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# Case Study on Different Controller Tuning for PI Controller in Networked Dc Motor System

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**Abstract:** Advanced fault detection and accommodation schemes are required for ensuring efficient and reliable operation of modern Networked DC Motor System. The control and filtering approach has received a lot of attention from the control community. So using a controller with better tuning method to reduce the error. This paper presents a flexible and fast tuning method based on Harmony Search Algorithm (HSA) to determine the optimal parameters of the PI controller for the desired system specifications. The HSA improvises, update and check operators obtain optimal solution for defined objective function. Two important control parameters have been adjusted to obtain better solution. The simulation results demonstrate that the designed HSA based controller realize a good dynamic behavior of the DC motor, a perfect speed tracking with less rise and settling time, minimum overshoot, minimum steady state error and give better performance compared to conventional PI controller.

**Keywords:** Sensor fault tolerant, Proportional-Integral (PI) controller, Networked Control System (NCS), Harmony Search Algorithm (HSA).

## I. INTRODUCTION

In Networked Control System (NCS), the system components such as sensors, controllers, and actuators are connected by using a communication network. So the communication between these components is done with the help of network connection. These network connection results a better connection and also reduces maintenance and system cost. NCS have several applications in various fields such as dc motors, mobile networks, remote surgery etc. This paper considers the application of NCS in dc motors. DC have been used various applications, but in the case of traditional dc motor the system components are located in the same place and are connected by point to point wiring. However in practical applications the controllers and motors are difficult to be located in the same place. So we use a networking system for connecting these components. The introduction of communication network will cause time delay and packet losses.

The classical tuning method such as Ziegler-Nichols Tuning method is used to find the controller parameters. The integral controller accumulates the errors, and generates its output according to the values of the errors at that particular instant. Therefore, this controller produces the output even when the $r(t) = y(t)$, if the error accumulated at that time is not zero. If the accumulated errors are positive, the controller drives the system response to overshoot and if the accumulated errors are negative, the controller will drive the response to undershoot. These two of the conditions are undesirable as these make system unstable. However, Integral controller reduces the steady state error under the condition of disturbances in the system.

In EDA Based speed control of a Networked DC System (NDCMS) [1], consider a Networked DC motor System with time delay and packet losses. It mainly focuses about the optimal output tracking problem. One assumption should be made such as dc motor has zero steady state tracking error for a step reference speed. Here the controller parameters are obtained by using Estimation of Distribution Algorithm (EDA), which is a stochastic optimization method. The optimization should be done as a series of incremental updates of a probabilistic model, starting with the model encoding the uniform distribution over admissible solutions and ending with the model that generates only the global optima. Advantages of such type of tuning is, first it eliminate the assumption that the time delays are less than two sampling periods. Second one is it generates better output tracking.

Fuzzy logic based PID controllers are commonly used to handle complex dynamic processes. In Tuning of an optimal fuzzy PID controller with stochastic algorithms for networked control system with random delay [2] considers a PID controller with a fuzzy tuning method to obtain controller parameters. Here using a combination of fuzzy PI and fuzzy PD controllers. Also error minimization criteria can be modified by introducing a

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suitable time domain performance index like Integral of Time multiplied Squared Error (ITAE). The controller can overcome the random variation in network delay by introducing Fuzzy Logic Controller (FLC) in normal PID controller and the parameters of controller are obtained with the help of two optimization method such as, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Another tuning method is further introduced for getting better performance such as multilayer neural network [3]. The artificial neural network is trained by Levenberg-Marquardt back propagation algorithm. While using this Artificial Neural Network (ANN), the difficult control problems of unknown non-linear systems can be tolerate. In order to overcome the difficulties in ANN, an Adaptive Neural Network Sliding Mode Controller (ANNSMC) is introduced. Sliding mode control method is studied for controlling DC motor because of its robustness against model uncertainties and external disturbances, and also its ability in controlling nonlinear and MIMO systems. Sliding mode control, or SMC, is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to "slide" along a cross-section of the system's normalbehavior. Sliding mode control can be used in the design of state observers. In the case of a networked DC motor system.

The Sliding Mode Observer (SMO) is used to find the rotor speed and unknown load torque. Here the controller is designed by using Fuzzy gain scheduling method [4]. It also used to overcome the sensor faults and to manage the network delay and packet dropouts. This type of controller design can provide the optimal controller action at different operating points with help of an algorithm. The fuzzy sub system can perform a fine tuning at each operating point. In recent years The Proportional Integral Controller is most widely used controller in industrial practice for more than 60 years for the speed control of DC motor drives system, because of its relatively simple structure and implementation and ability to maintain a zero steady state error to a step change in reference in comparison to the PID controller. In speed sensor less and sensor fault tolerant optimal Pi regulator for Networked DC motor System with unknown time delay and packet dropout [5].Here PI controller is tuned by using trial error method. It is characterized by repeated, varied attempts which are continued until success or until the agent stops trying. While using this type of tuning, the system takes higher time consumption with low step response. But it is better than classical tuning methods such as Ziegler-Nichols Tuning method.

In recent years, different methods are used for parameter identification such as fuzzy tuning method, Genetic Algorithm (GA), Bacterial Foraging Optimization Algorithm (BFOA), Harmony Search Algorithm (HSA) etc. HSA was first proposed by Zong Woo Geem in 2001 popularly known as metaheuristic algorithm. Harmony Search takes inspiration from the music improvisation process, where musicians improvise their instrument pitches searching for a perfect state of harmony. The same thing is mimicked in the case of an optimization process. The optimization techniques are used to find the optimal values of objective function and decision variables associated with it.

In this paper, proposes a case study on different tuning methods such as Ziegler-Nichols Tuning method, Astrom-Hagglund Tuning method and finally Harmony Search algorithm. While comparing these tuning method we can identify the Harmony Search Algorithm is better than other two tuning methods and the Harmony Search Algorithm based sensor fault tolerant optimal PI controller is proposed for NDCMS with unknown time delay and packet dropout. The controller parameters are obtained by using HSA, not only to stabilize the overall closed-loop system but also to minimize a linear quadratic or integral-square-error cost function. Thus, two critical problems in industrial networked dc motor drive systems are tackled: speed sensor fault/failure, or exclusion from the drive system for cost reduction, and controller performance improvement, besides overall stability. The rest of this paper is organized as follows. The modeling of the NDCMS is presented in Section II. In section III describes the Sliding Mode Observer (SMO). In section IV reveals about the case study of 3different tuning methods. In Section V, numerical simulation results of the networked dc motor are provided to show the validity of the proposed method. Finally, the conclusion is given in Section VI.

## II MODELING OF NDCMS

System model represents a certain property of the system in graphical, pictorial, analytical or mathematical form. Block diagram and signal flow graph are the graphical models.

Transfer function and state space representations are mathematical models. The speed control of DC motor is mainly governed by armature control. In armature control of DC motor, it is assumed that demagnetizing effect of armature Reaction is neglected, magnetic circuit is assumed to be linear and the field voltage is constant. This method is used to obtain the speed below the rated speed. Figure 1shows the equivalent model of armature controlled DC motor and Figure 2 shows the basic block diagram of Armature Controlled DC motor.

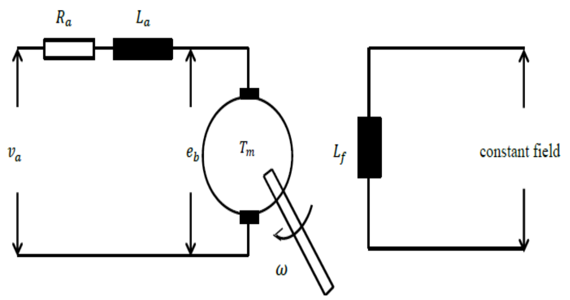


Figure 1: Armature controlled DC motor system

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The governing equations of a dc motor are given as follows:

$$v_a(t)=R_a(t)\, i_a(t)+L_a\frac{di_a}{dt}+e_b(t)$$
$$e_b(t)=K_b\, w(t)$$
$$T_m(t)=K_t i_a(t)$$
$$T_m(t)-T_L(t)=J_m\frac{d_{w(t)}}{d_t}+B_m\, w(t)$$

On taking Laplace transform of equation, we getting

$$v_a(s)=R_a i_a(s)+sL_a i_a(s)+K_b\, w(s)$$
$$Kt\, Ia(s)=sJ_m\, w(s)+B_m\, w(s)+T_L(s)$$

While considering the state space model, the dynamic equations become,

$$\begin{matrix}\dot{i}_a\\ \dot{w}\end{matrix}=\begin{bmatrix}\frac{-R_a}{L_a} & \frac{-K_t}{L_a}\\ \frac{K_t}{J_m} & \frac{-B_m}{J_m}\end{bmatrix}\begin{matrix}ia\\ w\end{matrix}+\begin{bmatrix}\frac{1}{L_a} & 0\\ 0 & \frac{-1}{J_m}\end{bmatrix}\begin{matrix}v_a\\ T_L\end{matrix}$$

It can also expressed as

$$X=A\dot{X}+BU$$

Where, X=ia w, U=Va Tl, $X$ is the state variable vector and $U$ is the input vector.
Where

$$A=\begin{bmatrix}\frac{-R_a}{L_a} & \frac{-K_t}{L_a}\\ \frac{Kt}{J_m} & \frac{-Bm}{J_m}\end{bmatrix}\qquad B=\begin{bmatrix}\frac{1}{L_a} & 0\\ 0 & \frac{-1}{J_m}\end{bmatrix}$$

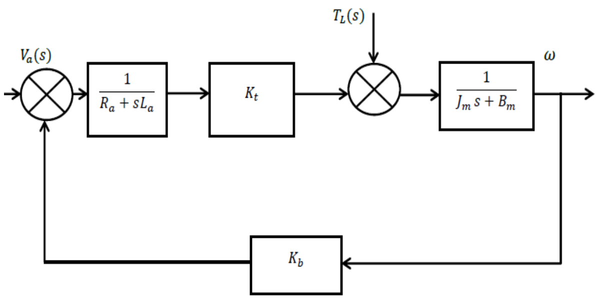


Figure2: Basic block diagram of Armature Controlled DC motor

### III. SLIDING MODE OBSERVER DESIGN

In control theory, sliding mode control, or SMC, is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behavior. Sliding mode control can be used in the design of state observers. These non-linear high-gain observers have the ability to bring coordinates of the estimator error dynamics to zero in finite time. Additionally, switched-mode observers have attractive measurement noise resilience that is similar to a Kalman filter. For simplicity, the example here uses a traditional sliding mode modification of a Luenberger observer for an LTI system. In these sliding mode observers, the order of the observer dynamics is reduced by one when the system enters the sliding mode. In this particular example, the estimator error for a single estimated state is brought to zero in finite time and after that time the other estimator errors decay exponentially to zero. Here, consider the LTI system,

$$\begin{Bmatrix} x = A\dot{x}+Bu \\ y=[1\;0\;0\;....]x=x_1\end{Bmatrix}$$

Where state vector $x \triangleq (x_1 x_2, ....x_r) \in R^n$ and $u \triangleq (u_1\, ,u_2, ...u_{n)} \in R^r$ is a vector of inputs and output $Y$is a scalar equal to the first state of the$X$ state vector.

- $a_{11}$ is a scalar representing the influence of the 1st state $x_1$ on itself.
- $A_{21} \in R^{(n-1)}$is a column vector representing the influence of the other state on the first state.
- $A_{22} \in R^{(n-1)*(n-1)}$ is a matrix representing the influence of other state on themselves and
- $A_{12} \in R^{1*(n-1)}$ is a row vector corresponding to the influence of the first state on the other states.

The goal is to design a high-gain state observer that estimates the state vector$x$using only information from the measurement$y = x_1$.Hence, let the vector be the estimates of $n$ vector such as, $\hat{x}=x_1,x_2\dots x_n \in R^n$.The observer takes the form,

$$\hat{x}=Ax+Bu+L_u(\hat{x}-x)$$

Where v: R→R is an observer gain vector that serves a similar purpose as in the typical linear Luenberger observer. Likewise, let

$$L=\begin{matrix}-1\\ L_2\end{matrix}$$

Where $L_2 \in R^{(n-1)}$ is a column vector. Additionally, $e=(e_1,e_2,\dots e_n) \in R^n$, be the state estimator error. That is, $e=\hat{x}-x$, the error dynamics are then

$$\{\dot{e}=\dot{\hat{x}}-\dot{x}\;=A\hat{x}+Bu+Lv(\hat{x}-x)=A(\hat{x}-x)-Ax-Bu=A(\hat{x}-x)+Lv(\hat{x}-x)=Ae+Lv(e_1)\}$$

The sliding mode control switching function is,

$$\sigma(\hat{x}.x)\triangleq e_1=\hat{x}-x.$$

To obtain sliding manifold,$\dot{\sigma}$ and $\sigma$must always have opposite signs. However,

$$\dot{\sigma}=\dot{e_1}=a_{11}e_1+A_{12}e_2-v(e_1)$$
$$=a_{11}e_1+A_{12}e_2-v(\sigma)$$

Where $e_2=(e_2, e_3\dots e_n) \in R^{(n-1)}$ is the collection of the estimator errors for all of the unmeasured states. To ensure that$\dot{\sigma}\sigma<0$, let

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$$v(\sigma)=M\ sgn(\sigma)$$

Where $M>\max\{|a_{11}e_1+A_{12}e_2|\}$
That is, positive constant $M$ must be greater than a scaled version of the maximum possible estimator errors for the system. If $M$ is sufficiently large, it can be assumed that the system achieves $e_1=0$.

## IV. CASE STUDY

### Ziegler-Nichols Tuning Method

According to this method, initially set the controller to P mode only. Next, set the gain of the controller value $(K_p)$ to a small value. Make a small set point (or load) change and observe the response of the controlled variable. If $K_p$ is low the response would be sluggish. Increase $K_p$ by a factor of two and make another small change in the set point or the load. Keep increasing $K_p$ (by a factor of two) until the response becomes oscillatory. Finally, adjust $K_p$ until a response is obtained that produces continuous oscillations. This is known as the ultimate gain ($K_u$). Also note the period of the oscillations($P_u$). The $K_u$ is the gain margin of the system and;

$$P_u = \frac{2\times\pi}{wcg}$$

Where, wcg is the gain crossover frequency.
The Ziegler-Nichols continuous cycling method is one of the best known closed loop tuning strategies. The controller gain is gradually increased (or decreased) until the process output continuously cycles after a small step change or disturbance. At this point, the controller gain is selected as the ultimate gain ($K_u$), and the observed period of oscillation is the ultimate period ($p_u$).

Table 1 Ziegler-Nichols Tuning Rules

| Controller | | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|---|
| Ziegler-Nichols Method | P | $0.5K_u$ | – | – |
| | PI | $0.45K_u$ | $P_u/1.2$ | – |
| | PID | $0.6K_u$ | $P_u/2$ | $P_u/8$ |

### Astrom-Hagglund Tuning Method

An improvement of the Ziegler-Nichols method is given by Astrom and Hagglund. They proposed to use a relay feedback. This nonlinear feedback includes a limit cycle oscillation. The period of this oscillation is $P_u$ and a good estimate for the ultimate gain can be calculated from the oscillation amplitude 'a' with:

$$K_u = 4d/\pi a$$

The major advantage of using relay feedback is that the system is not driven to instability. Further, it offers the possibility to identify different points on the Nyquist curve which gives more information about the course of the Nyquist plot.

Table 2 Astrom-Hagglund Closed Loop Method

| Controller | | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|---|
| Astrom-Hagglund Method (Closed loop) | PI | $0.32K_u$ | 0.92 | - |

### Harmony Search Algorithm (HSA)

The HS algorithm, which was developed by Zong Woo Geem, mimics a musical improvisation process in which the musicians in an orchestra try to find a fantastic harmony through musical improvisations. This musical process can be adapted into engineering optimization processes where the main objective is to find the global or near-global solution of a given objective function. In this approach, musical performances seek a best state (fantastic harmony) determined by aesthetic estimation, as the optimization problem seek a best state. In this paper the optimization problem is minimization of Integral Square Error rate. In order to achieve better performance, we have to find the $K_p$, $K_i$ values of PI controller with better tuning method as HS algorithm. That means tuning of the controller provide best controller parameter with minimum error. The main step in the procedure of Harmony Search Algorithm (HSA) is as follows,

1. Initialize optimization problem and HSA algorithm parameters.
2. Initialize Harmony Memory (HM).
3. Improvise a new harmony from HM.
4. Update harmony memory.
5. Check the stopping criteria.

### 1. Initialize the Problem and Algorithm parameter

The optimization problem is defined as follows: Minimizef(x) subjected to $x_i \in X_i$, i =1…N.Where f(x)the objective function, xis the set of each decision variable, that is $K_p$, $K_i$ values $(x_i)$, $X_i$ is the set of the possible range of values for each designvariable, that is $X_{iL} \le X_i \le X_{iu}$.Where $X_{iL}$ and $X_{iU}$ are the lower and upper bounds for eachdecision variables. The Harmony Search Algorithm (HSA) parameters are also specified in this step, they are the harmony memory size (HMS), or the number of solution vectors in the harmony memory, Harmony memory considering rate (HMCR), bandwidth (BW), pitch adjusting rate (PAR), number of improvisations (NI) or stopping criterion and number of decision variables (N).

### 2. Initialize the Harmony Memory (HM)

The harmony memory is a memory location where all the solution vectors (sets of decision variables) are stored. HM matrix is filled with as many randomly generated solution vectors as the Harmonic memory size (HMS).

$$HM=\begin{bmatrix} x_1^{'} & \cdots & x_n^{'} \\ \vdots & \ddots & \vdots \\ x_1^{HMS} & \cdots & x_N^{HMS} \end{bmatrix} = \begin{matrix} f(X^1) \\ \vdots \\ f(X^{HMS}) \end{matrix}$$

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**3. Improvise a new harmony**

A New Harmony vector $x' = (x_1', x_2', \ldots\ldots\ldots x_n')$ is generated based on the three rules:

1) memory consideration,
2) pitch adjustment and
3) random selection

Generating a new harmony is called 'improvisation'. The value of the first decision variable $x_1'$ for the new vector can be chosen from any value in the specified HM range such as $x_1'$-$x_1^{HMS}$.Values of the other design variables$(x_2', x_3' \ldots x_n')$are chosen in the same manner. HMCR, which varies between 0 and 1, is the rate of choosing one value from the historical values stored in the HM, while $(1-\text{HMCR})$is the rate of randomly selecting onevalue from the possible range of values such as,

$$x_{inew}=L(x_{old})+\text{rand}\in(0,1)\times BW$$

Every component of the New Harmony vector $x'=(x_1', x_2', \ldots x_n')$is examined to determine whether it should be pitch-adjusted. This operation uses the PAR parameter (the PAR parameter determines the probability of a candidate member from the HM matrix to be improved, the value of (1-PAR) sets the rate of doing nothing. If the pitch adjustment decision for$x'$isYes,$x'$is replaced as follows:

$$x_{new}=x_{old}+BW(\text{rand}-0.5)$$

Where BW is an arbitrary distance bandwidth for the continuous design variable and rand is random number between 0 and 1. In step 3, HM consideration, pitch adjustment or random selection is applied to each variable of the New Harmony vector in turn.

**4. Update harmony memory**

If the New Harmony vector,$x_i'=(x_1', x_2', \ldots x_n')$is better than the worst harmony in the HM, from the point of view of objective function value, the new harmony is included in the HM and the existing worst harmony are excluded from HM.

**5. Check the stopping criteria**

If the stopping criterion (i.e.) maximum number of improvisations is satisfied, computations terminated. Otherwise, step 3 and 4 are repeated. The flow chart of Harmony Search Algorithm is shown in figure 3.

## V. SIMULATION RESULT

In this section, numerical simulations and experimental tests are discussed to evaluate the feasibility of the proposed approach. Consider a DC motor with parameters given in Table 3.With these parameters, the augmented system matrices are:

$$A=\begin{matrix} -1436046 & -42.54 & 0 \\ 4666.67 & -22.22 & -2777.78 \\ 0 & 0 & 0 \end{matrix}$$

$$B=\begin{matrix} 552.49 \\ 0 \\ 0 \end{matrix}$$

$$C=\begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{matrix}$$

Table 3 Parameters of the DC motor

| Parameter | Value |
|---|---|
| $r_a$ | $3.27\Omega$ |
| $l_a$ | $1.8110^{-3}$H |
| $k_b$ | $7.7\times 10^{-3}$V. s/rad |
| k | $168\times 10^{-3}$N. m/A |
| j | $3.6\times 10^{-4}K_g.m^2$ |
| b | $80\times 10^{-4}$N. m. s/ |

**Flow chart of Harmony Search Algorithm:**

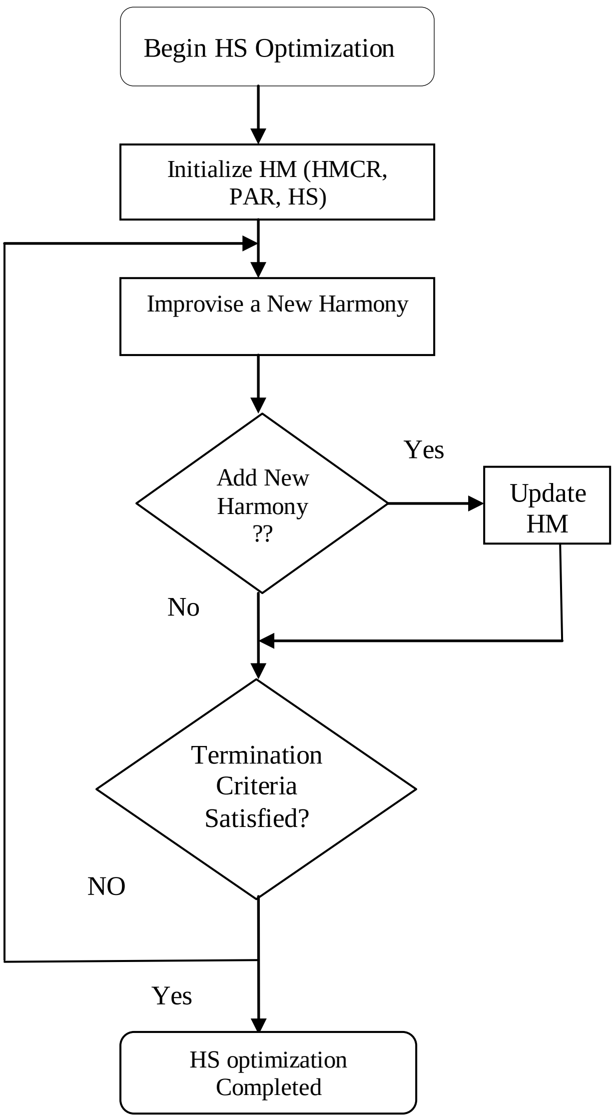


Figure 3: Flow Chart of Harmony Search Algorithm

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After initializing the DC motor parameters, we have to impose the following sinusoidal fault on the angular speed sensor.

$$f(t)=10u(t-16.5)\cos(0.45\pi t)$$

Where the load torque is $T_l=0.14u\,(t-38)$.Moreover, the reference input as $r_s=85u(t)-10u\,(t-22)$.Speed sensor fault tolerant PI controller is designed based on HS Algorithm based approach. To design a Sliding Mode Observer, choose $\rho=3.05$, $\epsilon=0.05$. Then initializing HS Algorithm parameters such as, Harmony Memory Size as 10, dimension as 2, Harmony Memory Considering Rate as 0.95, select bandwidth as 0.2, lower and upper bound as 0 an 10 respectively. The sinusoidal fault, reference input with load torque is shown in the figure 4, 5 and 6 respectively.

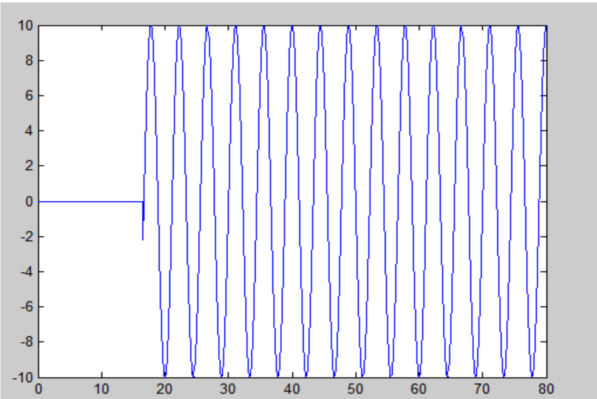
Figure 4: Sinusoidal fault generation

While comparing the proposed tuning method with the conventional PI controller, the system having several advantages such as

- Controller performance is higher
- Time consumption is less
- Error should be minimum
- Less computational complexity

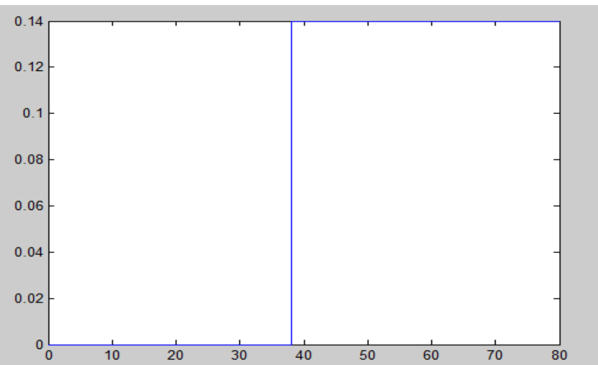
Figure 5: Load Torque when dc motor is in on state

Optimal controller parameters will result better DC motor response with minimum error. Minimization of error is a challenging method; Errors are obtained due to the communication network. That means the use of communication network wills loss the information. So we use proper tuning methods for avoiding such conditions. Using the controller without tuning leads distortions or oscillations in step output

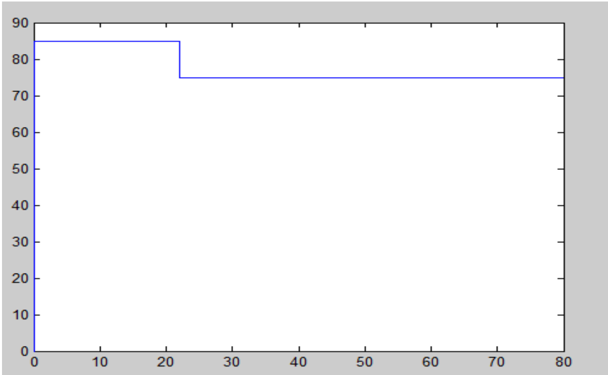
Figure 6: Reference Step Input

In HS Algorithm, the improvisation process is equivalent to the mutation operator and increasing the no .of improvisations will increases the better decision variables with better fitness function. Figure 7 showing the no. of iteration count and the better fitness value of optimization problem.

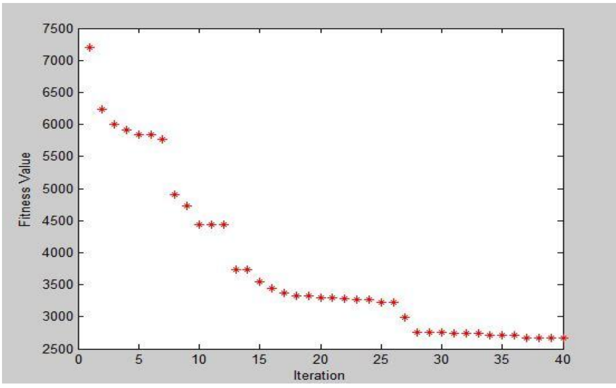

Figure 7: Iteration count after algorithm execution

Here also applying a fault tolerant approach instead of error minimization. Thus we can obtain a new method for industrial Networked DC motors by avoiding motor off condition while running state

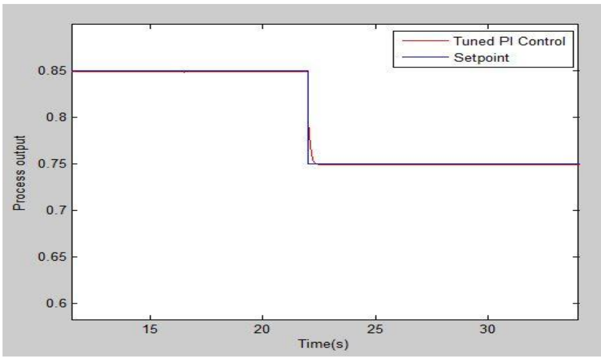

Figure 8: DC motor output for a step input

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Figure 8 showing the difference of existing and proposed result.

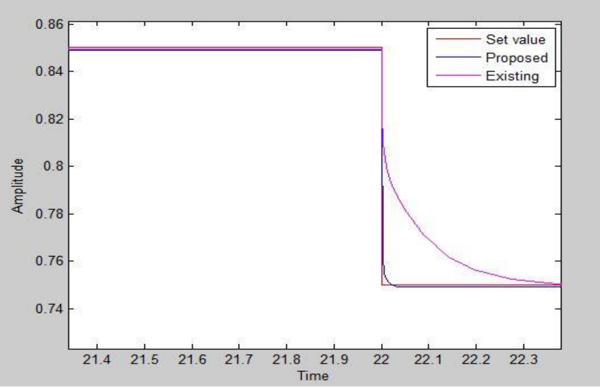


Figure 9: Comparison between existing and proposed dc motor step output

**Comparison**

Comparison of proposed output with existing one, we can see the difference of output. Table 4 showing the case study of existing and proposed method. Here we can see the difference between existing and proposed method of tuning. DC motor output response with better rise time and settling time.

Table 4 Comparison of Classical and Harmony search algorithm tuning method

| Tuning methods | Rise Time (seconds) | Settling Time (seconds) | Over shoot (percentage) |
|---|---|---|---|
| Ziegler-Nichols Method (Z-N) | 0.0277 | 0.1223 | 25.9367 |
| Astrom-Hagglund Method | 0.7844 | 2.6702 | 0 |
| Harmony search algorithm | 0.2866 | 0.0982 | 0 |

## VI. CONCLUSION

A speed sensor-fault-resilient networked dc motor in the presence of network-induced delays, packet dropouts, and un-known load torque has been developed with minimum Integral Square Error. Complete failure of speed sensor or, in other words, speed sensor less scheme is also covered with the proposed tuning approach. Also, flexible and fast tuning method based on Harmony search algorithm is proposed to determine the optimal parameters of the PI controller. Simulation and experimental verifications show that the proposed observer/controllers capable of dumping the adverse effects of unknown and time-varying delays and packet dropouts.

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