Comparative Performance of Induction Motor Speed Controller System with Flux Weakening Control

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Abstract. In general induction motor not work optimally because cannot reach the maximum speed of the rating. In this paper, simulation is used with several methods, named Maximum Torque Per Ampere (MTPA) and Field-weakening. Simulation of the methods used the function on MATLAB C-Mex and implemented on block of Simulink. The Field-weakening is control speed of the induction motor by decreased flux. The goal is to produce motor speed above the rating. The method of field-weakening control with addition of $|i_q|$ used as reference $i_d^*$, which will be used to limit $i_q^*$. The result of the study is a comparison between the two methods to verify reliability. Simulations results showed that induction motor speed controller using field-weakening control with addition $|i_q|$ better performance.

1. Introduction
The control method for optimization of characteristics on the performance of the induction motor grows fast. Various used induction motors cause there are various methods in matching the desired performance and specifications. One method is the Field-Weakening Method which is often used to increase motor speed above rating. This Field-Weakening method purposed to control $i_q^*$ by limiting it $i_d^*$ where there is $|i_q|$ input [1]. There is MTPA method (Maximum Torque Per Ampere) where in this method purposed to ensure that the current used is the minimum $i_d$ current for development on motor torque, with total flux stator controlled by MTPA criteria [2].

There is some research on Field-Weakening and MTPA methods. The Field-Weakening Method already has several modifications such as the "Predictive Control Based Field-Weakening Strategy for Traction EV Used Induction" [3] which used Predictive Control (MPC) based control where the MPC method is adopted to replace the PI regulator in the voltage loop to calculate the current reference that produces flux. Second, the title is "Overmodulation and Field Weakening in Direct Torque Control of Induction Motor Drives" [4] which used the Overmodulation method where this method only modifies torque errors and flux before fed to the look-up table. The third, the title is "High Performance Induction Motor Drive in Field Weakening Region" [5] which in the calculation of field-weakening method used iron losses. MTPA method has several various developments such as the title "Maximum Torque-per-Amp Tracking Control of Saturated Induction Motors" [7] which proposed to improve the torque-flux tracking performance and controller robustness. The next reference is titled "A Maximum Torque per
Ampere Control Strategy Drives" [8] which is proposed simply in structure and has the straightforward goal of minimizing the stator current amplitude for a given load torque.

This paper will compare the performance of induction motor system control method with several methods namely, MTPA (Maximum Torque Per Ampere), Flux-Weakening with the addition of $|i_q|$ and the combination of MTPA and Flux-Weakening Control.

2. Implementation of Controls with Matlab

Model of the induction motor system used in the comparison is the same for each method. The difference is found in the speed control adjusted to each method. It is a Rotor Flux Oriented Control (RFOC) of an induction motor (a three-phase, four-poles, 750 W, squirrel-cage induction motor)

2.1. Induction Motor Model

On the controller, the scheme requires a drive induction motor model. Induction motor models used in all methods used a synchronous frame of reference, with the following equation: [10]

$$\frac{d}{dt} i_α = \frac{R_s L_m - R_l L_s}{L_m^2 - L_s L_r} i_β - \frac{N_p \omega_r L_m}{L_m^2 - L_s L_r} v_α - N_p \omega_r L_r L_m i_γ - R_l i_α$$

(1)

$$\frac{d}{dt} i_β = \frac{N_p \omega_r}{L_m^2 - L_s L_r} v_β - N_p \omega_r L_r L_m i_γ - R_l i_β$$

(2)

$$\frac{d}{dt} i_γ = -R_s L_m i_α - \frac{N_p \omega_r}{L_m^2 - L_s L_r} v_γ - N_p \omega_r L_r L_m i_β - R_l i_γ$$

(3)

$$\frac{d}{dt} i_δ = \frac{N_p \omega_r}{L_m^2 - L_s L_r} v_δ - R_s L_m i_γ - R_l i_δ$$

(4)

Where $L_s$, $L_r$, and $L_m$ show each phase induction of stators, rotors. Whereas $\sigma$ is defined as $1 - \frac{L_m^2}{L_s L_r}$. $\varphi_{ds}$ and $\varphi_{qs}$ the components d and q axes on the flux stator parallel along the rotor flux axis.

2.2. MTPA (Maximum Torque Per Ampere)

In the MTPA method, the system is modified in such a way that the MTPA controller is designed along with a feedback-linearizing controller. The block diagram of MTPA control is as shown in Figure 1.

**Figure 1.** Block Diagram of MTPA (Maximum Torque Per Ampere)
In the process of identified MTPA conditions for specific motor torque, the current voltage is determined as a function of the d and q axes, so that the stator current components used are $i_d$ and $i_q$. Therefore, the proposed control used $T_e$ in its control so on the MTPA method, $T_e$ shows the electromagnetic torque of the equation given by (5),

$$ T_e = p(1 - \sigma)L_s i_{sq}^{*} \text{imr} \tag{5} $$

MTPA operated conditions on each of the d and q axis flux components within the synchronous reference framework can be provided by (6) and (7)

$$ \varphi_{ds|\text{MTPA}} = \frac{L_s}{L_m} \sqrt{\frac{2T_e}{p}} \tag{6} $$

$$ \varphi_{qs|\text{MTPA}} = \frac{\sigma L_s}{L_m} \sqrt{\frac{2T_e}{p}} \tag{7} $$

The values of the d and q flux axis components within the synchronous reference framework can be given by (8),

$$ |\varphi_s|_{\text{MTPA}} = \frac{L_s}{L_m} \sqrt{\frac{2L_r (1 + \sigma^2)T_e}{p}} \tag{8} $$

2.3. Flux-Weakening added by $|i_q|$  
In the conventional field, the induction motor-oriented control flux rotor is assumed to be constant so that torque can be controlled by controlling the current of the q axis. Weakens the flux to control the motor so that it can reach very high speeds, although it has a reduced risk of torque. This method adds $i_q$ current to the reference on the d-axis so that the right flux and torque can be generated automatically. Block diagram of the field-weakening method with the addition of $|i_q|$ shown by Figure 2.

![Figure 2. Block Diagram of Flux-Weakening added by $|i_q|$](image)

The operation is performed by limiting the current on the d ($i_{sd}$) and q ($i_{sq}$) axes which will limit the reference current on the d ($i_{sd}^{*}$) and q ($i_{sq}^{*}$) axes. Application of optimization restrictions is carried out Field weakening techniques by determining the reference d-axis current $i_{sd}^{*}$ which is limited to the rated value with the equation (9)
The voltage applied to the motor is limited, so the \( V_{\text{dc}} \) used is limited to \( m \cdot V_{\text{dc}}/2 \) where \( m \) is index modulation. This method used a filter to generate reference current on the d-axis (\( i_{s d}^* \)), which is expressed by equation (10):

\[
i_{s d}^* = K_{v p}(V_c^{*2} - v_{s \text{filter}}^2 + K_{abs} |i_{q s}|)
\]

Where \( K_{vp} \) represent proportional amplifier, \( v_c^* \) is the set \( V_{dc} \) voltage, \( v_{s \text{filter}}^* \) is the filtered signal, while \( K_{abs} \) is the absolute q-axis current gain. Besides \( i_{d}^* \) is fed to the d-axis current controller, it is also used to determine \( i_{q \text{max}} \) performing the current limiter as in (9).

2.4. Combined MTPA plus Flux-Weakening Control

In this method, the motor is controlled by combining the two previous methods. The block diagram of the system is shown in Figure 3.

![Figure 3. Block Diagram of MTPA with Flux-Weakening Control](image)

In this method, the MTPA controller is used to provide one of the references in the \( i_{s d}^* \), where the \( i_{s d}^* \) used is the one that has the lowest value followed by the PI gain. Field-weakening control is used as reference for \( i_{s q}^* \).

3. Experimental Results Of Control Methods

3.1. Experimental Settings

The proposed methods are simulated using MATLAB SIMULINK. Applied the algorithms for this system to an experimental system implemented by the embedded ‘C’ code. Parameters used are listed in Table 1.

| Parameter          | Symbol | Value  |
|--------------------|-------|--------|
| Number of pole pairs | \( P \) | 2      |
| Stator Resistance  | \( R_s \) | 2.76   |
| Parameter               | Symbol | Value |
|------------------------|--------|-------|
| Rotor Resistance       | \( R_r \) | 2.9   |
| Stator Inductance      | \( L_s \) | 0.2349 |
| Rotor Inductance       | \( L_r \) | 0.2349 |
| Mutual Inductance      | \( L_m \) | 0.2279 |

The value of the gain on the speed controller of each method is equalized, used \( K_i = 0.9 \) and \( K_p = 0.2 \) while for field-weakening is given a gain of \( K_p = 0.0009 \). Comparative simulations are conducted used 2 values \( \omega_r^* = 100 \) (955 rpm) and \( \omega_r^* = 300 \) (2865 rpm).

3.2. Method Comparison Results
The results of the MTPA, Field-weakening and combination of MTPA and Field-weakening method experiments are as shown sequentially in Figures 4-6.

![Figure 4](image1)

**Figure 4.** (a) MTPA in \( \omega_r^* = 954 \) rpm, (b) MTPA in \( \omega_r^* = 2865 \) rpm

![Figure 5](image2)

**Figure 5.** (a) Field-weakening in \( \omega_r^* = 954 \) rpm, (b) Field-weakening in \( \omega_r^* = 2865 \) rpm

![Figure 6](image3)
Figure 6. (a) MTPA with Field-weakening in $\omega_r^* = 954$ rpm, (b) MTPA with Field-weakening in a $\omega_r^* = 2865$ rpm

Comparison of three method results as shown in Figure 4(a), Figure 5(a), Figure 6(a) at $\omega_r^* = 955$ rpm, with a risetime of 233,809 ms. The MTPA method performs best among others. This is because the MTPA method reaches a value of 954 rpm with the minimum oscillation and the fastest settling-time in reaching its steady-state. The Field-weakening method with $T = 10$ still produced good graphics but not as fast as the MTPA method, which reaches 954 rpm with a risetime of 348.8 ms. While in the combination of MTPA method with Field-weakening with $T = 10$ the system still continues to oscillate and does not reach steady state.

Furthermore, as shown Figure 4(b), Figure 5(b), Figure 6(b) at $\omega_r^* = 2865$ rpm MTPA method seen in the system oscillates but can not reach the desired speed of about 2492 rpm with a risetime of 561,725 ms. The Field-weakening method with $T = 10$ has the best results, the system looks oscillating but already in the steady-state range. Field-weakening method can reach its steady state at 2864 rpm with the required risetime time of 497,851ms. While the MTPA combination method with Field-weakening has different response compared to the condition $\omega_r^* = 955$ rpm, at $\omega_r^* = 2865$ rpm, in the system there is a slight oscillation and achieved a steady-state condition but not reached the desired speed. In the combination method, the system reached 2421 rpm with a risetime of 330,989 ms.

Comparison of three method results confirmed that Field-weakening method with added $|i_q|$ has the best performance for high speed at $\omega_r^* = 2865$ rpm.

4. Conclusion
In all three methods proposed to be simulated on induction motor, it was obtained that the response of field-weakening method with the addition of $|i_q|$ have the best performance among the two other methods. The response of MTPA combination method with field-weakening does not produce better condition compared to field-weakening method with the addition of $|i_q|$. The addition of higher voltage can be done in the field-weakening method. Addition of $|i_q|$ can provide stimulation to the motor to increase the resulting flux thus affected the flux and torque of the induction motor.

Acknowledgement
The authors would like to thank all who always supported and all that involved in this research so that the Author can complete this research.

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