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New High Speed PMSM Flux-Weakening Strategy

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Abstract— High speed permanent magnet synchronous motor (PMSM) are increasingly used in the field of electric traction due to their high mass and power density. Usually the motor is piloted by a vector control associated with a flux-weakening algorithm which regulates the voltage norm. If the critical point is located within the current limit then it is discerning at very high speed to drive the motor with a Maximum Torque Per Volt (MTPV) strategy. In this article we propose to achieve a unified control algorithm to drive the motor theoretically whatever its speed by giving a torque closest to the desired torque while respecting the current and voltage limits and minimizing the current used. Consequently at high speed at full flux-weakening MTPV strategy is applied which comes to modify the saturation of the current reference magnitude given by the torque reference associated with flux weakening strategy. It enables us to have no switch of algorithms, nor look-up-tables (LUT) which are realized by experiments and depend on the motor, and to not add additional observers or regulators, while being precise and more robust to parameter variation than a direct calculation algorithm. The performance of this method is analyzed through a simulation.

Keywords—Flux weakening, MTPV, vector control, high speed permanent magnet synchronous motor.

I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are commonly used in the field of the electrical traction for their high mass power and volume power. Electric cars' motor are characterized by a high starting torque and a wide speed range at constant power. The volume and the weight of a PMSM are directly proportional to the maximum torque of the machine. Thus with a concern of autonomy and congestion we choose a lower torque at start motor but that can turn at much higher speed while maintaining the same power. We retrieve characteristic required for the car by adjusting the motor output gear. So the high speed PMSM has a better power density and mass density and so we use this motor.

Usually the control of a PMSM can be summarized in three major blocs shown in Fig. 1 where ω_{ref} is the reference speed, I_{dref} and I_{qref} are the current references in the d-q frame, V_{dref} and V_{qref} the voltages references in the q-d frame and u the PWM control with the indexes a, b, c for the three phases and h for the IGBT high and l for the IGBT low This study focuses on improving the calculation of the current references (bloc 1, Fig 1). The calculation of voltage references from current references (bloc 2, Fig1) is performed by vector current control

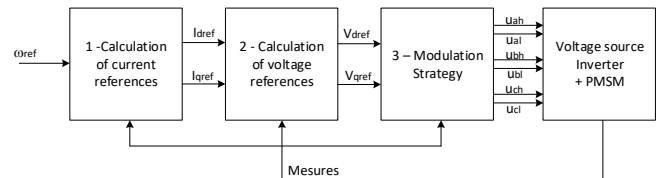


Fig. 1. General scheme of a PMSM control.

in d-q frame. Two polynomial regulators with discrete decoupling are used. Current variation and electrical angle variation between the moment of their measures and the moment of the application of the new voltage vector by the inverter in medium on the switching period, is also taken into account [1].

By Lenz's law, high speed involves a large electromotive force (EMF). From a certain speed that EMF exceeds a maximum voltage related to the maximum voltage that can provide the battery and the pulse width modulation (PWM). To keep increasing the speed and generating torque it is required to release a part of the voltage by flux-weakening, i.e. by adding negative current I_d to generate a flux which opposes the one of the magnet and thereby decreasing the rotor flux perceived by the stator.

Several flux-weakening strategies are exposed in the literature [2 to 23]. [2,3,4] present states of the art of flux-weakening techniques. We suggest to classify these techniques as follows: analytical direct calculation method [5,6], direct open loop algorithm with experimental LUT [7,8,9,10], Single Current Regulator (SCR) method [11,12,13,3], torque and flux control (TFC) method with LUT [14,15], Unified Direct Flux Vector Control (UDFVC) in the stator flux frame [16,17], and Vector Current Control (VCC) [14, 18 to 24]. This last method is divided into: regulation on the voltage magnitude [18,19,20,21,14], regulation on the voltage error [14,22,3], regulation on the current error [14,23], regulation on the cyclic ratio [14,24]. By taking these different methods the following remarks can be made. Open loop direct calculation from the machine equations is very sensitive to parameter variations. The use of open loop control with LUT or closed loop with TFC enables in particular to easily take into account the magnetic saturation effect, but these approaches are dependent on the motor and requires to carry on a set of experiments. The SCR method avoids the conflict between the two regulators of the d-axis and q-axis when the voltage operates in voltage

saturation. However when operating at PMSM low speed this method requires switching on another algorithm for example a Maximum Torque Per Ampere (MTPA) strategy. The UDFVC is an algorithm compatible for all alternative current machines but requires a flux observer and requires to find experimentally the maximum load torque making it dependent on the motor. VCC is the most conventional approach. However in the current error regulation the low pass filter (LPF) affects the dynamics of the regulation. The regulations of voltage error and cyclic ratios use the over modulation which increases the maximum voltage available at the expense of additional current harmonics and also uses a LPF that affects the dynamic performances. Finally regulating the voltage norm is the usual strategy that requests to set a voltage limit allowing or not to over modulate. We choose this VCC approach with regulation on the voltage norm for flux-weakening. However, if the critical point, i.e. the current I_d for total flux-weakening, is located inside the current limit circle then this strategy is not enough to drive the motor at very high speed. This requires using a deep-flux-weakening strategy.

The literature offers some methods for deep-flux-weakening [3 to 6, 11 to 13, 16 and 25 to 29]. Analytical direct open loop calculation method [6,25,26], direct open loop experimental LUT [27,3,4,5,6], SCR method [11,12,13] and UDFVC [16] enables to do deep-flux-weakening but all with the same limitations as set out above. The use of a VCC strategy associated with a maximum torque per volt (MTPV) strategy is proposed [28,29] but uses an algorithm switching. In this article we suggest to use a voltage norm regulation associated with a MTPV strategy in one unified regulator scheme for flux-weakening.

First the principle of flux-weakening will be presented with current references that theatrically achieve maximum torque with a minimum current while respecting the current and voltage limits regardless of the speed. Secondly our deep-flux-weakening strategy will be explained. The current saturation is modified by the MTPV strategy. Finally the efficiency of the method is analyzed trough a simulation.

II. FLUX WEAKNEING PRINCIPLE

The equations of the electrical model of the PMSM are described in (1), (2) and (3).

$$V_d = R.I_d + L_d \frac{dI_d}{dt} - \omega.L_q.I_q \quad (1)$$

$$V_q = R.I_q + L_q \frac{dI_q}{dt} + \omega.L_q.I_q + \omega.\phi_f \quad (2)$$

$$T = \frac{3}{2}.p.\phi_f.I_q + (L_d - L_q)I_d I_q \quad (3)$$

Where V_d , V_q and I_d , I_q are respectively the voltage and currents in the d-q frame, L_d and L_q the d-axis and q-axis armature winding inductances, ω the electrical rotation speedy, R the resistance of the armature winding, ϕ_f the flux linkage of the permanent magnet, T the electromagnetic torque.

There are two electrical limits: a current and a voltage limit. The current limit (4) is related to the motor's cooling capacity.

$$\sqrt{I_d^2 + I_q^2} \leq I_{\max} \quad (4)$$

where I_{\max} is the maximum current.

The voltage limit (5) is related to the maximum voltage of the battery and the selected PWM strategy.

$$\sqrt{V_d^2 + V_q^2} \leq V_{\max} \quad (5)$$

$$V_{\max} = \frac{V_{DC}}{\sqrt{3}} \quad (6)$$

V_{DC} is the maximum voltage of the battery and the selected PWM strategy is space vector modulation (SVM) of inverter.

Usually the resistance R is negligible at high speed operation and the derivate of the currents is zero in steady state, thus (7) is obtained.

$$\sqrt{(\omega L_q I_q)^2 + (\omega L_d I_d + \omega \phi_f)^2} \leq V_{\max} \quad (7)$$

The voltage and current limits in the I_d - I_q frame are shown on Fig. 2. The current limit (4) is a circle centered on the origin of the frame and of radius the norm of the maximum current. The current limit is an ellipse (7) centered on the critical point $(-\phi_f/L_d, 0)$ and whose size decreases with the increase of the speed. On Fig. 2 it is also represented the path traveled by the current references during de ramp-up of the speed in order to minimize the torque error from the desired torque, minimizing the norm of the current used and respecting the current and voltage limits.

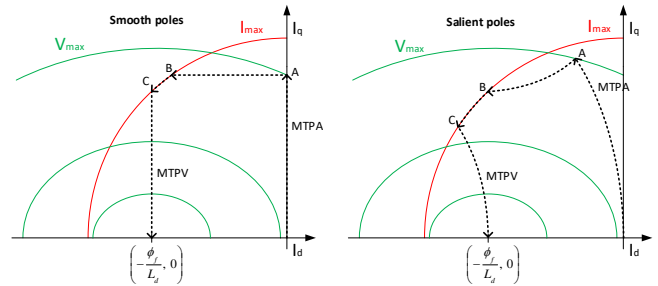


Fig. 2. Representation in the (I_d, I_q) frame of the current limit (red), the voltage limit (green) and the path traveled by the current reference when the speed increases (arrow dashed). Example of a non-salient poles PMSM on the left, and a salient poles PMSM on the right.

At low speed the current references are within the current and voltage limits. For a given required torque, that point ("A" on Fig. 2) of current references is located on the MTPA trajectory. This MTPA trajectory can be calculated by (8) in steady state that gives (9) and (10).

$$\frac{dC}{dI_d} = 0 \quad (8)$$

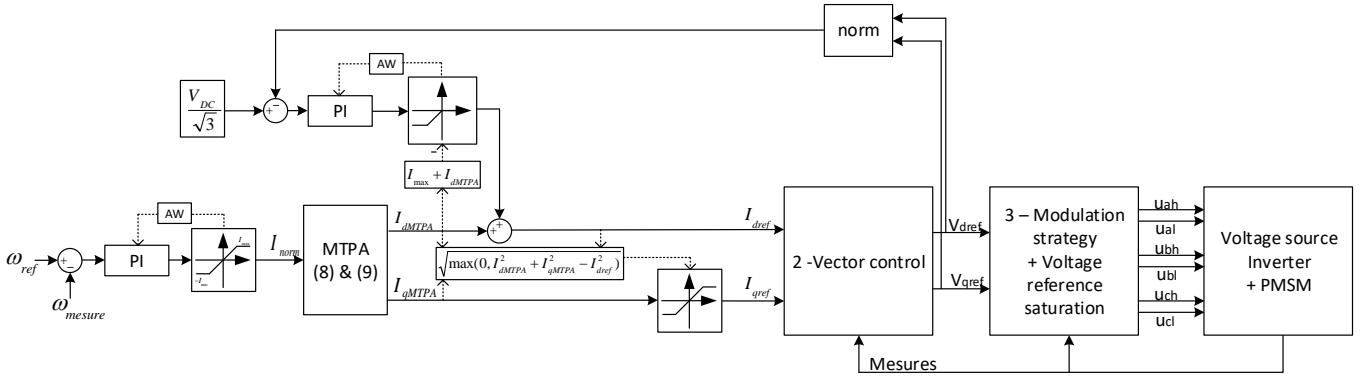


Fig.3. Scheme of the PMSM control with calculation of the current references by the VCC flux-weakening methode with voltage norm regulation. Where AW is an anti-windup structure.

$$I_d = \frac{\phi_f - \sqrt{\phi_f^2 + 8(L_q - L_d)^2 I_{norm}^2}}{4(L_q - L_d)} \quad (9)$$

$$I_q = \text{sign}(I_{norm}) \sqrt{I_{norm}^2 - I_d^2} \quad (10)$$

Note: for a non-salient poles PMSM the MTPA references become (11) and (12).

$$I_d = 0 \quad (11)$$

$$I_q = I_{norm} \quad (12)$$

As rotation speed increases the voltage saturation (7) tends to the critical point. From a certain speed the EMF becomes too large compared to the voltage V_{max} and it is necessary to add negative current I_d to respect the voltage limit at high speed. The trajectory of the current references goes on Fig. 2 from point "A" to "B". It's the flux-weakening: a flux is created which is opposed to the rotor magnet flux and reduces the rotor flux perceived by the stator. To maintain the torque to the reference torque the I_q reference is modified following (3). It is noticed that for a smooth poles machine I_q remains constant in this area.

When increasing the current norm the current limit is reached (point "B" on Fig. 2). From there it is necessary to reduce the current I_q to continue to add negative current I_d for flux-weakening (4). The current reference is thus the intersection between the current limit and voltage limit. If the critical point is outside the current saturation then the speed is electrically limited when the intersection between the current limit and the voltage limit no longer exists and the torque is zero. If the critical point is within the current saturation then it is possible to do a total flux-weakening of the magnet. This deep-flux-weakening makes that the whole voltage is used to generate the torque and it is preferable to move on a maximum torque per volt (MTPV) strategy from point "C" on Fig. 2 to the critical point. The MTPV trajectory can be calculated with (13) in steady state that gives (14) and (15).

$$\frac{dC}{dV_d} = 0 \quad (13)$$

$$I_d = \frac{\left(\frac{V_q}{\omega} - \phi_f \right)}{L_d} \quad (14)$$

$$I_q = -\frac{I_d}{L_q \omega} \quad (15)$$

Where:

$$V_q = \frac{\phi_f - \sqrt{\phi_f^2 + V_{max}^2 \left(\frac{L_d - L_q}{L_q \omega} \right)^2}}{-4 \left(\frac{L_d - L_q}{L_q \omega} \right)} \quad (16)$$

$$V_d = -\sqrt{V_{max}^2 - V_q^2} \quad (17)$$

Note: for a non-salient poles PMSM the MTPV references become (18) and (19).

$$I_d = \frac{-\phi_f}{L_d} \quad (18)$$

$$I_q = \frac{V_{max}}{L_q \omega} \quad (19)$$

In the case where the critical point is located within the current limit, at very high speed current saturation has no more real impact and the torque is limited by the voltage saturation. From an electrical point of view is theoretically possible to drive the motor when the speed tends towards infinity, the current reference tends to the critical point.

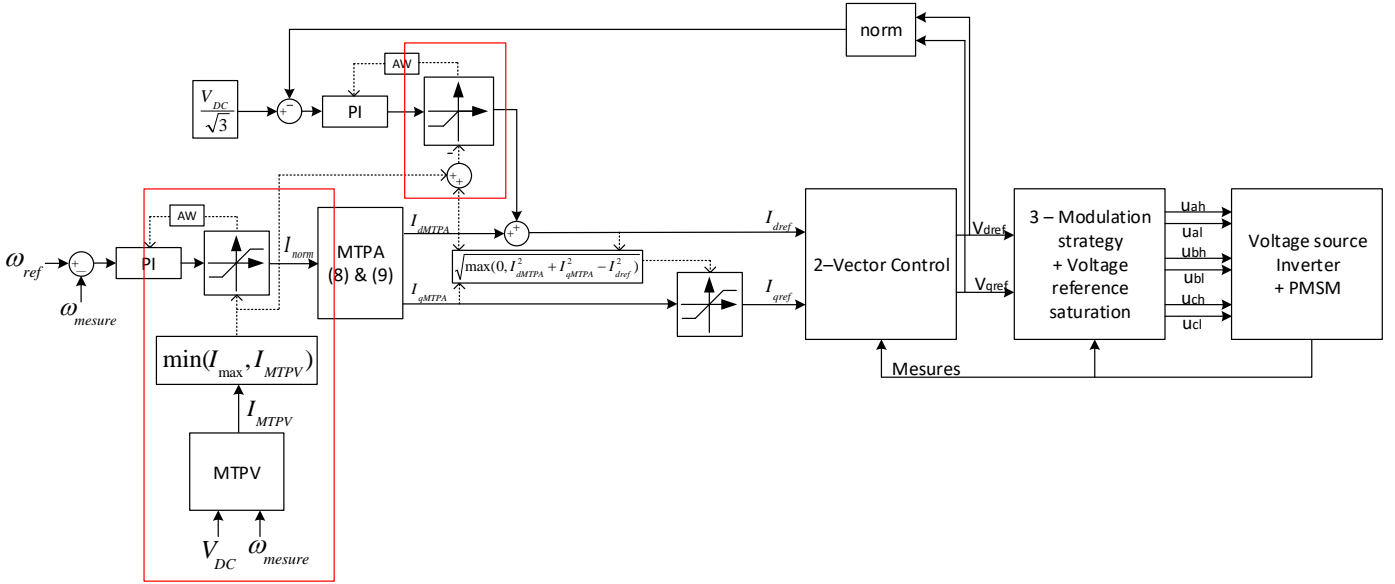


Fig.4. Scheme of the PMSM control with calculation of the current references by the VCC flux-weakening method with voltage norm regulation and with variable current norm limit saturation with consideration of the MTPV trajectory. The two red frame show what is modified from classical flux-weakening Fig. 3.

III. DEEP FLUX WEAKENING WITH MTPV CURRENT LIMITATION

This part presents a method to generate the current references following the path described in §II because it can get the nearest torque to the reference torque while minimizing the current norm and with respect to the current limit and the voltage limit.

This article's introduction presents a brief state of the art of flux weakening techniques. The voltage norm regulation is conventionally used and is shown schematically on Fig. 3. This Fig. 3 resumes Fig. 1 detailing the bloc 1. The blocs 2 and 3 are the same as for FIG. 1 i.e. a vector control followed by SVM.

At low speed this control strategy follows the MTPA trajectory (9) and (10). When the voltage saturation is reached the regulation on the voltage norm generates a negative current I_d for flux-weakening. If the added current I_d is lower than the total current norm initially required by the speed regulation then the control decreases the I_q reference current with a variable saturation in order to maintain the current norm initially required by the speed regulation. Otherwise the I_d reference current is fixed at zero and all the I_d reference current required by the flux-weakening is applied with respect to the current limit. The speed control will increase the current norm if it's necessary to generate torque. So when the current limit is reached the torque drops and the current reference is the intersection between the current limit and the voltage limit until there is no more torque. However this algorithm limits the upshifting of the speed if the critical point is located within the current limit. In that case it is necessary to switch on a MTPV strategy as described in §II.

To avoid switching between algorithms problems between a flux-weakening algorithm and a MTPV algorithm we propose to replace the current saturations located after the

speed regulation and after the voltage norm regulation Fig. 3 by variable saturations which depend on the MTPV strategy

Fig. 4. The current norm is saturation to the minimum value between the fixed current norm limit related to the electrical losses and the maximum current norm required by the MTPV strategy (14) and (15). The MTPV trajectory corresponds now to the intersection between the voltage limit and the new virtual current limit, which previous flux-weakening algorithm can follow. Thus in the case where the critical point is within the current saturation this new flux-weakening method can generate the current references regardless of the speed, and otherwise to the maximum speed, in order to be nearest to the asked torque, while minimizing the current norm used and respecting the current limit and voltage limit.

IV. SIMULATION RESULTS

Simulations results permit to validate the effectiveness of the method. Table 1 gives are the parameters of a salient poles PMSM used for the simulations. The voltage of the battery is 200V and the current limit at 8A. On Fig. 5 is plotted in blue circles the desired current reference trajectory in the I_d - I_q frame, explained in §II, which the current references follow when the speed increases. This trajectory is calculated using

TABLE I. SIMULATION IPMSM PARAMETERS

Simulation Motor Parameters	
L_d	5,77 mH
L_q	8,08 mH
R	0,97 Ω
Φ	$3,45 \cdot 10^{-2}$ Wb
P, number of pair of poles	5
Power	1,4 kW

(3), (4) and (7). On Fig. 5 is shown in red triangles in the I_d - I_q frame the current trajectory obtained by the classic flux-weakening strategy (Fig. 3 algorithm). It is observed that from 7krpm the current are not satisfying because they continue to follow the trajectory of the current limit rather than switching on the MTPV trajectory.

Fig. 6 shows the desired current reference trajectory (plotted in blue) and calculated analytically in the I_d - I_q frame. The current reference trajectory (plotted in red) obtained with the new flux-weakening strategy with modification of the current saturation by MTPV (Fig. 4 algorithm) is shown on the same Fig. 6. It is observed that the two paths coincide which

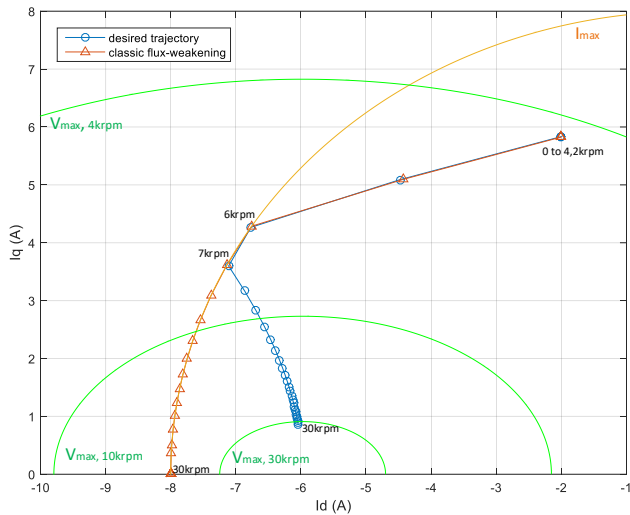


Fig.5. In the I_d - I_q frame. In green the voltage limit for the following speeds 4krpm, 10krpm and 30krpm. In orange the current limit. In blue circles the desired current reference trajectory analytically calculated. In red triangles the current reference trajectory obtained with the classical flux-weakening.

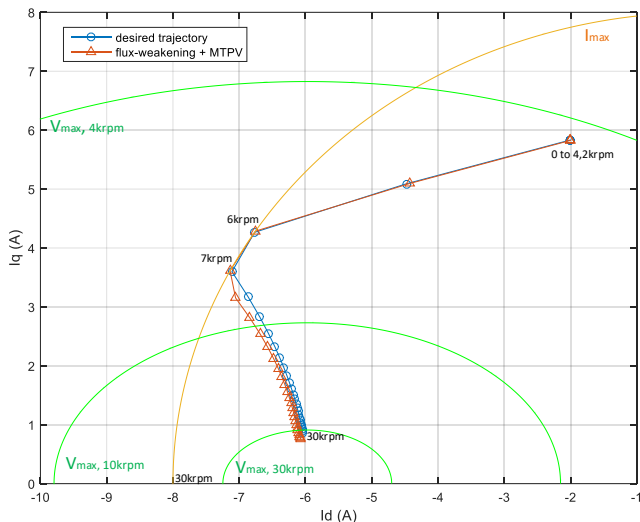


Fig.6. In the I_d - I_q frame. In green the voltage limit for the following speeds 4krpm, 10krpm and 30krpm. In orange the current limit. In blue circles the desired current reference trajectory analytically calculated. In red triangles the current reference trajectory obtained with the new flux-weakening method with modification of the current saturation by MTPV.

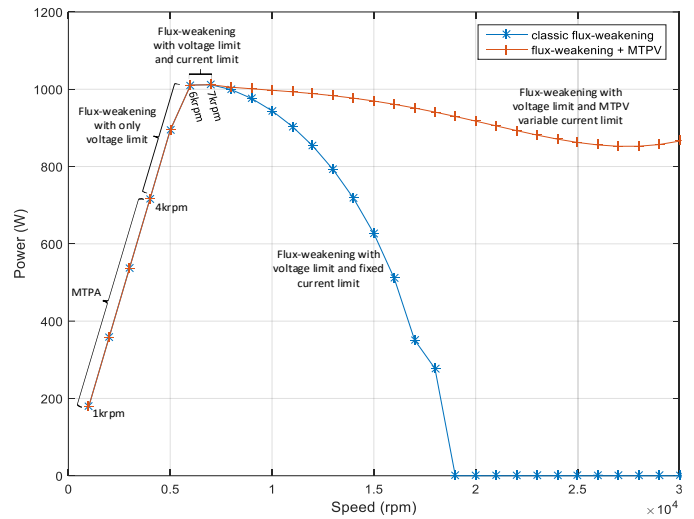


Fig.7. Power transmitted depending on the speed for the classic flux weakening strategy (blue stars) and for the flux-weakening with MTPV at high speed (red crosses).

validates the focus of our algorithm. So the very high speed PMSM drive with one unified algorithm is validated by simulation.

Fig. 7 shows the power transmitted between the common flux-weakening algorithm and the one with the variable current saturation with MTPV. It is observed that at high speed using the MTPV strategy can significantly increase the power transmitted. From 19krpm, for the classic flux-weakening, all the current is used for flux-weakening and the torque is zero. Above that speed the classic algorithm does not give current references respecting the voltage limit (7). At high speed MTPV strategy is a preferable solution.

V. CONCLUSION

This paper presents an algorithm to control a high speed PMSM whatever its speed if electrical limits allow it. It does not require prior experimental results as for the LUT strategy or switching between algorithms that could destabilize the system. The trajectory traveled by the current references when the speed increases enabling to obtain the closest torque to desired torque while minimizing the current magnitude and respecting de current limit and voltage limit is also presented. At high speed if the critical point is within de current limit then it is necessary to use a MTPV strategy to maximize the torque generated. To follow this trajectory a control algorithm is realized that is based on a classic flux-weakening strategy, with regulation of the voltage reference norm, which the current limit is modified by the current required by the MTPV strategy at high speed. The MTPV strategy is applied through a direct calculation so one can improve at high speed it's robustness against parameter variation. Finally the performance of this method is observed through simulation results.

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