

Flux-Weakening Control for Permanent Magnet Synchronous Motors: A Systematic Review of Challenges, Fundamentals, and Strategies

Wei Leng*

School of Mechanical and Automation Engineering, Zhixing College of Hubei University, Wuhan, 430000, China

Abstract. A permanent magnet synchronous motor (PMSM) is widely used in different scenarios such as electric vehicles, rail transit systems and so forth, due to its distinct advantages including high power density, high efficiency and high reliability, especially its wide speed range. However, as its rotational speed increases until it reaches the base speed, it will be constrained by the increasing back electromotive force (EMF) and the inverter's voltage limit. To address this bottleneck, the flux-weakening control (FWC, i.e. weak magnetic control) technology is developed to weaken the air-gap magnetic field by regulation of the d-axis current. This article provides a systematic review of FWC issues, including the main challenges faced by FWC, the basic principle of FWC, the classic FWC strategies and the innovative FWC strategies. Finally, this article summarizes and compares characteristics and the applications of different FWC strategies mentioned in the references, in order to provide the reference for the further research and the development of FWC technology.

1 Introduction

A PMSM plays a core role as the propulsion system in different scenarios including rail transit systems [1], electric vehicles [2], CNC machine tools [3], ship electric propulsion systems [4], etc. This is because the PMSM is known for its excellent features such as high power density, high starting torque, high efficiency and high reliability. Nevertheless, the back EMF will be induced in stator windings when the PMSM operates, and it is proportional to the motor's rotational speed. As the rotational speed increases, the back EMF continues to rise. When the back EMF approaches or reaches the upper limit of the voltage that the inverter can supply, the stator cannot establish enough effective current to generate torque, impeding the speed enhancement.

To solve the aforementioned problem, the FWC technology is initiated. This technology enables PMSM to break through the base speed limit, achieving a wide constant power operation region and greatly expanding its speed regulation range.

Challenges occur with the evolution of FWC, some main of which will be discussed in the following text, including parameter robustness, stability in deep flux-weakening regions,

* Corresponding author: bobleng2015@sina.com

smooth multi-region switching, etc. Before the introduction to FWC strategies, the basic principle and mathematical models of FWC will be explained and illustrated in this article. Furthermore, according to FWC's evolution, some of classic FWC strategies will be firstly introduced such as the voltage feedback/leading angle method and the formula/feed-forward method; and some of innovative FWC strategies will be given special attention, including the model predictive control method, the passive observer-based control method and the intelligent and adaptive control method. Finally, the comparison and the summary of some FWC strategies in the references will be conducted for the future research and the development.

2 Challenges faced by flux-weakening control

Air-gap magnetic field of PMSMs is weakened by regulation of i_d to achieve PMSMs' wide speed range within the inverter's limited voltage capacity. Nevertheless, with the expansion of speed regulation, a series of challenges are faced by the FWC technology. This section will introduce some of these challenges.

2.1 Parameter robustness

The FWC highly depends on the PMSM's mathematical model, of which parameters such as d-axis inductance L_d , q-axis inductance L_q and permanent magnet (PM) flux linkage ψ_f determine the FWC's performance. However, these parameters cannot keep constant during the PMSM's operation. Specifically, the high temperature may cause the PM flux attenuation [1], leading to the parameter fluctuations. This results in the inaccuracy of FWC. So enhancing the robustness of algorithms to parameter fluctuations is one of the main FWC challenges.

2.2 Dynamic stability in the deep flux-weakening region

As the PMSM operates in the deep flux-weakening region (i.e., MTPV curve), i_d changes little while i_q changes significantly. At this phase, the large i_q loop gain is easy to cause the current and the output electromagnetic torque ripple, resulting in the voltage command of the motor control system to deviate from the output voltage of the inverter, and there will be a large current error [3]. It is a key FWC bottleneck to maintain the dynamic stability of the deep flux-weakening region.

2.3 Harmonic errors

In order to improve the utilization rate of the bus voltage of the system, the over-modulation control is utilized in FWC. The collaboration of these two technologies can enhance the inverter's voltage limit and further expand the motor's running speed, but may cause large harmonic errors between the reference voltage and the actual voltage flowing into the motor. This will lead to errors in current reference and reduce the efficiency of the inverter and motor by using larger current [4]. So it is another critical FWC challenge to balance the bus voltage utilization and the reduction of harmonic errors.

2.4 Smooth switching between multiple operating regions

According to the FWC's basic principle which will be introduced subsequently, the PMSM passes through the MTPA region, the weak magnetic region I and II during its operation. It

is a significant performance indicator to realize the smooth switching between these regions. Due to the difference between control objectives and algorithms in different regions, improper switching algorithm design may cause problems such as torque or current fluctuations, doing harm to the PMSM's operational stability and smoothness [5].

3 Basic principle of flux-weakening control

FWC strategies derive from the analysis of PMSM mathematical models, of which the key points are to understand and utilize two significant geometrical constraints in the d-q plane, i.e. voltage limit ellipse and current limit circle. As is shown in Fig. 1.

3.1 Negative d-axis current-key element of weakening the magnetic field

In the d-q coordinate system, the stator current splits into two parts: the d-axis current (i_d) which is used to regulate the magnetic field, and the q-axis current (i_q) which is used to generate torque. On the basis of keeping a constant terminal voltage, a negative d-axis current component in the stator is generated to weaken the magnetic field of PMs (i.e., flux weakening), effectively reducing the back EMF and releasing the space for the speed increase within the inverter's voltage limit.

3.2 Voltage & current limits in the d-q plane

The voltage limit ellipse and the current limit circle are illustrated in Fig. 1. On the d-q plane, the operating point of the motor has to simultaneously meet both of these constraints.

Voltage limit ellipse. This ellipse represents the voltage constraint boundary of the stator current vector (i_d/i_q) at a given speed. As the rotational speed increases, the voltage limit ellipse will shrink towards the center, meaning that the available voltage space decreases. Equation (1) is the voltage limit equation.

$$u_d^2 + u_q^2 \leq u_{max}^2 \quad (1)$$

where u_{max} represents the maximum voltage provided by the inverter. The voltage limit ellipse can be symbolized by Equation (2):

$$(L_d i_d + \psi_f)^2 + (L_q i_q)^2 \leq (u_{max}/\omega_e)^2 \quad (2)$$

where L_d and L_q represent the d-axis and the q-axis inductor respectively; i_d and i_q represent the d-axis and the q-axis current respectively; ψ_f represents the rotor's permanent magnetic flux; ω_e represents the angular velocity of the motor.

Current limit circle. This circle is represented by Equation (3), in which the current vector has to lie inside this circle.

$$i_d^2 + i_q^2 \leq i_{max}^2 \quad (3)$$

where i_{max} represents the maximum current that the inverter can withstand.

3.3 Regions of operation

According to the operation status of the motor, FWC can be divided into three main regions that are constant torque region, weak magnetic region I & II.

Constant torque region (MTPA region). Below the base speed, the motor operates on the maximum torque to current ratio (MTPA) trajectory (i.e., from O to A , the constant torque region). At this phase, the current vector runs along the path that maximizes the torque-to-current ratio, usually aligning or approaching the q-axis.

Weak magnetic region I. When the speed exceeds the base speed, the voltage limit ellipse shrinks and the motor steps into the flux-weakening (i.e. weak magnetic) region. To keep acceleration, a negative i_d shall be introduced to weaken the magnetic field. At this phase, the current vector moves along the boundary of the current limit circle to remain within the voltage limit ellipse (i.e. from A to B , the constant power region).

Weak magnetic region II (MTPV/deep flux-weakening region). This region exists on the condition that $\psi_f/L < i_{smax}$. When the speed further increases and the voltage limit ellipse shrinks to its center inside the current limit circle, proceeding along the perimeter of the current circle becomes infeasible. At this phase, the optimal trajectory of the current vector will leave the current circle and move along the boundary of the voltage ellipse, which is called the maximum torque to voltage ratio (MTPV) trajectory (i.e. from B to C). This is the deep flux-weakening region and needs rigorous control to prohibit excessive flux attenuation. Furthermore, the stator current is only constrained by the voltage limit ellipse in this region.

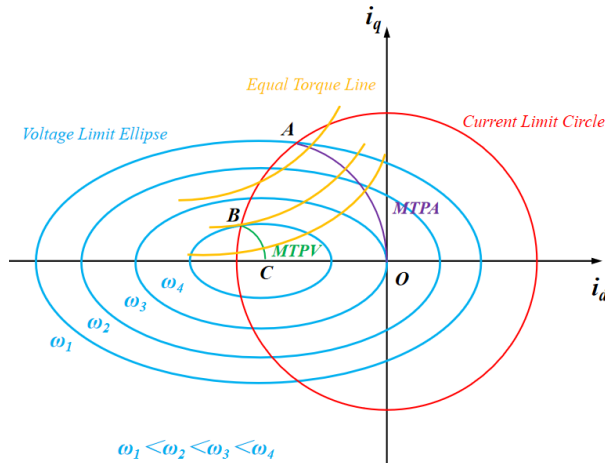


Fig. 1. Weak magnetic regions of PMSM.

4 Classic flux-weakening control strategies

Recently, classic FWC strategies can be broadly categorized into four types: feed-forward control, feedback control, lookup table methods, and stator current leading angle control. Various advanced FWC methods developed subsequently are all derived from these classic strategies [6-9]. This section will review some of the main classic FWC strategies according to theoretical foundations and specific application methods.

4.1 Voltage feedback / leading angle control method

This method is to dynamically regulate d-axis current or the leading angle γ using PI controllers via examining and determining whether or not the stator voltage reaches its limit. The basic forms are displayed below:

Directly regulate the leading angle γ to indirectly allocate i_d and i_q [5];
 $i_d=0 \rightarrow$ MTPA \rightarrow PI control $\rightarrow i_d$ offset [10].

Gao et al. [5] propose an FWC strategy for the PMSM with dynamically adjusting the leading angle γ via voltage feedback to achieve FWC. The leading angle γ is defined as the electrical angle by which the current vector leads the q-axis. The mathematical expression is shown in Equation (4). They develop a multi-closed-loop control system comprising a rotational speed loop, a voltage loop and two current loops, assisted by the current-feedback decoupling technology. Voltage-loop PI controllers saturate forward below the base speed with $\gamma=0$; and desaturate above the base speed with $-\pi/2 \leq \gamma < 0$ with the motor stepping into the constant-power high-speed weak magnetic region. Furthermore, the decoupling technology is utilized to reduce the nonlinear coupling in the d-q axis that degrades the system's dynamic performance, achieving the independent control and the accurate regulation of flux linkage and torque. By validation of MATLAB/Simulink, the speed increases to 14000rpm in 0.5s and 18000rpm in 1s, much higher than the initial target of 8000rpm. In addition, the smooth switching from the constant torque region to the weak magnetic region is realized, making the PMSM operate above the base speed for long and effectively expands the speed range.

$$\gamma = \arctan\left(\frac{i_d}{i_q}\right) \quad (4)$$

Yuan et al. [10] systematically realize the real-time dynamic switching between MTPA and the leading angle weak magnetic control verified by MATLAB/Simulink simulations. They also develop a mobile APP interface to real-timely view the motor's parameters and regulate control parameters in distance, broadening the dimension of human-machine interaction of control algorithms. Furthermore, they design and compare three control strategies called $i_d=0$ control, MTPA control and weak magnetic control (WMC) under different operation conditions via four sets of simulation experiments. The summary of simulation experiments is shown in Table 1. From this research, the characteristics of the three control strategies can be summed up below:

$i_d=0$ control. Its performance is limited, and it is adaptable to the simple and low-speed condition.

MTPA control. It is highly efficient, rapidly responsive and good at low-to-medium speed condition.

WMC control. It has strong capability of speed expansion, and it is applicable to high speed conditions.

4.2 Formula / feed-forward control method

This method is based on the steady-state voltage equation and the limit circle formula to calculate the optimal current pairs (i_d & i_q) under different speed-torque combinations, and make tables for lookup or use formula for calculation, achieving the MTPA and MTPV control.

Nie et al. [11] propose an improved MTPV FWC method. i_d and i_q are regulated simultaneously and proportionally in the MTPV region, and an MTPV control module without additional regulators is added based on the original negative i_d feedback control, achieving the smooth transition to the deep flux-weakening region. The experiment results show that with this method, the motor's maximum rotational speed can reach 3000rpm, five times its rated speed (600rpm); torque output capability is significantly enhanced in the deep flux-weakening region.

Table 1. Summary of simulation experiments.

Experiment NO.	Objective	Test Signal & Operation Condition	Control Strategy	Key Performance Indicator	Main Conclusion
1	-Low speed start performance; -Load surge response	-Step signal: 0→1000 rpm; -Initial load: 5N m; -Increase to 10N m in 0.5s	$i_d=0$; MTPA	-Maximum starting torque; -Time to steady state; -Recovery time of load surge	-MTPA starting torque: +165.6% (85N m vs 32N m); -Response time: +30.8% (0.09s vs 0.13s) -Recovery time: -42.9%
2	-Slope acceleration performance; -Load surge response	-Slope signal: 0→1500 rpm; -Initial load: 5N m; -Increase to 10N m in 0.5s	$i_d=0$; MTPA	-Speed overshoot; -Current in steady state	-MTPA's overshoot: smaller (1507rpm vs 1510rpm); -Current in steady state: -6.1% ($i_q=8.5A$ vs $i_q=9.0A$); -Allocation of negative i_d (-2.25A) by magnetic resistance torque
3	-High speed expansion limit	-Step signal: 0→6000 rpm; -Initial load: 5N m;	$i_d=0$; MTPA; WMC	-Actual maximum speed; -Increase time	-WMC: 6030rpm (above target); -MTPA: 4163rpm; - $i_d=0$: 2361rpm
4	-High speed stability -FWC mechanism verification	-Step signal: 0→4000 rpm; -Initial load: 5N m; -Increase to 10N m in 0.5s	WMC	-Accuracy in steady state; -Recovery time of load surge current allocation	-Error in steady state: <0.5%; -Well-definition of WMC mechanism: $i_d = -20A$ (accounting for 79.7%) $i_q = 5.1A$; -Verifying the feasibility of leading angle control

5 Innovative flux-weakening control strategies

Innovative FWC strategies are evolving towards the objectives of enhanced robustness, high adaptability and low computational complexity, laying a solid theoretical and technological foundation for meeting the increasingly rigorous performance requirements.

5.1 Model predictive flux-weakening control (MPFWC)

By evaluating impact on future current, torque and flux linkage via a predictive model in each control cycle, this method is to select the voltage vector from a set of finite ones that minimizes the cost function such as tracking errors.

Wang et al. [1] propose an improved MPFWC strategy with full speed range. With the incremental prediction equation and the delay compensation technology, it can effectively weaken the influence on control accuracy caused by permanent magnet flux attenuation. The simulation results in MATLAB/Simulink verify the improvement effects in the speed overshoot, the torque ripple amplitude, the current fluctuation amplitude and the steady-state response time, which are displayed in Table 2.

Table 2. Results of PMSM's performance improvement.

Indicator	Traditional PI Control	MPFVC	Improvement
Rotational Speed overshoot	5%	2.5%	50%
Steady-state Response Time	0.05s	0.045s	10%
Torque Ripple Amplitude	0.6N m	0.35N m	41.7%
Current Fluctuation Amplitude	$i_d=5A$; $i_q=4A$	$i_d=3A$; $i_q=2A$	40% (i_d); 50% (i_q)

5.2 Passive observer-based flux-weakening control (POFVC)

This novel method is to design an observer for PMSM to keep the system stable by system energy dissipation characteristics. Its robustness is strong, and the phase lag compensation is avoided.

Wen et al. [12] develop a passive observer to achieve precise calculation of the motor's rotor angle and speed, which is completely independent of motor parameters and flux linkage information. This strategy is verified by MATLAB/Simulink simulations. Under the collaborative effect of passive observers and voltage feedback FVC, the motor achieves the base speed (750rpm) in 0.018s and the peak speed at 2400rpm (3.2 times the base speed) in 0.11s. The system exhibits outstanding dynamic responsiveness and FVC effect during the two speed steps in 0.1s and 0.2s (750→1000→1500rpm). Although slight fluctuations in speed, current, and torque occur during the motor startup and the sudden changes in torque, the system quickly returns to the stable state under the sudden load torque increase to 5N m in 0.15s, exhibiting the outstanding load adaptability and interference resistance.

5.3 Intelligent and adaptive control solutions

Fang et al. [13] propose an improved fuzzy PI control strategy for the shortcoming of decreased sensitivity in the small error range in the traditional strategy, of which the improvement lies in the modification of part of fuzzy rules and the affiliation function. The simulation results show that the improved fuzzy PI control strategy outperforms the traditional one in both startup speed and load disturbance inhibition. The details are displayed in Table 3.

Table 3. Comparison of the improved & traditional fuzzy PI control strategies.

Performance Indicators	Traditional Fuzzy PI Control	Improved Fuzzy PI Control	Improvement
Startup Time (0→1000rpm)	0.0135s	0.0097s	Decrease of 28%
Overshoot of Torque Load Surge	13.7N m	12.4N m	Decrease of 1.3N m
Stability of Rotational Speed Response	-Slow startup; -Minimal fluctuations in the weak magnetic regions	-No significant drop in rotational speed in the weak magnetic regions	-Smoother flux-weakening switching
Resistance to Load Disturbances	Good	Better	Better torque recovery

Xu et al. [14] not only adopt the leading angle FVC, but also introduce the active disturbance rejection controller (ADRC) to replace the traditional controller in FVC, effectively improving the control accuracy and the robustness of the motor speed loop in the weak magnetic mode. By comparison of the ADRC and the tradition PI controller, ADRC features faster response, smaller overshoot and enhanced capability to resist disturbance in the simulation experiments. Specifically, in terms of the start without load, the speed curve

under ADRC control is smoother than that under PI control, with less overshoot; In terms of the robustness, the speed drop under ADRC control is significantly smaller and recovers faster than that under PI control, verifying ADRC's better robustness.

6 Comparative discussion

The previous sections outline the technological evolution of FWC from classic strategies to innovative strategies. Different strategies have their own pros and cons in different performance indicators, and their adaptability to application scenarios also varies significantly. In the light of this, this section will systematically compare the performance of different FWC strategies introduced in the references in order to provide reference for the scheme selection. As is shown in Table 4.

Table 4. Comparison of Performance in Different FWC Strategies.

Reference	FWC Strategy	Innovation	Pros	Cons	Application Scenario
Wang et al.	MPFWC	-Prediction model + One-step delay compensation	-Fast dynamic response; -Small speed overshoot (2.5%); -Torque ripple suppression (0.35N m); -Strong robustness	-High computational complexity; -Dependent on model accuracy	Rail transit traction
Gao et al.	Leading Angle	-Multi-closed-loop system + Current decoupling, adjusting leading angle γ via PI control	-Simple implementation; -Smooth mode transition; -Extended speed range	-Dependent on motor parameters	Electric vehicles
Nie et al.	MTPV	-Adds MTPV module at the basis of negative i_d compensation; -Adjusts i_d/i_q proportionally; -Linear approximation of MTPV curve	-No extra regulators, simple structure; -Peak speed up to 5 times rated speed; -Improved torque	-Linear approximation introduces errors; -Depends on characteristic current matching	Electric vehicles, electric ships
Wen et al.	Passive observer + Voltage feedback	-Passive observer estimates rotor angle/speed; -Combined with voltage feedback	-Sensorless; -Speed range up to 3.2 times the base speed; -Smooth switching, fast responsiveness, good robustness	-Observer gains require empirical tuning.	Electric vehicles
Xu et al.	Leading Angle + ADRC	-ADRC replaces traditional PI controllers, improving the dynamic and static features and the system's anti-interference capability.	-Small speed overshoot; -Strong load disturbance rejection; -Good robustness	-Complex ADRC parameter tuning	Electro-hydraulic coupled steering system

Fang et al.	Improved Fuzzy PI	-Optimized affiliation functions and fuzzy rules in small-error region	-Fast startup; -Small torque overshoot	-Relies on expert experience for fuzzy rule design	General IPMSM
Yuan et al.	MTPA + Leading Angle	-Comparison of $i_d=0$, MTPA, and FWC; -Designed APP for monitoring	-MTPA improves starting torque; -FWC achieves 6000 rpm; -Strong anti-interference	-Fixed PI parameters; -Switching requires logic	Electric motorcycles

7 Conclusion

The significance of FWC for PMSMs lies in its role as a core means of breaking through voltage limitations and expanding the range of constant power operation; optimizing efficiency, power density and speed range; and ensuring stable, reliable, and efficient operation of the system under complex high-speed conditions. This article summarizes not only the classic FWC strategies such as feedback and feed-forward method relying on precise mathematical models, but also the innovative FWC strategies such as MPFWC, POFWC, ADRC and so forth. These innovations effectively solve the problems such as parameter robustness that commonly arise in the deep weak magnetic region, achieving more excellent performance. Furthermore, it should be noted that the selection of FWC strategies strike a balance between performance indicators and complexity at the basis of specific application requirements. The research of advanced FWC control theories and applications will continue to drive the progress of PMSMs.

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