Investigation of Induction Motor Drive Performance under Various Current Controllers

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Abstract: A current controller is used in high performance ac drives to switch the voltage source inverter in such a way that the motor currents follow a set of reference current waveforms. This paper presents 1) a short review of the different current control techniques for three phase two level inverters 2) a detailed comparison of various current controller schemes, particularly hysteresis (fixed, sinusoidal, and mixed-band), ramp comparator and hybrid current controllers for the induction motor drive based on performance at different speeds. The hysteresis and the ramp comparator controllers are getting more attention due to their simplicity and high dynamic responses. Therefore, the hybrid current controller is used. The harmonic spectra of the motor line currents for various current controllers are obtained using a fast Fourier transform for comparison purposes. All current control schemes have been verified by using computer simulations.

[A.E.kalas, M.El-shahat Dessouki, E.E.Elkholy. **Investigation of Induction Motor Drive Performance under Various Current Controllers.** *Life Sci J* 2014;11(3):121-129]. (ISSN:1097-8135). http://www.lifesciencesite.com. 17

Keywords: Linear current control, nonlinear current control, hybrid current control, induction motor (IM) drives

1. Introduction

Vector controlled induction motor drives are increasingly used in many industrial applications where high performance torque and speed control are required. In such drive systems voltage-source, current-controlled space vector pulse width modulated (CC-PWM) inverters are widely used since the motor drive's performance is determined directly by the current controller. Due to existing cross coupling between the motor torque and flux, the currents error degrades the torque response. This results in an undesirable steady state and transient responses in the drive system. Therefore, stator current has to be precisely controlled in order to decouple the torque and flux producing currents. Thus, the current control technique plays the most important role in current-controlled pulse width modulation (PWM) inverters [1-4]. The field oriented control technique is implemented using both current and speed controllers. A typical closed loop indirect field oriented control (IFOC) scheme for the induction motor drive is shown in (Figure.1) [4]. The PWM process creates a switched equivalent of the demanded voltage which is then applied to the load. Nonlinear current controllers are based on hysteresis strategies, in which measured currents are compared to reference currents on an instantaneous basis. The current error is then compared directly against a hysteresis band using comparators to create the phase switching commands for the voltage source inverter (VSI).

Linear current controllers are characterized by a constant switching frequency, but have performance limitations caused by delays associated with the error calculation and PWM process. Non-linear current controllers are characterized by widely varying switching frequencies (unless sophisticated variable hysteresis band strategies are implemented [5-6]) but offer a rapid response to transient events. In case of the induction motor drives, the command currents are generated from the error between the command speed and the actual motor speed. Thus, the current controller plays an important role to follow the command speed. The speed response of the drive is significantly affected by the nature of various current controllers with speed and operating conditions. Therefore, an extensive performance analysis of various current controllers for the induction motor drive at various speeds is essential in order to choose a specific current controller for high performance drive applications over a wide speed range.

Therefore, this paper gives a short review of the available current control techniques for three phase two level inverters in addition; it investigates the performance of various current controller schemes, in particular, the hysteresis (fixed, sinusoidal and mixed bands), the ramp comparator controllers and hybrid current controller (hysteresis-ramp controller) for the induction motor drive at different operating conditions. The comparison is based on computer simulations.

2. Linear Current Control

The linear controllers are involved with conventional voltage-type PWM modulators [7-10]. Because the linear control schemes have clearly separate current error compensation and voltage modulation components, this allows us to take the advantage of open loop modulators (e.g., sinusoidal PWM, space vector modulator, etc.). Quite often, linear control schemes can be further classified into the following groups

2.1. PI Current Control:

The PI current control techniques are discussed in two categories: Ramp Comparison Current Controller and Synchronous Vector Controller.

2.1.1. Ramp comparison current controller:

The original idea of ramp comparison current controller (stationary controller or linear carrier-based current controller) can be traced back to the triangular sub-oscillation PWM scheme. With the modification by feeding back the output current ripple, a PI current controller is proposed to produce voltage commands by using the PI error compensator (Figure.2) [2]. This controller provides significant improvement in the control performance, compared with the original controller. The main disadvantage of this technique is an inherent tracking error in both amplitude and phase. To achieve compensation, other modifications can be made by using additional phase locked loop (PLL) circuits or feed-forward correction [11] and [9].

2.1.2 Synchronous vector controllers:

They are based on space-vector control schemes, and have wide applications in many industries. Since even small phase or amplitude errors may cause incorrect system operation, an ideal current control is desired. The PI compensators are used to reduce the error of the fundamental component to zero. The work in [15] has demonstrated that it is possible to perform current vector control in an arbitrary coordinates. Based on this work, a synchronous controller that woks in a stationary coordinates has been developed [9].

Due to the use of PWM modulators, the linear synchronous vector controllers can provide a well-defined harmonic spectrum; however, their dynamic behavior is inferior to those of bang-bang controllers.

2.2. State Feedback Control:

In the aforementioned PI control schemes, by substituting the conventional PI compensators in current error compensation parts with a state feedback controller, better current performance is usually achieved. Particularly, the state feedback controllers can be designed to work in stationary coordinates as well as synchronous rotating coordinates. Because the control algorithms can guarantee dynamically correct compensation, the control performance of the state feedback current controllers is usually superior to conventional PI controllers. However it may require more complexity in obtaining the feedback control law and is limited to applications in which the system states can be obtained in some way [7-8].

2.3. Predictive and Dead-Beat Control:

This technique makes a prediction of the current error vector based on actual current error and load parameters at the beginning of each sampling period. The voltage vector which is to be generated by PWM during the next modulation period is thus predetermined such that the forecasted error is minimized. The required voltage vector at n-th sampling instant is given by the following equation [13-15].

$$v(\mathrm{n}) = \frac{L}{T}[\mathrm{i}^*(\mathrm{n}+1) - \mathrm{i}(\mathrm{n})] + \mathrm{Ri}(\mathrm{n}) \tag{1}$$

Among the family of predictive control schemes, constant switching frequency predictive algorithms are typical and popular techniques. Their implementation involves space vector [13] and sinusoidal modulator [14]. It should be noted that the inverter switching frequency is constant, while the output current ripple is variable. The main disadvantage of this scheme is that it does not guarantee the inverter peak current limit. Sometimes it is desirable to choose the voltage vector such that the current error is reduced to zero at the end of the sampling period. In such cases, the predictive current controller is called a deadbeat controller [16-17]. One characteristic of this control scheme is that non-available state variables can be included in its control calculation, but the determination of the state variables can require the use of observers or other control blocks.

3. Nonlinear Current Control

Nonlinear current control may be the largest subset of current control techniques. This set of current control techniques is concisely discussed in three main categories: Hysteresis band control, Nonlinear carrier-based control, and Optimization-based current control

3.1. Hysteresis band control

In general, hysteresis-band current control can be regarded as an instantaneous feedback system, which detects the current error and produces directly the drive commands for the switches [18]. Hysteresis current control is probably the simplest technique used to control the phase motor currents for high speed drive system, because of its ease of implementation, fast current control response, and inherent peak current limiting capability. However, this scheme suffers from some drawbacks partially related to the variation of the switching frequency over a wide range [19-22 and 5]. The basic idea of hysteresis control is to switch each phase leg to the opposite voltage polarity whenever the measured current goes above or below a given boundary [5]. A simple diagram of a typical hysteresis current controller (HCC) is shown in (Figure.3). Based on the hysteresis band, conventionally, there are two types of hysteresis controllers, namely, fixed-band and sinusoidal band hysteresis controllers. In the sinusoidal band, the hysteresis band varies sinusoidally over the fundamental period. The advantage of this scheme is that the harmonic content of the current decreases. The disadvantage is that the switching frequency near zero crossing is very high [23]. As a result, the maximum switching frequency of the inverter increases. In the case of the fixed-band controller, the maximum switching frequency of the inverter is reduced, but the harmonic current is increased. In order to compromise between the maximum inverter switching frequency and harmonic content of the current, the mixed-band hysteresis controller is used. In the mixed-band controller, the hysteresis band varies sinusoidally around the reference and a constant value. The inverter output is switched according to the following rules

$$|i_{a,b,c}| > |i_{up}| \quad \text{output off} \qquad (2)$$

$$|i_{a,b,c}| < |i_{low}| \quad \text{output on} \qquad (3)$$

$$|i_{low}| < |i_{a,b,c}| < |i_{up}| \quad \text{no change} \qquad (4)$$

where i_{up} ($i^*_{a,b,c}$ + H) is the upper limit, i_{low} ($i^*_{a,b,c}$ - H) is the lower limit and H is hysteresis band. For a fixed band H = α_1, for a sinusoidal band H = β_1 sin (ωt), and for a mixed band H = α_2 + β_2 sin (ωt) where α_1, α_2, $\beta_1$and β_2 are constants.

3.2. Nonlinear Carrier Control:

The nonlinear carrier control (NLC) schemes are relatively new to the family of current control techniques. The proposed nonlinear carrier controller determines the switch duty ratio by comparing a signal derived from the main switch current with a periodic nonlinear carrier waveform. To achieve unity power factor rectification (in case of rectifiers), the shape of the carrier waveform is determined so that the resulting input line current is proportional to the input line voltage. The nonlinear carrier controllers have as distinctive feature of their suitability for simple integrated-circuit implementation.

3.3. Optimization-based Control:

The optimization-based controllers achieve very good stationary and dynamic behavior in most cases. This class of controllers is usually implemented on microprocessors because it performs a real-time optimization, which often requires complex on line calculations [11]. The Minimum Switching Frequency Predictive Algorithm (MSFPA) [24] is based on space vector analysis of hysteresis controllers. With an objective function to minimize the average switching frequency of the inverter, the voltage vector is determined by solving an optimization problem. However, due to the complexity of the calculations needed by the prediction and optimization, it is difficult for these techniques to achieve a high switching frequency.

Several control schemes that belong to Trajectory Tracking Control have been proposed [25]. In such schemes, an off-line optimized PWM pattern for steady-state operation is combined with an on-line real-time optimization, and the dynamic tracking errors of inverter currents are well compensated.

4. Other Advanced Current Control

Compared with the current control techniques discussed in previous sections, the current control strategies to be introduced are relatively new and regarded as more advanced because they are an integrated of other control techniques.

4.1. Fuzzy and Neural Control

Recently, new technologies such as Neural Networks (NN) and Fuzzy Logic Control (FLC) have been introduced from computing science to PWM current control, aiming to overcome the limitations of the classical control methods. With the capabilities of fast learning and parallel processing, NN controllers find extensive applications for PWM current control [26-29]. Apparently, an important issue for NN controllers is the neural network training data. In practice, both off-line and on-line training methods have been developed. More research is still in progress to achieve fast on-line training with limited data. Similar to the applications of FLC in other areas, such as process control, the FLC can be used as a substitute for the conventional PI controllers in PWM current control. Generally, the implementation of FLC controllers is easy and of low hardware cost, but the design of FLC controllers is difficult and requires a large amount of expert knowledge [18].

4.2. Hybrid Current Control

The main purpose here is to present a subset of current control techniques that are developed based on a combination of two or more classical or advanced control strategies [31-33]. An adaptive hysteresis current controller has been developed by introducing the idea of FLC to hysteresis current control. The proposed system adjusts the hysteresis band and determines the switching pattern according to pre-specified fuzzy logic rules. Besides the improvement in control performance over traditional hysteresis controllers, the proposed hybrid controller can be easily implemented on line using digital signal processors without time constraint problems. However, due to the incorporation of FLC, the design of this hybrid controller may require a lot of expertise for designing the FLC rule base. Although the past literature treats the hysteresis controller and ramp-comparison controller separately as independent current control schemes, hybrid current controllers, which can be regarded as an integration of the above two, have been extensively investigated [31-33]. To take the good features of both these two controllers, the design and software implementation of a hybrid current controller are presented. The developed intelligent controller, which gives better performance than the classical schemes, is a simultaneous combination and contribution of the hysteresis current controller and ramp comparator without a switching mode level between them. The principle of the developed hybrid current controller is based on the superposition of a high and a fixed frequency triangular signal to the current references. New current references are obtained; these are given by the following equations.

$$i_{anref} = i_{aref} + i_{tr} \quad (5)$$

$$i_{bnref} = i_{bref} + i_{tr} \quad (6)$$

$$i_{cnref} = i_{cref} + i_{tr} \quad (7)$$

The new references signals are compared to the actual currents and the error signals become then the inputs to the hysteresis block control as illustrated by (Figure. 4).The upper and lower bounds of the hybrid current controller could be then defined using the new current references and the hysteresis band size H.

$$i_{up} = i_{nref} + H \quad (8)$$

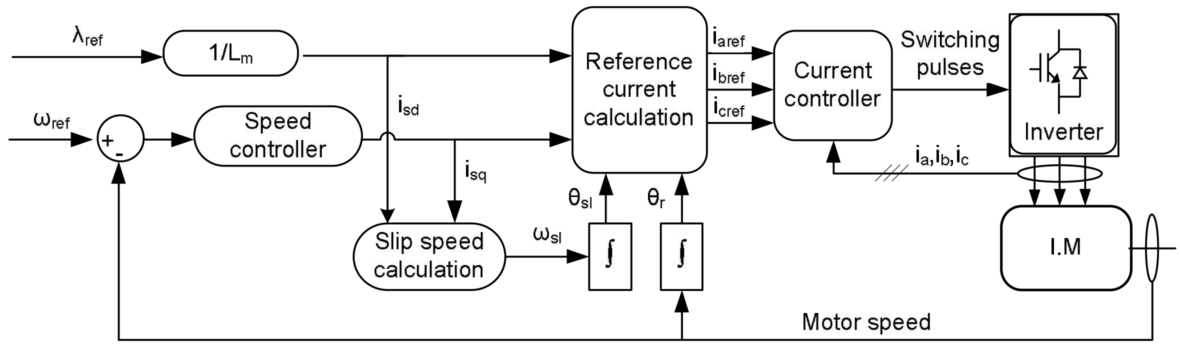
$$i_{low} = i_{nref} - H \quad (9)$$

5. Simulation Results

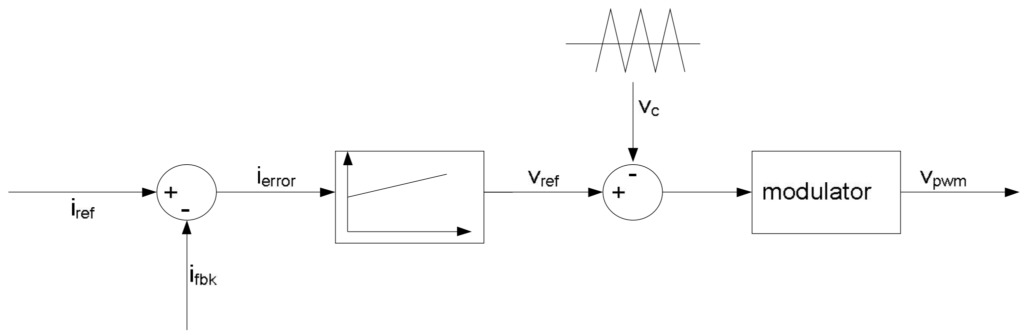
The control algorithms of all hysteresis and ramp comparator versions for induction motor under the indirect field orientation control system have been developed and implemented on the MATLAB/SIMULNK programming environment. The performance of various current controllers at various speeds is evaluated by performing many simulations. Here are some of these results. The drive responses of fixed band HCC for 1500 rpm speed command at rated load (7.5 Nm) are shown in (Figure. 5). It is shown that the drive follows the command speed without any steady state error and without overshoot in transient condition. The actual motor current also follows the command current with a hysteresis band. The developed torque reaches its steady state value at 0.4 sec. The similar drive responses for the same controller at rated load and 200 rpm speed command are shown in (Figure. 6). It is shown that, although the drive follows the command speed, the speed response is not so smooth even at steady-state condition. Therefore, the drive response of hysteresis controller is not so good at low speed condition. The speed and actual phase "a" current are shown in (Figures. 7(a) and (b)) respectively for step change of speed (750 rpm to 1500 rpm at 0.45 sec.) at the rated load for the fixed band HCC. It is shown that the motor can follow the command speed very quickly even after an abrupt change of command speed. For the same controller, the similar responses of the drive are shown in (Figures. 8(a) and (b)), for a sudden increase of load (3 Nm to 7.5 Nm at 0.65 sec.) at rated speed. It is shown that the motor can follow the command speed even after some disturbance of load. It is observed during the simulation that the speed responses of the induction motor drive at different command speeds for all current controllers show some discrepancy. And this is due to the different nature of the actual motor currents for various current controllers at different speed conditions. Therefore, we focus on the analysis of current responses for the different current controllers.

The analysis is performed on the steady state current for the motor phase "a". The current responses and their harmonic spectrum at high and low speeds are shown in (Figures. 9 and 10) respectively, in case of sinusoidal band HCC. It is shown that total harmonic distortion (THD) is less at high speed, and we can notice the same result is achieved in the fixed band HCC (Figure. 5(d)) and (Figure. 6(d)). It is also observed that, the THD in the case of the sinusoidal band controller is low as compared to the fixed band controller. However, the maximum inverter switching frequency is very high in case of the sinusoidal band controller near zero crossing. In the fixed band controller, the maximum inverter switching frequency is reduced as compared to the sinusoidal controller. The current responses for mixed band HCC at high and low speed are shown in (Figures. 11 and 12) respectively. We can find from the results a compromise between the THD and the inverter switching frequency as compared to the fixed and sinusoidal band controllers. (Figures. 13 and 14) show the current responses for ramp controller at high and low speeds respectively. From which it is clear that the motor current has magnitude and phase errors at high speed, hence the motor can't follow the high command speed accurately.

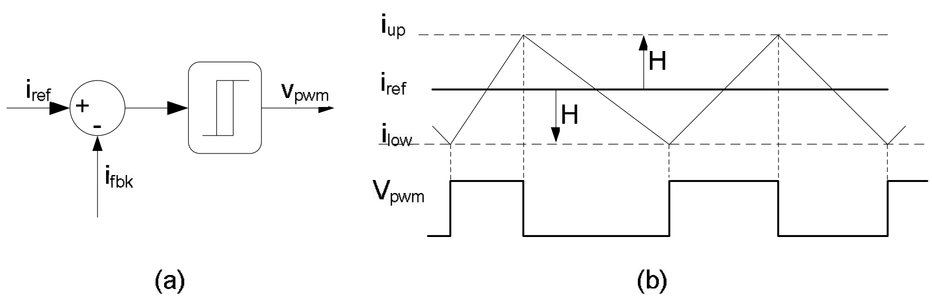
On the other hand, at low speeds the motor current can follow the command current more accurately (without magnitude and phase errors) as compared to high speed condition. (Figures 15 and 16) show the performance of the hybrid current controller for 1500 rpm and 200 rpm speed commands at rated load respectively. It is deserved to advert that the motor current can follow the command current at high speed (similar to hysteresis band controller) and low speed (similar to ramp comparator controller), and this validates the controller combination features of both hysteresis controller and ramp comparator controller.



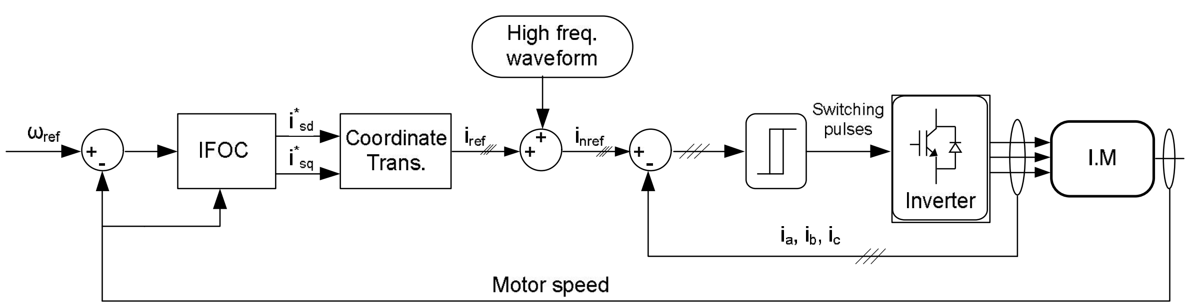
(Figure. 1) IFO control scheme for induction motor



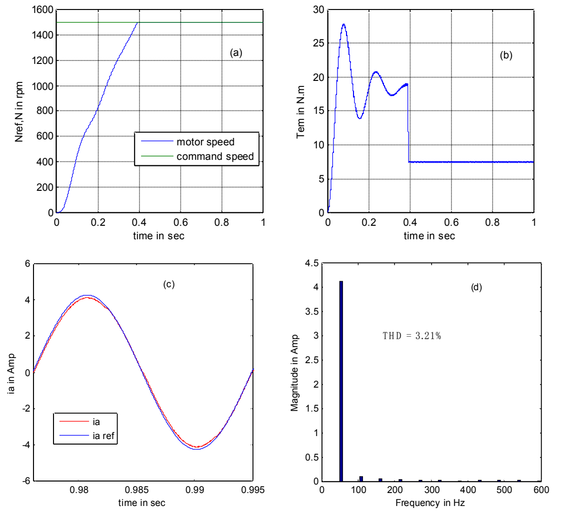
(Figure. 2) Carrier based current control scheme



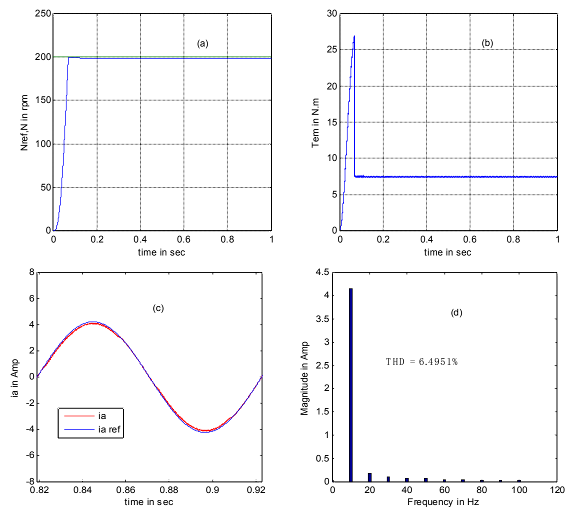
(Figure.3) General hysteresis current control scheme
(a) Functional diagram (b) Current and PWM waveforms



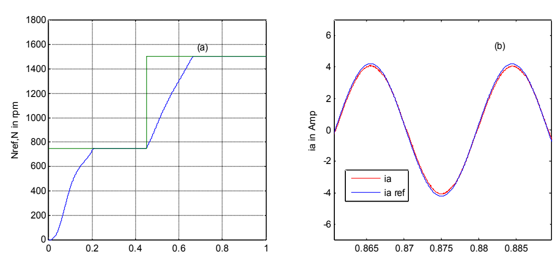
(Figure. 4) Hybrid current controller.



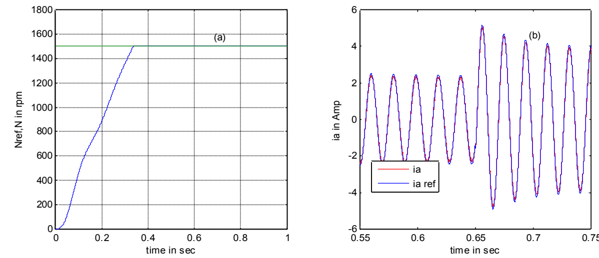
(Figure. 5)Drive responses of fixed band HCC at high speed
(a) Speed response (b) Torque response
(c) Phase current (d) Harmonic distribution



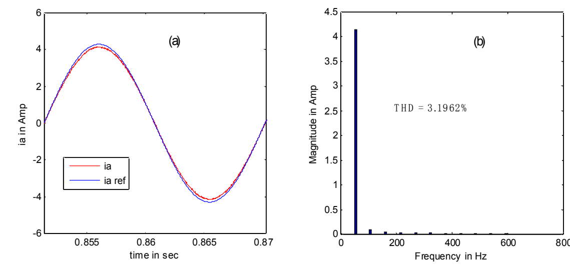
(Figure. 6) Drive responses of fixed band HCC at low speed
(a) Speed response (b) Torque response
(c) Phase current (d) Harmonic distribution



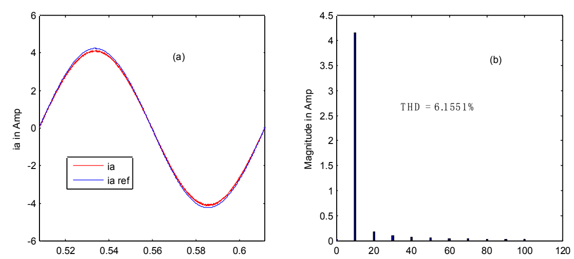
(Figure. 7) Drive responses at a step change of speed (750 rpm to 1500 rpm) and full load conditions for the fixed band HCC
(a) Speed response (b) Phase current (at 1500 rpm)



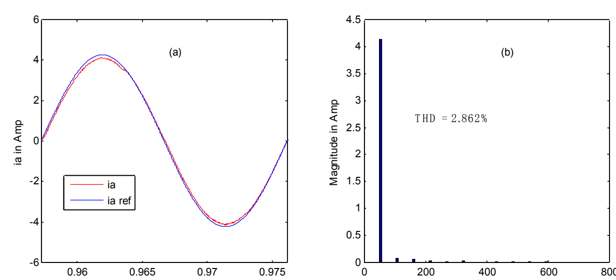
(Figure. 8) Drive responses at a step increase of load (3 Nm to 7.5 Nm) and rated speed conditions for the fixed band HCC
(a) Speed response (b) Phase current



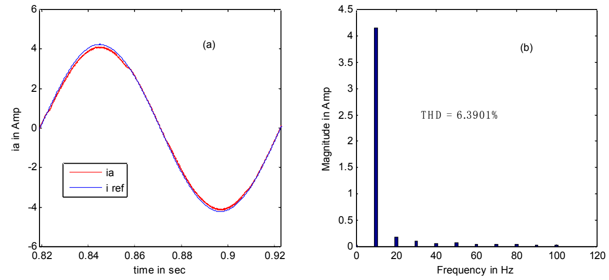
(Figure. 9) Drive responses for sinusoidal band HCC at high speed
(a) Phase current (b) Harmonic distribution



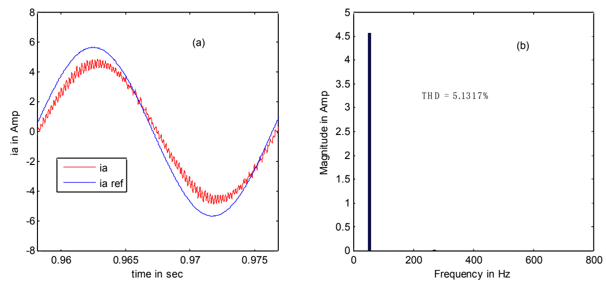
(Figure. 10) Drive responses for sinusoidal band HCC controller at low speed
(a) Phase current (b) Harmonic distribution



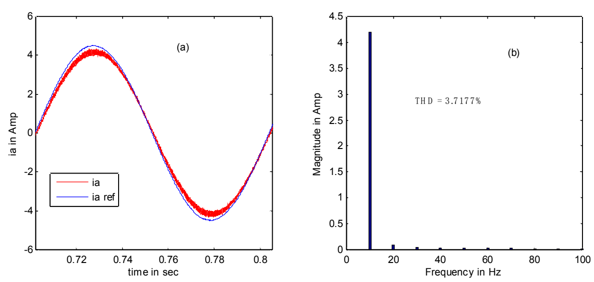
(Figure. 11) Drive responses for mixed band controller at high speed
(a) Phase current (b) Harmonic distribution



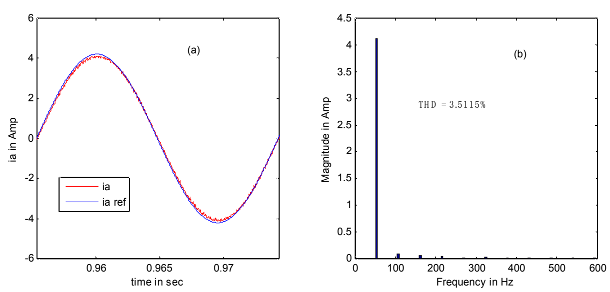
(Figure.12) Drive responses for mixed band controller at low speed
(a) Phase current (b) Harmonic distribution



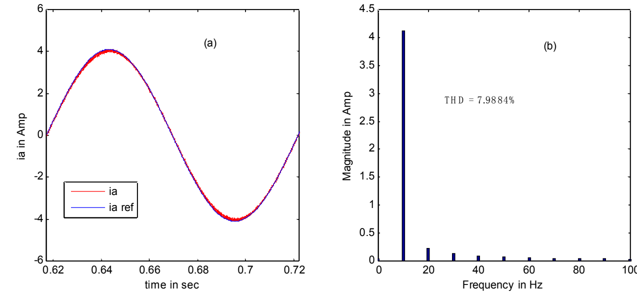
(Figure. 13) Drive responses for ramp comparator controller at high speed
(a) Phase current (b) Harmonic distribution



(Figure. 14) Drive responses for ramp comparator controller at low speed
(a) Phase current (b) Harmonic distribution



(Figure. 15) Drive responses for hybrid current controller at high speed
(a) Phase current (b) Harmonic distribution



(Figure. 16) Drive responses for hybrid current controller at low speed
(a) Phase current (b) Harmonic distribution

5. Conclusion

A brief review of the available current control techniques applicable to VSI is given. The basic approaches and performance of various methods are summarized. There is a trend to develop hybrid current controllers by taking advantages of multiple existing current techniques. A complete analysis and comparison of various current controllers for induction motor drive has been presented at different operating speed conditions. It has been shown that good performance at high speed drive may be achieved by using the hysteresis current controller whereas; at low speed conditions the ramp comparator controller is the most suitable controller. To take the advantage of both controllers, a hybrid current controller has been developed and validated by computer simulation.

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2/3/2014