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Enhanced Speed Regulation Of A DC Motor Using An Augmented Crone Controller

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ABSTRACT
In this work, Chaotic Smell Agent Optimization PID based Speed Control of Permanent Magnet Direct Current Motors was developed to achieve a robust and more effective speed control. One of the fundamental factor that affect PMDC motor's speed control, is the generated uncertainty known as disturbance torque on shaft of the motor due to increase in temperature and decrease in frequency of the system. Proportional Integral Derivative (PID) controllers are commonly used in the speed control of PMDC motors. But PID controllers often do not fully eliminate external disturbances in the system. As such, the CRONE controller based speed control of PMDC motors was developed to address the limitations of PID control. To achieve this, a PMDC motor model was adopted. A second generation CRONE controller was equally adopted and then applied speed control of the PMDC motor. The performance of the developed controller was then compared with that of a Proportional Integral Derivative – Particle Swam Algorithm (PID-PSO) controller for speed control of PMDC motor. A step input test of the second generation CRONE controller for the speed control of PMDC motor gave a settling time of 0.018s and overshoot of 0.0001%, while PID-PSO controller based speed control of the PMDC motor obtained a settling time and overshoot of 0.2s and 1.42% respectively. The PMDC system was then subjected to a disturbance (unit impulse signal) of duration 0.02s and periods 0.3s, 0.6s, 0.9s, 1.2s and 20s. The CRONE controller guarantees better system performance in the presence of disturbance while PID-PSO controller is not robust to disturbance rejection. The CRONE controller outperformed the PID-PSO based controller by 99.1% and 99.99% in terms of settling time and overshoot respectively. This was an evident that the CRONE controller-based speed control of PMDC motor is more robust than the PID-PSO controller.
Keywords: CRONE controller, speed control, Permanent Magnet Direct Current Motors

1.0 INTRODUCTION

In the present day, practically all electric power generation, trans-arrangement, transmission, and distribution systems are AC because of the fact that generation of a lot of electric power is simpler with AC. Notwithstanding, in most electrical apparatuses in homes, and in unique applications, for example, in trains, electric vehicles, and procedure control, it is worthwhile to change over AC into DC so as to utilize DC motors, which have turned into the most vital machine in charge systems (Charles et al 2015) .

The reason is that speed/torque characteristics of DC motors are better than that of AC motors. DC motors are specifically well known in high power and exact servo applications because of their simplicity of control, Permanent Magnet DC motors (PMDC) are employed in a number of applications, from battery fueled gadgets like wheelchairs and power devices, to transports and entryway openers, welding gear, X-beam and tomographic frameworks, and siphoning hardware. They have the capacity to create high torque at low speed which make them reasonable substitutes for gear motors in numerous applications. (Grignion, 2012). PMDC uses permanent magnet to produce field flux. It has a great torque which aid in effective speed control (Gerada et al., 2014).

It is a strong, dependable, economical and easy to use electromechanical machine. Its tractability has permitted PMDC motors to be conventional in today's society through numerous applications such as automation, modern supermarket and lift. Modern vehicles comprise several PMDC drives which control numerous automobiles moving parts act, and offer additional comfort besides relaxation of motorist or customers (Geest, et al., 2015). Considering the applications of PMDC motors, it shows clearly that research on the design of the motor and control is of great importance. Permanent magnet motors emerge over other DC motors since they don't require an outside field circuit, subsequently, dispensing with misfortunes in the field copper circuit (Bon, et al., 2016).

Motor speed control is achieved using armature current or field current. Numerous algorithms for position and speed control of the PMDC drive exist. Considering its remarkable speed control features, speed control of PMDC attracts substantial research which prompted the development diverse methodologies. A standout amongst the most broadly utilized strategy for position and speed control of PMDC motor is Proportional Integral Derivative (PID) controllers (Aravin et al.,2017).

A lot of factors may disturb PMDC motor's performance, notable amongst them are the environmental loading conditions and working temperature, which plays an important role. For instance, a variation in the motor's loading conditions produces a disturbance torque which causes equal variation in armature current and speed respectively. 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).

PID control has been broadly used to solve the PMDC motor speed control issue. In any case, PID controller may not be adequate in taking care of the disturbance torque. It frequently results in long settling time and extensive system overshoot. Consequently, there is the need for improvement of the performance achieved with PID controllers and a further developed control plan might be required.

2.0 Problem Statement/Justification

Permanent magnet direct current (PMDC) motors is widely used in many systems. PMDC motors are characterized by large torque which causes rotation in the system. This torque is control using the system states which are fundamental parameter that affects the speed control 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. This in turn causes decrease in the motor's speed. However, good control of the disturbance torque can allow for compensation of these negative effects, thereby enhancing the robustness of the system to load changes. PID control has been widely used to solve the PMDC motor speed control problem. However, PID controller may not provide sufficient control to handle the disturbance torque. Therefore, a CRONE based controller for speed control of PMDC motor is indeed developed to address the limitations of PID control.

3.0 Objective (s) of the study

i. To develop Simulink model of PMDC motor
ii. To apply a second generation CRONE controller-based for speed control of PMDC Motor
iii. To compare the performance of the developed controller with that of PID-PSO based controller using settling time and overshoot as performance metrics

4.0 Literature Review

Some literatures relevant to the subject area are reviewed to establish the state of the art in speed control of PMDC motor.

Rathod et al., (2014) worked on PMDC motor's control of speed with an advanced controller. This scheme used two controllers. 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. PMDC motor model was implemented on PI as advanced controller and the slave.Classical tuning of the PID parameters was done using Ziegler-Nichols method. The result shows that cascade PI controller outperformed the ordinary PID controller. This was significance in industrial application not necessarily of PMDC Motor and automated system. However, both the cascade PI and PID controllers did not sufficiently handle disturbance torque which directly affects the motor's speed.

Taha et al., (2015) improved the work of Rathod et al., (2014) by comparing the classical method of PID parameter tuning for speed control of PMDC Motor while tuning the PID parameter with Bacteria foraging algorithm and Genetic algorithm. The simulation results showed, Bacteria Foraging obtained better dynamic response performance of the PMDC drive in both transient response and stability than the classical approach and the genetic algorithm. However, the effect of disturbance torque was not sufficiently handled as it affects the motor's speed.

Muaz et al., (2015) work on speed control of PMDC motor using PID controllers' with different configurations to solve speed problems of PMDC motors with respect to parameter variation of PMDC motor and environmental condition. In their work, the Simulink model of the PMDC motor with and without load was developed. The simulation result shows PID controller gives an improve speed control of PMDC motor with respect to both parameter variation and environment condition. However, variation due to disturbance torque was not properly controlled by PID controller.

Charles et al. (2015) Presented speed control of PMDC motor which was designed to rotate at a speed of 45rad/sec. In the work, ordinary PID controller and cascade PI controllers were used for speed control of PMDC drive with MATLAB Simulink model of the PMDC motor for appropriate study of the controller's time response. The torque of 10Nm was used to test the consistency of the system model and the responses shows that the cascade PI outperformed the PID controllers in stability, reliability and robustness with sensitivity though the ordinary PID controller is highly sensitive with less response stability of the system. However, the problem of disturbance torque was not considered in the research.

Tang et al., (2015) presented a criteria based on disturbance rejection and system robustness to evaluate the performance of PID controllers. The robustness is measured by a two-block structured singular value, and the disturbance rejection is measured by the minimum singular value of the integral matrix. Also, performance of different PID tuning formulas was compared. Specimens in the work show 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 nt addressed.

Harshitha & Shettiga(2016) proposed position control of servomechanism using fractional order PID controller by considering actuator saturation and shaft torsional flexibility. A modified approximation method was introduced for actual implementation of the designed fractional order PID controller. Several simulation comparisons presented in the work indicates that, the fractional order PID controller, if properly designed and implemented, will outperform the conventional integer order PID controller.

However, the problem of disturbance torque was not considered in the design of the controller for position control of servomechanism

5.0 METHODOLOGY

The methodology adopted is as follows:

5.1 Designing the Simulink model of PMDC motor

The development of the PMDC Simulink models considered the following steps. The transfer function of PMDC motor is obtained from the state space model equation (1). It is obtained by taking the Laplace transform with zero initial conditions:

$$A = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_v}{L_a} \\ \frac{K_t}{J_m} & -\frac{B_m}{J_m} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix}, C = [1 \quad 0], x = \begin{bmatrix} i_a \\ \omega_m \end{bmatrix}, \quad u = v_t \; y = i_a \quad (1)$$

$$\frac{Y(s)}{U(s)} = [C[sI - A]^{-1}B] \quad (2)$$

The transfer function $\frac{Y(S)}{U(S)} = G(s)$ (3)

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{K_t}{(sJ+B)(R+sL)+K_tK_b} \quad (4)$$

Where G(s) is the plant transfer function, $\omega(s)$isspeed of PMDC motor as actual output, V(s) is the desired output as 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.

Table1**:** Permanent Magnet DC Motor Parameters (Obeng &Karims, 2018)

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

3.2.1.2 Designing the model using Simulink blocks

The model transfer function of equation (4) and the system dynamics of Table 1 were used in designing the Simulink model using MATLAB Simulink blocks, as shown in Figure 1

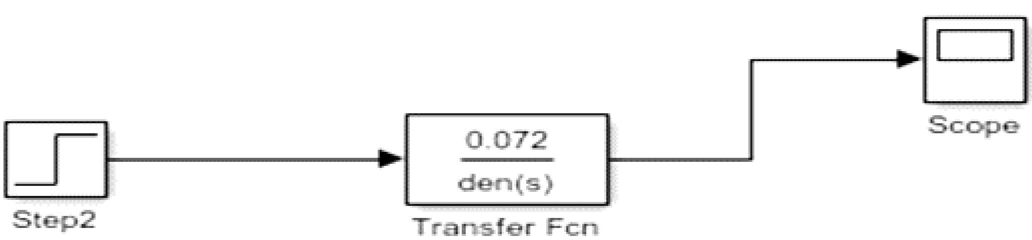

Figure 1: PMDC Simulink Model

From Figure 1, it consists of a step input signal block, PMDC model transfer function and a scope for visualizing the step response of the system.

5.3 Application of second-generation CRONE controller for speed control of the developed PMDC model

The implementation of the second-generation CRONE controller for speed control of PMDC motor is achieved using Simulink environment of MATLAB. The three generations of CRONE control are given by equations (5), (6), (7) respectively.

$$C_F(s) = C_o\left(\frac{\omega_1}{s}+1\right)^{n_1}\left(\frac{1+s/\omega_1}{1+s/\omega_h}\right)\frac{1}{(1+s/\omega_h)^{nF}} \quad (5)$$

$$\beta(s) = k_0\left(\frac{1+\frac{s}{\omega_1}}{\frac{s}{\omega_1}}\right)^{n_1}\left(\frac{1+\frac{s}{\omega_h}}{1+\frac{s}{\omega_1}}\right)^{n}\frac{1}{\left(1+\frac{s}{\omega_h}\right)^{n_h}} \quad (6)$$

$$\beta(s) = C^{\mathrm{sign}(b)}\left(\frac{w_l}{s}+1\right)^{n_1}\left(\alpha_0\frac{1+\frac{s}{w_h}}{1+\frac{s}{w_l}}\right)^{a}\times\left(\frac{\mathrm{Re}}{i}\left(\alpha_0\frac{1+\frac{s}{w_h}}{1+\frac{s}{w_l}}\right)^{ib}\right)^{-q\,\mathrm{sign}(b)}\left(\frac{1}{\left(1+\frac{s}{w_h}\right)^{n_h}}\right) \quad (7)$$

To ensure active speed control of PMDC motor, second generation CRONE control technique was used because speed control problem is a transient problem which is best tackled with the second-generation CRONE controller and due to the fact that the specific gain crossover frequency ω_{cg} is not in a constant frequency phase range. The controller can ensure robustness when plant variation lead only to gain variation around ω_{cg}. The second-generation CRONE approach is based on regulator design from the open loop constraints (robust loop shaping). The open loop transfer function for the second generation is given by equation (6).

Figure 2 represent the Simulink model for internal structure of the second-generation CRONE controller

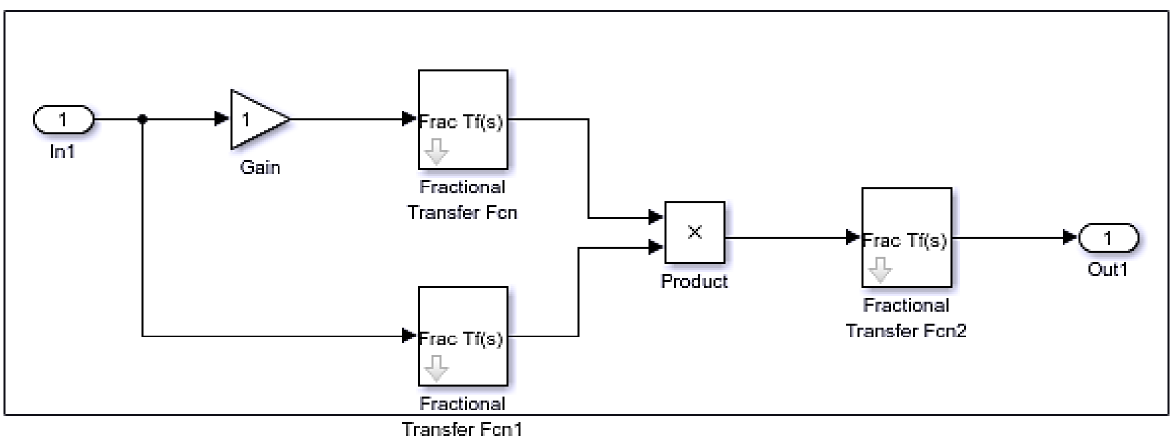

Figure 2: Internal structure of the second-generation CRONE controller

Figure 2 is the model of the second generation CRONE controller developed using equation (6). The two fractional order transfer function blocks are multiplied in the product block and later with a gain block. Figure 2 presents the Simulink model of the developed second generation CRONE controller for speed control of PMDC motor.

Figure 3 presents Simulink diagram of second generation CRONE controller for speed control of PMDC motor.

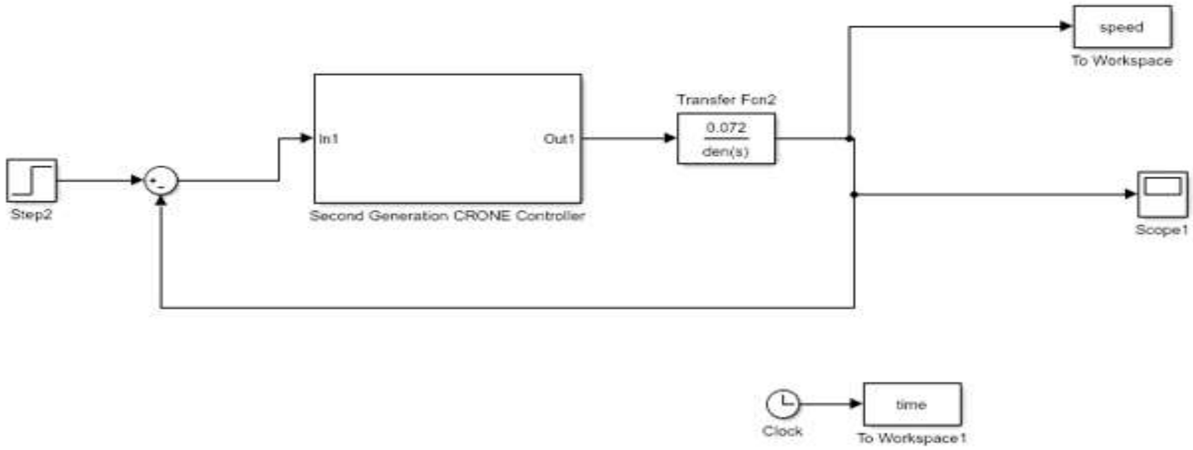

Figure 3: Simulink Diagram of Second Generation CRONE Controller for Speed Control of PMDC motor

From Figure 3, a step input signal is used as the reference input signal connected to a comparator that computes the error between the input signal and the actual output. The second generation CRONE controller accepts the error and generate a manipulated variable or control action to mitigate the effect of error.

5.4 Development of PID-PSO based Speed Control of PMDC Motor

To develop the PID based speed control of the PMDC motor, there is the need to obtain the best possible combination of the PID gain parameters. The PID based speed control of PMDC motor scheme was implemented using Simulink block of the PMDC Motor plant. Particle swamp optimization (PSO) algorithm was used to obtain the best possible combination of the PID gains (Kp, Ki and Kd). This aimed at achieving good performance in terms of settling time and overshoot. To achieve this, the Integral time absolute error (ITAE) was used as the objective function for the PSO algorithm as shown in equation (8)

$$J = \int_0^\infty t|e(t)|dt \qquad (8)$$

where e(t) is the error between the reference input and the plant output at time t.

. Figure 4 presents the Simulink model of the PID-PSO based with PMDC motor Simulink model.

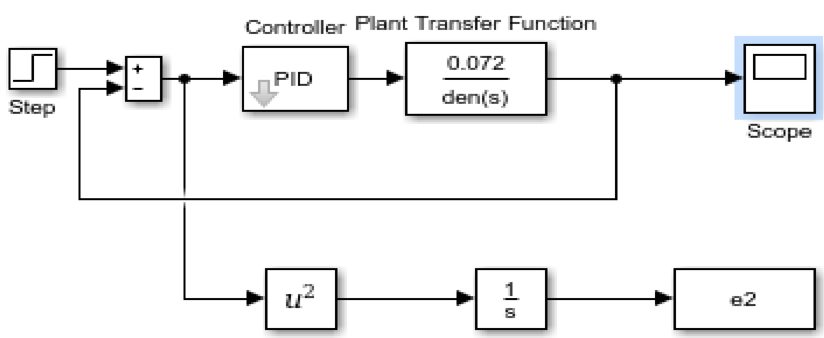

Figure 4: Implementation of ITAE for PID Tuning

Figure 4 shows the Simulink design of the implementation of the ITAE in conjunction with the PSO for tuning the optimal PID parameters. It consists of the step input signal block, a comparator that compares the output and the desired signal, ITAE block that compute the error signal, PID controller, model transfer function and the scope for visualizing the output signal.

6.0 RESULTS

This section presents the results obtained from the step responses of the PMDC system before and after the application of the second-generation CRONE control technique. It also presents the results obtained when second generation CRONE technique was applied within a certain range of frequency.

6.1 Time Response for PMDC Motor

This section shows the result obtained when a MATLAB command 'ltiview'of PMDC motor model using the transfer function .Figure 1 presents step response of PMDC motor.

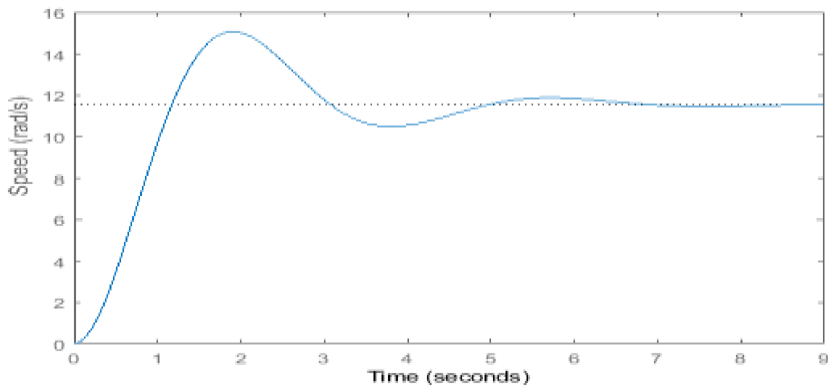

Figure 5: Step Response of PMDC Motor

Figure 5 shows the step response of the PMDC motor without the application of a controller. From the step response, the following characteristics were obtained: settling time of 6.2s, rise time of 0.793 s, 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. From Figure 5, it is observed that the system model exceeded the desired speed of 1rad/s and it takes 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 6 shows the response of the controller's output which is the manipulated variable that was used to modify the controlled variable for desired speed of the PMDC motor control system. Figure 6 presents the out of the second-generation CRONE Controller.

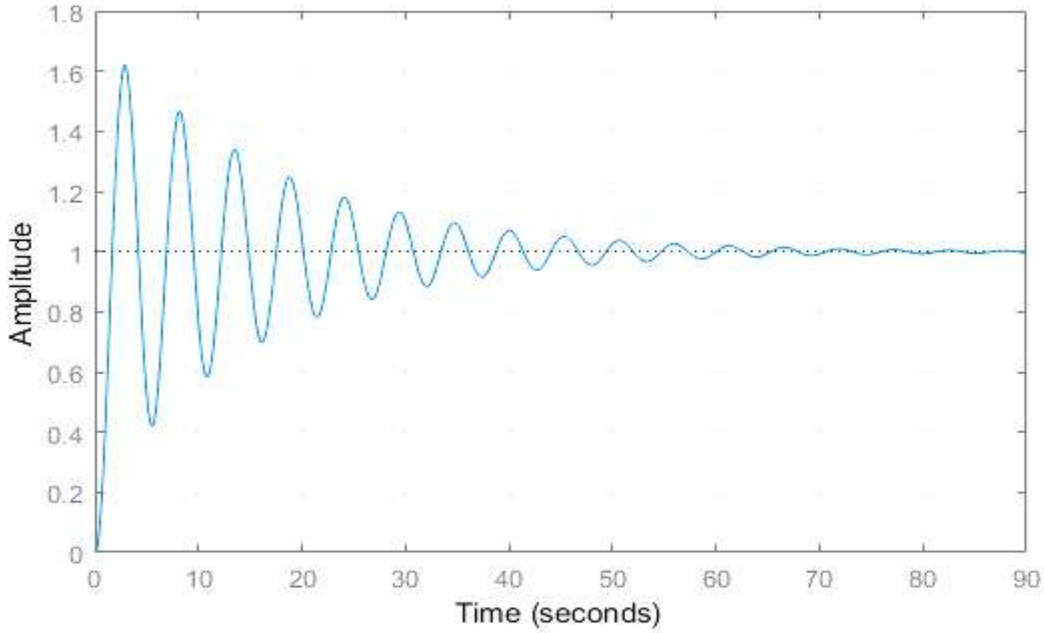

Figure 6: Second-Generation CRONE Controller Output Response

Figure 6 present a step response of the second generation CRONE controller's manipulating signal response which is used to manipulate the control signal.

6.2 Time Response for Second Generation CRONE Based Speed Controller

The response of second-generation CRONE based speed controller for PMDC motor system obtained from Simulink model of Figure 7 when a nominal unit step signal was applied is shown in Figure 7

Figure 8 presents the Response for second generation CRONE Controller base Speed Control of PMDC motor.

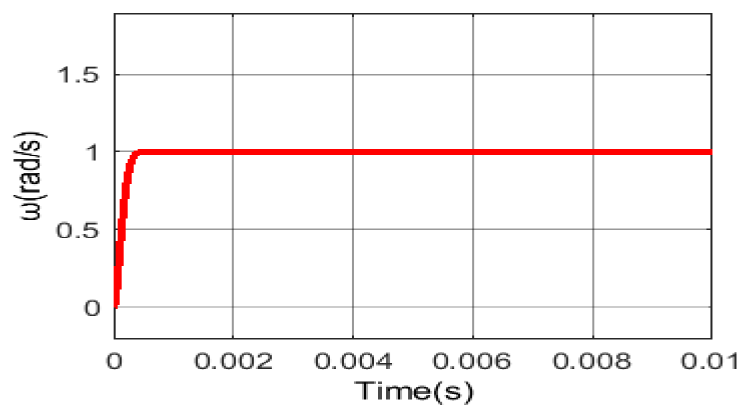

Figure 8: Response for second generation CRONE Controller based Speed Control of PMDC

From Figure 8, the controlled variable settled at 0.0018s with an overshoot of 0.001%. This implies that the CRONE controller was able to stabilize the speed of the PMDC from zero to steady state reducing peak overshoot and low settling time.

6.3 Time Response for PID-PSO Speed Controller

The response of the PID-PSO based speed controller for PMDC motor obtained from the Simulink block of Figure 8 when a nominal unit step signal was applied is shown in Figure 4.2. The optimal PID gains obtained at the termination of PID-PSO optimization process were: K_p = 155.45, K_i =21.81 and K_d =0.24.

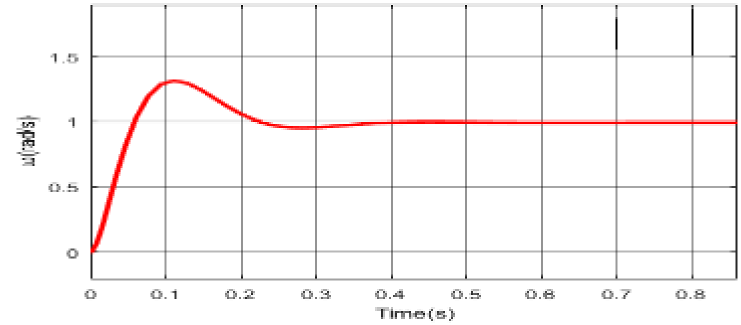

Figure 9: Response of PID-PSO based speed Control of PMDC Motor

From Figure 9, the PID-PSO based controller settled the controlled variable at 0.43s with an overshoot of 14%. The control system met the design specification (settling time less than 1s and overshoot less than 2%) with aid of the PID-PSO based controller. However, the second generation CRONE controller obtained a faster settling time with a minimal overshoot. This shows that the second generation CRONE controller is superior to the PID-PSO based controller.

6.4 Disturbance Rejection of the Controllers

Impulse signal of period 0.3s, 0.6s, 0.9s, 1.2s and 20s were respectively introduced as an input disturbance to determine the effectiveness of the CRONE and PID-PSO based controllers with respect to disturbance rejection. The introduced 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.

6.5 Disturbance rejection for second generation CRONE based controller

The responses 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 10 – 13. The time response when a disturbance (an impulse signal) of duration of 0.02s and period0.3s was introduced into the system is presented in Figure 10.

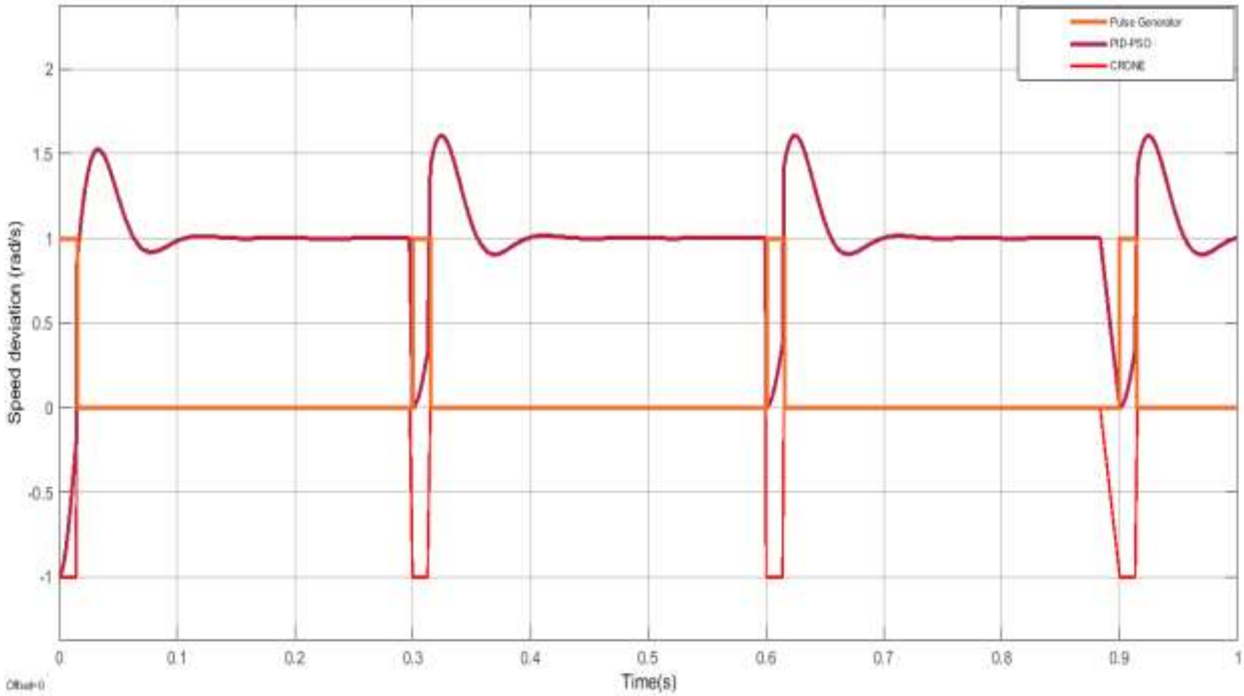

Figure 10: Response for Second Generation CRONE based and PID-PSO based Speed Controller (0.3s Impulse Period)

From Figure 10, 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 guarantee 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 11 shows time response of the system with the injection of disturbance (impulse signal) of Period 0.9s introduced.

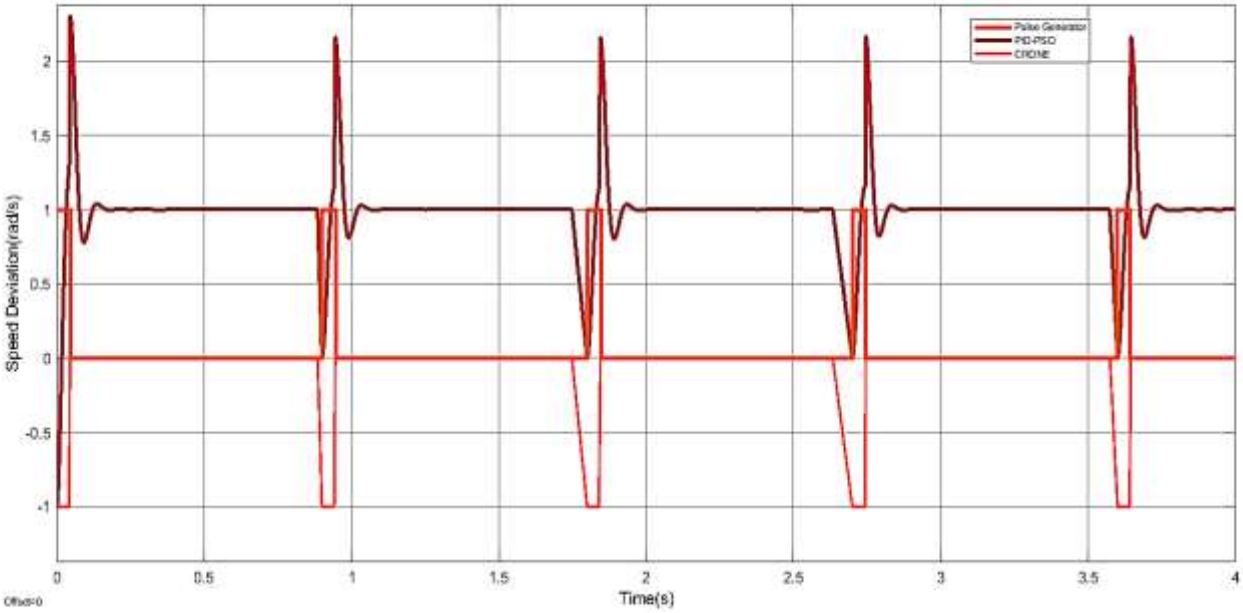

Figure 11 shows time response of the system with the injection of disturbance (impulse signal) of Period 0.9s introduced.

From Figure 11, the response of the second generation CRONE controller, PID-PSO based controller with respect to the input disturbance at 0.9s intervals. It is obvious from the Figure that the CRONE controller takes 0.031s to totally stabilize the system when the disturbance was introduced. While the PID - PSO based controller was able to bring the system to steady state at 0.056s after the introduction of disturbance of duration of 0.02s with period of 0.9s. The PID-PSO based controller takes more time to reject the disturbance.

7.0 CONCLUSION

In this work CRONE controller based speed control of PMDC Motor was developed. The system has minimized overshoot in the PMDC model response in order to avoid the problem of jacking in conveying system.

Also the system robustness was tested by injecting disturbance (from signal generator) to the system at intervals of 0.3s, 0.6s, 0.9s, 1.2s and 20s. This was done to test the two controller's robustness. The CRONE controller outperformed the PID-PSO controller for settling time and overshot as compared with the work of Obeng &Karims (2018).For robustness of the speed controller at the injection of disturbance, the CRONE controller outperformed the PID-PSO based controller by 61.25.% as duration of the disturbance periods varied between 0.3s to 20s.

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