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REPETITIVE CONTROL BASED PWM INVERTER DEAD-TIME COMPENSATION FOR AC SERVO DRIVE

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ABSTRACT

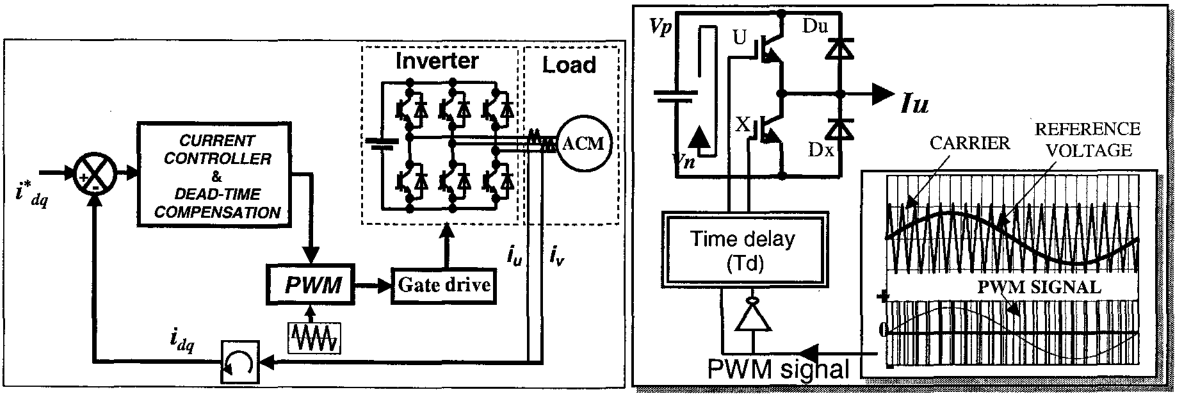
AC servomotor speed or current controller based on PI control and/or optimal control, can not eliminate the cyclical fluctuations of speed or current when subject to periodic disturbances. However, repetitive control performs well when the disturbance is cyclical with constant period (frequency). For a PWM (Pulse Width Modulated) inverter driven AC servomotor, a time delay is inserted between the switches of the same leg, to prevent the phase shortage of inverter arms. This time-lag causes serious distortions of the output current of the inverter. This is known as dead-time effect. This effect is cyclical as it is repeated at every period of the sinusoidal motor current. Conventional dead-time compensation method based on current reference polarity, is widely used in industry to improve the output current waveform. The improved waveforms however still suffer from the zero current crossing phenomenon which is cyclical in angle domain not in time domain. This paper analyses the origins of waveforms distortions around the zero current crossing in PWM inverters. A proposed method, based on angle domain repetitive control to reduce the distortions in the PWM inverters output waveforms caused by the dead-time and the zero crossing problem is described. Theoretical analysis as well as simulation results, to verify the proposed method, are described in this paper.

1. INTRODUCTION

Repetitive control is a method of iterative control, characterized by its capability of eliminating cyclical fluctuations. It is therefore useful for any periodic disturbances. However, the period of disturbance should be constant. From this point of view, the use of repetitive control with variable frequency (period) is useful. We propose to use a repetitive controller in angle domain rather than time domain, to eliminate disturbances with variable frequency.

On the other hand, PWM Inverters are widely used in AC motor drives and UPS (Fig.1(a)). In inverters, time delay must be inserted in switching signals to prevent a short circuit in the dc link. Although, this time delay guarantees safe operation of the inverter, it causes serious distortion in the output voltages. It results in a momentary loss of control, and the output voltage deviates from the reference voltage. Since this is repeated for every switching operation , its effect may become significant. This is known as the dead-time effect. This effect is still apparent even with the recently developed fast switching devices such as MOSFET, IGBT and others. Therefore, the understanding of the dead-time effect is crucial to the improvement of the performance of PWM inverters. Furthermore, in some applications such as sensor-less vector control and direct vector control, the inverter output voltages are needed to calculate the rotor flux.

Unfortunately, it is very difficult to measure the output voltage as it is a PWM signal (see Fig.1 (b)) and it requires additional hardware. The most desirable method to obtain the output voltage is to use the reference voltage instead. However, the relation between the output voltage and the reference voltage is nonlinear due to the dead-time effect. Thus unless the dead-time is properly compensated, the reference voltage can not be used instead of the output voltage. Beside that, the zero crossing phenomenon is still not fully understood and not well resolved. Several approaches for dead-time compensation were proposed [1]-[7]. These approaches succeeded in eliminating the effect of dead-time but not the current zero crossing problem. New optimal approaches to eliminate the zero crossing and the dead-time effect as well were proposed in [8], [9] and [10]. This paper presents another new approach of compensation of the dead-time and the zero crossing phenomenon. This new optimal compensation is based on repetitive control technique. A preliminary study of this new approach was published in [9]. This paper analyses the new approach that shows improved output waveforms of the PWM inverter.



(a) AC motor drive using PWM inverter (b) one phase leg of inverter and its PWM

Fig. 1 Basic configuration of PWM inverter based AC motor drive system

2. OUTPUT WAVEFORM DISTORTIONS

Fig. 2 shows the leg of one phase of the PWM inverter, where power transistors are used as switching devices. To turn off transistor X, U should be off and if the turn on speed is faster than the turn off speed, a dc link short-circuit will occur, therefore a delay time or dead-time (generally with IGBTs is in the order of 20μs) is inserted for safety. Although this dead-time is very short, it causes considerable distortions in the output waveforms (see right part of Fig. 2). To analyse the distortions caused by the dead-time, we assume the following:

1. The turn off time of the switching device is neglected.
2. The switching frequency is greater than the fundamental frequency.
3. Current ripples are neglected

Under the above assumptions, the dead-time effect can be analysed quantitatively. These assumptions will facilitate the understanding of the compensation techniques. Let n_p *be t*he number of pulses per period caused by the dead-time. n_p depends on the switching frequency of the inverter and is expressed by the relation:

$$n_p = \frac{f_c}{f} \tag{1}$$

where f_c is the carrier or switching frequency and f is the operating frequency of the inverter. The average deviation voltage Δv_1, caused by the cumulative of the dead-time pulses, is given by:

$$\Delta v_1 = \frac{n_p}{2}\frac{T_d V_d}{T/2} = n_p f T_d V_d = f_c T_d V_d = \frac{T_d}{T_c} V_d \tag{2}$$

where *Td* is the dead-time, *Tc* the carrier period, and $V_d(=V_p-V_n)$ is the DC link voltage

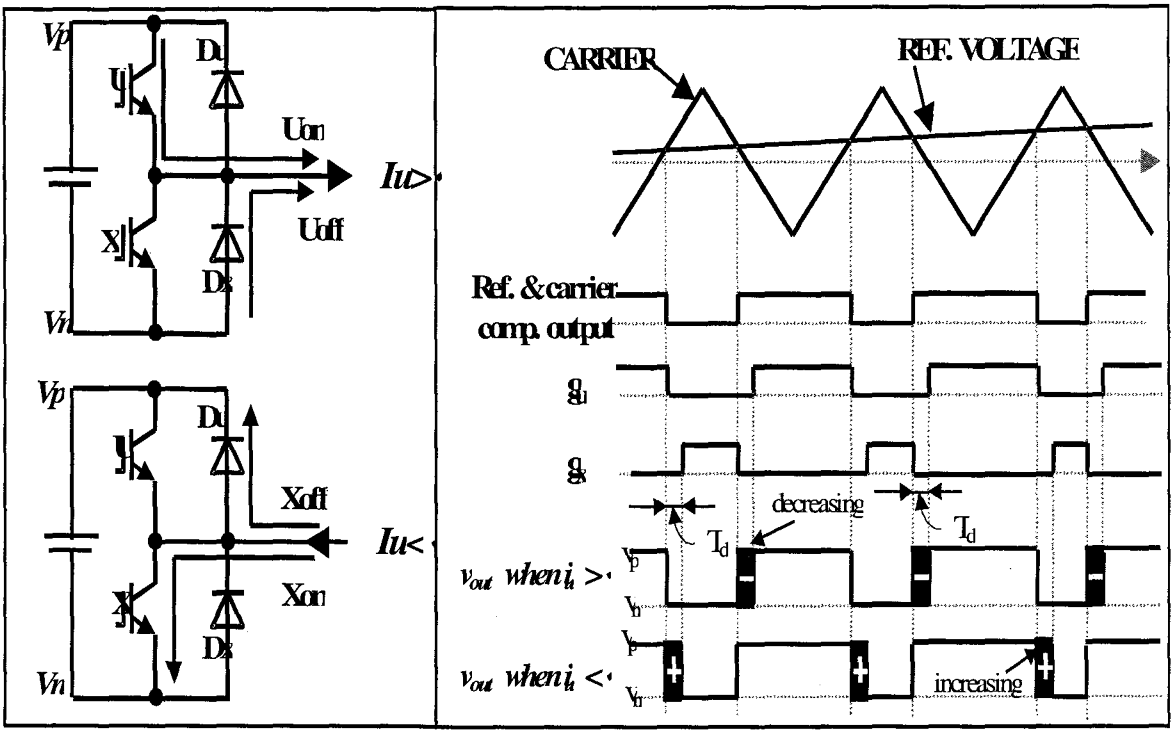


Fig. 2 Dead – time phenomenon

As the sign of the deviation depends on current polarity as shown in Fig. 3, the voltage distortion caused by the dead-time is given by:

$$\Delta v = -\frac{T_d}{T_c} V_d \times sign(i_u) \tag{3}$$

This average voltage deviation is shown in Fig. 3.

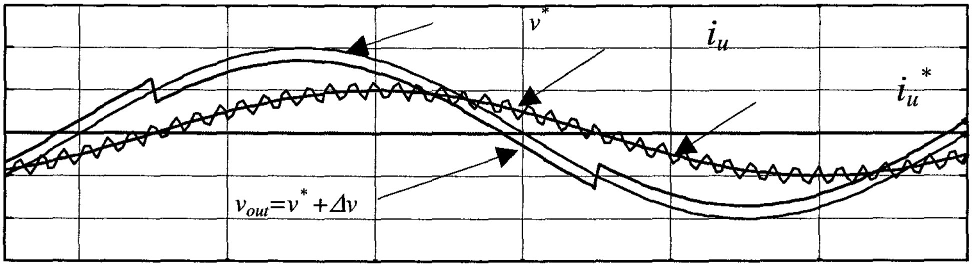


Fig.3 Dead-time effect

3. CONVENTIONAL (FEED-FORWARD) METHOD FOR DEAD-TIME COMPENSATION

Many approaches have been proposed to compensate for the dead-time effect but the most used method in industrial drive system is the one based on feed-forward compensation technique to compensate for the average deviation as shown in Fig.4.

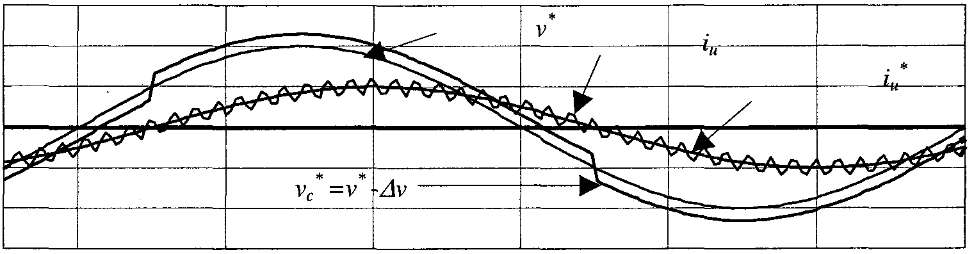


Fig.4 Dead-time compensation in conventional method

The conventional compensation method is based on equation (3) to calculate the new reference voltage, which takes into account the polarity of the current. For simplicity, this compensation uses the current reference to compensate for the dead-time effect instead of the actual current as shown in Fig. 5.

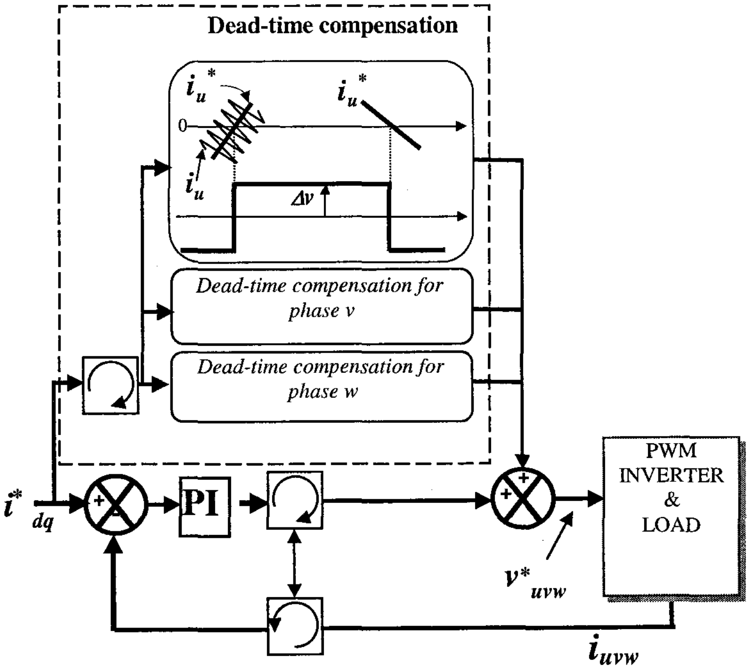


Fig.5 Conventional method of dead-time compensation (feed-forward technique)

$$v^*_c = v^* + \frac{T_d}{T_c} V_d \times sign(i_u^*) \tag{4}$$

This technique of compensation, a feed-forward control technique, is valid under the assumption that the current ripples are neglected. However, in most practical cases, especially for high power drive systems, the current has significant ripples and this will affect the compensation around the zero-crossing zone of the current. The presence of significant ripples around zero-zone will lead to several zero-crossing of the actual current and with each zero-clamping the current polarity changes. This makes the conventional compensation method improper as it is using the reference current polarity to cancel the effect of the dead-time. The conventional compensation described so far performs well when current ripples are very small.

4. PROPOSED METHOD FOR DEAD-TIME AND ZERO CURRENT CROSSING EFFECT COMPENSATION

Repetitive Control Based Compensation

As the dead-time and the zero-clamping effects are repetitive in nature, a proposed method based on repetitive control is used [9].

The repetitive control [11] is effective when the same amount of distortion appears repetitively at constant intervals. This control assumes that a distortion similar to that appeared in the previous output cycle will also occur in the next cycle, and generates a compensating signal to offset the possible distortions. Fig.6 shows the principal configuration of repetitive control which is an iterative control type.

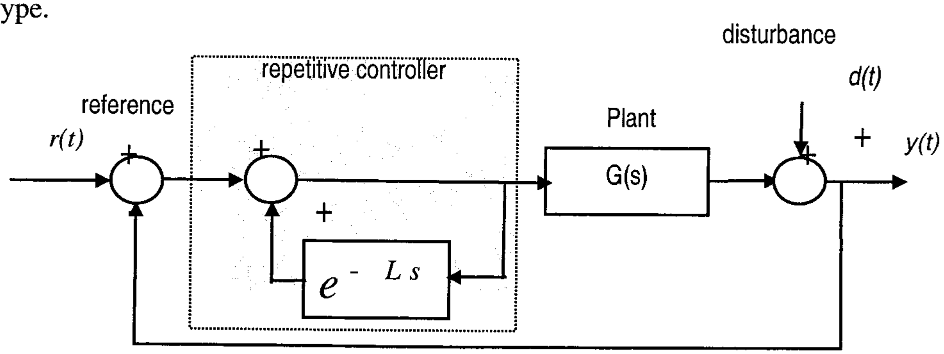


Fig. 6 Continuous time repetitive control system

The controller containing a delay in a feedback path, is the key component. The length L of delay time, e^{-Ls}, should be exactly equal to the period of the input or/and disturbance signal. Since the transfer function of the repetitive controller is $\frac{1}{1-e^{-Ls}}$, the gain curve shows infinite peaks at frequencies of $\frac{2n\omega}{L}$ ($n=\pm 1, \pm 2, \ldots$), as e^{-Ls} equals 1 for this condition. It is known that, when the loop gain is ∞, the input-output error becomes zero. In another words, the output of Fig.6, in its steady state, is equal to the input, if the input and disturbance consist of frequency components, of $2n\omega/L$ and of no other components. Implementation of the repetitive control is better performed in discrete time, as data in these systems, are processed at constant time interval. Fig. 7 shows a discrete repetitive controller where z^{-1} is a delay function of one sampling period. The disturbance repetitive period L is related to the sampling period by the relation;

$$L=nT$$

where n is the number of delay function elements. An equivalent discrete-time model, equivalent to the analog system of Fig. 6, is shown in Fig. 7. The repetitive gains g_{r1}, g_{r2} and the term z^{1-n} are the main components of the repetitive controller. The pulse transfer function $E(z)/Y(z)$, for the controlled system in Fig. 7, is:

$$F_1(z)=\frac{E(z)}{Y(z)}=\frac{1-z^{-n}}{1-z^{-n}((g_{r1}+g_{r2}-g_{r1}z^{-n})zG(z))} \tag{5}$$

where $E(z)$ is the error function.]

Similarly, the pulse transfer function $E(z)/D(z)$ from disturbance to the error is exactly the same as $F_1(z)$. The frequency transfer function corresponding to (5) is

$$F(j\omega)=F(z)\Big|_{z=e^{j\omega T}} \tag{6}$$

The numerator of (6) is given by:

$$1-e^{-j\omega L} \tag{7}$$

If the reference r(t) is a sinusoidal signal with angular frequency $\omega=2\pi mf$ ($m=0,1,2\ldots,n/2$), then equation (7) becomes

$$1-e^{-j2\pi m}=0 \tag{8}$$

Thus, if the system is stable, then

$$\lim_{\omega \to \omega_m} |F(j\omega)| = 0 \tag{9}$$

where $\omega_m = 2\pi m f$

Equation (9) means that no steady state error is obtained with the repetitive control for any periodic disturbance or reference whose frequency equals or is a multiple of f.

Although repetitive control is characterized by its accuracy even when the plant G(s) is not known (the only requirement is a closed-loop stability), it has one disadvantage: L, the length of feedback time delay in the controller, should be equal to the disturbance period. Therefore, a repetitive control is not useful when the period of input/disturbance signal varies with time. For ac motor drive systems, the dead-time disturbance frequency changes linearly with the operating frequency of the inverter. Therefore the above repetitive control as it is, is not useful for dead-time compensation. However, it is worth noting that the dead-time is repetitive not in time domain but in angle domain. Therefore, the time domain repetitive controller is transformed into angle domain repetitive controller.

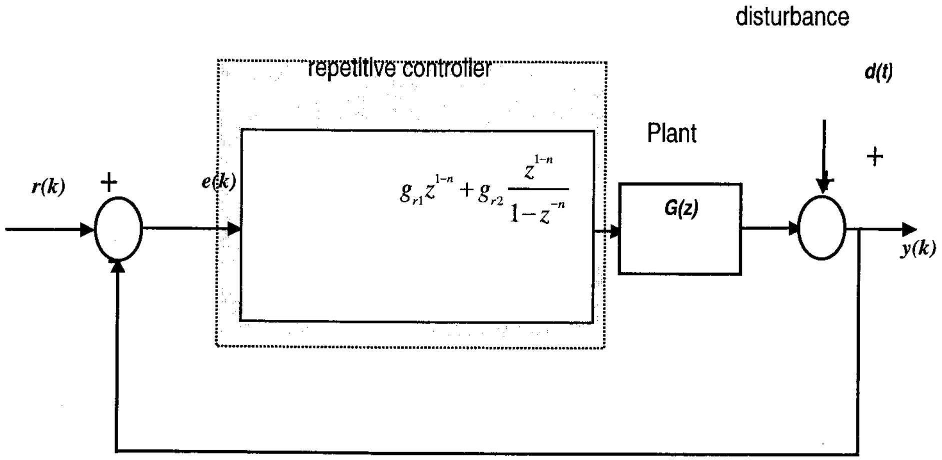


Fig. 7 Discrete time repetitive control system

The angle domain repetitive control is exactly similar to the time domain repetitive control, except that the period L now is an angle based period instead of time based period. This repetitive control could be applied to any model in angle domain. Any time based model could be transformed to angle based model [12]. Then the controller described above could be applied to the new model.

Figure 8 shows an extra repetitive controller inserted in parallel with the conventional PI current controller. The repetitive gain, $G_R = g_{r1}$, is a repetitive gain and L is the period in angle domain of current zero-crossing disturbances (for three phase PWM inverter, L equals to one-sixth of the current period, $L=60^o=\pi/3$). The proposed controller combined with the conventional PI current controller reduces the effect of disturbances introduced by the dead-time as well the current zero-crossing effect.

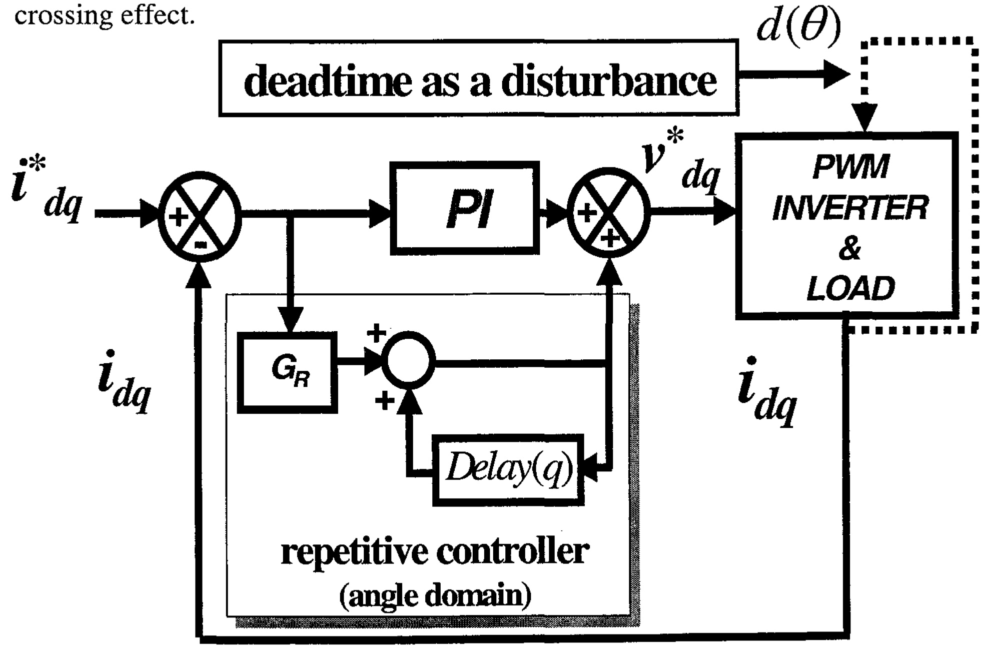


Fig. 8 Angle domain repetitive control

5. SIMULATIONS

Simulations were carried out to verify the proposed methods. An RL load with back-emf is used for the simulations. Data used for simulations are given in Table 1.

Table 1 Simulation parameters

$R=$	1Ω	Load resistance
$L=$	$3mH$	Load inductance
$V_{dc}=V_p-V_n$	290V	DC link voltage
$T_d=$	$21\mu s$	Dead-time
$f_c=1/T_c$	2kHz	Carrier frequency

Fig. 9 shows the simulation results without a dead-time compensation. I_u, I_d and I_q are the current waveforms and are depicted in the simulation Figures.

A large current distortion due to the effect of dead-time is obvious. Fig. 10 shows the current waveforms using the conventional compensation method. In this Figure the dead-time effect away from the zero crossing area is canceled. However the zero-crossing phenomenon effect is visible. Around the zero current crossing the polarity of the actual current due to ripples is different from the reference current. The bigger the current ripples are, the bigger current distortions are obtained.

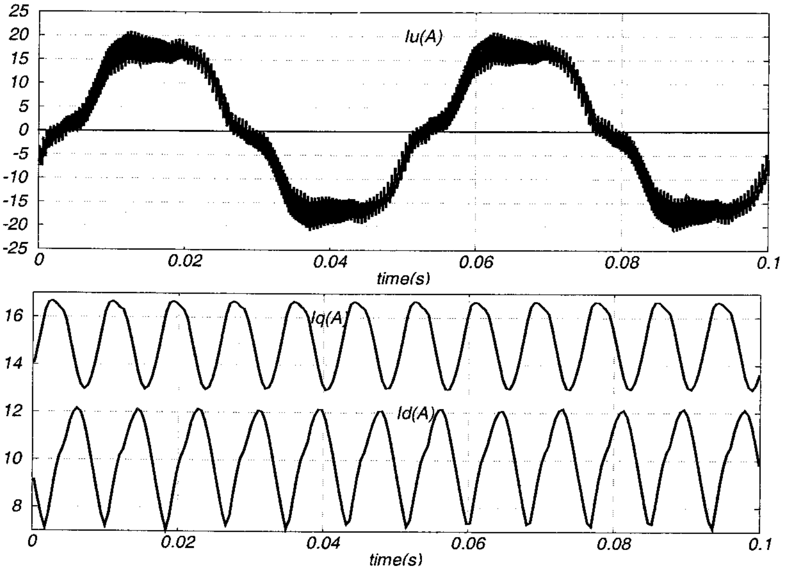


Fig. 9 Current waveforms, at f=20Hz, without dead-time compensation

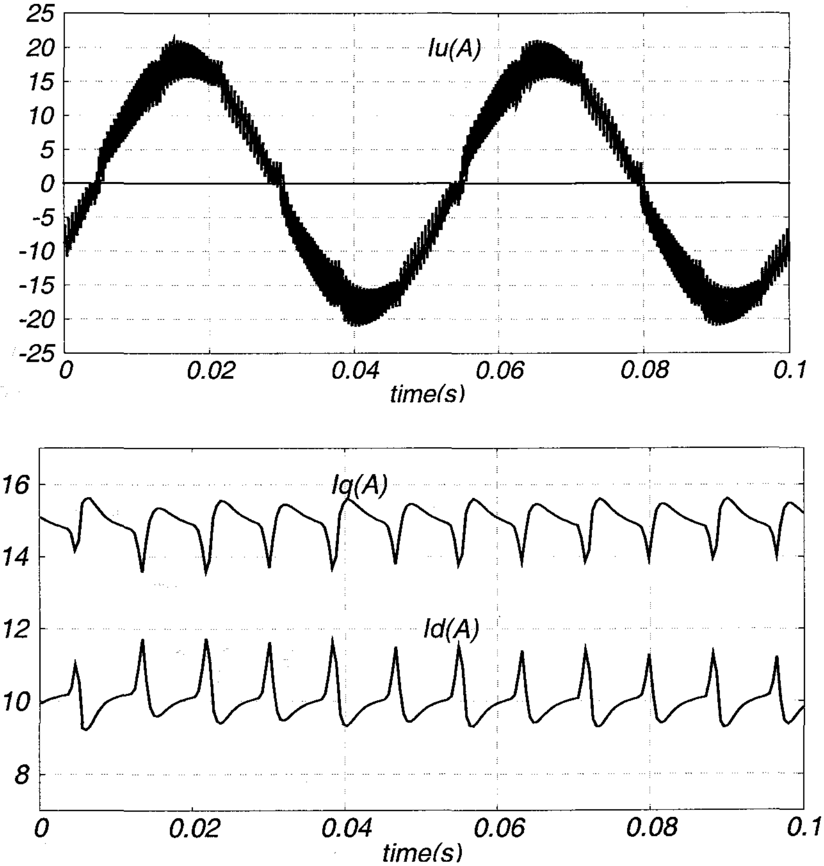


Fig. 10 Current waveforms, at *f=20Hz,* with conventional dead-time compensation

The repetitive control based compensation simulations are shown in Fig. 11. The waveforms depicted in this Figure shows that the effects of dead-time and zero current crossing are both eliminated. The proposed method based on repetitive control in angle domain, improves the current waveforms by eliminating the effect caused by the zero-crossing phenomena.

The above simulations were carried out for an operating frequency of 20Hz. As the repetitive controller proposed in this paper can work for any operation frequency, a simulation is carried out to verify this capability. Fig. 12, 13 and 14 shows the current waveforms for an operating frequency of 10Hz, with no compensation, conventional compensation and the proposed compensation respectively. These Figures show that near sinusoidal output current waveforms are obtained for the proposed method.

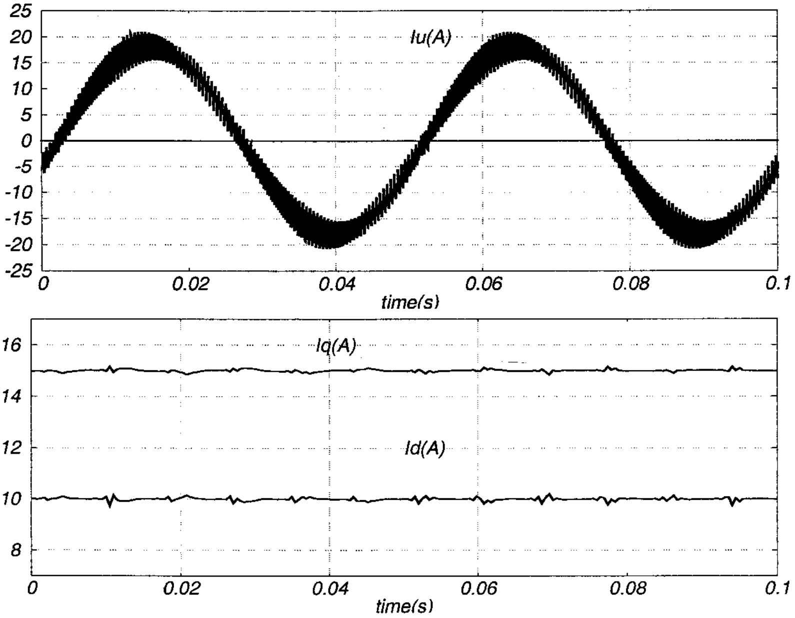


Fig. 11 Current waveforms, at *f=20Hz*, with repetitive based dead-time compensation

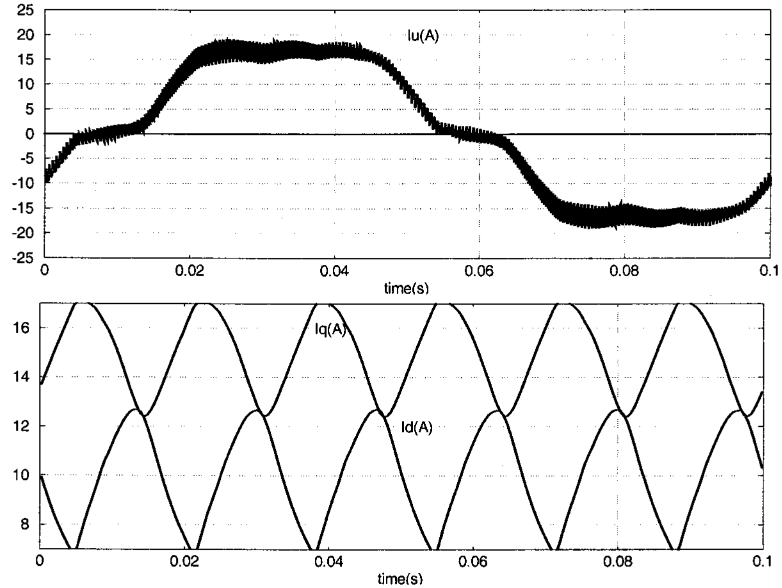


Fig. 12 Current waveforms, at *f=10Hz*, without dead-time compensation

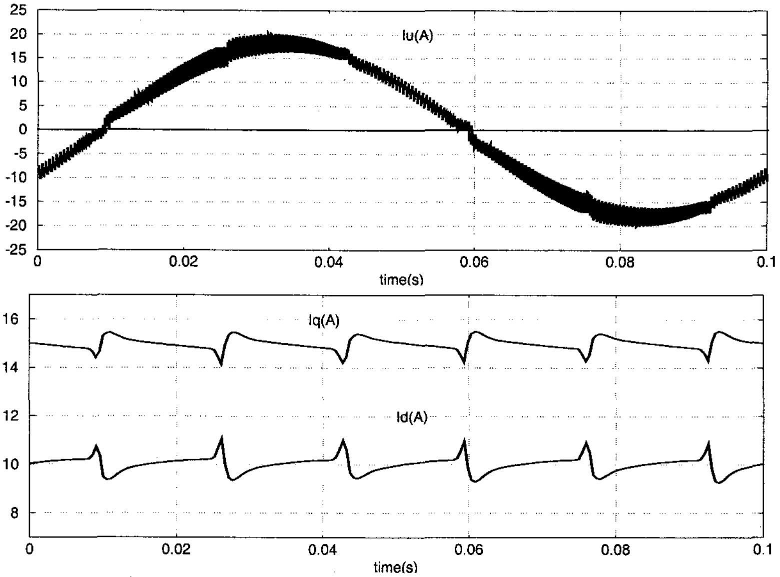


Fig. 13 Current waveforms, at *f=10Hz,* with conventional dead-time compensation

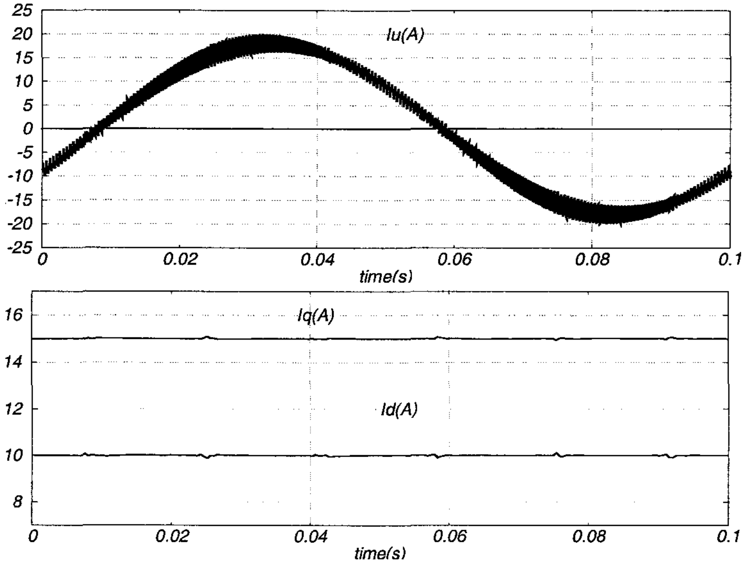


Fig. 14 Current waveforms, at f=10Hz, with repetitive based dead-time compensation

The Total Harmonic distortions (THD) which is a measure of how the waveforms are close to a pure sinusoidal is shown in Fig. 15. This figure shows that the THD is greatly reduced for the proposed method. The THD for the repetitive control is less than 3% while for conventional is around 5%.

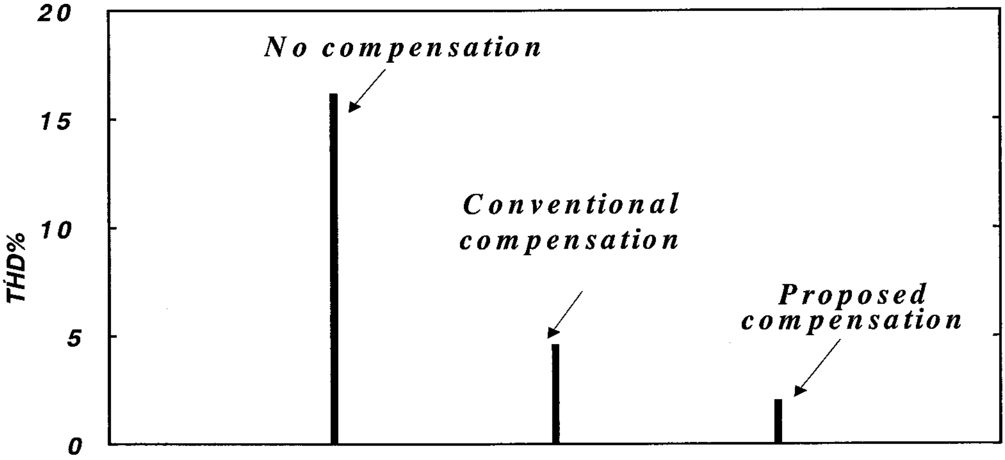


Fig. 15 THD Comparison between the conventional and the proposed compensation

Note that the selection of G_R depends on the operating frequency as shown in Figure 16. At higher frequency the current ripples are bigger and therefore smaller gain should be used to guarantee a stability of the controller.

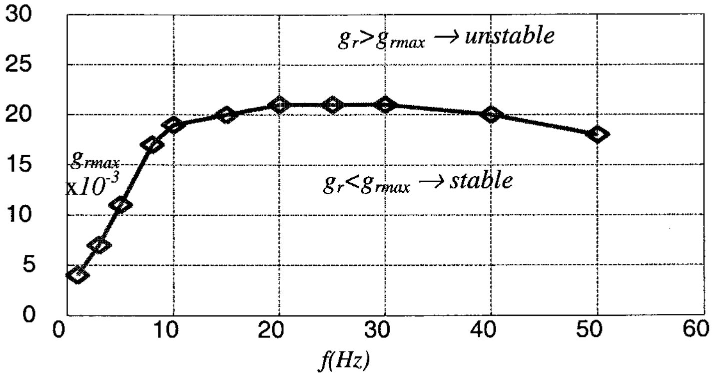


Fig. 16 Stability of the repetitive controller as a function of frequency

6. DISCUSSIONS

A repetitive control based PWM inverters dead-time and zero current crossing compensation method is proposed, analyzed, and verified. Its merit compared to the conventional method is outlined.

The conventional method is based on feed-forward technique using the polarity of the reference current. This method is very simple and effective when the output current ripples are very small. However, when current ripples are relatively large, the output current exhibits a large distortions around the zero crossing region. To eliminate these distortions, we proposed in this paper an optimal compensation for dead-time and zero current crossing.

The proposed method of dead-time and zero current crossing compensation is based on repetitive controller. The repetitive controller is known to be successful only for constant disturbance frequency.

As the dead-time disturbance is repetitive in angle domain, we used an angle based repetitive control. This method is efficient in eliminating the dead-time and zero current crossing at any operating frequency. The repetitive controller operating in parallel with the main PI current controller had contributed to a sinusoidal output current waveform, and reduces the total harmonic distortions. The gain of repetitive controller should be selected so that the stability of current controlled system is achieved.

CONCLUSIONS

The PWM inverters dead-time and current crossing effects as well as conventional compensation method are analysed. Then a proposed method for dead-time and zero current crossing compensations based on angle domain repetitive control, is described in this paper. The elimination of the zero current clamping effects in a voltage-fed PWM inverter is achieved for a wide range of operating frequency. Digital simulations are carried out to verify the proposed scheme for dead-time compensation. The simulation shows that the inverter output current waveforms are improved when using the proposed method.

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