on the electrostatic capacitor. The conventional circuit of having these two components is in fact some how bulky and costly.

This paper described a new control method for an indirect matrix converter with the combination of batteries. Indirect matrix converter is high efficiency and has an easy set up configuration [6-7]. The proposed circuit does not require DC link electrolytic capacitor to achieve a high DC link voltage as compared with conventional method. The proposed connection utilizes the neutral point of a motor to manage the power system between a motor and batteries. An appropriate control over the inverter is possible to use the neutral point of the motor in high power factor ac/dc converters [8].

Nevertheless, the leakage inductance from motor puts into a good uses to replace a normal boost-up reactor. A boost up chopper is included in the circuit to control the inverter zero vector periods and gain control of the battery current. Simulation and experimental results demonstrated that the proposed circuit is capable of generating sinusoidal input and output currents and confirmed the operation of the DC chopper.

2. Proposed circuit topology

Fig.2 shows the proposed circuit diagram. Indirect matrix converter is a direct type of AC/AC power conversion system and capable of bidirectional power flow. The circuit operation is simply divided into a rectifier stage and an inverter stage. Rectifier stage consists of 12 units reverse blocking IGBT and inverter stage consists of 6 units of IGBT. The input current and output voltage can be controlled separately. As seen from Fig.2, the neutral point of motor is connected to the battery and the battery is connected to a DC chopper. A DC chopper is included in the DC link of an indirect matrix converter. A boost up chopper is designed to control the battery current during zero vectors.

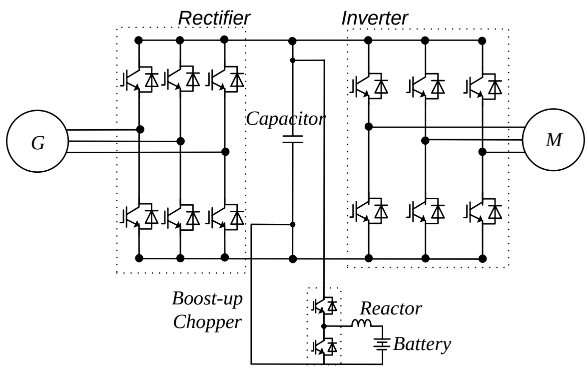

Fig. 1 Conventional circuit diagram

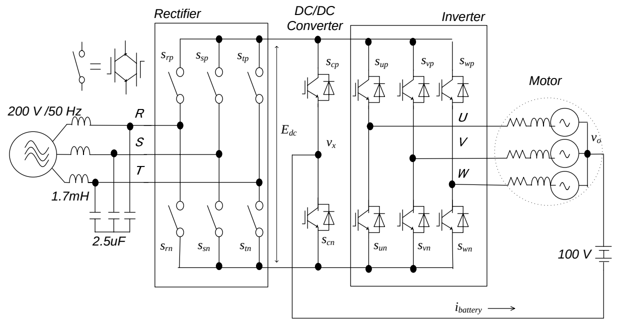

Fig. 2 Proposed circuit diagram

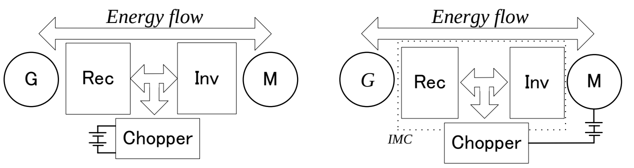

Fig.3(a) Conventional method *Fig.3(b) Proposed method*

Fig.3 Energy flow block diagram

Battery shows a degree of difficulty in control for the rate of being charge and discharge in an AC/AC converter [9]. Battery needs to be charged frequently since it has low storage energy. Fig 3 shows both the power flow diagrams of the conventional circuit and the proposed circuit, respectively. Both the conventional and the proposed circuits actually are having the same characteristic but with a different configuration. The battery is able to charge and discharge accordingly depends on the controller.

The proposed converter can reduce the size of the system by using lesser components. First, capacitor is no longer requires in indirect matrix converter and thus improves the operation life time of the system. Second, motor leakage inductance has a similar function to a boost up reactor where it can increase battery voltage by a proper control.

The proposed system is capable of six kinds of energy flow as shown in table 1 below

Table 1 Energy flow modes of the proposed circuit

Mode	**Generator**	**Battery**	**Motor**
I	Generation	Discharge	Motoring
II	Generation	Charge	Motoring
III	Generation	Discharge	Regenerating
IV	Regeneration	Charge	Motoring
V	Regeneration	Discharge	Regenerating
VI	Regeneration	Charge	Regenerating

This paper explains about motoring condition only, other modes will be discussed in the future paper. One reason is the voltage regulator that used in experimental setup does not work in regeneration mode.

3. Control Block diagram

Fig. 4 shows the control block diagram of the proposed method. Rectifier, DC chopper and inverter are controlled individually by their own commands. Control strategy is performed by carrier comparison method [10]. It is a combination of normal rectifier PWM method and inverter PWM method. Equation 1 shows the relationship between output voltage and the input voltage. DC chopper is controlled as a fourth leg of an inverter.

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

where s_{xy} stands for the switching function of the switches shown in equation 1. When S_{xy} is turned on, s_{xy} =1 and when S_{xy} is turned off, s_{xy} =0. $[v_u\ v_v\ v_w\ v_c]^t$ is the output voltage and $[v_r\ v_s\ v_t]^t$ is the input voltage.

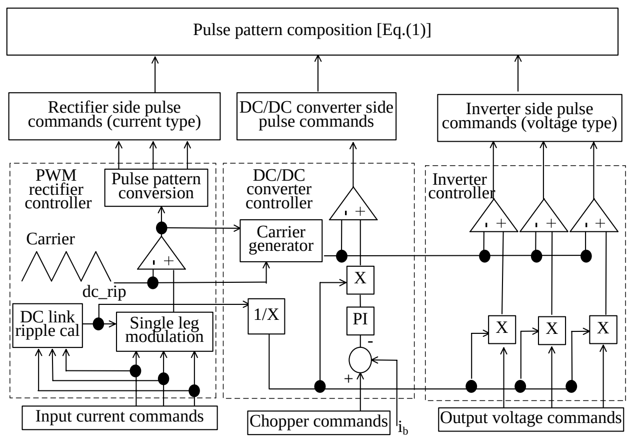

Fig. 4 Control Block Diagram of the proposed circuit.

Rectifier controller is designed with current type PWM rectifier command. It is a pulse pattern conversion to convert the PWM pulses of the voltage source type rectifier into the PWM pulse of the current source type rectifier. High DC link voltage can be achieved by using this method. Further, single leg modulation is used to reduce the switching losses to π /3 per period. A voltage source type inverter is applied for the inverter controller. In addition, a lean controlled carrier modulation of the inverter is designed. The length of triangle carrier is controlled by the duty ratio of the rectifier side pulse. Then this new carrier is used in inverter and DC chopper like a normal PWM comparison method. As written earlier, a chopper leg is designed in this system because during zero vectors it is able to operate similarly like a normal step up chopper. A PI controller is designed in the DC chopper in order to control the battery current. One important point of the control is to achieve zero vectors in inverter side. The importance of zero vectors will describe in the next chapter.

Fig. 5 shows an example of relationship between rectifier carrier and inverter carrier. The length of triangular carrier is controlled by the duty ratio of the rectifier pulse as shown at the upper graph of Fig. 5. Chopper commands along with the inverter output voltage commands are compared with this new carrier to obtain desired switching patterns. The zero vectors period is achieved and show at the lower graph of Fig. 5.

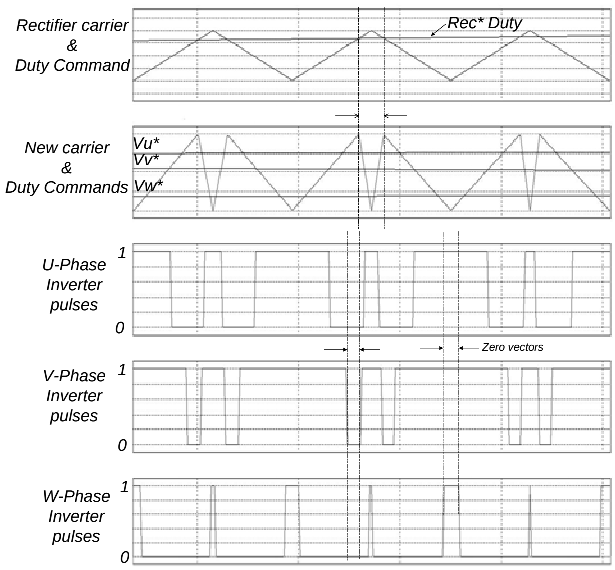

Fig.5 Relationship between rectifier carrier and inverter carrier

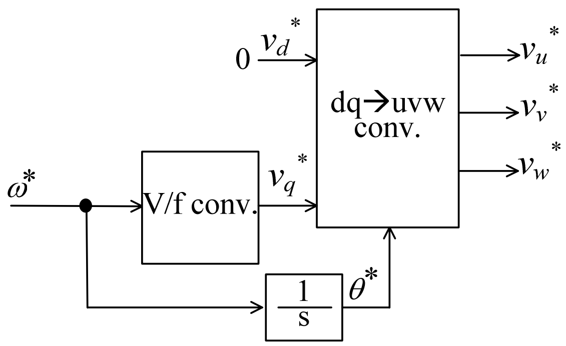

Fig. 6 Control block diagram of the motor

Fig.6 shows the control block diagram of the motor. The *V/f* control method for an induction motor is applied in the inverter system for the proposed circuit. One advantage of the *V/f* controller is easy to control to a wide range of motor parameters [11]. Fig.6 explains the conversion from d-q rotational frame into 3-phase voltage commands for inverter system.

4. Zero vectors

The importance of zero vectors explains the behavior of step up chopper along with the neutral point of motor. During zero vectors two difference sequences will occur, one especially important is known as zero-phase sequence. Fig. 7 shows the positive-phase sequence and Fig. 8 shows the zero-phase sequence. In zero phase sequence, no voltage goes to motor and motor is considered as a leakage inductance. Inverter can be considered as a single leg topology when inverter switching patterns are having either all upper arms or all lower arms are turned on at one time. During the zero phase sequence, the circuit has similar characteristic like a step up chopper. Battery voltage can be increased and provided an accumulated amount of power to the system. Furthermore, battery can be charged or discharged according to the controller. The relationship between neutral point of the load and the battery will determine the battery current flows direction.

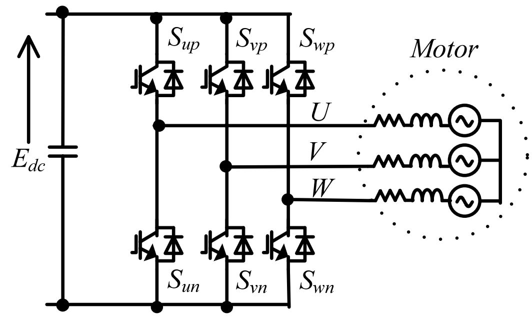

Fig.7 Positive-phase sequence equivalent circuit.

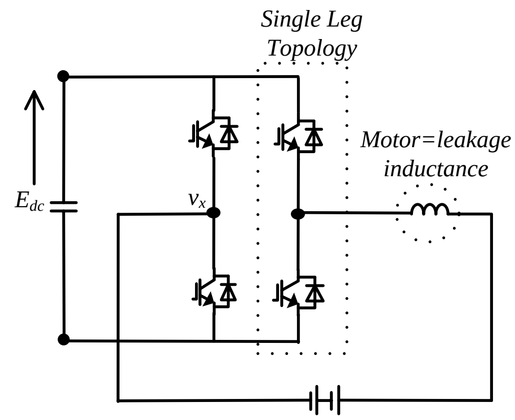

Fig. 8 Zero-phase sequence equivalent circuit

A three-phase inverter composed of eight output voltage space vectors. Zero vectors are two particular vectors that will generate zero line voltage to load. Where can be described by,

$$vo = \frac{E_{dc}}{2} \qquad \text{When all upper arms are on}$$

$$vo = \frac{-E_{dc}}{2} \qquad \text{When all lower arms are on}$$

Where E_{dc} is the dc link voltage
And v_o is the induced voltage at neutral point of motor

In order to control zero vectors, a high DC link voltage is compulsory. Equations below explain the relationship between DC link voltage (E_{dc}), inverter voltage (v_{inv}) and battery voltage (V_{bat}). The inverter output voltage, v_u, v_v, v_w referred to the neutral point voltage of the dc link is expressed as

$$v_u = a\frac{E_{dc}}{2} Sin\ \omega t + v_o .$$
$$v_v = a\frac{E_{dc}}{2} Sin\ (\omega t - \frac{2\pi}{3}) + v_o \qquad (2)$$
$$v_w = a\frac{E_{dc}}{2} Sin\ (\omega t - \frac{4\pi}{3}) + v_o$$

Where

a amplitude ratio of a conventional motor voltage, $0< a <1$

v_o neutral point voltage of the motor (during zero phase sequence)

ω inverter output frequency

The inverter line voltage is given by

$$v_{uv} = a\frac{\sqrt{3}}{2} V_{dc}\ Sin\left(\omega t + \frac{\pi}{6}\right). \qquad (3)$$

For a three phase inverter, the DC link voltage E_{dc} is expressed as

$$E_{dc} \geq 2\frac{\sqrt{2}}{\sqrt{3}} V_{inv} . \qquad (4)$$

The maximum line voltage between v_u and v_x can be expressed as

$$v_{ux} = \frac{\sqrt{2}}{\sqrt{3}} V_{inv} + V_{bat} . \qquad (5)$$

Since both v_u and v_x are referred to the neutral point of DC link voltage, it must be smaller than $E_{dc}/2$ and it leads to another expression as below

$$E_{dc} > \frac{\sqrt{2}}{\sqrt{3}} V_{inv} + V_{bat} . \qquad (6)$$

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

$$E_{dc} \geq \begin{cases} 2\frac{\sqrt{2}}{\sqrt{3}} V_{inv} & When\ \frac{Vinv}{\sqrt{3}} > V_{bat} \\ \frac{\sqrt{2}}{\sqrt{3}} V_{inv} + V_{bat} & When\ \frac{Vinv}{\sqrt{3}} < V_{bat} \end{cases} . \qquad (7)$$

5. Simulation Results

Simulation results presented the proposed circuit running in motoring condition. First section of the simulation results confirmed the control of a step up chopper in inverter during zero vectors. Second section of the simulation results illustrated a good power management between input power and battery power. Table 2 shows the simulation parameters for both sections.

A resistor (25Ω) is connected to replace the battery in order to observe the performance of the DC chopper. Then, an ACR is used to control the desired battery current in positive value and negative value. Fig. 9 shows the result where battery current is controlled to 5A.The result shows that both input current and output current are in good sinusoidal waveforms. In Fig.10 ACR controls battery current to -2A. Battery is being charged in this time. The results also proved that in charging mode both the input current and output current are in good sinusoidal waveforms. These two results confirmed that the dc chopper is able to operate during zero vectors and control over battery current is possible.

Table 2 Simulation parameters

Input voltage	200V
Input frequency	50 Hz
Carrier frequency	10 kHz
Output frequency	35 Hz
Output voltage	173V
DC source	100V

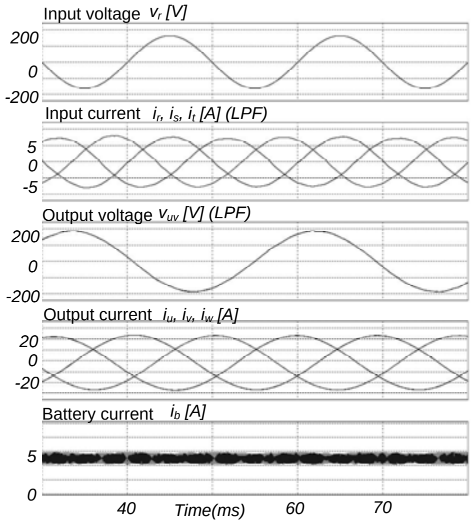

Fig. 9 Input and output waveform when battery is being discharged.

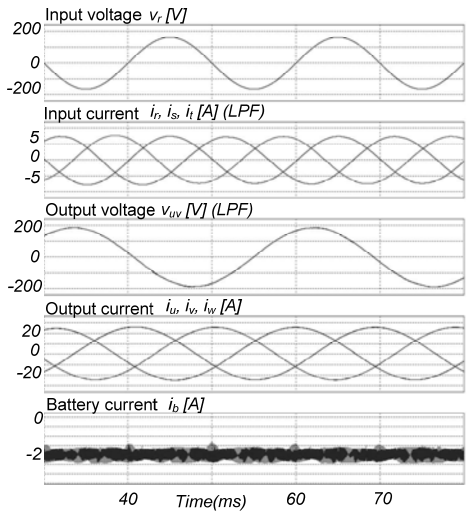

Fig. 10 Input and output waveforms when battery is being charged.

This section discusses about input power's behavior in respond to the changes of battery power. Fig. 11 and Fig. 12 show the simulation results using the proposed control method and monitor the input power and output power condition. An ideal current source load (i_s) which is controlled by a PI

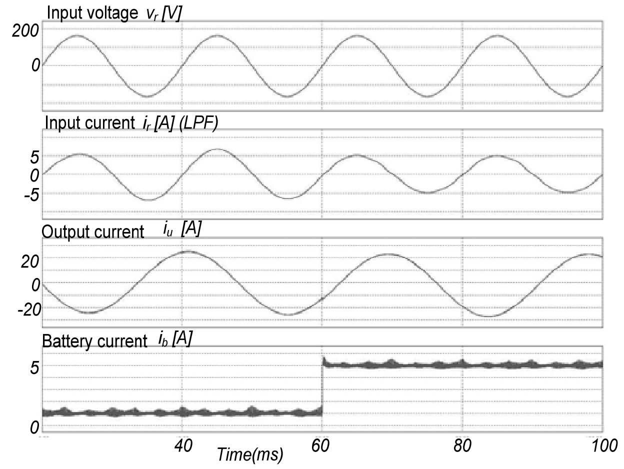

Fig. 11 Motoring condition –Mode I: Battery discharge.

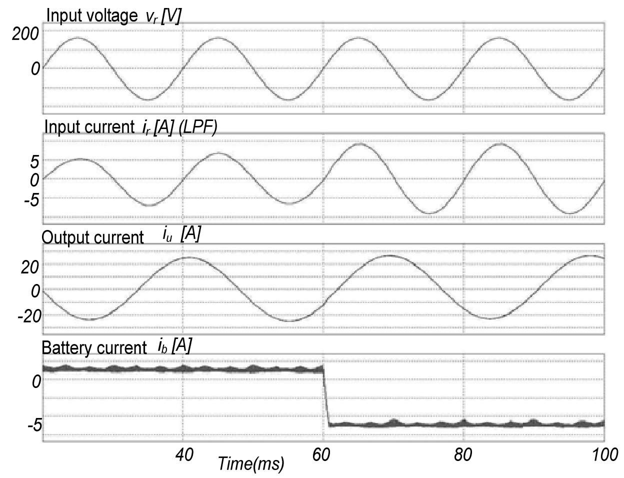

Fig. 12 Motoring condition –Mode II: Battery charge.

controller, is purposely increased at specific time to check the proposed strategy. These two waveforms show the power supply R phase voltage (v_r), the input current (i_r), the output line voltage ($v_{uv(LPF)}$) and the output current (i_u).

In Fig. 11, i_s is in positive value which means the battery is being discharge. Notice at time 60ms, i_s increased, it results input currents magnitude decreased. In this mode, the increasing of battery power leads to a decreasing in input power.

Fig. 12 shows that i_s is in negative value and the battery is in charge mode. At 60ms, i_s decreased, input current increased to charge the battery. As the battery needed to be charged, the input power increases accordingly. These two waveforms proved a good power management picture between the generator and battery.

6. Experimental results

Experiment is set up and tested in two various conditions.
Mode I: Battery discharges under motoring operation.
Mode II: Battery charges under motoring operation.

Both modes use the same parameters as shown in table 3

Table 3 Experiment parameters

Input voltage	200V
Input frequency	50 Hz
Carrier frequency	10 kHz
Output frequency	35 Hz
DC source	DC power supply
LC Filter Cut-off frequency	2.4kHz
Inductor	1.7mH
Capacitor	2.5uF
Motor Power	750W
Rated current	3.6A
Rated voltage	200V
Leakage inductance	4.42mH

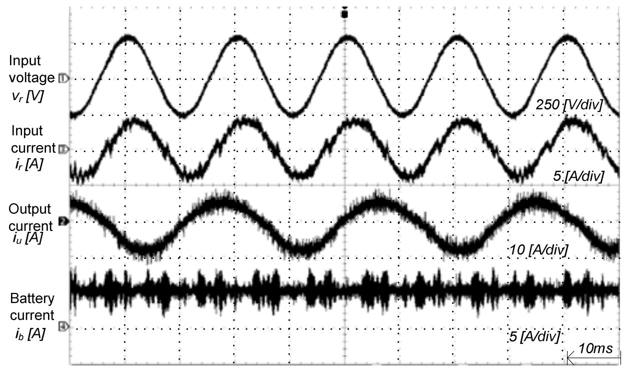

Fig. 13 Motoring condition –Mode I: Battery discharge.

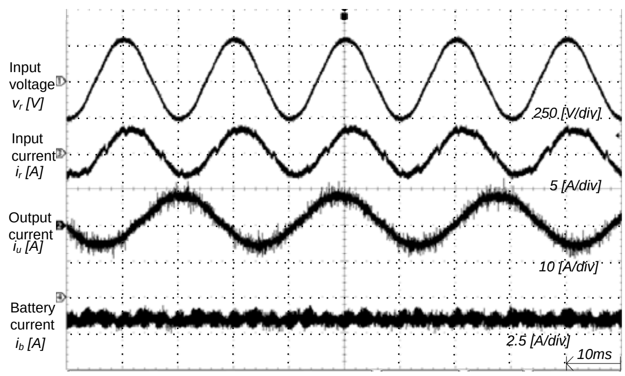

Fig. 14 Motoring condition –Mode II: Battery charge.

Fig.13 shows Mode I operation. DC power supply is set to 100V and battery current is controlled to 5A. Both input and output current showed good sinusoidal waveforms. Note that a resistor is connected between the DC power supply and the neutral point of motor to prevent sudden damage. This result the decreasing magnitude of input current is not obvious because the battery power was absorbed by the resistor. Fig. 14 shows Mode II operation. Good sinusoidal waveforms have been achieved in both input and output current as well. Fig 15 and Fig. 17 shows the input power factor for discharge mode and charge mode respectively. The highest input power factor obtained during discharge mode is 0.97 at output power 600W. And 0.99 during charge mode at output power 600W. Fig. 16 and Fig.18 shows the input current THD and output current THD for both modes. The lowest output THD obtained during charge mode is 4.00% and during discharge mode is 7.70%.

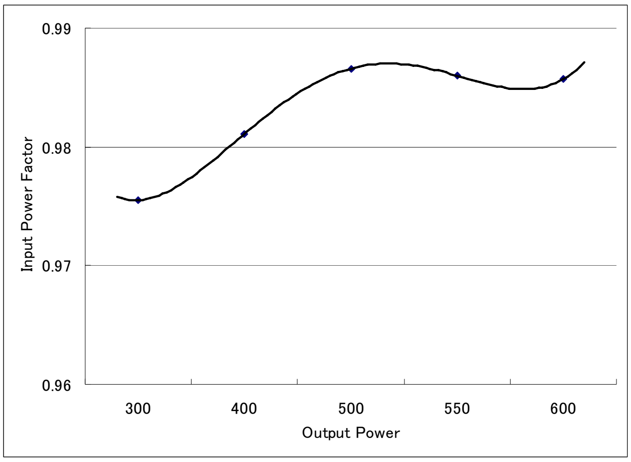

Fig. 15 Input power factor for Mode I

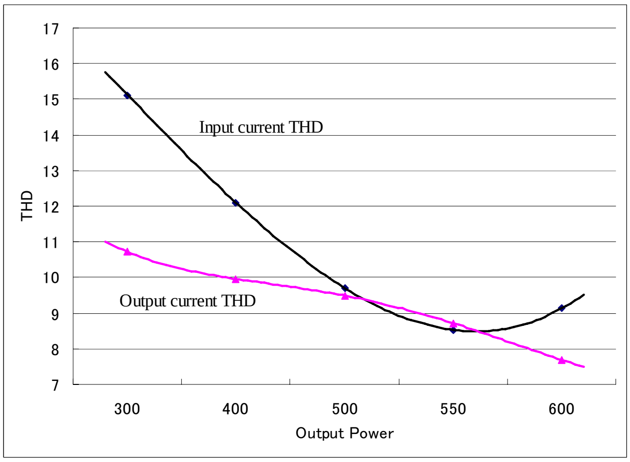

Fig. 16 Input current THD and Output current THD for Mode I.

7. Conclusion

This paper proposed a new control method by utilizing neutral point of motor and applied it in an indirect matrix converter for motor drive application. An indirect matrix converter is proved to be achieved high DC link voltage without an electrolytic capacitor. The control of inverter's zero vectors period enable the additional chopper leg to perform like a step up chopper with a connection to the neutral point of the motor. Zero phase equivalent circuit explains the uses of motor leakage inductance results a common boost-up reactor that used in a step up chopper can be removed. Simulation and experimental results demonstrated good sinusoidal waveforms and confirmed the validity of the proposed method.

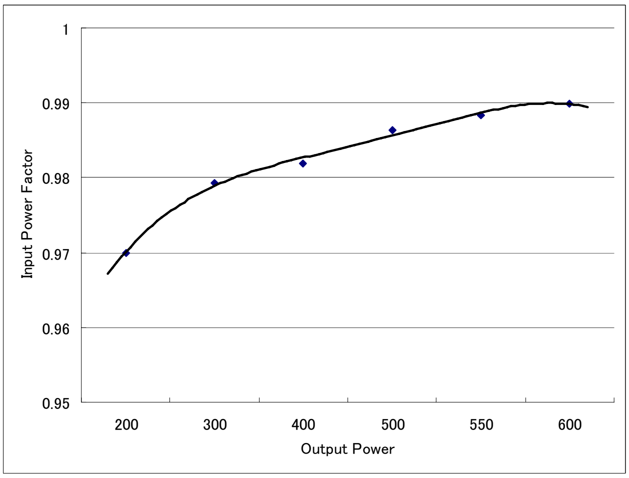

Fig. 17 Input power factor for Mode II.

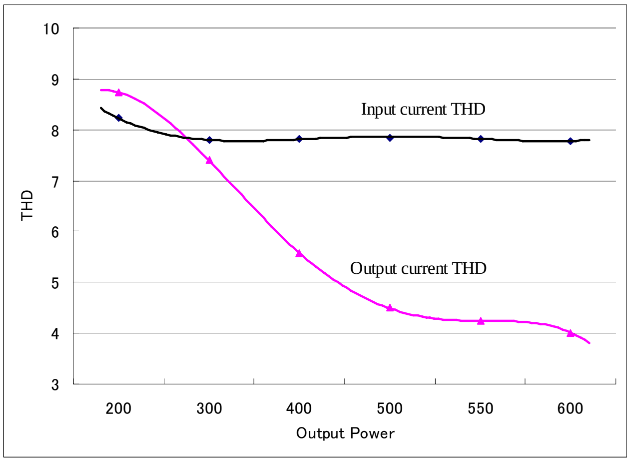

Fig 18. Input current THD and Output current THD for Mode II.

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