speed Anti-Windup PI strategies review for Field Oriented Control of Permanent Magnet Synchronous Machines

Jordi Espina, Toni Arias, Josep Balcells and Carlos Ortega

TIEG, Dep. d'Enginyeria Electrònica. Universitat Politècnica de Catalunya. C. Colom 1. 08222 Terrassa. Catalonia. Spain. espina@eel.upc.edu

Abstract - This paper presents a review and a comparison between different Anti-Windup PI strategies used in speed motion control for electrical drives. Usually, when facing PI tuning of real systems the plant is modeled as a linear system and therefore simplified disregarding its physical limitations such as maximum current and voltage values. Consequently, the PI output may increase indefinitely its value. This phenomenon is know as Windup. The end result is a clear performance degradation which may even result in instability.

Firstly, this paper models and tunes the current and speed PI controllers with the root locus method for Field Oriented Control of a Permanent Magnet Synchronous Machines. Secondly, it is shown the mentioned unwanted Windup phenomenon in the speed loop. Finally, the Anti-Windup strategies are simulated and their behavior are compared when driving a Permanent Magnet Synchronous Machine with Field Oriented Control.

I. 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 PMSM, 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 unstabilize the system; phenomenon known as Windup [4].

In order to avoid the unwanted Windup phenomenon, a maximum integrator output value will be kept within 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 has 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 analog 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 analog approaches are considered to be a bit more accurate since its AW method 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

![Fig. 1. Field Oriented Control of Permanent Magnet Synchronous Machines scheme with speed AW PI.](image-url)
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 analog 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], it is continuously comparing its output to the actual plant. In [13] and 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 a PMSM with a FOC.

II. FOC of PMSM

Fig. 1 illustrates the speed and control loops when driving a PMSM with well known FOC scheme [1].

In motion control, the abc to aβ transformation is widely used, known as a Clarke and aβ to dq transformation or Park. These transformations allow to simplify the 3 phase system to a 2 phase one, where d axis current components controls directly the flux-linkage and q controls torque. Moreover, SISO linear controllers might be easily applied [5].

The electrical part of PMSM is modeled in the dq frame coordinate [1] by the following set of equations.

\[
\frac{d}{dt} i_d = \frac{V_d}{L_d} - R \cdot i_d + \frac{L_q}{L_d} \cdot \omega \cdot i_q \\
\frac{d}{dt} i_q = \frac{V_q}{L_q} - R \cdot i_q - \frac{L_d}{L_q} \cdot \omega \cdot i_d - \frac{\lambda_m}{L_q} \cdot \omega
\]

Finally, a third equation (3) which models the electromechanical PMSM torque is needed to complete the model.

\[
T_e = \frac{3}{2} \cdot P \cdot \left[ \lambda_m \cdot i_q + \left( L_d - L_q \right) \cdot i_d \cdot i_q \right]
\]

PMSM in standard operation do not require to create the flux since the permanent magnet (\(\lambda_m\)) already provide it and the d axis is aligned with it. Therefore, q current component controls proportionally the motor’s torque as shown in (3) if d current is kept to zero.

FOC is composed of two inner current loops and an outer speed control loop. The inner loops are controlled by two identical PI. The speed control loop will be connected in cascade with torque, i.e. q current, control loop as shown in Fig. 1. It must be pointed out that the current loops dynamics are faster than the speed loop and therefore, can be tuned independently.

From (1) and (2), it can be deduced that the plant dynamics just depends on the electrical pole; therefore, these two equations can be simplified, just for tuning reasons, to (4), which clearly shows a first order system.

\[
i_{dq}(s) = \frac{V_R}{\left( \frac{L_d}{L_q} s + 1 \right)} \cdot \omega
\]

In Fig. 2, the electrical pole (R/L\(_{dq}\)) is placed in the root locus plane and Matlab™ computer software is used to tune the PI parameters. The conditions used to determine the PI parameters are Damping factor \(\zeta = 0.707\) and Settling Time \(T_s = 5/T_R\). Fig. 3 shows the closed electrical loop with the PI controller.

The resultant PI(s) is as (5) shows:

\[
PI(s) = \frac{20200 \cdot (1 + 0.0081 \cdot s)}{s}
\]

\[
K_p = 16.06 \quad K_i = 20200
\]

\[
\omega(s) = \frac{V_R}{\left( \frac{D}{D} \cdot s + 1 \right)} \cdot T
\]

From Table I the mechanical parameters have been considered to adjust the speed control with the same root locus technique. The PI obtained is given in (7).
The speed loop will be the main control used to apply the different AW. Firstly, the speed PI together with the mechanical plant will be reduced to a pure second order system as shown in (8).

\[ T(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]  

(8)

The closed loop transfer function from the mechanical loop with the tuned PI gives not only the desired pure second order system, but also an unwanted zero, which worsens the transient response.

\[ T(s) = \frac{G}{1+GH} = \frac{K_p}{s^2 + s\left(\frac{D}{J} + \frac{K_n}{J}\right) + \frac{K_n}{J}} \]  

(9)

The solution to have a pure second order system is to insert a pre-filter \( F(s) \) to get rid of the unwanted zero (10).

\[ F(s) = \frac{s}{K_p s + 1} \]  

(10)

Fig. 4 shows the closed loop with the pre-filter, and then the system’s behavior is equal to the desired second order like in (8).

**III. REAL SYSTEM WITH THE WINDUP PHENOMENA.**

Every real system presents some physical 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.

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. 5 shows, and the second appears when the Voltage Source Inverter (VSI) DC-bus is restricted as Fig. 6 illustrates.

These two limitations, implies not only an instability problem as shown in Fig. 5 and 6, but also brings the Windup problem in the integral part of the PI control.

**IV. 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. 7 shows the basic AW PI compensator, where an integrator limiter has been added which do not depend on the Saturation.

\[ PI(s) = \frac{123 \cdot (1 + 0.00032 \cdot s)}{s} \]

\[ K_p = 0.393, \ K_i = 123 \]  

(7)
Fig. 8 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.

V. DIFFERENT ANTI-WINDUPS STRATEGIES

In this section the structure and performance of different AW strategies are introduced. An important highlight is that the AW inserted in the speed PI loop, makes the PI and the whole speed loop non linear. However, non-linear PI can always be divided in three different parts, each of them being linear itself.

A. AW PI with dead zone.

In this case the limit is controlled by a dead zone element as Fig. 9 shows. Whenever the integral value does not 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].

B. AW PI conditioned

The working principle of the Fig.10’s AW is really simple and robust thanks to its discrete behavior. When difference between Saturation’s input and output appears, the integrator holds its last value. When the input and output Saturation difference vanishes, the integral action works again.

C. AW PI tracking

The AW PI shown in Fig.11 is a bit different than the above ones. In fact, this one uses the difference between input and output Saturation block to reduce the Integrator’s value [7][9].

Where: $e_{sat}$ is the maximum output value when Saturation is turned-on.
D. AWPI tracking with gain

The generic case of the AW PI tracking includes a gain (G), whose margins are within 0 < 1 (14) as Fig. 12 illustrates, to vary the non linear feedback action. This gain also controls the overshot response, increasing the gain (G) get decrease the overshoot.

\[
e_0 = \begin{cases} 
\text{out}(t) = K_p \cdot e(t) + K_i \cdot \int e(t) \\ 
\text{out} = e_{\text{sat}} \\
\end{cases} 
\]

(14)

VI. SIMULATION RESULTS

All the AWs schemes shown above have been tested to know their behavior and a comparative has been made between them. Fig. 13 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.

Figure 14, illustrates a speed reversal from nominal speed to minus one third of the nominal speed. During the start up the PMSM was at full load and it is removed at 0.3 (s) for the speed reversal.

Fig. 15. Zoom of Fig. 14, zone of positive step reference. The left part is the overshoot produced by all PI after applied a step at the input. The right part is the response due to a change of load.

Fig. 16. Zoom of Fig. 14, response detailed of all PI to negative step or inverse reference input.

Figure 17 is the response of the PIs when applying a load impact equal to 2.5 times the nominal torque.
This paper analyses and reviews different AW PIs to overcome the saturation problems. Simulations are carried out to compare all AW performance and a summary of the different responses is provided.

The waveforms obtained 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 known, and therefore the PI can not be tuned precisely, the PI conditioned performs with a reasonable overshoot at the expense of getting slower transient response with a bit larger rise time.

Currently, some experimentation is being carried out with the same motor used for simulation and it is expected to corroborate all experimental work for further servo drive applications.

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REFERENCES


Table II and Table III summarizes the comparison of all AW strategies under no load and full load conditions and variables which parameterize the second order system are given.

**TABLE II**

<table>
<thead>
<tr>
<th>TL = 0%</th>
<th>Dead zone</th>
<th>Tracking</th>
<th>Tracking with gain</th>
<th>Conditioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>tₚ(ms)</td>
<td>50.2</td>
<td>50.3</td>
<td>50.2</td>
<td>50.9</td>
</tr>
<tr>
<td>tᵣ(ms)</td>
<td>52.7</td>
<td>52.5</td>
<td>53.2</td>
<td>53.2</td>
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<tr>
<td>Mₚ(rad/s)</td>
<td>3.4</td>
<td>1.2</td>
<td>4</td>
<td>0.8</td>
</tr>
<tr>
<td>t₀(0.5%)(ms)</td>
<td>58.2</td>
<td>56.6</td>
<td>58.5</td>
<td>56.1</td>
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</tbody>
</table>

**TABLE III**

<table>
<thead>
<tr>
<th>TL = 100%</th>
<th>Dead zone</th>
<th>Tracking</th>
<th>Tracking with gain</th>
<th>Conditioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>tₚ(ms)</td>
<td>79.3</td>
<td>81.5</td>
<td>79.3</td>
<td>80.6</td>
</tr>
<tr>
<td>tᵣ(ms)</td>
<td>82.1</td>
<td>81.8</td>
<td>82.5</td>
<td>82.5</td>
</tr>
<tr>
<td>Mₚ(rad/s)</td>
<td>2.4</td>
<td>0.8</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>t₀(0.5%)(ms)</td>
<td>86.9</td>
<td>84.3</td>
<td>87</td>
<td>83</td>
</tr>
</tbody>
</table>

From Tables II and III it can be concluded that AW PIs perform load independently (despite all numbers are re-scaled due to the difference in the applied load).

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 poorest transient performance.

VII. 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. All three PI tunings process are clearly overviewed with the root locus technique. 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.

Fig. 17. AW speed PI load impact response.