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SIMULATION OF ANTI-WINDUP PI CONTROLLER, SIPIC ON FOC OF PMSM

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Abstract. *Windup is a phenomenon that occurs when a control system falls under a saturated control state that causes the system to experience overshoot and even instability. Windup is common for PI controlled electric motors especially when it is designed to work close to its saturation region. The tuning gain coupling of PI controlled system causes difficulty in tuning the contribution of proportional or integral control independently for short settling time with no overshoot performance. A novel anti-windup PI controller with closed-loop integral fed with input command and external torque that possess decoupling effect, SIPIC, was proposed and shown to have a good response in permanent magnet synchronous motor speed control application with field oriented control. PSIM simulation result shows that SIPIC exhibits little to no overshoot and faster recovery speed performance compared to the conventional PI controller for both no load and loading step response conditions.*

Keywords: Anti-windup, Proportional-integral, Speed control, Permanent magnet synchronous motor, Field oriented control

1. **Introduction.** The proportional-integral (PI) controller still gained a lot of interest in motor speed and position control on field oriented control for direct current (DC) motor, induction motor (IM) and permanent magnet synchronous motor (PMSM) [1]. Some works show that fuzzy pre-compensated PI [2] and model predictive control (MPC) [3] are better than conventional PI controller. Although PI controller is easy to implement in the control system with established tuning theory and analytical study, PI suffers from saturated control state due to the integral control which is termed as windup. Windup phenomenon happened when the PI control output exceeds the limit of the system plant input that gives non-controllable saturated control system which may even introduce instability. Furthermore, PI controller also experiences difficulty in tuning. Despite having comprehensive tuning method, the PI control structure leads to the coupling of proportional tuning parameter, k_p, and integral tuning parameter, k_i. Since the two are dependent to each other, tuning of k_p will affect the contribution of k_i and vice versa which results in the complication in having short settling time with no overshoot performance.

A variety of anti-windup controllers that aim to bring the control back to the unsaturated state as soon as possible were introduced. Frequently discussed anti-windup techniques include the conditioning [4], tracking back calculation [5] and integral state prediction [6] methods. Each of these methods requires switching mechanism between two different integral control structures and operation in regaining the unsaturated control.

Knowing this, in year 2015, [7] studied on the possibility in decoupling the tuning gain and later [8,9] proposed a new anti-windup, steady-state integral PI controller (SIPIC) which contains the ability to decouple the tuning gains without the need to switch between two control methods. SIPIC has its separate closed integral loop fed by the steady state integral value that consistently drives the integral control towards the steady state integral value. SIPIC [8,9] has shown better DC motor speed response with smaller overshoot as compared to the conventional PI and other anti-windup PI controllers. SIPIC has better flexibility in tuning the rise and settling time with the decoupling effect.

Field oriented control (FOC) of PMSM application has been commonly used in motor control industry and research. SIPIC is a new controller and has only been simulated and experimentally tested so far on a DC motor speed control application. In order to evaluate the performance of SIPIC on other machines, this research intends to investigate the performance of SIPIC on FOC of PMSM on speed control through simulation approach. This paper will continue with Section 2 that explains the dynamical equation and decoupling. Sections 3 and 4 discuss the SIPIC and FOC respectively. Simulation setup and results will be discussed in Sections 5 and 6 respectively. This paper ended with a conclusion in Section 7.

2. **Derivation of Dynamical Control System.** Figure 1 shows a block diagram of a general PI control system, where y_r, e, u, v, k_T, T_L and y represent the input reference, error signal, controller output, plant input, torque constant, load and system output respectively. The limiter which is responsible in saturated control, will restrain the PI control output from exceeding certain safe voltage/current value to prevent any damage to the hardware.

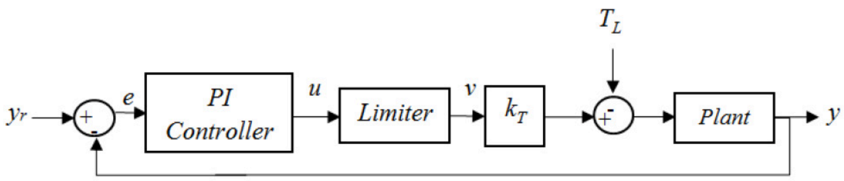


Figure 1. PI controller in a closed-loop system

From Figure 1, the Laplace form of the controller output $U(s)$ can be deduced as Equation (1) with $C(s)$ and $P(s)$ denoting the controller and system plant respectively.

$$U(s) = \frac{Y_r(s)C(s) + T_L(s)P(s)C(s)}{1 + C(s)P(s)} \tag{1}$$

Since both PI controller and SIPIC consist of the proportional and integral controls, the controller Laplace form can be expanded into (2) and substituting into (1) results in (3).

$$C(s) = \frac{k_p s + k_i}{s} \tag{2}$$

$$U(s) = \frac{Y_r(s)(k_p s + k_i) + T_L(s)P(s)(k_p s + k_i)}{s + (k_p s + k_i)P(s)} \tag{3}$$

By referring to [7], an nth order plant can be represented with a generic transfer function as described in Equation (4). The general error dynamic equation [7] for a closed loop PI controlled system is given by Equation (5). Tuning gains are said to be decoupled if they can be individually located in separate poles, which is in the denominator of (5). $E(s)$, $Q(s)$, $p(s)$ and $d(s)$ are the Laplace form for error, integral component, numerator and denominator of the system plant respectively, a_i and b_j are the coefficients, and i, j, k, m

and $n \in \mathbb{N}^+$, $m < n$ while q_{ss} is the steady state integral respectively.

$$P(s) = \frac{a_m s^m + a_{m-1}s^{m-1} + a_{m-2}s^{m-2} + \cdots + a_0 s^0}{b_n s^n + b_{n-1}s^{n-1} + b_{n-2}s^{n-2} + \cdots + b_0 s^0} = \frac{p(s)}{d(s)} = \frac{\sum_{i=0}^{i=m} a_i s^i}{\sum_{j=0}^{j=n} b_j s^j} \tag{4}$$

$$E(s) = \frac{\sum_{k=0}^{k=n-1}\left\{\frac{e^{(k)}(0)}{s^{k+1}}\left[\frac{d(s) - \sum_{j=0}^{j=k} b_j s^j}{p(s)}\right]\right\} + k_i k_T\left[\frac{q_{ss}}{s} - Q(s)\right]}{\frac{d(s)}{p(s)} + \frac{a_0}{b_0} + k_p k_T} \tag{5}$$

3. **SIPIC.** [8,9] discussed that any controller that requires zero steady state error must satisfy condition (6). Many possible controllers can be developed from this condition. The authors proposed a new anti-windup PI controller, SIPIC with the structure described by Equation (7) which consists of a separate integral control loop that is fed with integral steady state value. Equation (7) gives tuning gain in separate poles in its error dynamic equation which decouples the k_p and k_i. Hence, SIPIC can be tuned to have no overshoot and still maintain a zero steady state error. In conventional PI controller, a short rise time response will give overshoot which is not the case in SIPIC.

$$\lim_{s\to 0} k_T k_i s\left(\frac{q_{ss}}{s} - Q(s)\right) = 0 \tag{6}$$

$$\frac{q_{ss}}{s} - Q(s) = \frac{1}{k_i}\left[sQ(s) - q(0)\right] \tag{7}$$

4. **Field Oriented Control.** FOC consists of Park, Clarke and their respective inverse transformations that convert fixed/rotating referencing axes signal type by transforming different signals (abc-$\alpha\beta$-dq) in different phases of the control system. The inverter converts direct current to alternating current (AC) and its conversion can be done with the space vector modulation (SVM) method. The SVM operates with 6 insulated-gate bipolar transistors (IGBTs) to produce 3 phase voltage and current. The generated switching pattern from the pulse width modulation (PWM) gives the switching sequence for the IGBTs in producing the corresponding AC with respect to the desired angle within each period of time.

5. **Simulation Setup.** Figure 2 shows the block diagram used to compare the performance of conventional PI and SIPIC using the common space vector pulse width modulation (SVPWM) FOC circuit. The simulation was performed using the PSIM & CPad for Borland C++ compiler software. In PSIM, the PWM function was developed using a dll block created using the CPad for Borland C++ compiler. Table 1 shows the specification of the PMSM used for the simulation.

SIPIC circuit was built based on Equation (7) in the simulation. The simulation was performed in two cases that require different speed input commands and loading conditions as detailed in Table 2. The selected speed inputs are typical speed for low to medium speed range application testing. For each of the cases, the tuning parameters of the speed regulator will be simulated for $k_p = 1$ and $k_i = 1$, $k_p = 1$ and $k_i = 2$, $k_p = 1$ and $k_i = 3$, $k_p = 2$ and $k_i = 1$, and $k_p = 3$ and $k_i = 1$. This selection of tuning parameters is meant to show a significant difference of the performance between the two controllers. Only the performances for $k_p = 1$, $k_i = 3$ and $k_p = 3$, $k_i = 1$ which show the impact of high k_p and k_i are illustrated in the result for each case.

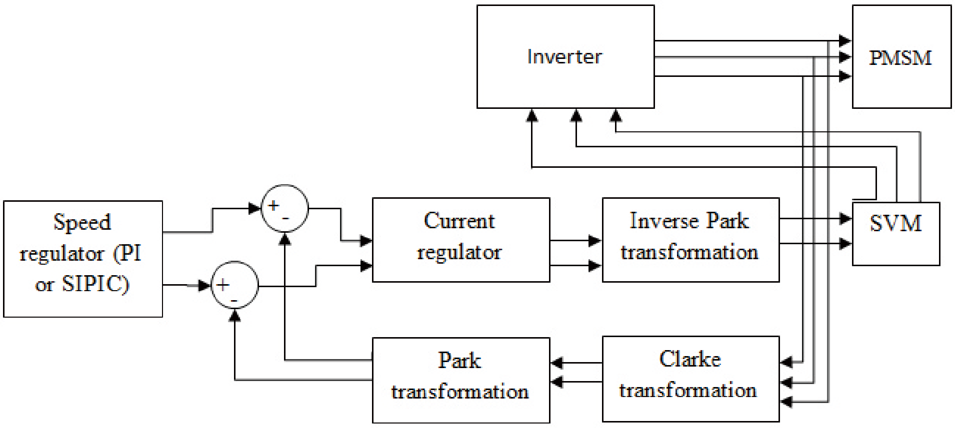


FIGURE 2. Block diagram for simulation

TABLE 1. Specification of the PMSM

Parameter	Specification
Stator resistance (R)	4.3 [Ω]
d-axis inductance (L_d)	0.027 [H]
q-axis inductance (L_q)	0.067 [H]
Peak voltage per unit speed ($V_{pk}/krpm$)	98.67 [V/krpm]
No. of poles (P)	2
Moment of inertia (I)	0.00179 [kg·m^2]
Mechanical time constant (T_m)	1 [s]

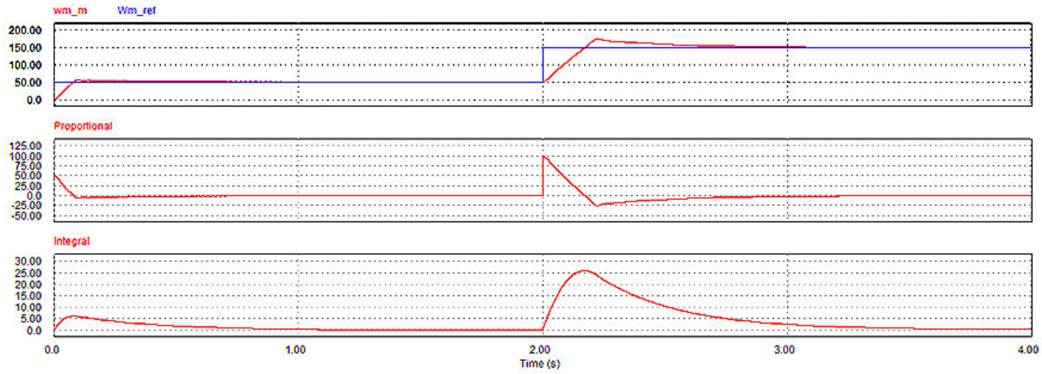
TABLE 2. Simulation cases

Case	Speed command	Load condition
1	Step 50 rad/s to 150 rad/s at 2 s	0
2	Step 50 rad/s to 150 rad/s at 2 s	0.0001 [kg·m^2]

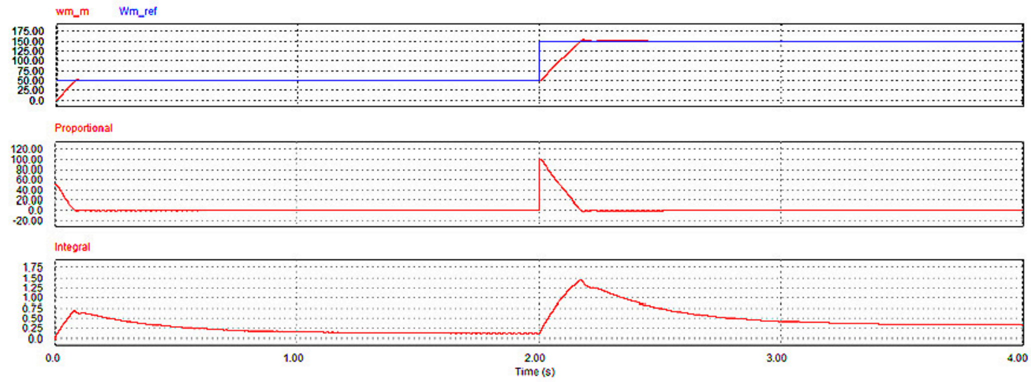
6. Simulation Results.

6.1. **Case 1.** Figures 3 and 4 give the speed response, proportional and integral control comparison between a PI controller and SIPIC for case 1 with respect to different tuning parameters. This simulation was aimed to test the application of SIPIC with FOC on PMSM for changing input speed command. A sudden change of input speed will introduce saturated control state and usually this can be observed at the point where the speed response is overshooting. Figure 3(b) and Figure 4(b) show that SIPIC still have lower overshoot and shorter settling time as compared to PI controller. This can be observed when the speed response of PI controller needs longer time to attain the steady state speed. The integral control of SIPIC quickly reaches the steady state integral value which allows fast regaining into the unsaturated control state (after overshoot).

6.2. **Case 2.** As illustrated in Figures 5 and 6, the changing input command with load, case 2 also exhibits similar speed response to that in case 1 but with longer settling time due to the load. The separate integral control loop in SIPIC gives the capability to response quickly to sudden changes in input command. This gives lower overshoot and shorter settling time for SIPIC.

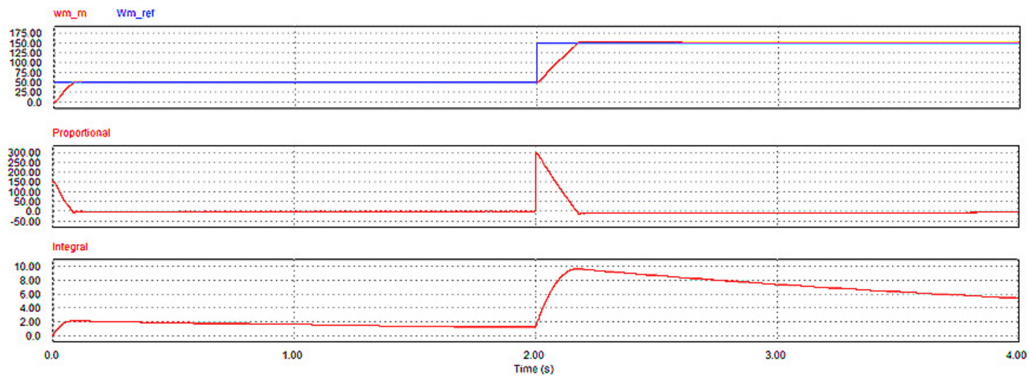


(a)

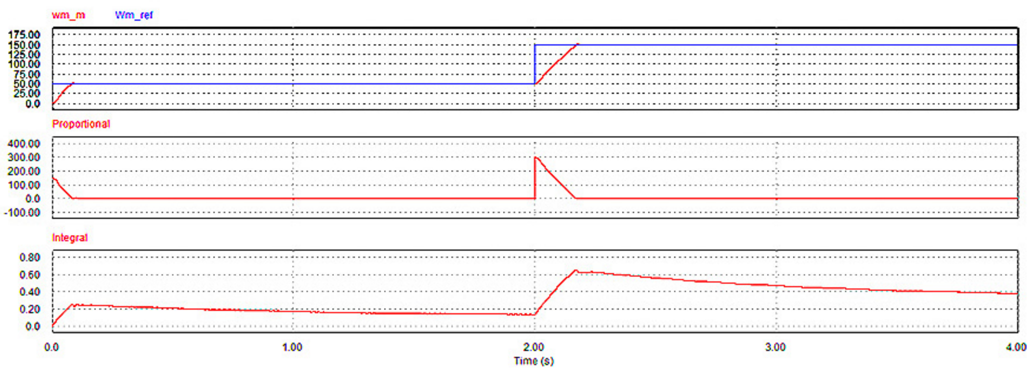


(b)

FIGURE 3. Simulation result for case 1 at $k_p = 1$ and $k_i = 3$: (a) PI, (b) SIPIC

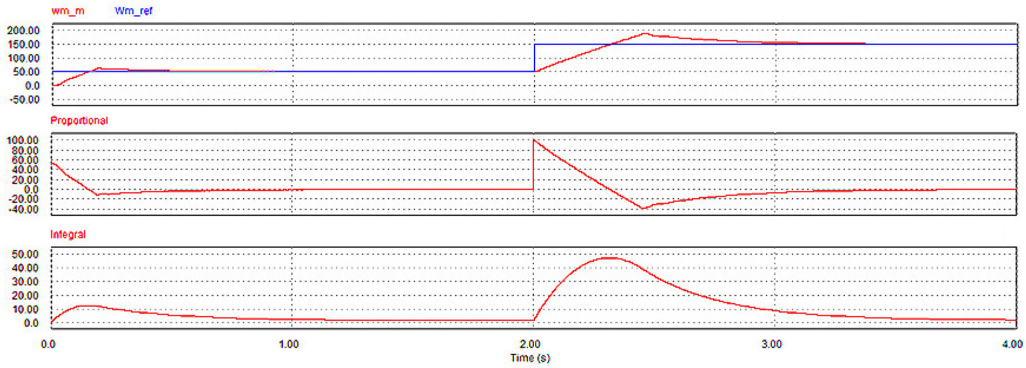


(a)

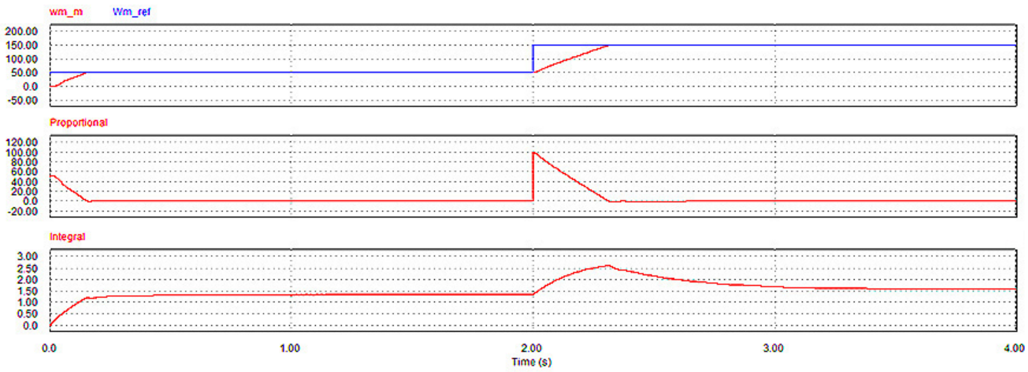


(b)

FIGURE 4. Simulation result for case 1 at $k_p = 3$ and $k_i = 1$: (a) PI, (b) SIPIC

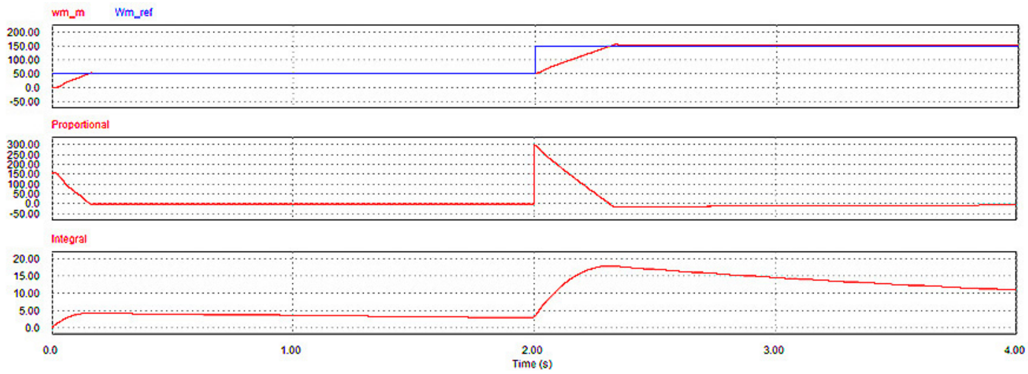


(a)

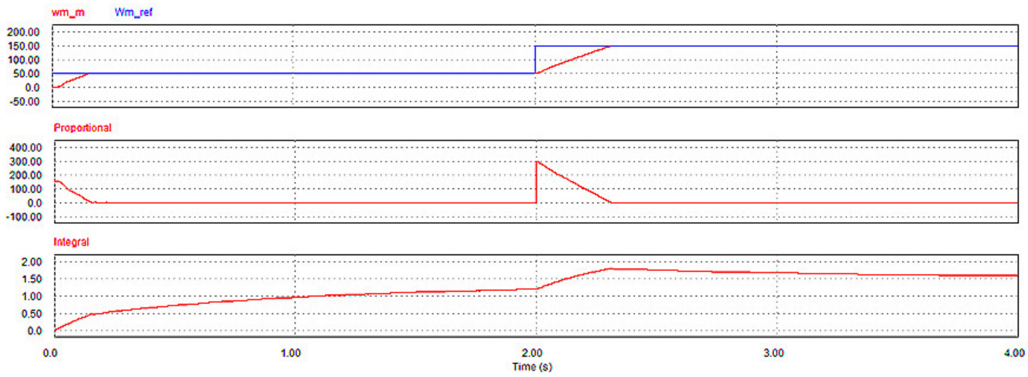


(b)

FIGURE 5. Simulation result for case 2 at $k_p = 1$ and $k_i = 3$: (a) PI, (b) SIPIC



(a)



(b)

FIGURE 6. Simulation result for case 2 at $k_p = 3$ and $k_i = 1$: (a) PI, (b) SIPIC

7. **Conclusion.** SIPIC shows an improved motor speed performance on the FOC PMSM control as compared to the conventional PI controller. The simulation result shows that SIPIC has lower overshoot percentage and short settling time regardless of the loading condition. PI controller may have smaller rising time in loading condition; however PI controller exhibits larger overshoot. In future work, SIPIC will be experimentally tested for different speed commands and other applications for further verification.

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