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NONLINEAR INTEGRAL CONTROL DESIGN FOR DC MOTOR SPEED CONTROL WITH UNKNOWN AND VARIABLE EXTERNAL TORQUE

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Abstract: In this work, a nonlinear integral controller is proposed for a Direct Current (DC) motor model in the presence of a variable and unknown external load and for a constant and variable reference velocity. The nonlinear integral term is designed simply by replacing the integral of the error function by the integral of a saturation error function to the error. By adjusting the saturation function parameters the proposed controller will have a robust properties against the uncertainty and the variation of unknown external torque. The numerical simulations explore the ability of the proposed controller in controlling the DC motor speed to a desired value for the constant and variable load and also for sinusoidal desired speed. In addition the results also compared with the classical integral controller to clarify the feature of the present controller.

Keywords: *DC motor*, *Speed control*, *Nonlinear integral control, Variable external torque*, *Constant and sinusoidal desired motor speed*.

تصميم مسيطر تكاملي غير خطي لغرض السيطرة على سرعة محرك تيار مستمر بوجود حمل خارجي متغير و غير معلوم القيمة

الخلاصة: في هذا البحث تم اقتراح مسيطر تكاملي غير خطي لغرض السيطرة على سرعة محرك تيار مستمر بوجود حمل خارجي متغير و غير معلوم القيمة. تم تصميم الميسطر باستبدال تكامل دالة الخطأ بدالة اشباع لتكامل دالة الخطأ. ان قابلية المسيطر على مقاومة الحمل الخارجي يمكن الحصول عليها من خلال اختيار القيم الصحيحة لمعاملات دالة الاشباع. تم اجراء محاكاة باستخدام الحاسوب لفحص قابلية الميسطر المقترح على السيطرة على سرعة المحرك الكهربائي و جعله يدور حسب السرعة المطلوبة سواء كانت ثابتة او متغيرة. بالاضافة الى ذلك تم مقارنة نتائج المسيطر المقترح مع نتائج مسيطر تكاملي خطي لايضاح خصائص المسيطر المقترح.

1. Introduction

D.C. motors are the most popular devices used to convert electrical energy to rotational motion, or, with some gearing, to deliver a translational motion. In many applications it is desired to keep the D.C. motor running at a specified angular velocity. However, this is not always an easy task for some reasons. One of the facing

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the D.C. motor speed control is the parameter identification. Mainly the D.C. motor model involves four parameters: armature resistance, armature inductance, armature moment of inertia and viscous friction. Obtaining these values is not as easy job and often requires a specialized measurement devices, and will not be such accurate as the real values.

Another major problem in the D.C. motor speed control is the unknown external load applied to the motor. If the load value is constant and known then it is possible to preset the power delivered to the motor to obtain the desired speed, but when the load value is unknown or variable then it is not possible to control the D.C. motor speed without referring to feedback control schemes.

The Proportional-Integral (PI) controller is one of the conventional controllers and it has been widely used for the speed control of dc motor drives. The major feature of the PI controller is its ability to maintain a zero steady-state error to a step change as reference input. However, the problem of tuning the PI controller emerges. Although many tuning methods were proposed in order to find the appropriate values for the PI controller gains such as Ziegler-Nichols tuning process, Cohen–Coon tuning process, etc., the tuning methods results could be inaccurate and the tuned PI controller gains might be far from the ones which give a satisfying performance. In addition, different operating speeds require different gains in order to avoid overshoots and oscillations [1].

Robust control schemes are widely applied to the D.C. motor speed control since they are developed to overcome uncertainties in plant model and external loads. Adaptive control methods are widely used since it’s not necessary to know the exact model.

Kassem and Yousef [2] were scheduling adaptive controller to overcome changes in external load. The controller gains are designed in order to keep the motor running at the desired speed.

Butler et al [3] assigned an adaptive model reference control where the real time motor output is compared with a pre-assigned model and the difference between them was fed to the controller in order to make the real time model follows the assigned model.

Another famous robust control scheme is the sliding mode control which is widely applied to systems where the exact model of the physical plant is unknown or has uncertain parameters. The most powerful aspect for the sliding mode controller is its high insensitivity to the model parameters variation within certain bounds.

Afrasiabi and Yazdi [4] designed a sliding mode controller (SMC) for the D.C. motor speed control and compared with the performance of both a conventional PID controller and fuzzy controller and the results showed that the sliding mode controller gave the most satisfactory performance especially dealing with overshoot damping.

Rhif [5] proposed the sliding mode controller for disturbance rejection (i.e. external loads and torques) acting on the D.C. motor which mostly affects the steady state performance. The simulations showed that the load was almost ineffective but within certain bounds. However, two problems are limiting the applicability of the sliding mode controller to the DC motor speed control. The first is the chattering in system response which it is the well-known drawback of the sliding mode control and the matching condition. The DC motor model does not satisfy the matching condition since the external load not acting in the same control input channel which it is (the matching property) the required property for the robustness of the SMC.

In the present work a nonlinear integral controller for the permanent magnet DC motor speed control is proposed in the presence of unknown and variable external load and for constant and variable desired speed. The nonlinear PI controller is simply constructed from a linear PI controller but with integral term using the saturation function rather than a linear relation with the state.

2. Mathematical Model and Problem Statement

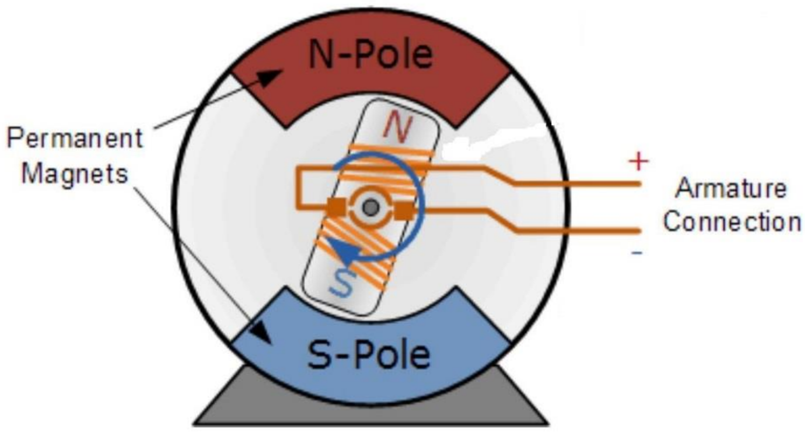


Figure (1): Basic sketch for permanent magnet DC motor.

The state space model of the permanent magnet D.C. motor in figure (1) above is represented as below [4].

$$\dot{x} = Ax + Bu + Hd \tag{1}$$

Where

$$x = [x_1 \quad x_2]^T = [\omega \quad i_a]^T$$

$$A = \begin{bmatrix} -\dfrac{b}{J} & \dfrac{K_t}{J} \\ -\dfrac{K_b}{L_a} & -\dfrac{R_a}{L_a} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \dfrac{1}{L_a} \end{bmatrix}, H = \begin{bmatrix} -\dfrac{1}{J} \\ 0 \end{bmatrix}$$

In this model ω is the angular velocity (rad/sec), i_a is the armature current (Amp). K_t and K_b are the motor torque and back emf constants respectively. J, b, L_a and R_a are the armature moment of inertia $(kg \cdot m^2)$, rotational friction coefficient (N·m·sec/rad), armature inductance $(Henry)$ and armature resistance (Ohm) respectively, d is the disturbance torque acting on the motor $(N \cdot m)$ and u is the control action $(Volts)$.

The disturbance d can be expressed as below:

$$d = t_L + \Delta \tag{2}$$

where t_L is the external load torque and Δ is the un-modeled torques that may acting on the motor like the coulomb friction.

In order to design a suitable controller for the D.C. motor speed it is often preferred to determine the above motor parameters. However, as mentioned earlier in section (1), determining the values of motor parameters is not a straight forward task especially when they are not supported by the manufacturer and requires specialized measuring equipment and the estimation might be approximate but not accurate. Besides, some of the parameters may change during the motor operation such as load friction, load moment of inertia and armature resistance. In addition, the electrical motors; including the D.C. motors, are subjected to a wide range of external loads depending on the application the motors are used for and may vary even for the same application which adds another challenge for the work. For this reason its necessary do develop a controller which can overcome the variation in the D.C. motor model and the external load torque which supposed to be varying with time.

3. Steady State Conditions and the Nonlinear PI Controller Design

In this section the steady state condition is derived for the DC motor model and then the nonlinear PI controller is designed for it.

First, let the error vector be defined as follows: $e = [e_1 \quad e_2]^T = [(x_1 - \omega_d) \quad i_a]^T$ where ω_d is the desired angular velocity (rad/sec), then the system represented in Eq. (1) is rewritten as below:

$$\dot{e} = \begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \end{bmatrix} = \begin{bmatrix} \dot{x}_1 - \dot{\omega}_d \\ \dot{x}_2 \end{bmatrix} = \dot{x} + \begin{bmatrix} -1 \\ 0 \end{bmatrix} \dot{\omega}_d = Ax + Bu + Hd + \begin{bmatrix} -1 \\ 0 \end{bmatrix} \dot{\omega}_d$$

Add and subtract ω_d from x_1 in the above equation then we get

$$\dot{e} = A \begin{bmatrix} x_1 - \omega_d + \omega_d \\ i_a \end{bmatrix} + Bu + Hd + \begin{bmatrix} -1 \\ 0 \end{bmatrix} \dot{\omega}_d = A \begin{bmatrix} e_1 + \omega_d \\ e_2 \end{bmatrix} + Bu + Hd + \begin{bmatrix} -1 \\ 0 \end{bmatrix} \dot{\omega}_d$$

Note that

$$A \begin{bmatrix} e_1 + \omega_d \\ e_2 \end{bmatrix} = Ae + A \begin{bmatrix} 1 \\ 0 \end{bmatrix} \omega_d = Ae + A_2 \omega_d$$

Where

$$A_2 = A \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} a_{12} \\ a_{22} \end{bmatrix} = \begin{bmatrix} -\frac{b}{J} \\ -\frac{K_b}{L_a} \end{bmatrix}$$

$$\dot{e} = Ae + A_2\omega_d + Bu + Hd + \begin{bmatrix} -1 \\ 0 \end{bmatrix} \dot{\omega}_d$$

Let

$$A_2\omega_d + \begin{bmatrix} -1 \\ 0 \end{bmatrix} \dot{\omega}_d + Hd = D\delta$$

Where

$$D = \begin{bmatrix} -\frac{b}{J} & -1 & -\frac{1}{J} \\ -\frac{K_b}{L_a} & 0 & 0 \end{bmatrix}$$

and δ is the perturbation term which it is given by

$$\delta = \begin{bmatrix} \omega_d \\ \dot{\omega}_d \\ d \end{bmatrix}$$

Finally the system of Eq. (1) can be written in error dynamics as equation below

$$\dot{e} = Ae + Bu + D\delta \tag{3}$$

Note that δ consists of the desired reference and its derivative, and the unknown but bounded disturbance ($d = t_L + \Delta$).

Let the PI controller be given by [6];

$$u = -k_1e_1 - k_2e_2 - k_3\int_0^t f(e_1)\,dt \tag{4}$$

Where $f(e_1)$ is continuous function of e_1. Now define $e_3 = \int_0^t f(e_1)\,dt$, then Eqs. (3) and (4) become;

$$\left.\begin{aligned} \begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \end{bmatrix} &= \begin{bmatrix} -\frac{b}{J} & \frac{K_t}{J} \\ -\frac{K_b}{L_a} & -\frac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} u + \begin{bmatrix} -\frac{b}{J} & -1 & -\frac{1}{J} \\ -\frac{K_b}{L_a} & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega_d \\ \dot{\omega}_d \\ d \end{bmatrix} \\ \dot{e}_3 &= f(e_1) \end{aligned}\right\} \tag{5}$$

$$u = -k_1e_1 - k_2e_2 - k_3e_3 \tag{6}$$

Where k_1, k_2 and k_3 are the controller gains associated with the PI controller and can be assigned using any possible tuning method which could be trial and error, Ziegler-Nichols or Cohen–Coon tuning process, etc.

For linear PI (LPI) controller $f(e_1) = e_1$, and hence Eq. (5) becomes;

$$\begin{bmatrix}\dot{e}_1\\ \dot{e}_2\\ \dot{e}_3\end{bmatrix}=\begin{bmatrix}-\frac{b}{J} & \frac{K_t}{J} & 0\\ -\frac{K_b}{L_a} & -\frac{R_a}{L_a} & 0\\ 1 & 0 & 0\end{bmatrix}\begin{bmatrix}e_1\\ e_2\\ e_3\end{bmatrix}+\begin{bmatrix}0\\ \frac{1}{L_a}\\ 0\end{bmatrix}u+\begin{bmatrix}-\frac{b}{J} & -1 & -\frac{1}{J}\\ -\frac{K_b}{L_a} & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\omega_d\\ \dot{\omega}_d\\ d\end{bmatrix} \quad (7)$$

If the poles of the error dynamics are selected with negative real values then the steady state conditions for the DC motor system dynamics, when δ is constant (i.e., ω_d and $d = t_L$ are constant values), is calculated as follows;

At the steady state condition $\dot{e} = 0$, then we have

$$\dot{e} = 0 = Ae + Bu + D\delta = (A - BK)e + D\delta$$

$$\Rightarrow e_{ss} = \begin{bmatrix}e_{1ss}\\ e_{2ss}\\ e_{3ss}\end{bmatrix} = -(A - BK)^{-1}D\delta \quad (8)$$

The most interesting result of Eq. (8) is the solution for $\dot{e}_3 = 0$. It is solved as;

$$e_{1ss} = 0 = x_1 - \omega_d$$

$$\Rightarrow x_1 = \omega = \omega_d \quad (9)$$

Equation (9) represents the control system objective which it also a consequent of using the integral term in the control formula. Note that the steady state conditions (Eq. (8)) for LPI controller is the equilibrium point.

For the general case where the perturbation term is variable the linear PI controller is no longer able to force the angular velocity to track the desired value. According to Khalil [7] when the perturbation term is not constant but bounded (i.e., $|\delta| < \hat{\delta} \;\; \forall t$) then the linear PI controller will be able only to bring the error state e to a region neighborhood to the $e_1 = 0$ i.e., the steady state is regulated to a region around the system equilibrium point. In this case a steady state error exists ($e_{1ss} \neq 0$) and the angular velocity of the D.C. motor will equal the reference value with steady state error e_{1ss}. This region is known as the area or region of attraction [Khalil 2002]. The following nonlinear PI (NPI) controller is used for the case of variable perturbation term and the goal is to minimize the steady state error e_{1ss}. The nonlinear PI control law that proposed in this work is:

$$u = -k_1 e_1 - k_2 e_2 - k_3 \int_0^t Sat_{\epsilon,\gamma}(e_1)\, dt \quad (10)$$

where $f(e_1) = Sat_{\epsilon,\gamma}(e_1)$ is the saturation function given by

$$Sat_{\epsilon,\gamma}(e_1) = \begin{cases} \frac{\gamma}{\epsilon} * e_1 & for\ |e_1| \le \epsilon \\ \gamma * sign(e_1) & for\ |e_1| > \epsilon \end{cases} \quad (11)$$

Where ϵ specifies the sensitivity of the saturation function and $\gamma(\epsilon, \gamma)$ a is function to the design parameters ϵ and γ and specifies the bound on the steady state error.

The e steady state condition is still as given in Eq.'s (8) and (9) but with the aid of the design parameters ϵ and γ, the area of attraction can be adjusted to become within the following interval;

$$|e_{1ss}| \leq \gamma(\epsilon, \gamma)$$

Accordingly the DC motor angular velocity will be bounded at steady state by

$$\omega_d - \gamma(\epsilon, \gamma) \leq \omega \leq \omega_d + \gamma(\epsilon, \gamma) \tag{12}$$

4. Nonlinear PI Controller Properties

Some useful properties are mentioned here for the proposed nonlinear PI (NPI) controller when compared with the LPI controller as follows;

1) Disturbance attenuation property: This property is a direct result of using a nonlinear integral term. A proper selection of the extra design parameters ϵ and γ will attenuate the disturbance effects δ. Note that the NPI controller use the same LPI control parameters (k_1, k_2 and k_3) and additionally add ϵ and γ to attenuate δ.
2) Lowering control effort: In general the integral term will yield large control value due to integration process. Replacing the linear integral function $\int_0^t e_1 \, dt$ by the nonlinear one $\int_0^t Sat_{\epsilon,\gamma}(e_1) \, dt$ will reduce the integration value especially for the time interval where $Sat_{\epsilon,\gamma}(e_1) < e_1$. Note that this property will also help to prevent the control wind up and in all cases will not exceed the control effort spent by the linear controller but batter performance.

5. Robustness of the Proposed Controller

As mentioned above the idea behind the present work is simply replacing the linear integral term by a non-linear one using the saturation function for the error instead of the linear traditional one. The question is from where the proposed nonlinear integral controller will have a stronger robustness property when compared with the linear integral one? The answer is adding two extra design parameters ϵ and γ help, with this proper selection, in attenuating the perturbation term effect and forcing the angular velocity to follow the desired reference. On the other hand, one can also outline a robustness prove of the NPI controller when compared with LPI as follows;

When the perturbation term is constant, the LPI will reject its effect and forcing the angular velocity to track the desired value. But for a bounded variable perturbation term the state will be regulated to a region around the origin (the origin here refer to $e_1 = \omega - \omega_d = 0 \Rightarrow \omega = \omega_d$) and the size of this region is directly depends on the perturbation bound and the LPI control parameters. In all cases (whether in linear or nonlinear structures) the perturbation attenuation ability depends mainly on the integral term, since it will integrated and increased with time trying to reject the perturbation. Unfortunately the integral term cannot remove variable perturbation term, rather than that the state will enters a certain invariant region near the origin and stay there for all future time without reaching the origin, because of a non-vanishing perturbation ([6] pp. 346) (where the perturbation term δ described above dose not vanish at $\omega = \omega_d$). The size of the invariant region (the region around the reference velocity) can be reduced via increasing the integral gain. The idea which is proposed here is to use an integral control for the error function with large gain when the state is near the origin ($\frac{\gamma}{\epsilon} k_3$) and with constant value outside it. In this case we preserve the integral control activity when the state starts away from the origin and the linear integral control ability in maintaining the state near the origin with a desired size. In this context a proper selection of the control parameters will enable our controller strongly attenuate to the non-vanishing perturbation with the desired steady state error.

6. Simulations and Results

The controller designed in section (3) is applied to the D.C. motor model in simulation performed using MATLAB. In a comparative view, the conventional PI controller is also applied to the motor in the simulation to show the difference. The desired angular velocity is taken first to be $\omega_d = 10 \frac{rad}{sec} = (300/\pi)\ rpm.$

To assign the values of the controller gains k_1, k_2 and k_3, the Ziegler-Nichols first method tuning rule is applied giving the following values:

$$k_1 = 0.566,\ k_2 = 0.566,\ \text{and}\quad k_3 = 0.8466.$$

Moreover for the nonlinear PI controller, the design parameters ϵ and γ are selected as;

$$\epsilon = 0.5 \ \text{ and } \ \gamma = 50$$

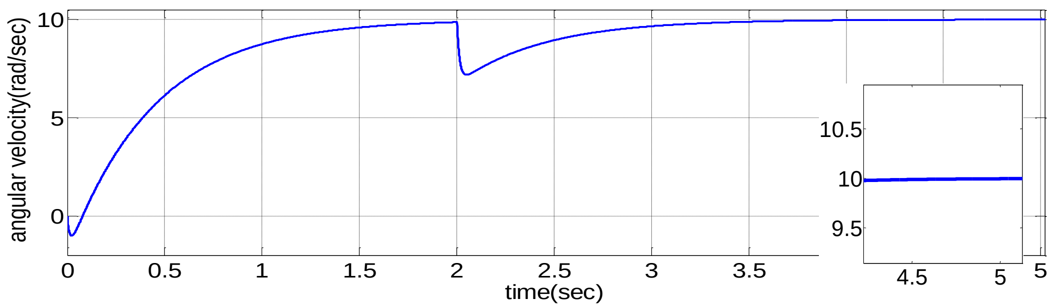
The motor parameters considered in the simulations are as in table (1) below:

Table (1): Permanent magnet DC motor parameters [8].

Parameter	Symbol	value	Units
Moment of inertia	J	0.0025	$kg \cdot m^2$
Rotational friction coefficient	b	0.136	$N \cdot m \cdot sec/rad$
Armature inductance	L_a	0.01	$Henry$
Armature resistance	R_a	5	Ohm
Motor torque constant	K_t	0.245	$N \cdot m/A$
Motor back emf	K_b	0.245	$V \cdot sec/rad$

The simulations are made in three parts, each considering a case for the external load as follows:

In the first simulation the load torque considered to be constant (i.e. $t_L = 0.5\ N.m$) and was applied after 2 seconds of running the motor. The results of applying the LPI controller are plotted in Fig. ٢. Then after that the results of applying the NPI controller are plotted in Fig.٣. As noted from the figures below, initially both the controllers succeed in driving the motor to the angular velocity. However, it's noted that with the linear PI controller the motor angular velocity reaches the desired value within about 2 seconds, while with the nonlinear PI controller the angular velocity reaches the desired value within about 1 seconds. In addition the control input voltage attains the same maximum or steady state value of NPI and LPI controller.



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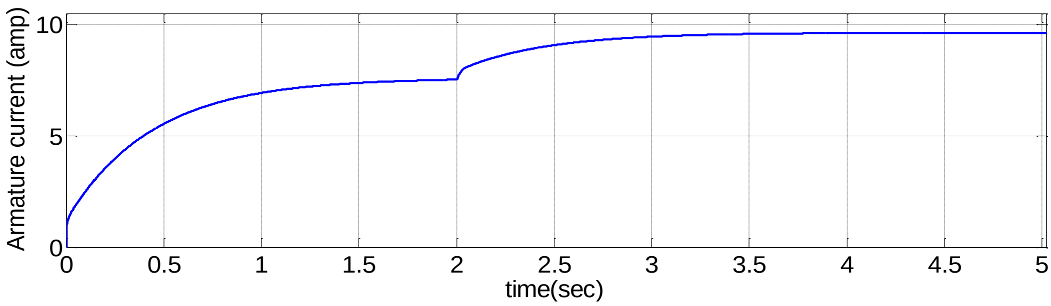

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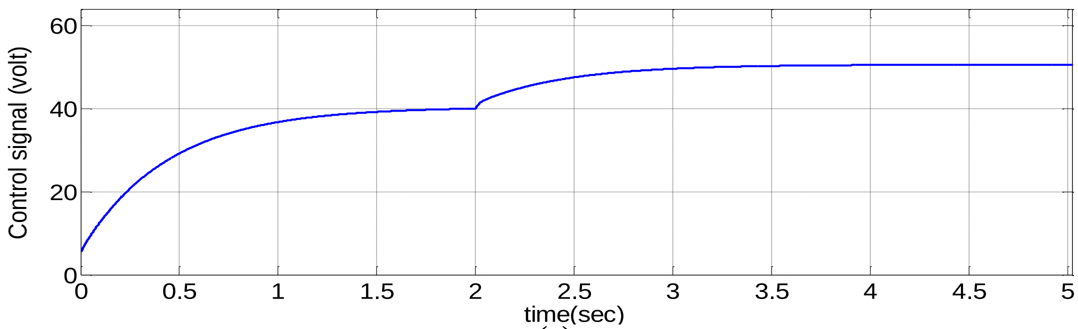
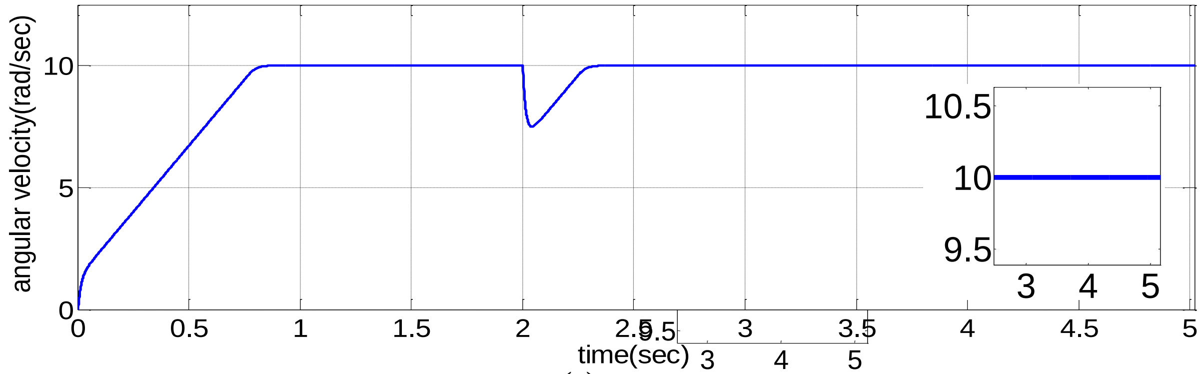


(c)

Figure (2): First simulation, load torque constant with the linear PI controller (a) Angular velocity (rad/sec), (b)Armature current (Amp), (c) Control voltage (volts).



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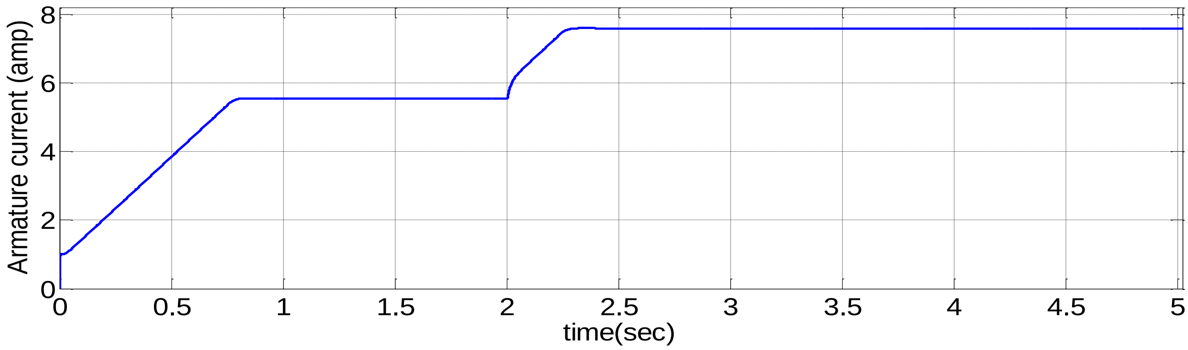

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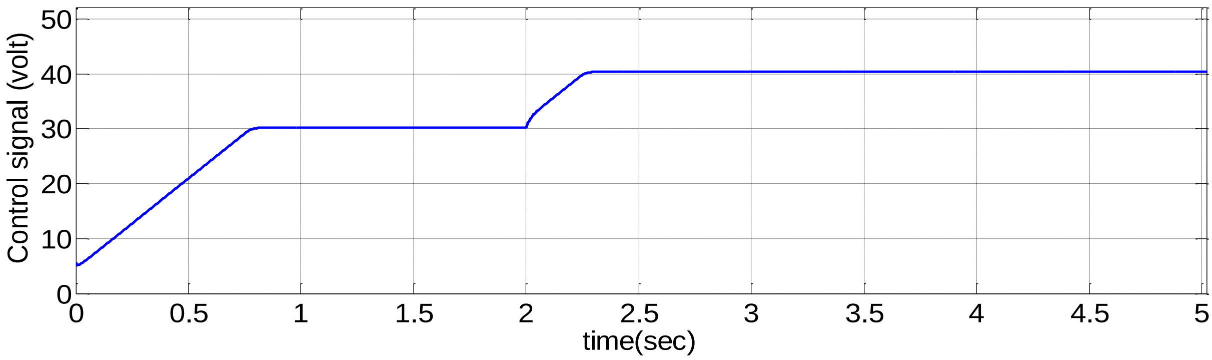


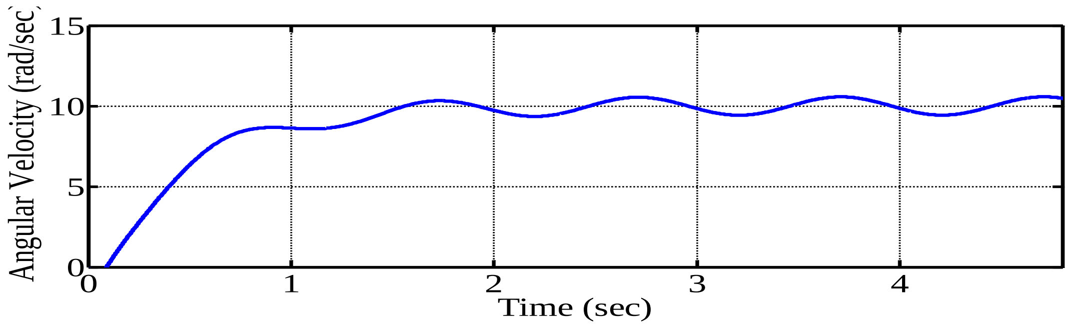
(c)

Figure (3): First simulation, load torque constant with the nonlinear PI controller
(a) Angular velocity (rad/sec), (b) Armature current (Amp), (c) Control voltage (volts).

In the second simulation, the load torque considered to be variable:

$$t_{L2} = 0.5 + 0.1 * \sin\left(\frac{2\pi}{10}t\right) \;\; N.m$$

The results of applying the LPI controller are shown in Fig. ٤, while the results of applying the NPI controller are shown in Fig. ٥. Simulations show that while the LPI controller struggles to keep the angular velocity oscillating near the desired angular velocity while the NPI controller force the angular velocity to reach the required value. The NPI compensates the change in the external load torque and consequently able to regulate the error between the angular velocity and the desired value to approximately zero within about 1.2 second. For comparison, the angular velocity in both linear and nonlinear PI controllers was plotted together in Fig. ٦ to give a more detailed point of view for the difference between the two cases.



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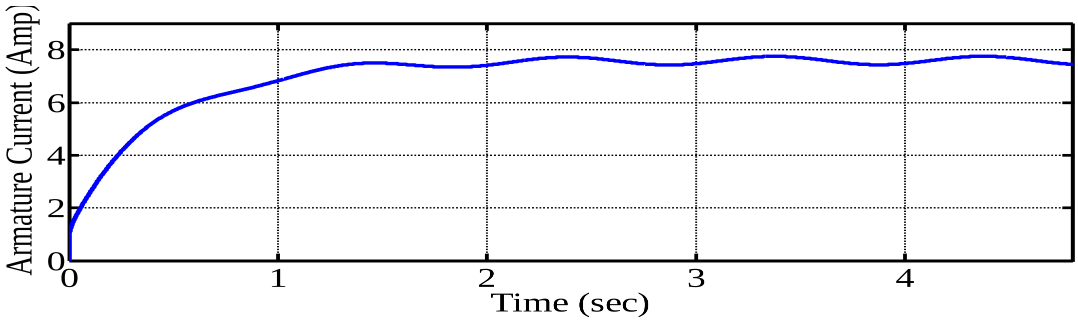

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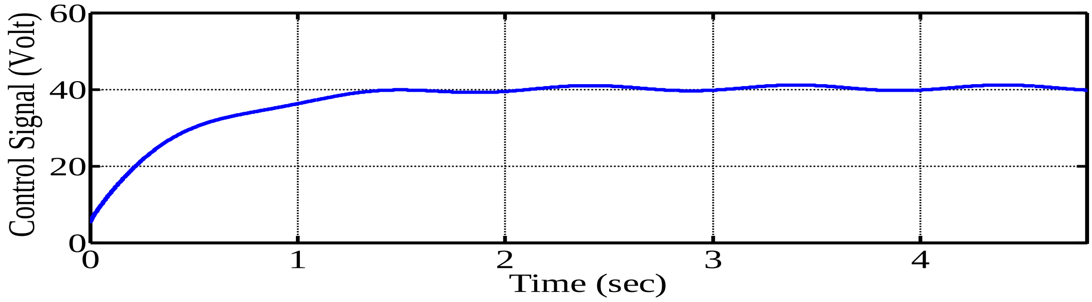


(c)

Figure (4): Second simulation, the load torque is varying with linear PI controller (a) Angular velocity (rad/sec), (b) Armature current (Amp), (c) Control signal (volts)

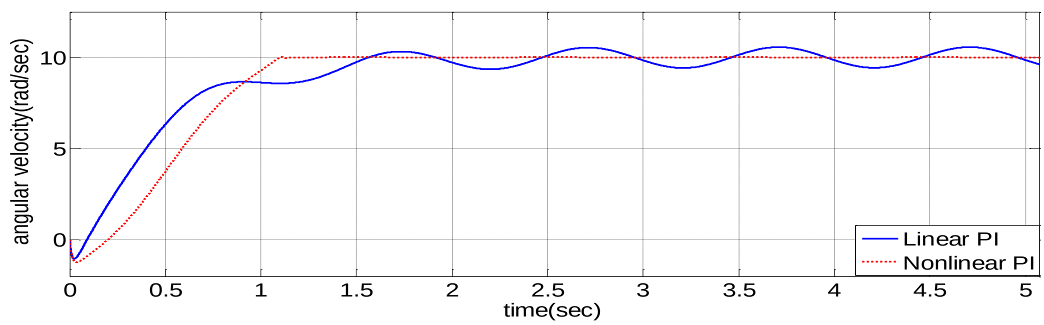
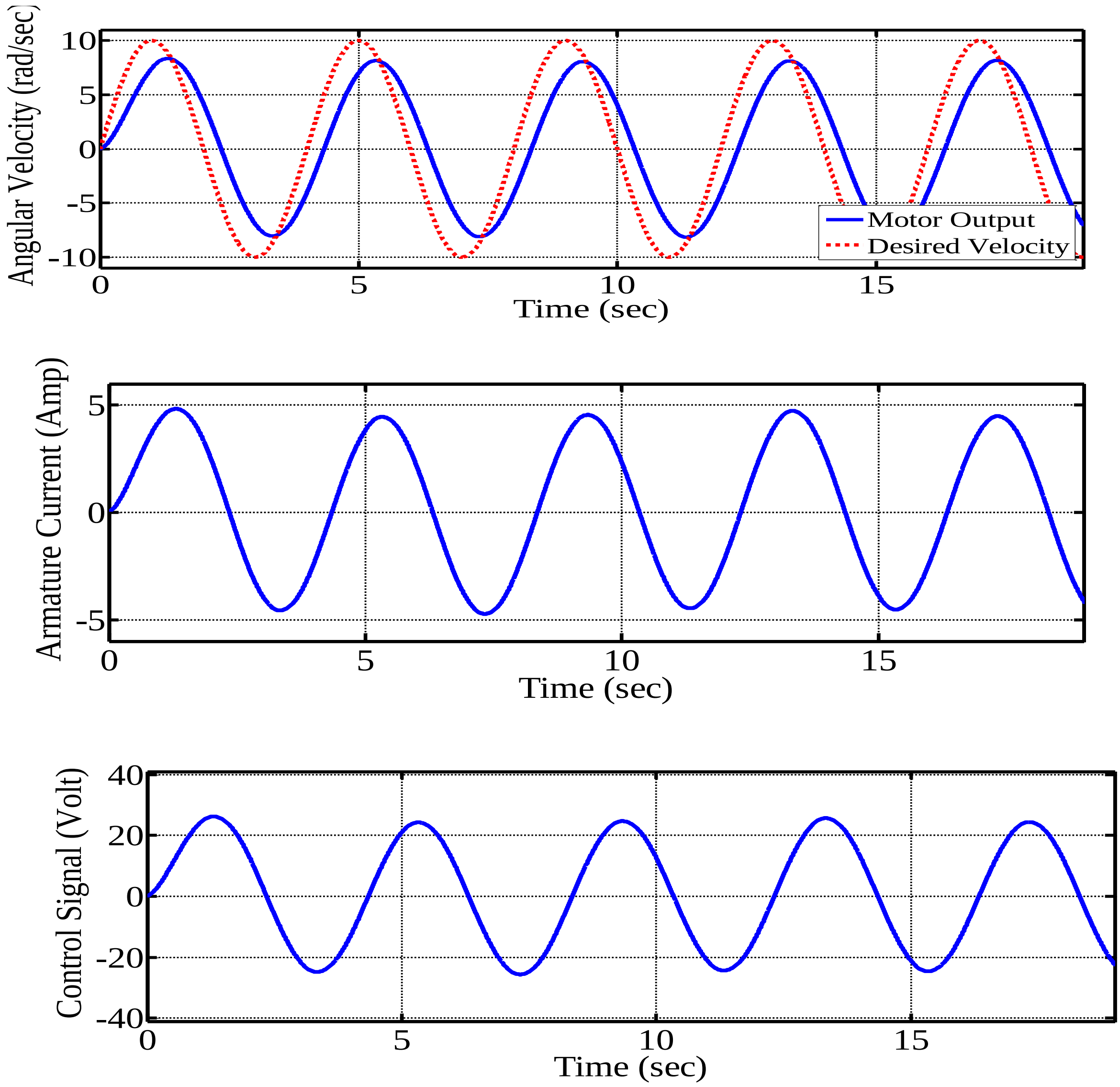


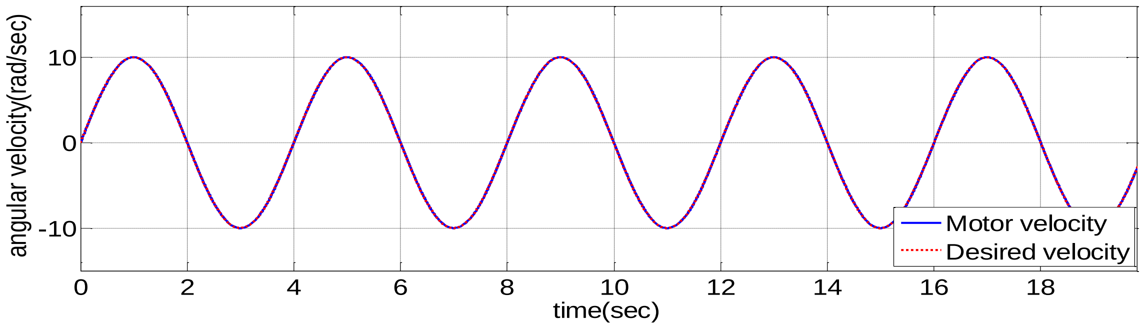
Figure (6): Comparison between linear and nonlinear PI controller.

Another simulation is held but this time with variable desired angular velocity in order to show the set point tracking ability for both linear and nonlinear PI controllers. The desired angular velocity is taken as $w_d = 10\sin(t)$ rad/sec. The results for the LPI controller are shown in Fig. ٧ and for the NPI controller are shown in Fig. ٨. The nonlinear PI controller shows the ability to track the desired value with a little error amount while the linear PI controller is not able to achieve that. In order to make the motor track the desired angular velocity the values of ϵ and γ have been changed to $\epsilon = 0.1$ and $\gamma = 100$.



(c)

Figure (7) Simulation with variable desired angular velocity for linear PI controllers (a) Angular velocity (rad/sec), (b) Current (Amp), (c) Control signal (volt).



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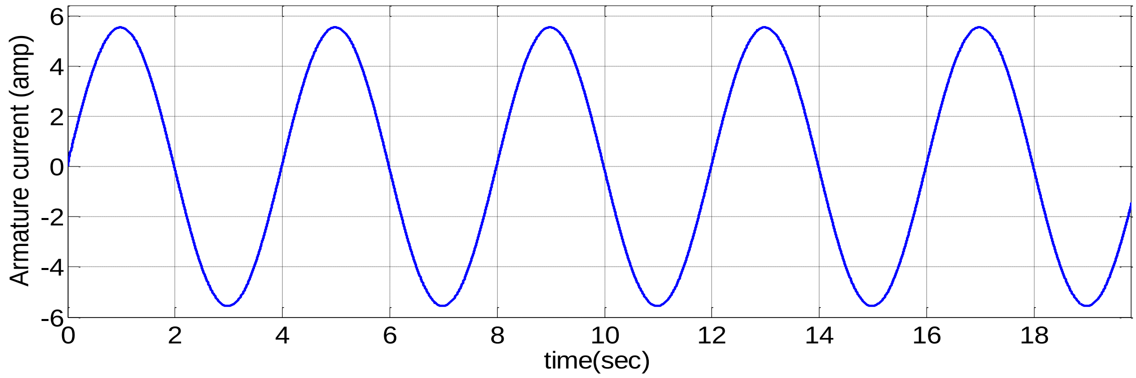

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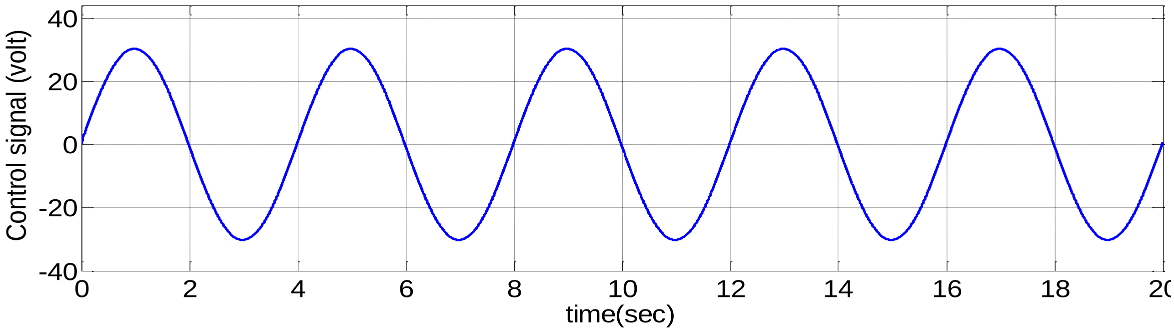
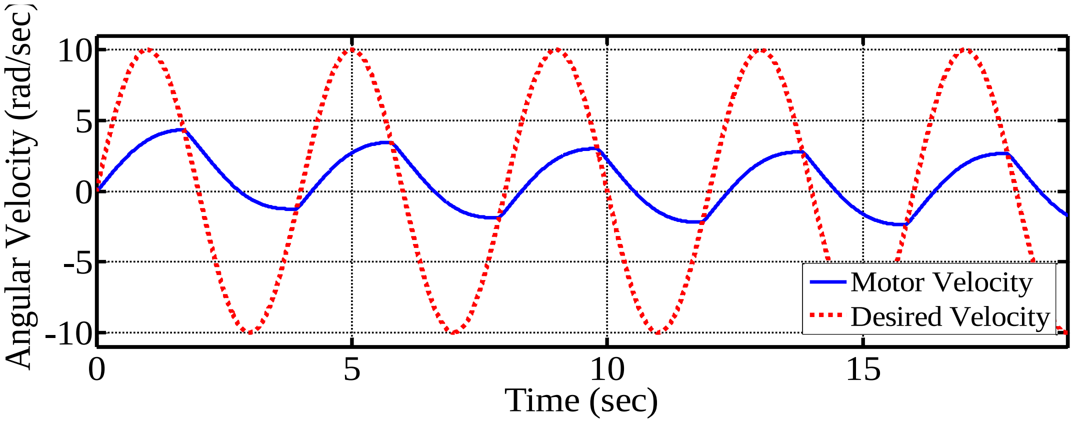
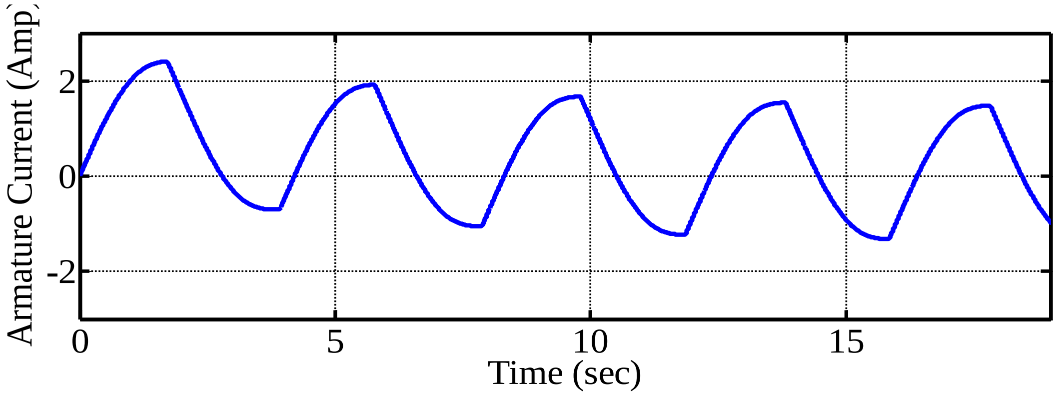


(c)

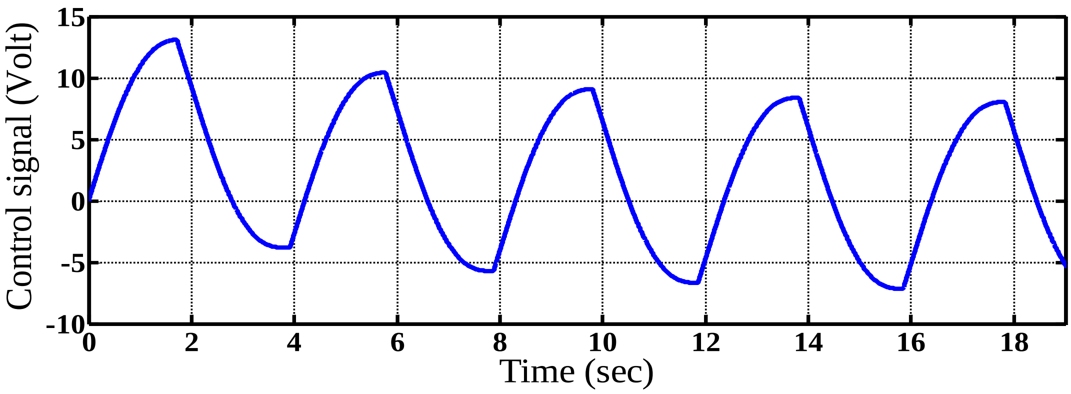
Figure (8) Simulation with variable desired angular velocity for nonlinear PI controllers (a) Angular velocity (rad/sec), (b) Armature current (Amp), (c) Control signal (volt).

Although the above simulations shows that the nonlinear PI controller have a better performance in both tracking and disturbance rejection, the performance of the nonlinear PI controller is mainly relies on the correct choice of both ϵ and γ and if an incorrect choice is made then the performance might be even worse than the linear PI controller. To view this point, a simulation was made taking an arbitrary value as $\epsilon = 0.1$ and $\gamma = 10$ and applied them to the case of variable desired angular velocity ($w_d = 10\sin(t)$ rad/sec.). The following simulations are aimed to show that unsuitable choice may lead to an undesired performance rather than improving it.





(b)



(c)

Figure (9) Simulation for the case of unsuitable choice for ϵ and γ in nonlinear PI controller (a) Angular velocity (rad/sec), (b) Armature current (Amp), (c) Control signal (volt).

6. Summary and Conclusion

A nonlinear PI controller is addressed in this study for the D.C. motor speed control. The motor model assumed to be linear with certain values for the parameters but the external load was considered uncertain and may vary its value during the motor operation. The proposed NPI controller use the same LPI control parameters (k_1, k_2 and k_3) and additionally added ϵ and γ to attenuate δ. Moreover, it can be noted that the extra design parameters ϵ and γ must be selected properly while a bad or unsuitable choice leads to a bad performance rather than improving it as shown in the final simulation test. Simulations were held to show the motor performance under the proposed controller and compared it with linear PI controller to show the difference. When the load considered being constant the motor took about 2 seconds to reach the desired angular velocity with the linear PI controller while with the nonlinear PI controller took less than about 1.2 second to reach the desired angular velocity.

Another simulation was made considering variation of external load torque during the motor operation. The nonlinear PI controller was able to bring the motor to the desired angular velocity while with the linear PI controller the motor will ripple around it. In both simulations shows that the nonlinear PI controller have the better performance whether it comes to improving the system speed or robustness and eliminating steady state error. Finally the performance of the proposed controller is tested where the requirement is to make the motor speed to follow a sinusoidal reference. The results prove the effectiveness of the NPI controller and it ability in forcing the motor speed to follow a variable speed.

7. References

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