Speed Anti-Windup PI strategies review for Field Oriented Control of Permanent Magnet Synchronous Machines Servo Drives with Matrix Converters

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Keywords

Anti-Windup, Matrix converter, PMSM, Servo drive, PI.

Abstract

When facing real systems PI tuning, the plant is modeled disregarding its physical limitations. Consequently, the PI output may increase indefinitely its value; phenomenon called Windup. This paper presents a review and a comparison between different Anti-Windup PI strategies used in speed motion and position control for Matrix Converter PMSM servo drives.

Introduction

Recently fully integrated adjustable speed drive applications have attracted more attention for a wide range of industrial applications such as hybrid electrical drives, more electrical aircrafts actuators, robots and machine tool drives. [1] [2]

With the improvements in the rare magnet materials such as (NdFeB), Permanent Magnet Synchronous Machines (PMSM) are gaining market when compared to other AC Machines due to its higher efficiency, lower inertia, weight reduction and volume[3].

In order to get a fast PMSM performance in terms of speed and torque, the Field Oriented Control (FOC) is one of the best vector control strategies [1]. Figure 1, shows the FOC scheme, where three PI controls are used, one for the outer speed control loop and two for the inner current loops. However, linear PI controllers do not have output magnitude limiters, and therefore, the output can take values relatively large and as a consequence, the real system can be damaged by the large control action [4] [5]. For instance, in the FOC PMSM drive, an excessive current and voltage might end up damaging the PMSM itself and the power electronics converter. In order to protect PMSMs, these commanded values are limited and consequently the outer speed PI accumulates error, producing a big overshoot on the speed response which, in the worst case, could even destabilize the system; phenomenon known as Windup [4].

In order to avoid the unwanted Windup phenomenon, the integrator output value will be kept within a maximum limits; strategy which is known as Anti-Windup (AW). Another solution might be to continuously tune the PI parameters to keep the response undamped at all times [6].

This paper reviews different AW strategies, providing a general classification, which is firstly divided between the methods which do depend on the Saturation and the ones which do not. The latter are normally named as "PI limited" or "PI dead zone" which have the advantage of being easy to implement whereas its drawback is the tuning difficultness [7].

Methods depending on the Saturation might be divided into two different subgroups, the digital and analogue ones. There are mainly two different digital approaches, the one which resets the integral action of the PI when the Saturation is reached and the second one which holds the integral value when the Saturation is also reached [8]. The analogue approaches are considered to be a bit more accurate since its AW method depends not only in the fact that the system is saturating but also considers the amount of this Saturation to proportionally compensate the integral action. Among them, "the PI tracking or Back calculation " is based on removing from the input, of just the integral part, either the difference between the non saturated output and the saturated one multiplied by a gain factor from 0 to 1 [7] [9] [10] or just the input of the Saturation block [11]. Another approach is the analogue compensation of not only the integral action but in both the proportional and integral [8].

Other more complex techniques are based on internal plant models [12], where the model output is continuously compared with the actual response. In [13], an H-infinite feedback controller is in charge of getting rid of the overshooting troubles.

This paper reviews all non model dependent AW strategies introducing a comparison of its performance when driving PMSMs with FOC using Matrix Converters.

Voltage Source Inverters with Pulse Width Modulation (PWM) are normally used to drive PM AC motors, but Matrix Converters (MC) can also be used, especially in high-power-density applications where electrolytic capacitors are inappropriate. MCs are also inherently bidirectional, draw sinusoidal input current, and have similar efficiencies to bidirectional PWM inverters. Although the MC can only output 86% of the input voltage, this is not a disadvantage if the machine is designed specially for a given application. These characteristics of the MCs have led to interest in the MC-PM AC drive for aerospace applications [14]. In addition, MCs have been exploited for integrated induction motor drives in which the converter is placed in the machine frame [15].

Note all the anti-windup strategies presented in this paper could be implemented as well in the traditional VSI converter. However, this paper is focused in the use of MC for all the above mentioned advantages and the possible industrial market that this type of converter might achieve.

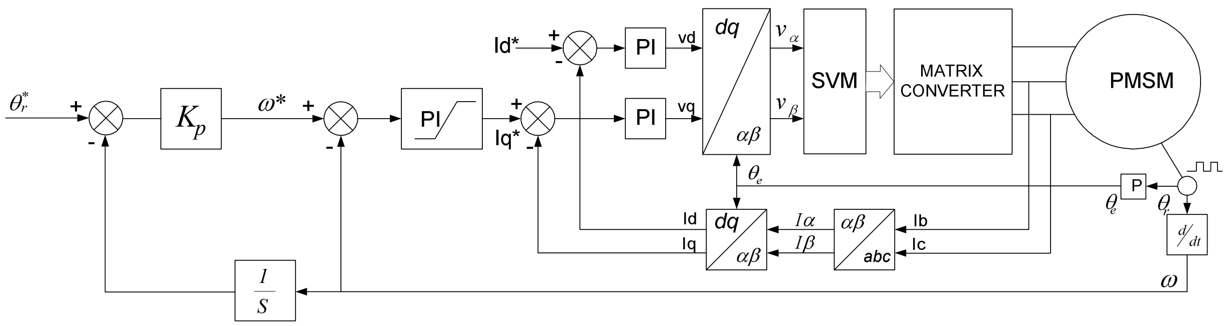


Fig. 1. Matrix Converter Field Oriented Control of Permanent Magnet Synchronous Machines scheme with speed AW PI.

Table I: Motor PMSM Yaskawa

Output power	200 W	Magnet flux	0.046 Wb
Current/Voltage	2A/100V	Rated torque	0.64 Nm
Pole pairs	4	Rated speed	3000 r.p.m
Rs	2.5 Ω	Friction	0.05 Nm·s
Ld/Lq	8.3/8.6 mH	Inertia	0.008 kg·m^2

Real System with the Windup phenomena.

Every real system presents some physic limitations or has some control constraints to safeguard system's integrity. The ideal control, which has been introduced above, is completely valid, although it fails when the input reference or load are deeply changed. Under these conditions, because of the Windup phenomena, the system's performance worsens and eventually it may become unstable.

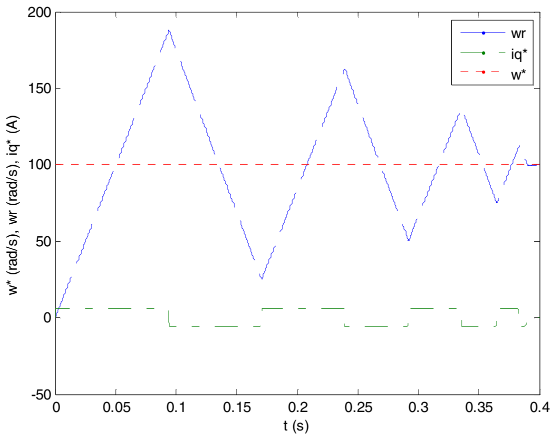


Fig. 2. Effect of current limitation.

This section shows the two types of possible unstable responses. The first one arises when the current reference command is limited to protect the system as Fig. 2 shows, and the second appears when the Voltage Source Inverter (VSI) DC-bus is restricted as Fig. 3 illustrates.
These two limitations, implies not only an instability problem as shown in Fig. 2 and 3, but also brings the Windup problem in the integral part of the PI control.

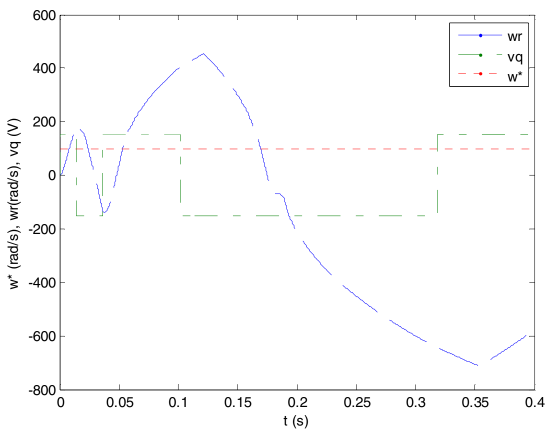


Fig. 3. Effect of D.C voltage limitation.

Next points summarize how this Windup phenomena emerge:

- Difference between input reference and the feedback generate a large error.
- PI acts in consequence applying an output value according with PI's gains. The integral action starts accumulating error, increasing its value.
- Eventually, the PI output value, mainly due to the integral accumulated magnitude, can be larger than the Saturation limit level. Under this condition the Saturation block acts providing the maximum tolerable value to the plant.
- Once the actual output reaches its reference, the error is again zero, but the integral accumulated value still remains at a value which can be much higher than the Saturation limit bringing the responses previously shown in Figs 2 and 3.

Basic Anti-Windup

The main goal of AW scheme is to avoid the over value in the Integrator, therefore the Integration output will be kept within a limited range.
Fig. 4 shows the basic AW PI compensator, where an integrator limiter has been added which does not depend on the Saturation.

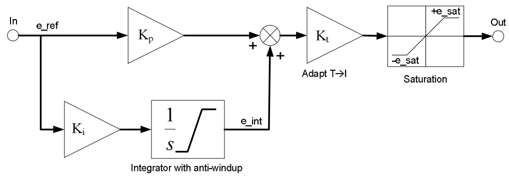


Fig. 4. AW PI-limited.

Fig. 5 shows the speed responses with and without the AW. Notice how the AW slows down the speed response when compared to the ideal one without any type of saturation. On the other hand, the overshoot has been reduced.

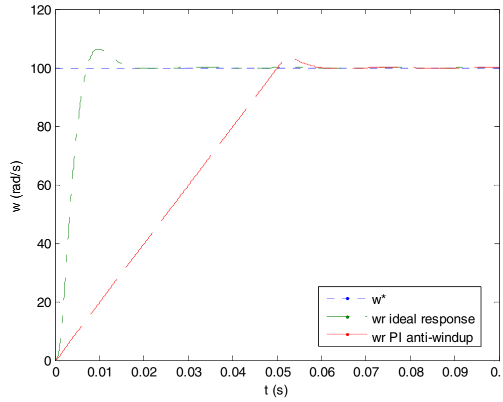
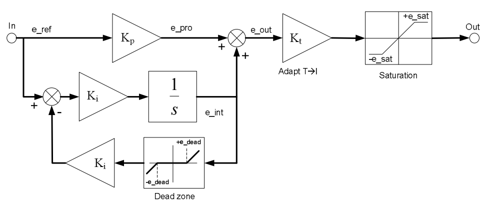


Fig. 5. Ideal and AW speed responses.

Anti-Windups Strategies

AW PI with dead zone.
In this case the limit is controlled by a dead zone element as Fig. 6 shows. Whenever the integral value doesn't achieve the dead zone limit, the integral value remains linear and therefore, unchanged. On the contrary, when the integral output is larger than the dead zone limit, the total integral value is reduced due to the self subtraction action [7].

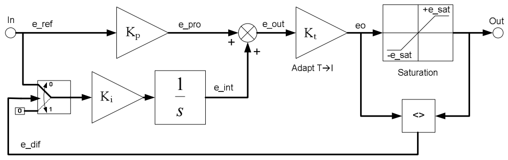


$$
\begin{aligned}
&|K_t \cdot e\_out| < |e\_sat| \\
&\quad \begin{cases} out(t) = K_t \cdot \left(K_p \cdot e\_ref(t) + K_i \cdot \int e\_ref(t) \cdot dt\right) & |e\_\mathrm{int}| < |e\_dead| \\ out(t) = K_t \cdot \left(K_p \cdot e\_ref + K_i \cdot \int (e\_ref(t) - K_i \cdot e\_\mathrm{int})\right) & |e\_\mathrm{int}| \geq |e\_dead| \end{cases} \\
&|K_t \cdot e\_out| \geq |e\_sat| \\
&\quad \{ out(t) = e\_sat
\end{aligned}
\qquad (1)
$$

Fig. 6. AW PI with dead zone.

A possible drawback may appear due to integrator's limit, which works independently of the Saturation element, so if the limit value is not correctly adjusted, the PI could produce either a large overshoot or an undershoot as if the integral part wasn't working.

AW PI conditioned
The working principle of the Fig.7's AW is really simple and robust thanks to its discrete behavior. When difference between input and output Saturation appears, the integrator holds its last value. When the input and output Saturation difference vanishes, the integral action works again.

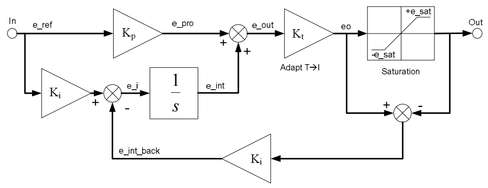


$$\begin{array}{ll} eo = out & \{ out(t) = K_p \cdot e(t) + K_i \int e(t) \\ eo \neq out & \begin{cases} out = e\_sat \\ eo(t) = K_p \cdot e(t) + e\_\mathrm{int} \end{cases} \end{array} \qquad (2)$$

Fig. 7. AW PI conditioned.

AW PI tracking

This AW PI compensates for any excess of integrator's value through the difference between Saturation's input output.[7][9], as shown in Fig 8.

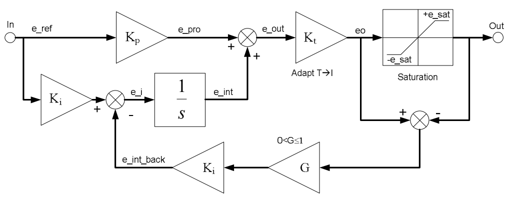


$$\begin{array}{ll} eo = out & \{ out(t) = K_p \cdot e(t) + K_i \int e(t) \\ eo \neq out & \begin{cases} out(t) = e\_sat \\ eo(t) = K_p \cdot e(t) + K_i \int \left(e(t) - \left(eo(t-\Delta t) - e\_sat\right)\right) \end{cases} \end{array} \qquad (3)$$

Fig. 8. AW PI tracking.

AW PI tracking with gain

The generic case of the AW PI tracking includes a gain (G), whose margins are within 0 and 1 (4) as Fig. 9 illustrates, to vary the non linear feedback action. This gain also controls the overshoot response; The larger the gain (G) the smaller the overshoot.



$$\begin{array}{ll} eo = out & \{ out(t) = K_p \cdot e(t) + K_i \int e(t) \\ eo \neq out & \begin{cases} out = e\_sat \\ eo(t) = K_p \cdot e(t) + K_i \int \left(e(t) - G \cdot \left(eo(t-\Delta t) - e\_sat\right)\right) \end{cases} \\ 0 < G \leq 1 & \end{array} \qquad (4)$$

Fig. 9. AW PI tracking with gain.

Simulation Results

All the AWs schemes shown above have been tested to analyze their behavior and a comparative has been made between them

Fig. 10 shows a zoom of the response when a speed step with no load is applied at one third of the nominal speed, i.e. 100 rad/s, where it is possible to observe accurately all different overshoots.

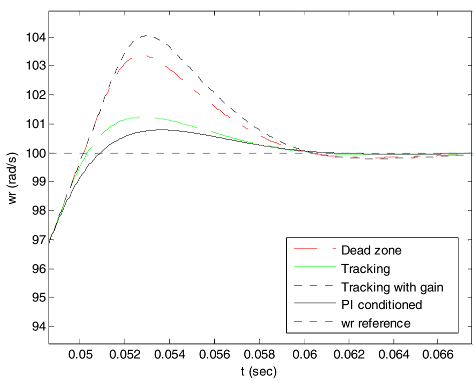


Fig. 10. Different AW PI responses against speed step input reference

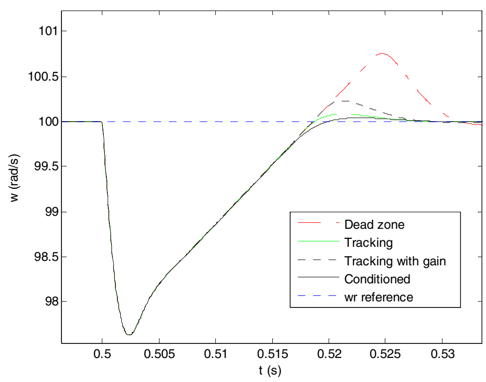


Fig. 11. AW speed PI response when applying a load impact equals 2.5 times the nominal torque.

All the AWs schemes shown above have been simulated to know their behavior and a comparative has been made between them. Fig. 10 shows a zoom of response when a speed step with no load is applied at one third of the nominal speed, i.e. 100 (rad/s), where it is possible to observe accurately all different overshoots. Fig. 11 is the response of the PIs when applying a load impact equal to 2.5 times the nominal torque.
This study also deals with the AW behavior as a position servo drive. Fig. 12 shows the AWs performance when a step position reference is applied.

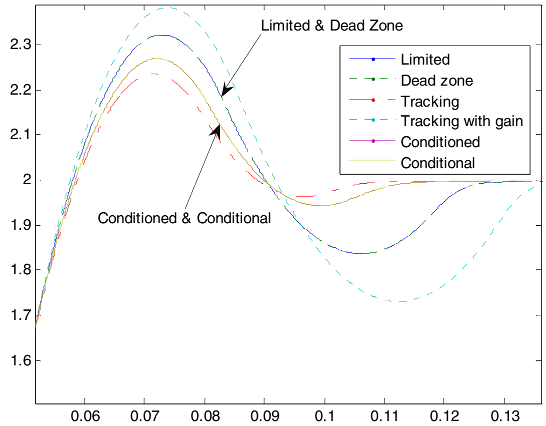


Fig. 12. Servo drive response when applying a step position reference and nominal load.

From Fig. 12, it can be concluded that, likewise in the speed control, the AW Tracking performs faster and with less overshot. On the contrary, the AW Tracking with gain has the worst behavior with the largest overshoot and settling time.

Table II: AW speed PI response at one third of nominal speed with no load

TL = 0%	t_r (ms)	t_p (ms)	M_p (rad/s)	t_s (0.5%) (ms)
Dead zone	50.2	52.7	3.4	58.2
Tracking	50.3	52.5	1.2	56.6
Tracking with gain	50.2	53.2	4	58.5
Conditioned	50.9	53.2	0.8	56.1

Experimental Results

The work bench used to test the AWs is showed in Fig 13. It is a four quadrant work bench based on the MC which drives the PMSM and a DC drive driving a DC machine which is in charge of simulating the load. Main characteristics of the PMSM are shown in Table I.

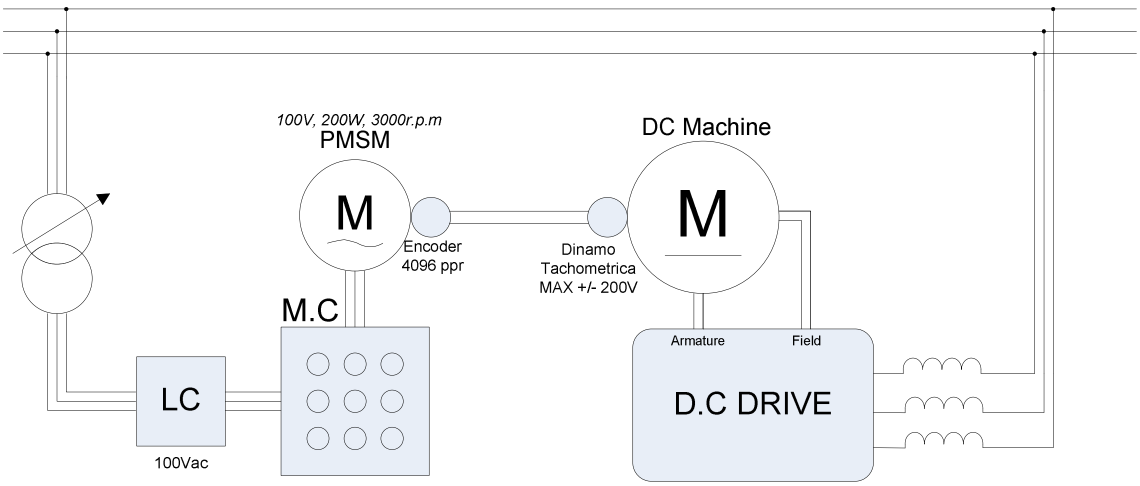


Fig. 13 Experimental work bench.

Fig. 14 shows the experimental results obtained with the set up of Fig.1 and the motor parameters shown on Table I. It is apparent that the PI conditioned response is much better than the dead zone as expected from the simulations. The larger overshoots in both AW PIs might be due to the PWM natural delay in the real plant systems. Despite all AW PI speed responses are rather similar, AW PI conditioned and AW PI tracking perform with less overshoot and have faster settling time.
However, the AW PI tracking strongly depends on the plant parameters, while the AW PI is more plant and parameters independent.
On the other hand, the AW PI dead zone is the one with the poorest transient performance.

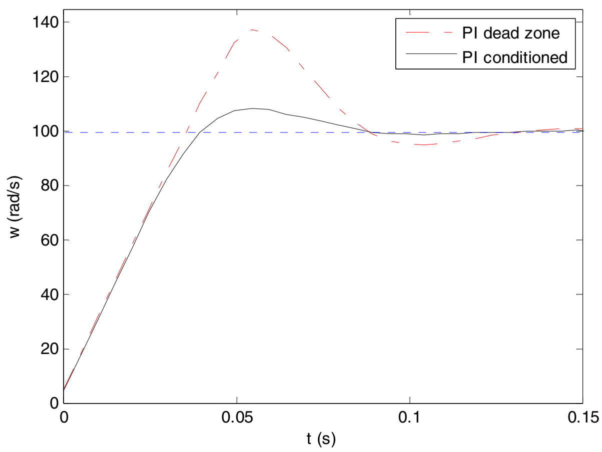


Fig. 14. Experimental AW PI dead zone and conditioned responses against speed step input reference

Conclusions

This paper has stated the well known effect of the Windup phenomenon when standard PIs are used to drive a PMSM. In such drives there are three PIs, two inner ones to control the currents and an outer one to control the speed. In case of a position servo controller, an extra outer P loop is also added. The speed PI Saturation due to the slower dynamics of the PMSM is the one to be protected and hence the inner loop is automatically protected against the Windup phenomenon.
This paper analyses and reviews different AW PIs to overcome the saturation problems. Simulations, in speed and position control, are carried out to compare all AW performance and a summary of the different responses is provided. Also, some initial experimentation is carried out with the same motor used for simulation corroborating the simulations.
The waveforms obtained, in both the speed and position control, show that the best AW response is obtained with the PI tracking. Its behavior is a good balance between speed response and overshoot. However, it is necessary to know the system to tune the PI precisely; otherwise, an improper response with an unwanted overshoot could arise.
When the plant is not know, and therefore the PI can not be tuned precisely, PI conditioned performs with a reasonable overshoot at the expense of getting slower transient response with a bit larger time rise.

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