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Enhanced FS-PTC: Dynamic Weighting Factors for Optimal Flux and Torque Control

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Abstract: Recently, Finite State-Predictive Torque Control (FS-PTC) of induction motors has gained significant interest in high-performance motor drive applications. The effectiveness of FS-PTC relies on the successful minimization of a cost function achieved by selecting an appropriate voltage vector. Typically, the cost function for FS-PTC is composed of errors between the predicted and reference values of torque and flux; hence a weighting factor, $\boldsymbol{\lambda}$, is normally employed to establish different priorities between torque and flux. However, determining the optimal is a complex undertaking, since an incorrect or suboptimal choice can needlessly compromise torque or flux responses. This paper introduces an online tuning approach for the weighting factor, based on the dynamic change of flux error. Instead of using a fixed value, the weighting factor is dynamically adjusted using a simple Proportional (P) or Proportional Integral (PI) controller. The proposed method's performance is evaluated in this paper, considering various configurations of the controller's settings. Simulation results demonstrate that the proposed technique enhances the overall torque and flux ripples across a broad range of operating speeds, surpassing the performance of the fixed value weighting factor technique.

Keywords: flux weighting factor, flux ripple, induction motor (IM), predictive torque control (PTC), torque ripple

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1. INTRODUCTION

The control of induction motors (IM) presents a significant challenge in electrical engineering due to the complexity of the IM's dynamic model. However, this topic has attracted a great deal of attention from researchers due to the growing utilization of renewable energy and electric vehicles. Furthermore, advancements in microprocessors have provided researchers with an opportunity to develop more powerful control strategies.

In industrial applications, two main control strategies, namely Field Oriented Control (FOC) and Direct Torque Control (DTC), are extensively employed to control IMs [1]. FOC utilizes a linear control strategy, which involves the utilization of a linear controller to generate a reference voltage which is then implemented using a pulse width modulator (PWM). The objective of FOC is to precisely control the flux and torque by aligning the stator current with the rotor flux. By accurately manipulating the VVs applied to the motor, FOC achieves high-performance motor control with efficient torque production and reduced losses [2, 3]. However, the inner current loops require precise tuning to achieve optimal torque performance and flux control [4]. On the other hand, DTC utilizes a pre-determined switching table and two hysteresis controllers to identify the optimal VV selection for the IM [5]. Even so, the hysteresis characteristics may lead to fluctuating switching frequencies and significant torque ripples [6, 7].

Recently, numerous initiatives have been undertaken to find an alternative to FOC and DTC techniques. A new high-performance IM drive control method called Predictive Torque Control (PTC) has recently gained attention among researchers [8]. For power electronics converters with fixed switching states, a Finite state - Predictive Torque Control (FS-PTC) technique simplifies implementation and reduces execution time [9]. FS-PTC involves minimizing a cost function by selecting an optimal VV. The conventional cost function in FS-PTC focuses on minimizing torque and flux errors. A weighting factor (λ) is employed to assign priorities to torque and flux. The selection of λ affects the dynamic characteristics of torque and flux control. However, determining the optimal value for λ remains an unresolved issue until today.

One way to determine λ is to employ an empirical method using trial-and-error or branch-and-bound algorithms [10], which are time-consuming and heuristic. Several studies have proposed alternative approaches, such as using a nondominated sorting genetic algorithm (NSGA-II) [11]. In [12], a similar method is employed where λ is acquired through an iterative simulation procedure that is based on the multiobjective optimization approach of the Genetic Algorithm. However, these methods are dependent on operating points and system parameters, requiring repetitive design processes for any changes.

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To address this issue, several online tuning methods for λ have been reported in the literature. In online tuning methods, λ is updated for every sampling period to minimize the cost function, leading to an improved torque and flux responses. In [13], the weighting factor is calculated for every sampling period with the aim ofreducing the torque ripple. Researchers have also explored online tuning using multi-objective optimization strategies such as fuzzy decision-making (FDM)[14], VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR)[15], Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)[16, 17], and Artificial Neural Network (ANN)[18]. While these methods offer better solutions compared to offline methods, they are more complex, time-consuming, and expensive due to their computational requirements and training processes using offline simulations.

To overcome the tuning problem of the weighting factor, several researchers have proposed to completely eliminate the weighting factor. For example, one method introduced a lookup table with four vectors for cost function optimization [19], while another proposed a parallel predictive torque control approach that concurrently optimized flux and torque [20]. In another study, the results of the cost function for each parameter were ranked, and the vector with the highest rank was selected as the best solution [21]. Additionally, a different approach converted the flux and torque reference values into equivalent vectors [22]. Although weighting factor elimination methods simplify the reduction of flux and torque ripples, the computational burden increases with a higher number of switching states or prediction horizons.

Therefore, this paper proposed an enhanced FS-PTC with an online tuning method of λ, utilizing a Proportional (P) or Proportional-Integral (PI) controller. The proposed method is based on the analysis of the weighting factors patterns of the conventional FS-PTC. A low λ leads to significant flux errors at low speeds but improves at high speeds. Conversely, a high λ maintains flux regulation at low speeds but results in a high torque ripple at high speeds. To address this, a simple controller, either a Proportional (P) or Proportional Integral (PI) controller, adjusts the weighting factor based on flux error, ensuring that the actual flux tracks the reference flux at low speeds with small ripple.

2. THE DESIGN APPROACH

Finite state – Predictive Torque Control (FS-PTC) is a method based on a finite control set which simplifies the implementation in the IM drive. In FS-PTC, the number of acceptable switching states in the VSI is limited for torque and stator flux control. The algorithm uses a predefined cost function to determine the optimal switching state that minimizes torque and flux ripples.

2.1 The Modelling of Induction Motor (IM)

The IM can be described using space vector equations in a rotating reference frame with an arbitrary rotational speed. For this paper, a squirrel cage IM represented in the stationary reference frame is modelled using equations (1) to (4):

$$\boldsymbol{u}_s = R_s \boldsymbol{i}_s + \frac{d\psi_s}{dt} \tag{1}$$

$$0 = R_r \boldsymbol{i}_r + \frac{d\psi_r}{dt} + j\omega_r \psi_r \tag{2}$$

$$\boldsymbol{\psi}_s = L_s \boldsymbol{i}_s + L_m \boldsymbol{i}_r \tag{3}$$

$$\boldsymbol{\psi}_r = L_r \boldsymbol{i}_r + L_m \boldsymbol{i}_s \tag{4}$$

In these equations, $\boldsymbol{u}_s$ and $\boldsymbol{i}_s$ are the stator voltage and current space vectors, $\boldsymbol{i}_r$ is the rotor current space vector, $\boldsymbol{\psi}_s$ and $\boldsymbol{\psi}_r$ are the stator and rotor flux linkages space vectors. R_s and R_r are the stator and rotor resistances, L_s and L_r are the stator and rotor inductances, L_m is the mutual inductance and, ω_r is rotor speed.

Meanwhile, the electromagnetic torque, T_e can be expressed as in d-q axis (a scalar quantity):

$$T_e = \frac{3p}{4}\left[(\psi_{sd} i_{sq}) - (\psi_{sq} i_{sd})\right] \tag{5}$$

where p is the number of poles. All of these equations are used for the estimations and predictions of control parameters in PTC.

2.2 Three-phase Voltage Source Inverter (VSI)

This paper utilizes a two-level three-phase voltage source inverter (VSI) comprising six power IGBT switches. Generally, there are a total of eight possible switching states for the VSI, two of which are the zero voltage vectors (VVs). Equation (6) defines the stator voltage space vector ($\boldsymbol{V}_s$) based on these switching states. The variables S_A, S_B, and S_C represent the switching states of each leg of the three-phase VSI, which can either be 0 or 1, and V_{dc} denotes the input DC voltage of the VSI.

$$\boldsymbol{V}_s = \frac{2}{3}\left[V_{dc}(S_A + \boldsymbol{\alpha} S_B + \boldsymbol{\alpha}^2 S_C)\right] \tag{6}$$

where $\boldsymbol{a} = e^{j2\pi/3}$ and $\boldsymbol{a}^2 = e^{j4\pi/3}$

2.3 Finite State-Predictive Torque Control (FS-PTC)

It is well acknowledged that the conventional method of FS-PTC has suffered with the weighting factor problem. In order to address this challenge, this paper proposes the utilization of a P or PI controller to dynamically adjust the weighting factor. The details are elaborated in the subsequent sections.

2.3.1 Conventional Method

Figure 1 depicts the conventional FS-PTC control drive system. Generally, it involves three stages: estimation, prediction, and optimization.

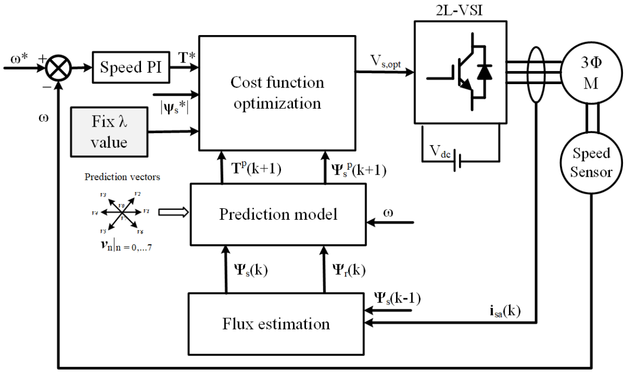


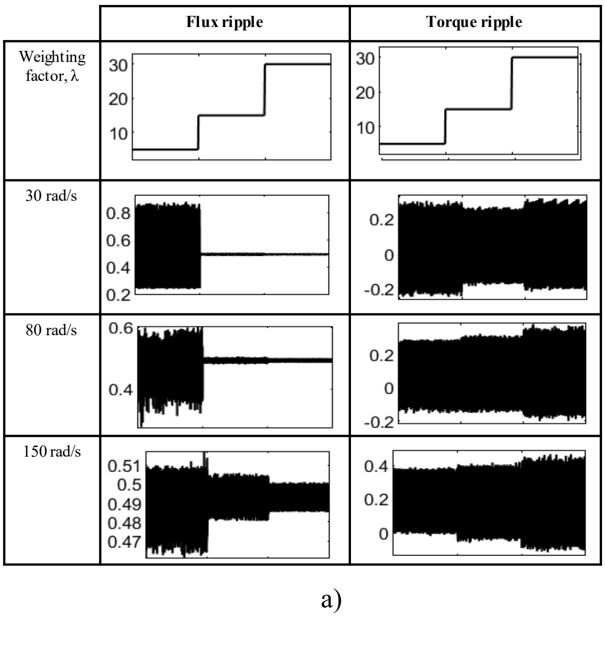
Figure 1: Conventional FS-PTC

During estimation, the flux linkages of the stator and rotor are determined. Using the estimated fluxes, the prediction stage forecasts the stator flux linkage and electromagnetic torque at the next sampling point. In the optimization stage, the predicted torque and stator flux are computed using all possible voltage vectors (VVs). However, only the VV that resulted in minimum cost function is chosen. The cost function, g, is typically defined as the errors between the predicted and reference values of torque and stator flux given by equation (7).

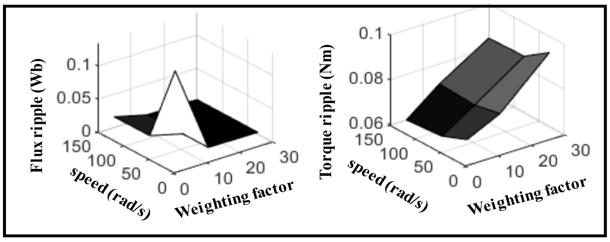
$$g = \left|T_e^* - T_e^p(k+1)\right| + \lambda\left|\psi_s^* - \psi_s^p(k+1)\right| \quad (7)$$

where T_e^* and ψ_s^* are the reference torque and reference stator flux

The weighting factor, λ determines the relative importance of torque and flux control. To study on how λ affects the performance of the drive, in terms of torque and flux ripple, a simulation of FC-PTC for the machine given in Table 1 was conducted. In the simulation, 3 values of λ is used (5, 15 and 30) at three different speeds (low speed: 30 rad/s, medium speed: 80 rad/s and full rated speed: 150 rad/s) and the torque and flux ripples are recorded. Figure 2 (a) and (b) summarize on the simulation results. The results indicate that prioritizing flux at low speeds and torque at high speeds is favorable.



a)



b)

Figure 2(a) and (b): Flux and Torque ripple based on various weighting factor

Table 1: Parameters and rating for IM

Induction motor parameters		
Rated power	P_{rated}	186 W
Rated speed	ω_{rated}	150rad/s
Rated Frequency	f_{rated}	50 Hz
Rated line voltage	$V_{rated, LL}$	190 V
Rated current	I_{rated}	1.4 A
Pole pairs	P	2
Stator resistance	R_s	9.9 Ω
Rotor resistance	R_r	8.15 Ω
Stator inductance	L_s	278.6 mH
Rotor inductance	L_r	285.3 mH
Mutual inductance	L_m	265.1 mH

When using a low weighting factor ($\lambda = 5$), the conventional method exhibits high flux ripple but the torque ripple remains tolerable. Conversely, with a high weighting factor ($\lambda = 30$), the method shows higher torque ripple with a small flux ripple. It can be observed that keeping flux ripple small can ensure acceptable torque ripple, but the opposite is not true. The simulation results also have demonstrated that it is possible to ensure minimal flux error and tolerable torque ripple by adjusting λ based on flux error (discrepancies between flux reference and estimated flux).

2.3.2 Proposed Method

The block diagram in Figure 3 illustrates the proposed enhanced FS-PTC drive system. Unlike the conventional method, a controller is used to adjust the flux weighting factor, λ based on the stator flux error. It must be noted that the controller's purpose is not to minimize the flux error to zero since the optimal VVs selected based on the minimum value of the cost function already handle the task of minimizing the flux error. The proposed method's step is depicted in Figure 4, where the shaded block represents the enhanced portion of the algorithm.

In contrast to using a fixed value of λ for conventional method, the controller takes on the responsibility of determining the suitable value of λ based on the flux error. This dynamic adjustment allows the drive system to adapt and optimize the performance of the algorithm continuously. The controller evaluates the current flux error and dynamically updates λ to ensure accurate flux tracking. By incorporating this enhanced approach, the proposed method able to improve the responsiveness and efficiency compared to using a fixed λ value.

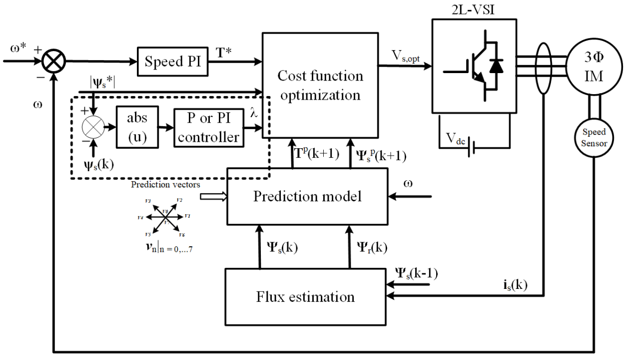


Figure 3: Proposed FS-PTC

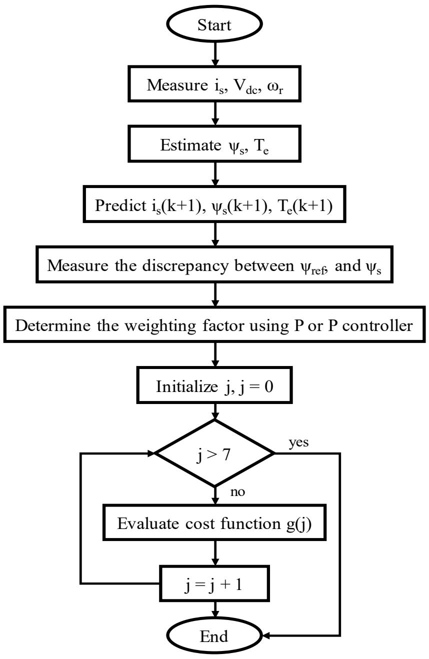


Figure 4: Flowchart of proposed method

To design the controller effectively, it is important to develop a linearized model of the system. However, this study primarily focuses on showcasing the applicability of a Proportional (P) or Proportional Integral (PI) controller to generate the λ. In this regard, various P-gain values, k_p (300, 3000, and 30000) are experimented with to determine the optimal k_p for the controller. Subsequently, with the best k_p value identified, the I-gain value, k_i is varied (10, 100, and 1000). Finally, the performance of FS-PTC drive using P controller versus PI controller is compared.

3. RESULTS AND ANALYSIS

In this work, simulations at different speeds (30rad/s, 80rad/s, and 150rad/s) using a P controller and PI controller to generate λ is conducted. The chosen parameters, such as the proportional gain (k_p) and integral gain (k_i), play a crucial role in determining the system's performance.

The simulation is based on the parameters and ratings of the IM presented in Table 1. To emulate the sampling time of the processor in actual implementation, the discrete sampling time for the controller in the simulation, T_s, is set to $40\mu s$.

The simulation is first conducted with only P controller. Figure 5 illustrates the dynamic weighting factors obtained from the simulations, which indicate how the weighting factor varies at different speeds. Additionally, Figure 6 and Figure 7, along with Figure 8, provide detailed insights into the torque and flux ripples observed in the proposed method using P controller.

The results in Figure 5 demonstrate that there is a direct relationship between the k_p and the weighting factor. When k_p is set to 300, the maximum weighting factor, λ_{max} recorded is 13.03. As k_p increases to 3000, the λ_{max} value increases to 37.34, and when k_p is set to 30000, the highest λ_{max} value of 272.40 is achieved. This observation indicates that as the value of k_p increases, the system places more emphasis on flux control, resulting in a reduction in flux ripple (Figure 8). However, a higher λ value also leads to an increase in torque ripple for IM.

Based on the simulation results, it is found that the best performance is obtained when k_p is set to 3000; a balance between minimizing both flux and torque ripples is achieved. With this value of k_p = 3000, the IM achieves relatively low ripples in torque and flux compared to the other k_p values.

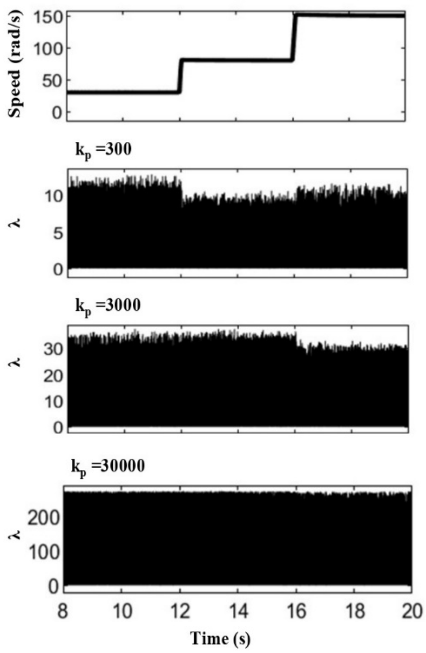


Figure 5: Simulation results of weighting factor under various speed conditions with P controller

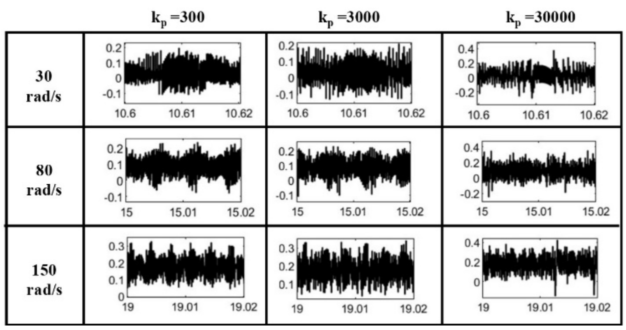


Figure 6: Torque performance under various speed conditions with P controller

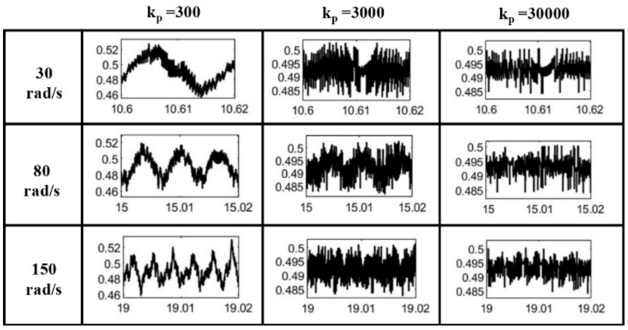


Figure 7: Flux performance under various speed conditions with P controller

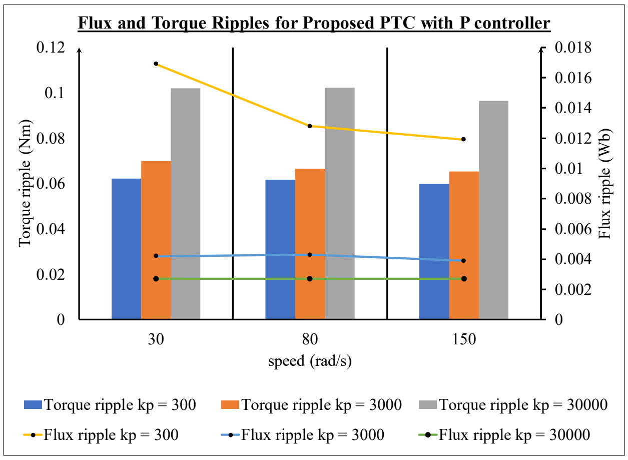


Figure 8: Simulation results of torque and flux ripples under various speed conditions with P controller

Subsequently, the simulations were performed with a PI controller, utilizing the value k_p =3000 and varying the integral gain (k_i) between 10, 100, and 1000. The simulation results, as shown in Figure 9, highlight the torque and flux ripples achieved under different k_i values.

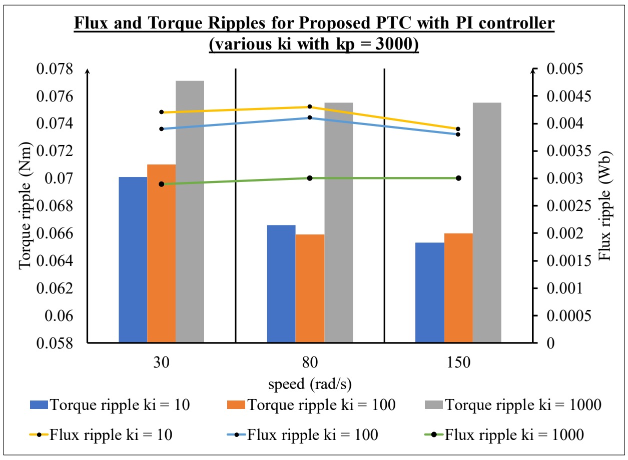


Figure 9: Simulation results of torque and flux ripples under various speed conditions with PI controller

Interestingly, the results obtained for both P and PI controllers show minor differences in terms of torque and flux ripples. This finding suggests that a P controller can successfully be used with the proposed FS-PTC drive system to tune the λ, which produces torque and flux ripples within acceptable values.

In short, the research findings offer significant insights regarding the relationship between parameter selection and the performance of the proposed method. The study emphasizes the crucial role of choosing suitable values for the k_p and highlights that satisfactory results in minimizing flux and torque ripples can be achieved without necessarily employing a PI controller. These insights contribute to a better understanding of optimizing the proposed method and can guide future applications and implementations in IM drive systems.

4. CONCLUSION

This paper introduces a new method for adjusting the weighting factor in a Finite State-Predictive Torque Control (FS-PTC) for IM drive. The proposed method employs a simple controller to determine the appropriate weighting factor, λ. Based on the analysis conducted on the conventional FS-PTC, it is possible to achieve dynamic adjustment of the weighting factor by utilizing a Proportional (P) or Proportional-Integral (PI) controller, depending on the flux error. It is found out that with a proportional gain (k_p) of 3000, acceptable flux and torque ripples across all speed conditions is achieved. Notably, the use of a PI controller did not significantly impact the performance of torque or flux, indicating that a P controller is sufficient for the proposed method

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