



Crone Controller Based Speed Control of Permanent Magnet Direct Current Motor

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Abstract

Permanent magnet direct current (PMDC) motors are widely used in many systems. PMDC motors are characterized by large rotational torque. This torque is controlled using the system states, which are fundamental parameters, that affect the speed of PMDC Motors. Additionally, external influences like loading effect and environmental conditions generate disturbance torque on the motor's shaft. This affects the performance of the overall system by increasing the temperature and decreasing the frequency, which in turn affect the speed of PMDC motor. This paper presents the development of a CRONE Controller based Speed Control system for the Permanent Magnet Direct Current Motor in order to achieve a robust and more effective speed control. The PMDC motor speed control problem is transient in nature which is well suited for control using second generation CRONE control technique. Therefore, a second generation CRONE controller was used for the control of a PMDC Motor model developed in MATLAB Simulink. The performance of the developed controller was compared with that of particle swarm optimization (PSO) based PID controller using transient response performance measures, settling time and overshoot, as performance metrics. The second generation CRONE speed controller for the PMDC motor obtained a settling time of 0.018s and overshoot of 0.0001%. The PID-PSO controller based speed control of the PMDC motor obtained a settling time and overshoot of 0.2s and 1.87% respectively. The work is significant in conveyance systems due to its ability to reduce overshoot in the system thereby guarding against jerking in moving system.

Keywords: PMDC motor, disturbance torque, speed control, crone controller, PID-PSO

1. Introduction

PMDC motor poles are made of permanent magnets. The magnets, which are radially magnetized, are mounted on the inner part of the cylindrical stator which serves as a return path for the magnetic flux. Because of their adaptability, high quality, and ease of operation, PMDC motors are generally utilized over a wide range of applications; from toys to simple household tools and even complex systems such as rocket. Considering its applicability, the control of PMDC motors have attracted substantial research, which prompted the development of diverse methodologies. As such, numerous algorithms for position and speed control of the PMDC drive exists (Rathod *et al.*, 2014; Tang *et al.*, 2015; Dursun & Durdu, 2016; Aravid *et al.*, 2017; Obeng & Karam 2018).

A lot of factors may affect the performance of PMDC motors. Notable amongst them are the environmental loading conditions and working temperature. For instance, a variation in the motor's loading conditions produces a disturbance torque which causes equal variation in armature current and speed respectively. Consequently, information about the disturbance torque is usually used to achieve control of PMDC motors (Zwysig *et al.*, 2009). Similarly, disturbance torque is generated as a result of the motor temperature increase producing a variation in resistive circuit of the motor (Grignion, 2012).

Owing to simplicity in both structure and control strategy of PID, it is the most widely used control scheme for both position and speed control of PMDC motors (Charles *et al.*, 2015, Aravin *et al.*, 2017). However, PID control may not be always be adequate in mitigating the effects of disturbance torque on transient motor performance, especially in applications that are prone jerking such as conveyor systems. Hence, there is the need for the improvement of performance in such systems regulated by PID controllers. An approach to achieving this is via a more advanced control scheme. In this paper, a second generation CRONE based speed control strategy for PMDC Motor control is designed to address the limitations of PID control. This controller was considered because of its effect on improving transient response performance. Various industries use PMDC motor in conveyor system. In such systems, speed control has been one of the major challenges because of Jerking due high overshoot.

2. Related Works

Rathod *et al.*, (2014) presented an advanced controller, which uses two controllers, for the speed control of PMDC motors. The master PI controller handles the speed control as an outer loop and the current control was handled by the slave controller as inner loop in cascade arrangement. The output of the PI controller serves as the input to the current controller. In this work, the Ziegler-Nichols method was used to tune the controller. The cascade PI controller outperformed the ordinary PID controller in certain industrial applications. However, the control of PMDC motors was not explicitly considered. Taha *et al.*, (2015), on the other hand, compared the performance of a PID controller tuned using classical approach (Ziegler-Nichols), Bacteria foraging algorithm and Genetic algorithm for the speed control of PMDC motor. The simulation results showed that, Bacteria Foraging obtained a better dynamic response performance of the PMDC drive in both transient response and stability when compared to both the classical approach and the genetic algorithm. However, the effect of disturbance torque on motor's speed was not sufficiently handled.

Tang *et al.*, (2015) presented a criterion based on disturbance rejection and system robustness to evaluate the performance of PID controllers. The robustness was measured by a two-block structured singular value, and the disturbance rejection was measured by the minimum singular value of the integral matrix. Also, the performance of different PID tuning formulas were compared. Specimens in the work showed that the criteria can be applied to a variety of processes, whether they are stable, integrating or unstable, integrating or unstable; single loop or multi loop. This work provides a good range for robust measure to ensure good tradeoff between performance and robustness. However, the issue of disturbance torque was not considered.

Dursun & Durdu (2016) presented the speed control of DC motor with variable load using Sliding Mode Control (SMC) which is built on variable structure control to handle instability due modeling error of the DC Motor. The modeling of the DC Motor, designing the controller and overall analyses are performed using actual data. The simulation result shows that SMC gives improved results in terms of settling time, steady state error and rapid responses to disturbance as compared to PID controllers.

Aravid *et al.*, (2017) presented the speed control of PMDC motor with Linear Quadratic Gaussian (LQG) and extended Kalman filter (EKF). The LQG was implemented with the use of Kalman filter (KF) as an optimal estimator. The KF was unable to handle deviations in the system parameters that results in change from the estimated optimal performance. EKF permits for estimation of system parameters standards along with the unknown states of the system. The estimated values are frequently used to update the plant model and calculate

the gain for best performance. The simulation results showed improvements in tracking performance with the use of the EKF estimation along with the LQG controller.

More recently, Obeng & Karam (2018) presented PID speed control of PMDC motor tuned using Particle Swarm Optimization (PSO) algorithm with the goal of obtaining overshoot of less than 2% and settling time of less than 1ms. In the work, the PID gains were first determined using manual tuning, this led to an overshoot (OS) of 30.23% and settling time of 2.9ms from unit-step response of the PMDC motor angular speed. A PID-PSO algorithm was then developed to optimize the PID controller gains so as to achieve the optimization goal of reducing the OS and settling time. The simulation result showed that the OS reduced to 1.89% and settling time to 0.43ms. The developed PID-PSO based controller has much faster response than the response of the manual tuned PID controller.

From the reviewed literature, it is evident that speed control of PMDC motor has received significant research attention that leads to the development of different controllers. PID controller is one of the most widely used controllers for regulating the speed of the PMDC motor. However, the effect of disturbance torque which increases the temperature of the shaft of the motor and in turn decreases frequency of rotation has not been completely addressed. Therefore, the need for the development of robust controller (second generation CRONE controller) for speed control of PMDC motor that will guarantee steady motor speed irrespective of the variation of the system parameters.

2.1 Theoretical Review

In this section, the fundamental concepts to this work such as, the DC Motor model, Permanent Magnet DC Motor (PMDC) drive and fractional order controllers (CRONE) are reviewed.

2.1.1 Crone Control Techniques

The CRONE controller is a fractional order robust control scheme using fractional order derivatives as high-level design parameters. This controller is a frequency domain method based on unity feedback arrangement which allows linear robust control systems to be simple and rationally designed. CRONE is the French acronym of 'Commande Robuste d'Ordre Non Entier' were given in the second half of 1970s, when Oustaloup synthesized fractional order controllers for strong control of continuous colorant lasers (Oustaloup, 1975; Oustaloup & Coiffet, 1983; Sabatier et al., 2002).

The CRONE controller is structured dependent on the normal solidarity input design (Figure 1), which the vigorous controller or open-circle exchange work is characterized utilizing vital separation with non-whole number (or fragmentary) arrange (Lanusse et al., 2008). The required strength is that of both dependability edges and execution and especially the heartiness of the pinnacle esteem (called full crest) of the corresponding affectability function (Lanusse et al., 2013).

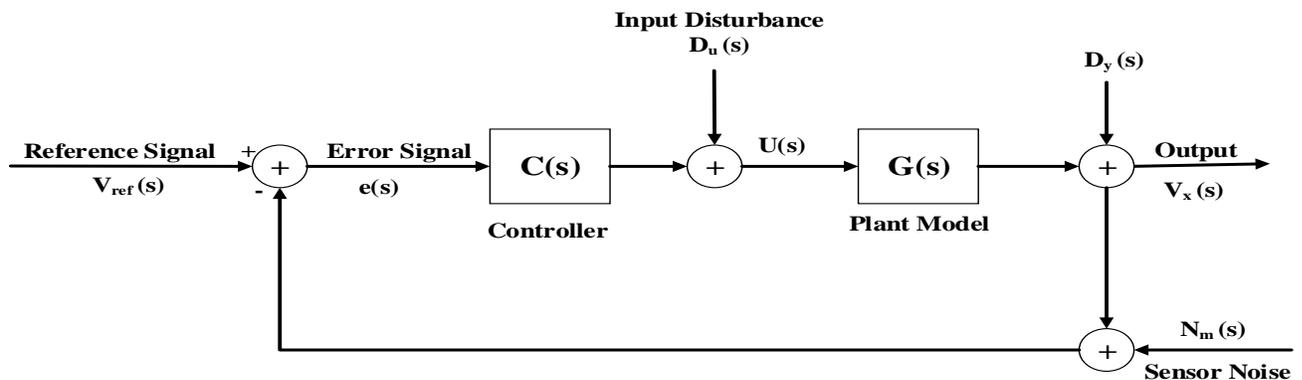


Figure 1: Common CRONE Control System Diagram (Lanusse *et al.*, 2008)

2.1.2 Second generation CRONE control strategy

This is connected to a framework, when varieties of the plant are increase like around crossover frequency ω_{cg} , the control dropped the plant phase variety, as for frequency. The controllers give a consistent open-loop phase (genuine fractional-arrange combination) whose Nichols locus is an opposite straight line called a frequency layout as appeared in Figure 2. This additionally speak to what Bode, in 1945, accepted could be conceivable (Bode, 1945). This model ensures the quality of phase and modulus edges and of booming peaks of corresponding sensitivity and sensitivity capacities.

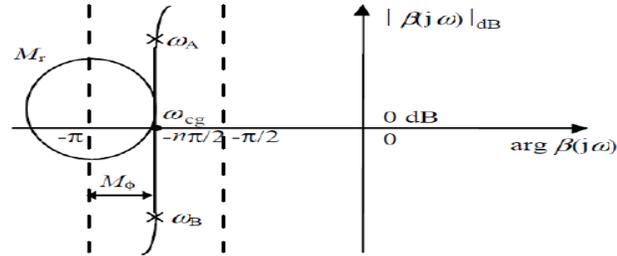


Figure 2. Frequency Template whose Nichols Locus is a Vertical Straight Line (Sabatier *et al.*, 2002)

The second generation CRONE approach describes the open-loop transfer function about the crossover frequency (ω_{cg}) as the transfer function of a fractional-order integrator, as follows (Lanusse *et al.*, 2013)

$$\beta_F(s) = \left(\frac{\omega_{cg}}{s}\right)^{n_1} \text{ with } n \in \mathbb{R} \quad (1)$$

For the nominal open-loop transfer function for the CRONE second generation controller to handled accuracy, robustness and control effort problems, using integer order n_l and n_h , is defined by (Lanusse *et al.*, 2013):

$$\beta(s) = k_0 \left(\frac{1+s}{w_1}\right)^{n_1} \left(\frac{1+s}{w_h}\right)^n \frac{1}{\left(1+\frac{s}{w_h}\right)^{n_h}} \quad (2)$$

Where k_0 is a gain; w_l and w_h are the transitional low and high frequencies, respectively; n_l is the order at low frequencies; n is the order around crossover frequency w_u ; n_h is the order at high frequencies;

When the nominal open-loop transfer is determined, the fractional controller $C_F(s)$ is defined by its frequency response (Lanusse *et al.*, 2013):

$$C_F(j\omega) = \frac{\beta(j\omega)}{G_0(j\omega)} \quad (3)$$

whose phase is variable and where $G_0(j\omega)$ designates the nominal frequency response of the plant.

The iterative conveyance of poles and zeros of the entire open circle fractional integrator exchange function $\beta(s)$ results in sound request open circle fractional integrator exchange function $\beta_R(j\omega)$. Beginning with this attainable normal order Second generation CRONE controller $C_R(j\omega)$ is attained as (Lanusse *et al.*, 2013):

$$C_R(j\omega) = \left(\frac{\beta_R}{G(j\omega)}\right) \quad (4)$$

2.1.3 Speed Control of Permanent Magnet Dc Motor

The Circuit diagram representing the dynamics of PMDC motor is as shown in Figure 3.

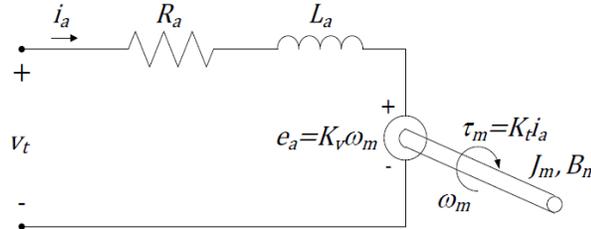


Figure 3: Schematic Diagram of PMDC Motor (Grignion, 2012)

From Figure 2.8 above, V_t is the input voltage, i_a is the armature current, R_a is the armature resistance, L_a is the inductance resistance, e_a is the back e.m.f, T_m is the torque, J_m is the inertia, K_b is the back e.m.f. constant, B_m is the damping ratio, K_t is the torque constant and ω_m is the angular speed. The transfer function $G(s)$ of the PMDC motor is defined in equation (2.24) (Grignion, 2012):

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{K_t}{(sJ+B)(R+sL)+K_tK_b} \quad (5)$$

Where $G(s)$ is the plant transfer function, $\omega(s)$ is speed of PMDC motor as output, $V(s)$ is the input voltage, K_t is the torque constant, K_b is the back electromotive force (e.m.f.) constant, R is the armature resistance, L is the Armature Inductance, J is the Inertia and B is the damping ration. Table 1 shows the values of PMDC motor parameters used in this work.

Table 1: Permanent Magnet DC Motor Parameters

| Parameter | Value | Unit |
|-----------|---------|---------------------------|
| K_t | 0.072 | Nm/A |
| J | 0.0005 | Kgm^2/rad |
| B | 0.00021 | Nms/rad |
| R | 0.5 | ohms (Ω) |
| L | 0.002 | H |
| K_b | 0.072 | Vs/rad |

Substituting the parameters of the PMDC motor in equation;

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{0.072}{0.002s^2+0.002504s+0.06234} \quad (6)$$

2.1.4 Crone Controller Design

The crone controller was developed using Simulink design and crone control tool box respectively.

Figure 4 presents the developed Simulink model for Crone controller speed control of PMDC. A unit step signal was applied to the system as desired output and the controller accept the error between it and the actual output to generate a manipulated signal as control input to the system. This is to ensure that the controller keeps track of the desired speed even in the presence of input disturbance. Three performance indices were used to evaluate the performance of the controller: Integral Square Error (ISE), Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE). Transient response of the system is obtained to determine the characteristics of the system under each performance index.

However, to evaluate the performance of the developed Crone controller under different scenario of input disturbance, a PID-PSO controller based speed of PMDC by (Obeng & Karam 2018) was considered. The Simulink model of the controlled system is presented in Figure 5:

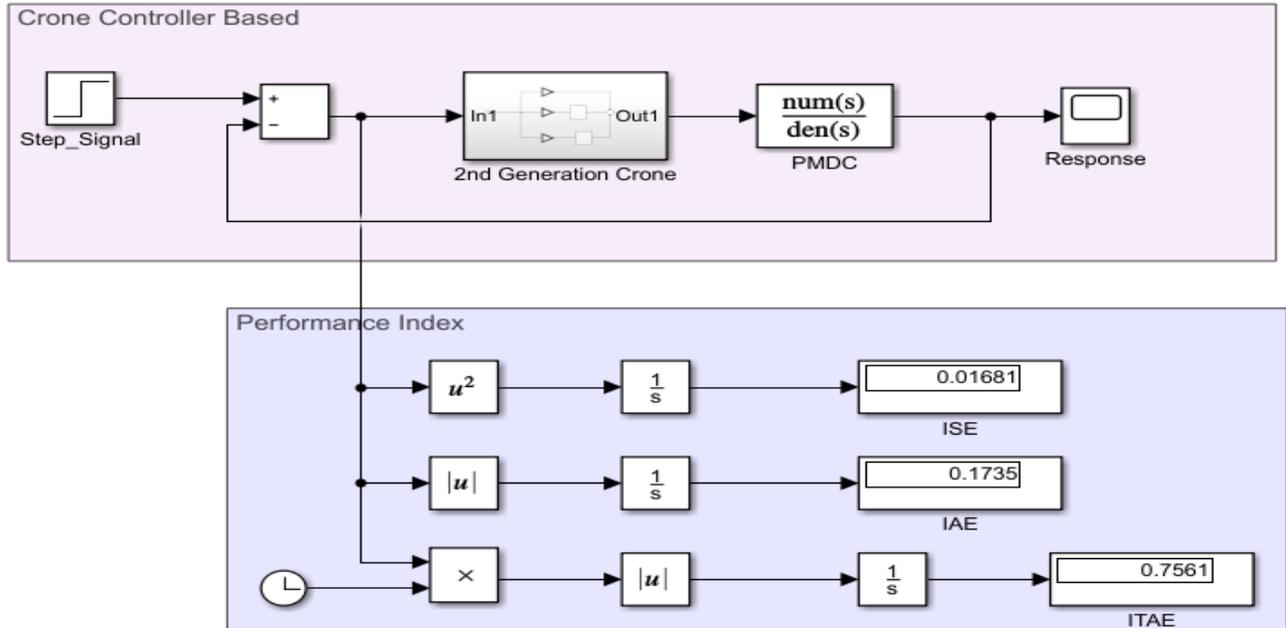


Figure 4: Simulink Model for Crone Controller based Speed Control of PMDC

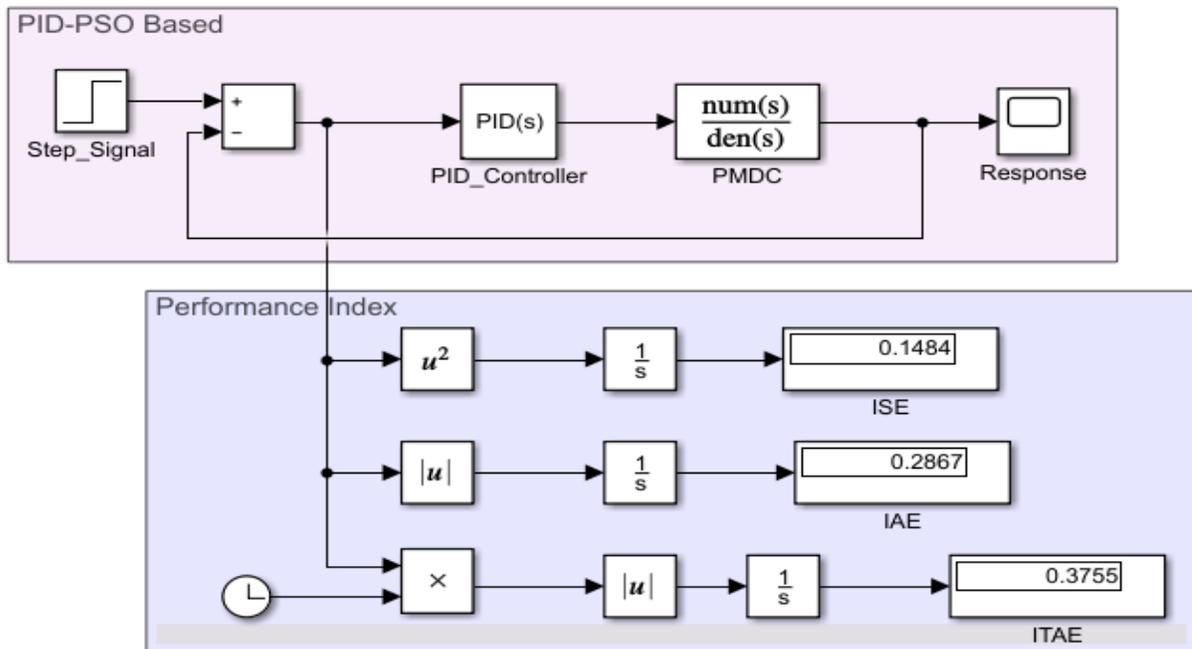


Figure 5: Block diagram for testing the performance of CRONE based PMDC speed controller

3. Result and Discussion

This section presents the results of the uncontrolled and controlled systems.

3.1 Time Response for PMDC motor

This section shows the step response of PMDC motor obtained from the transfer function in equation (7).

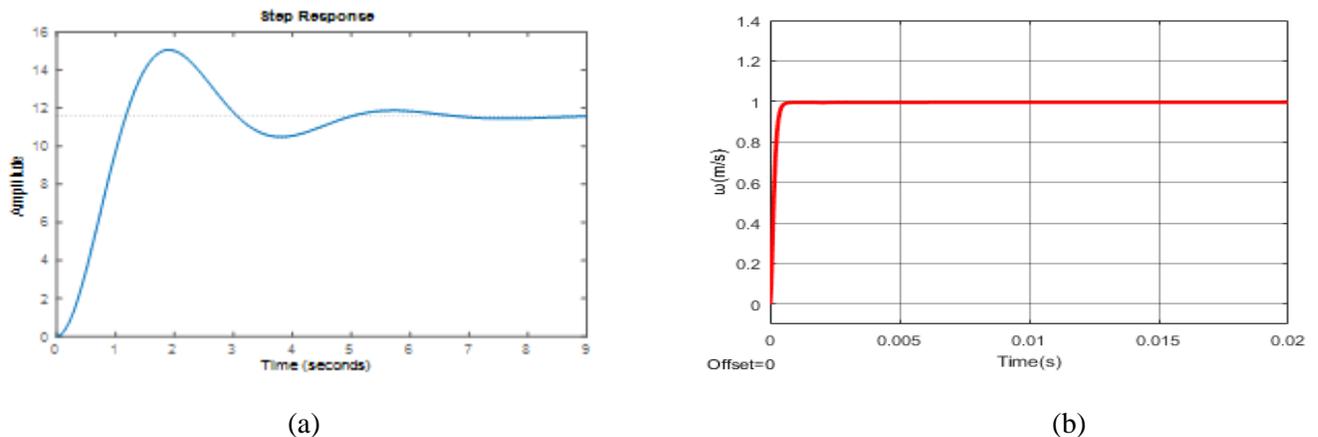


Figure 6: Step Response of Uncontrol and Control System (a) System Response of PMDC and (b) Crone Controller Based Speed Response of PMDC

Figure 6 shows the step response of the PMDC motor without controller (uncontrol system) and PMDC motor with controller (control system). From the step response of Figure 6(a), the uncontrol system has a settling time of 6.2s, rise time of 0.793 s, steady state error of 0.0001m and overshoot of 30.4%. This clearly shows the need for a controller so that the system can meet up with the design specification (settling time of less than 1second and overshoot of less than 2%) irrespective of the external disturbance. It can be observed from Figure 6(a) that the actual speed exceeded the desired speed of 1rad/s and which take more than 2s to settle down. It is clearly observed that the open loop test will not satisfy the desired design requirements. So, the system needs closed loop robust controller in order to achieve the design requirements.

Figure 3(b) shows the time response of the CRONE based speed controller, the model response and the controlled variable. The controlled variable was able to settle at 0.0018s with overshoot of 0.001%. This implies that the CRONE controller is adopted in speed control of PMDC motor to stabilize speed of the PMDC motor as well as to exhibit better dynamic behavior such as nullification of peak overshoot and get less settling time. Hence, it is suitable for control of system where robustness is desired.

3.2 Performance Comparison of Crone Controller and PID-PSO Based Speed Controllers for PMDC

The performance of the developed Crone based controller is compared with that of the PID-PSO based controller using settling time, overshoot and steady state error as performance metrics. The results are compared based on the three performance indices (ISE, IAE and ITAE). Figure 7 present the response of the two controllers on PMDC. From Figure 7, it can be seen that the Crone based controller was able to track the desired with minimum or no overshoot while the PID-PSO controller tracked the desired speed but with an overshoot. The characteristics of the system under both controllers are tabulated in Table 2:

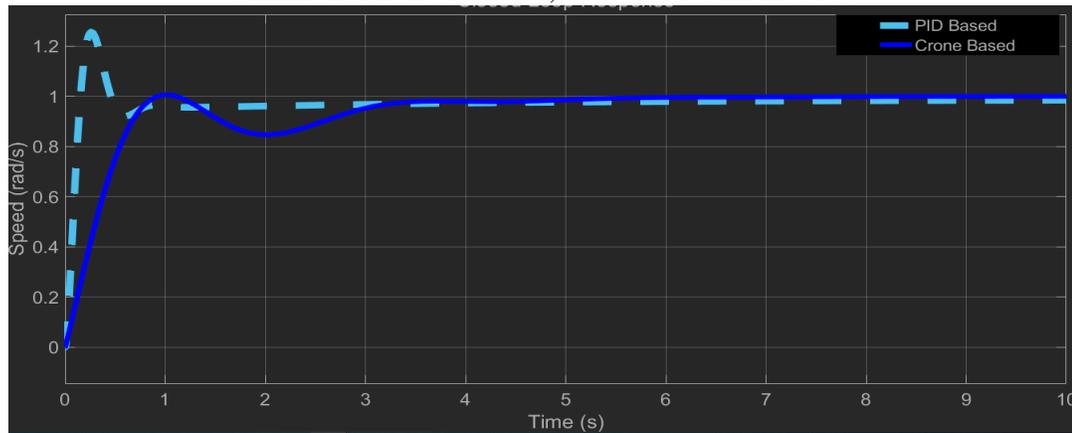


Figure 7. Response for Crone and PID-PSO Based Controllers

Table 2. Performance Indices of the Speed Controllers

| | PID-PSO CONTROLLER | | | CRONE CONTROLLER | | |
|--------------------|--------------------|--------|--------|------------------|--------|--------|
| | ISE | IAE | ITAE | ISE | IAE | ITAE |
| Settling Time | 6.950 | 12.040 | 11.110 | 2.810 | 0.182 | 0.184 |
| Peak Overshoot | 1.24 | 1.32 | 1.27 | 0.0078 | 0.0001 | 0.0012 |
| Steady State Error | 0.24 | 0.32 | 0.27 | 0.922 | 0.0921 | 0.9079 |

Table 2 shows the characteristics of the system under the action of the two controllers with respect to the performance. The result shows that the Crone based controller outperformed the PID-PSO based controller with regards to settling time, overshoot and steady state error. This shows the effectiveness of the Crone based controller in generating a better system response as compared to the PID-PSO. However, the PID-PSO based controller obtained better steady state error when the performance index is ISE. This implies that, in any application that requires steady state error and the performance index is ISE, the PID controller can be considered.

3.3 Performance Comparison of the Controllers Based on Disturbance Rejection

The developed control system is subjected to disturbance rejection test using an input impulse signal introduced for a duration of 0.3s, 0.6s and 0.9s so as to determine the effectiveness of the CRONE and PID-PSO based controllers. The disturbance is introduced into the system periodically to check for controller's disturbance rejection capability. The distinctive durations are illustrative of the conceivable periods of disturbances such as loading effect or environmental condition. These conditions cause increase in temperature that leads to the decrease in frequency of the system which in turns decreases the speed of the PMDC motor. The chosen intervals are to give an idea of the behavior of the system irrespective of the magnitude of the input disturbance signal to the system. The response for second generation CRONE based speed controller and that of a PID-PSO based speed controller with respect to disturbance rejection are shown in Figures 8.

From Figure 8, the response of the second generation CRONE controller and that of the PID-PSO based controller with respect to the input disturbance are respectively presented as CV (control variable) CRONE and CV (control variable) PID-PSO. It is obvious from the Figure that the CRONE controller was able to track the reference signal and it takes 0.03s to totally stabilize the system, when the disturbance was introduced. This shows clearly how CRONE controller guarantees better system performance in the presence of a disturbance. While the PID - PSO based controller was able to trace the desired reference signal and bring the system to steady state at 0.06s after the introduction of disturbance of duration of 0.02 and period of 0.3s. The PID-PSO based controller was not able to completely reject the disturbance. This shows that it is highly sensitive to disturbance but has less capability to disturbance rejection.

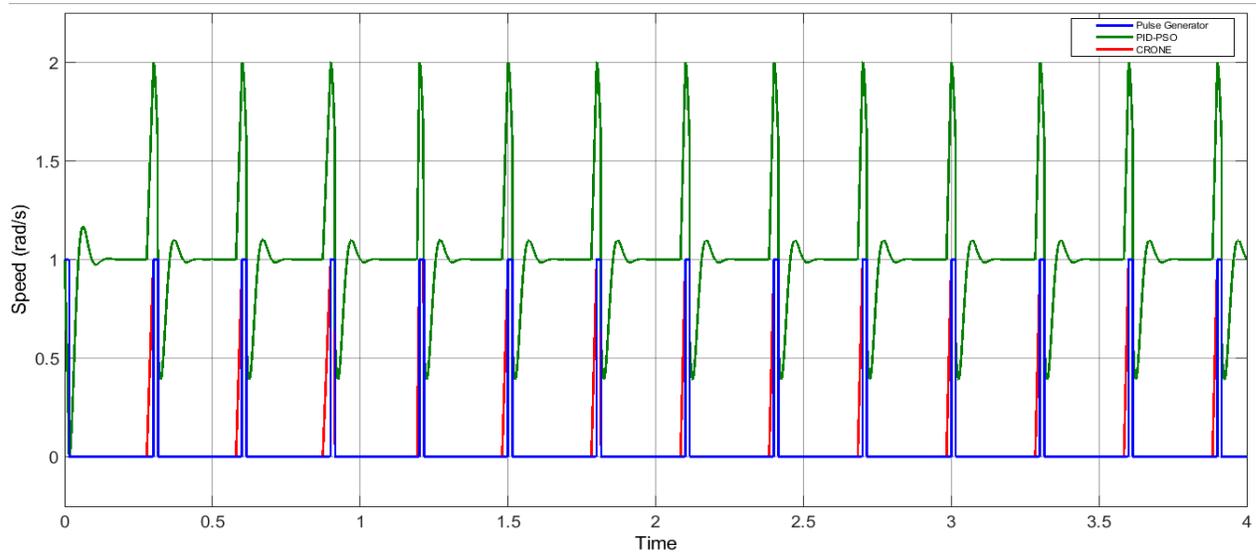


Figure 8. Response for Second Generation CRONE based and PID-PSO based Speed Controller (0.3s Impulse Period)

Table 3: Disturbance rejection time

| Period of Impulse Signal | Time taken to reject disturbance | |
|--------------------------|----------------------------------|--------------------------|
| | Crone based Controller | PID-PSO based Controller |
| 0.3 | 0.030 | 0.060 |
| 0.6 | 0.030 | 0.061 |
| 0.9 | 0.031 | 0.056 |

Table 3 presents the simulation results of the two controllers based on the introduction of impulse disturbance with different periods. It is obvious that the Crone controller is a robust controller as it maintains its effectiveness in controlling the system with or without the introduction of the disturbance.

4 Conclusions

The development of a CRONE controller based speed control of PMDC Motor has been presented. The second generation CRONE based-controller was used for the speed control of Permanent Magnet DC Motor. The performance of the developed controller was compared with that of PID-PSO based controller in terms of settling time, overshoot and steady state error using three different performance indices (ISE, IAE and ITAE). The second generation CRONE speed controller for the PMDC motor obtained a settling time of 0.018s and overshoot of 0.0001% while the PID-PSO controller based speed control of the PMDC motor obtained a settling time and overshoot of 0.2s and 1.87% respectively. These results show that the second generation crone controller outperformed the PID-PSO based controller in terms of settling time and overshoot across all the three performance indices. This proves the robustness of the Crone based controller under different types of input disturbance. The work has applications in conveyance systems due to its ability to reduce overshoot in the system thereby guarding against jerking in moving system.



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