A Novel Control of Three-Phase PWM Rectifier Using Single Current Sensor

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Abstract This paper proposes a control method for three-phase PWM rectifier using only single current sensor in DC link. A PWM modulation strategy for reconstructing three phase currents from the DC link current is given. The states of the rectifier switch are modified so that all phase currents can be reconstructed in a switching period although one of active vectors is applied only for a short time. Therefore, a novel current control using an adjustment scheme of the modulation signal for a three-phase PWM rectifier will be discussed, and verified with the experimental results.

Introduction

Several studies related to three-phase active rectifiers have been presented with an increasing concern as a method to improve power quality in a utility interface. In addition to reduced input current harmonics and high input power factor, PWM rectifiers provide bi-directional power flow and controllable DC voltage in the field of industrial applications such as adjustable speed ac drives. For the successful operation of a PWM rectifier, it is required to detect and control the input phase currents precisely. Usually it is achieved by CRPWM(Current Regulated Pulse Width Modulation) using at least two current sensors, in addition to current sensor in DC link for a fault protection. The efforts to reduce the number of the expensive sensors have been studied especially in the field of motor drive applications [1]. The relationship between the DC link current and the phase currents for various inverter switch states has been reported [2]. That is, samples of two-phase currents may be extracted from the DC link current, using an information on a given voltage vector every PWM period.

However, under any operation conditions, practical difficulties unable to extract two phase currents from the DC link current can be occurred when an active vector in a PWM period is only present for a short time. Therefore, the minimum time for an active vector should be preserved to sample a reliable DC current in a given modulation cycle. In this paper, The violation against the minimum time, which has an effect on deterioration of the control performance, is avoided by adjusting a modulation signal properly. Also, practical aspects of controller-implementation will be studied in the case of using only single current sensor to reduce the overall cost of PWM rectifier. Experimental results will show that the exact reconstruction of the three-phase currents through the proposed voltage vector adjustment improves the performance of three-phase PWM rectifier using single DC current sensor.

Modeling of three-phase PWM rectifier

The circuit diagram of three-phase PWM rectifier is shown in Fig. 1. The voltage equation of the PWM rectifier can be expressed as follows:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = (R + \frac{d}{dt}L)\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

where, e_a, e_b and e_c are source voltages, i_a, i_b and i_c, phase currents, V_a, V_b and V_c, control voltages, respectively

It is assumed that the source is a balanced three-phase sinusoidal voltage with the amplitude E and angular

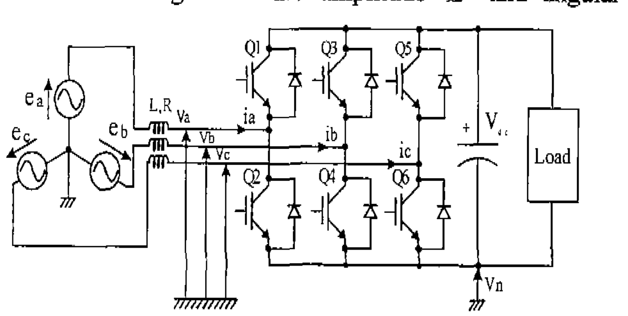


Fig. 1. Three-phase PWM rectifier system.

frequency ω as expressed in equation (2).

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = -E \begin{bmatrix} \sin \omega t \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} e_d^s \\ e_q^s \end{bmatrix} = E \begin{bmatrix} -\sin \omega t \\ \cos \omega t \end{bmatrix} \tag{3}$$

The form expressed as equation (2) is determined such that the amplitude E is placed in e_q instead of being placed in e_d, as represented in equation (5). The voltage equations and input voltages in the synchronous d-q reference frame rotating at the source angular frequency ω are expressed in equation (4) and (5).

$$\begin{bmatrix} e_d^e \\ e_q^e \end{bmatrix} = \begin{bmatrix} R + pL & -\omega L \\ \omega L & R + pL \end{bmatrix} \begin{bmatrix} i_d^e \\ i_q^e \end{bmatrix} + \begin{bmatrix} v_d^e \\ v_q^e \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} e_d^e & e_q^e \end{bmatrix}^T = \begin{bmatrix} 0 & E \end{bmatrix}^T \tag{5}$$

Basic Principle for Reconstruction of currents

A voltage vector patterns determining the direction of current flow are shown in Fig.2 and Fig.3. In the figures, current flows corresponding to each of active vectors are illustrated with the bold line. When voltage vectors (000) and (100) are applied as shown in Fig. 2(a), corresponding current flow is shown in Fig 2(b) and Fig. 2(c). Fig. 3 shows the reverse current of i_a. The reconstruction of phase currents from DC link current sensor can be made easily only if two active vectors are at least present for a long time enough to be sampled. One active voltage vector takes it to reconstruct one phase current and another voltage vector is used to reconstruct a second phase current, using values measured from DC current sensor. In other word, each of switch states composed of different active vector provides the information on phase currents although only single DC link sensor is used. Furthermore, the information on phase currents in the DC link during a zero vector interval can be used for fault detection. A relationship between the applied active vectors and the phase currents measured from DC link sensor is shown in TABLE 1, which is based on eight voltage vectors composed of six active vectors and two zero vectors.

Modulation Signal Correction

However, a problem arises when either of two active vectors is not present, or is applied only for a short time.

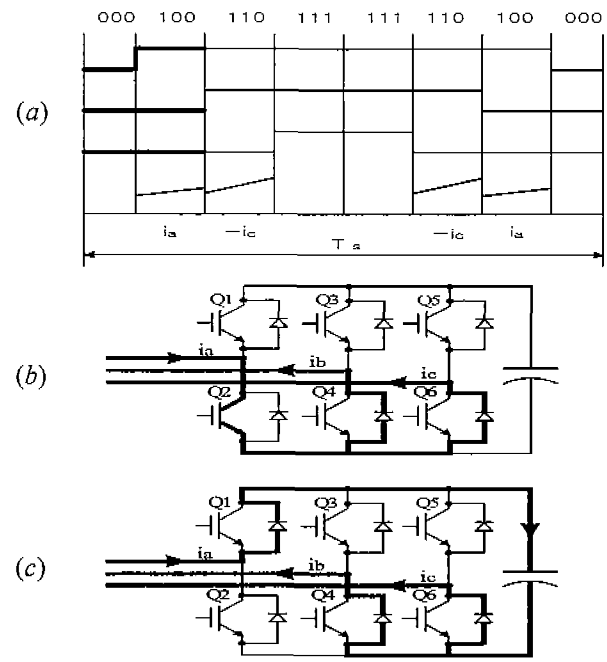


Fig. 2. PWM signals and DC link current in sector 1

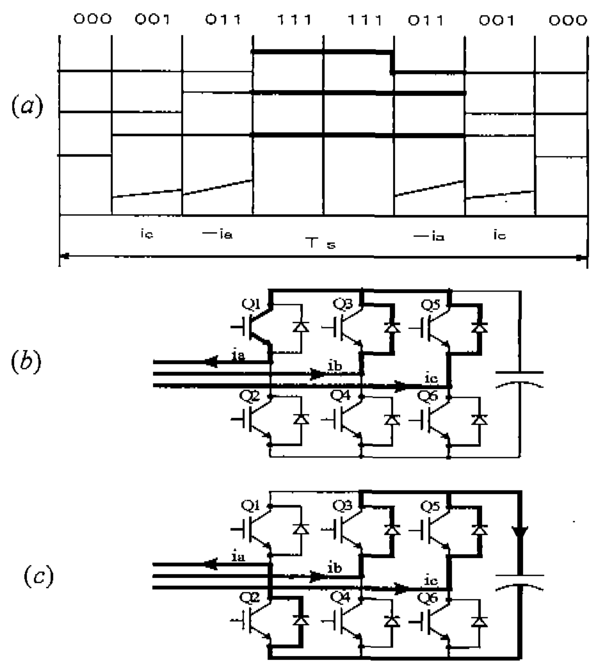


Fig. 3. PWM signals and DC link current in sector 1

Table 1. DC link current corresponding to active voltage vectors.

Voltage Vector	DC link current i_{DC}
V1 = (100)	+ia
V2 = (110)	-ic
V3 = (010)	+ib
V4 = (011)	-ia
V5 = (001)	+ic
V6 = (101)	-ib
V0 = (000)	0
V7 = (111)	0

In such a case, it is impossible to reconstruct phase currents. It is occurred in the case of a reference voltage vector passing one of the six possible active vectors or a low modulation index [3]. The former is illustrated in Fig. 4(a). In such a case, only one phase current is correctly sampled. In the case of the latter, the magnitude of a space vector is relatively small. Therefore, a time distribution to adjacent active vectors is not enough to sample reliable phase currents. The region representing a low modulation index is illustrated in Fig. 4(b).

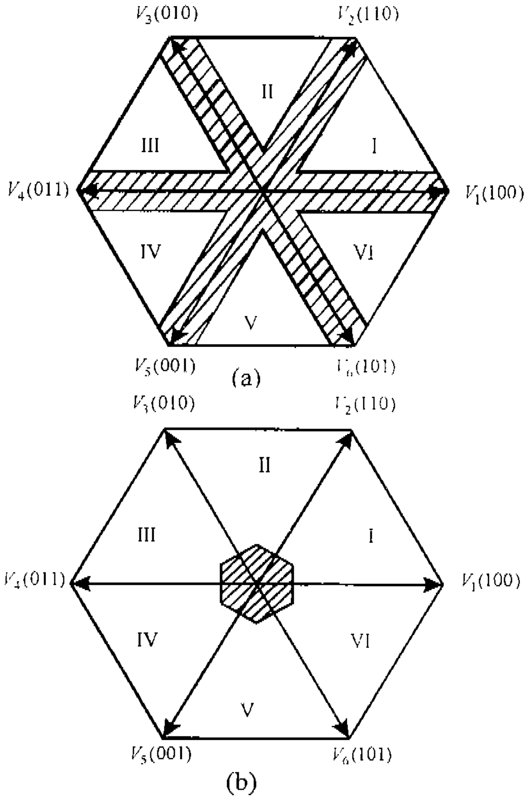


Fig.4. Voltage vector area requiring the adjustment of PWM signals
(a) When a reference voltage passes one of possible six Vectors
(b) In case of low modulation index

To avoid these undesirable cases, it is required to modify a modulation signal and compensate it. There are several methods to obtain the information of phase currents from DC link current. Now, the methods are investigated, and then another method is proposed.

Reference papers, [3] and [4], proposed the method to reconstruct phase currents for a permanent magnet machine. In paper [3], it is achieved by sampling DC link current in the center of each active vector. Also, two adjustment methods are proposed to change the PWM signals in a single-ended modulation strategy. In method 1, when an active vector time duration is not enough to sample reliable phase currents, zero vector duration time is reduced so that the time allocated to the active vector is increased in order to preserve minimum time. Method 2 uses two complementary voltage vectors closest to those already used. It gives more switching, but all of three phase currents are obtained in one sampling period.

In [4], an observer is used for the problem of a phase shift of the two samples. Recently two methods to obtain a correct phase current reconstruction are proposed. One method adjusts the duty cycles within one switching period without changing the average voltage [5]. In this time, even though there are no more switching, the reconstruction of the three phase currents is acquired. The other uses two switching period to adjust the PWM signals [6].

There is a shaded region difficult to obtain minimum time as shown in Fig.4. In this region of Fig. 4(a) one of the phase currents is always sampled correctly, but the other phase current cannot be sampled directly because the duration of active vector associated with it is too short. The shaded region in Fig. 4 occurs six times with prominent signals every fundamental cycle, as shown in Fig. 5. The switching sector changes from I to VI in turn. Whenever the sector is changed, a reference voltage vector passes one of possible six vectors and duration time less than minimum time occurs around it. Fig. 4(b) shows that active voltage vector is not being used long enough to ensure a proper sampling of the DC-link current. To obtain the proper sampling, it is necessary to generate a minimum time. If the PWM signal is not adjusted, proper phase current reconstruction can't be done

Fig.6 shows the proposed method of this paper. When a voltage reference vector V_{ref} sits in switching sector I, it is synthesized by the output voltage vectors V_0, V_1, V_2 and V_7. The on-times of the references vectors which correspond to V_1 and V_2 are T_1 and T_2, respectively, and the on-time of the zero vector is T_0. In Fig.6 (a), it is shown that the on-time of vector V_2, T_2, is less than the minimum time T_{min}. So, T_2 is replaced by T_{min} in order to obtain the minimum time, and then during $\Delta T = T_{min} - T_2$, the vector V_5 is compensated.

In this example the sequence of sample current is $+i_a, -i_c$ and $+i_c$. Two of three phase-currents are reconstructed by sampling the DC link current at active vector which has the greatest duration in a period. Therefore, input currents, $+i_a$ and $-i_c$, are selected as reconstruction currents.

Fig.6 (b) illustrates the adjustment scheme of PWM signals in the case of low modulation index. In such a case, T_1 and T_2 are replaced by T_{min} to preserve the minimum time because both T_1 and T_2 are less than the minium time. And then, two complementary voltage vectors, V_4 and V_5, are applied during $\Delta T_1 = T_{min} - T_1$ and $\Delta T_2 = T_{min} - T_2$, respectively. In both cases, the mean voltage vector V_{ref} is unchanged in magnitude and phase. Therefore, it is possible to sample the DC link current while maintaining the magnitude and phase of the mean voltage vector. On the other hand, practical restrictions on this method arise due to the fact that the active status must exist for a minimum time to ensure that reliable current samples can be acquired. In general, the minimum time, T_{min} may be determined as equation (6).

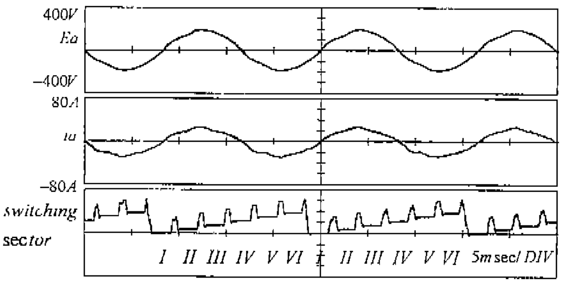
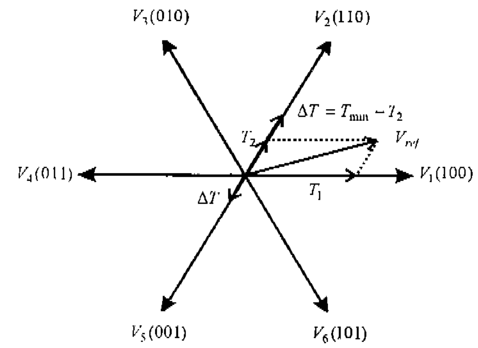
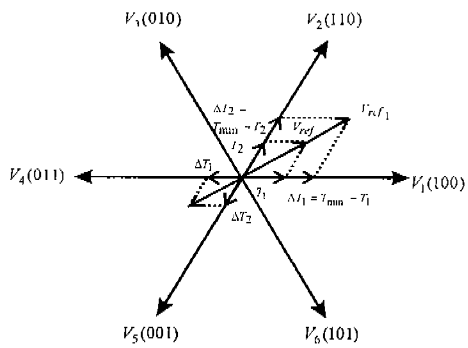


Fig. 5. The occurrence of duration time less than minimum time
(Ea : input voltage , ia: input current, switching sector and shaded zone)



(a)



(b)

Fig.6. Space vector diagram of the proposed method
(a) When a reference voltage passes one of possible six Vectors
(b) In case of low modulation index

$$T_{min} = t_d + t_{sett} + t_{conv} \quad (6)$$

Blanking time, t_d, is required to prevent a shoot-through condition across the DC supply. A finite settling time, t_{sett}, must also be allowed to ensure that the DC link current is well established before a sampling takes place. It also includes the time delay for IGBT and drive circuit. The t_{conv} is the A/D conversion time.

Experimental Results

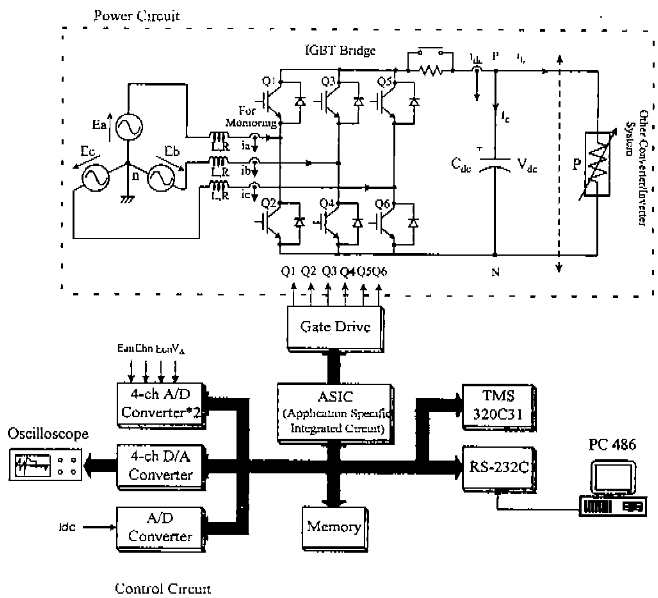


Fig.7. Experimental configuration

Table 2. The parameters used for experiment

Input voltage	3 phase 230V
Output DC voltage	DC 370V
Output rating	10kVA
Input reactor	1.3mH
DC link capacitor	13,000uF

Fig.7 shows the block diagram for experimental configuration. The i_a, i_b and i_c are just the currents for monitoring.

The d-axis current is regulated to zero for unity power-factor control, and the feedfoward compensation for decoupling is applied to reject disturbances and coupling terms. Single 32-bit floating-point DSP, TMS320C31, with the single-cycle execution time of 60 ns is used to implement all algorithms. The switching period for PWM is 200 μs. The 12-bit A/D converter is used for the acquisition of the DC link current and its conversion time is 3.5 μs. Timer interrupt is used to determine the instants of sampling DC link current . DC link current is sampled in the center of the active vector through the timer interrupt.

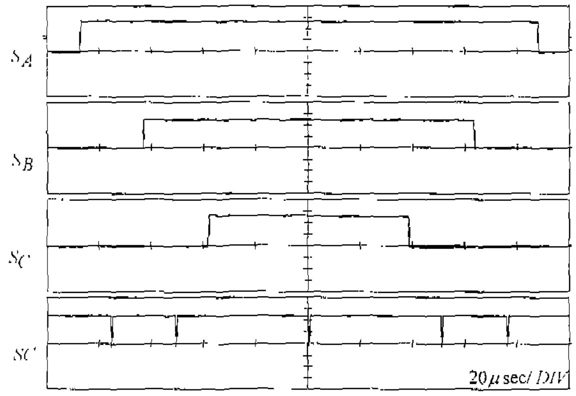


Fig.8. PWM-signals and sample signals from DSP (SC: start conversion signal in A/D converter)

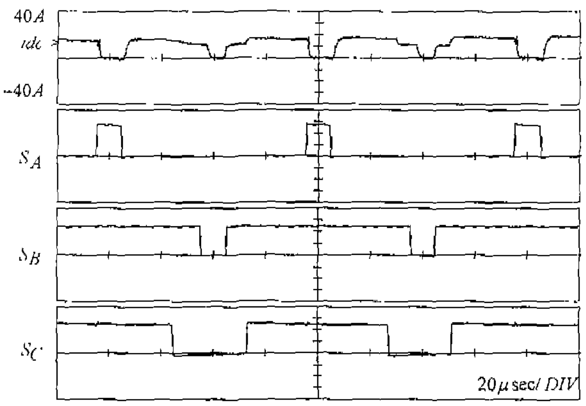


Fig.9. Measured dc-link current and PWM signals (i_{dc} : DC link current)

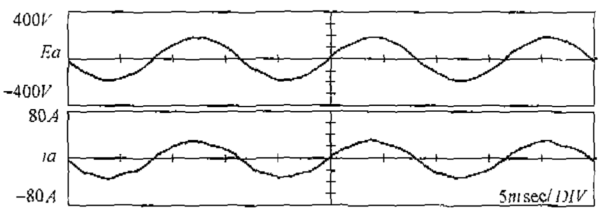


Fig.10. Steady state source voltage and current using two line-current sensors (E_a : input voltage, i_a : input current)

But actually, time delay, about 1 μs, in IGBT and IGB' drive circuit is considered. The minimum time, 10 μs, i used to ensure proper sampling. It can be easily increase or decreased.

Fig.8 shows that two phase-currents are sampled in th center of the active vector and the current for faul detection is sampled in the zero vector. It is performed b timer interrupt routine in DSP. Fig.9 shows that DC-linl current changes according to the different PWM signals.

To prove the validity of the proposed method, it performance is compared with conventional ones. One i to detect input current through the two line current sensors It is shown in Fig.10. The other is to reconstruct inpu

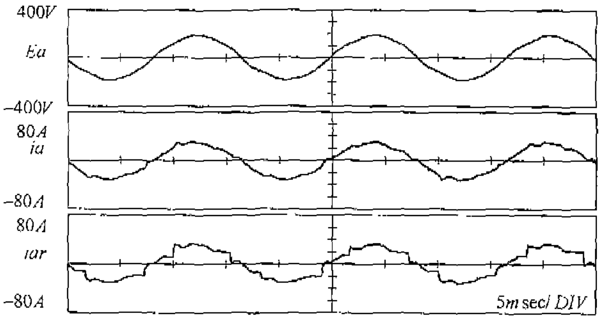


Fig.11. Steady state source voltage and current using unmodified PWM signal and previous current detected from DC current sensor (E_a : input voltage, i_a : input current, i_{ar} : reconstructed input current)

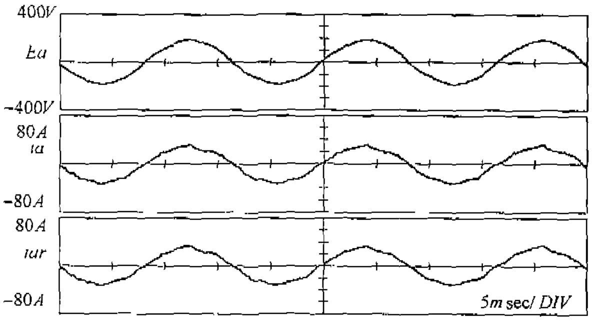


Fig.12. Steady state source voltage and current using modified PWM signal (E_a : input voltage, i_a : input current, i_{ar} : reconstructed input current)

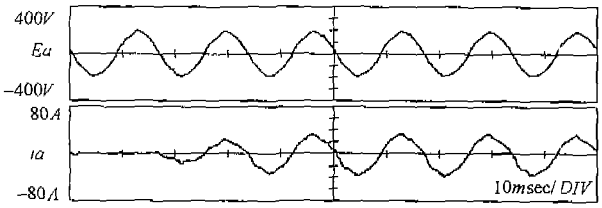


Fig.13.Transient response using two line-current sensors when step load of 23A is applied. (E_a : input voltage, i_a : input current)

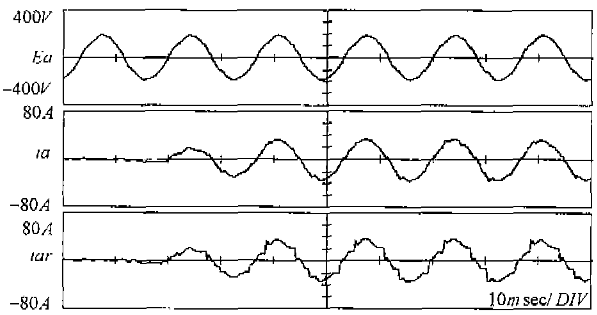


Fig.14. Transient response using unmodified PWM signal and previous current detected from DC current sensor when step load of 23A is applied. (E_a : input voltage, i_a : input current, i_{ar} : reconstructed input current):

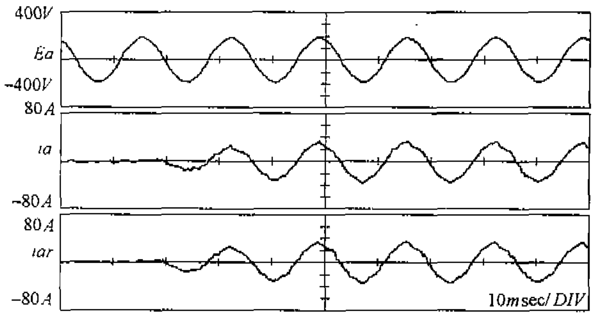


Fig.15. Transient response using modified PWM signals when step load of 23A is applied. (E_a : input voltage, i_a : input current i_{ar} : reconstructed input current)

current through DC current sensor, but when active vector duration time is too short to reconstruct, the reconstructed current at previous cycle is used for current information. In this case, reconstructed current, i_{ar}, is distorted considerably and it deteriorates input line current. It is shown in Fig.11. Fig.12.shows the proposed method modifying PWM pattern when an active vector period is less than minimum time. The reconstructed current is not distorted, compared to Fig11. Therefore, input line current shows a good waveform.

Fig.13, Fig.14 and Fig.15 also show input line current, voltage, reconstructed current when load current is applied from 0 to 23A. It is similar to the results of Fig.10, Fig. 11 and Fig. 12.

Conclusion

It is required to detect the three phase currents accurately for a better three-phase PWM rectifier. This paper proposes a new method that the three phase currents are reconstructed from the current information in the DC link. When the duration time of one active voltage vector is less than the minimum time, it is overcome by replacing with the minimum time and by compensating with the complementary vector. Experimental results showed the validity of proposed method. And additional analysis and experimental results will be shown.

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