Optimized controller design of pantograph system by applying different performance indices using PSO

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Abstract. In this paper, the different optimization algorithms of Particle Swarm Optimization (PSO) are developed to choose best solution among many possible groups of solutions, by minimizing the different fitness functions. In these algorithms, the different performance indices namely Integral Time Absolute Error (ITAE), Integral Square Error (ISE) and Integral Time Square Error (ITSE) are chosen as the fitness functions. The step responses of original and reduced order models thus obtained are compared to show the effectiveness of the algorithms developed. Finally the controller is designed corresponding to each reduced order model obtained to meet the desired specifications of the pantograph control system.

Keyword: Particle Swarm Optimization, Model Order Reduction, Integral Time Absolute Error (ITAE), Integral Square Error (ISE) and Integral Time Square Error (ITSE), Pantograph System.

1 High-Speed Rail Pantograph Control System

A pantograph is a device that collects electric current from overhead lines for electric trains or trams. The most common type of pantograph today is the so called half-pantograph (Also known as 'Z'-shaped pantograph) as shown in Fig.1.

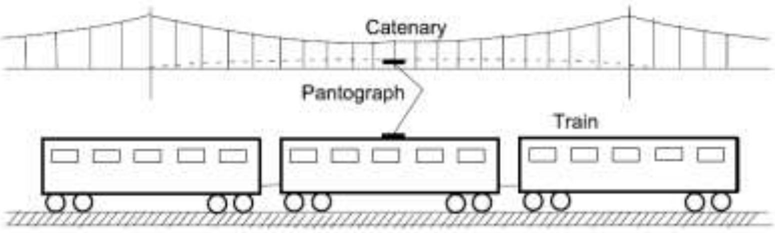

Fig.1. High-Speed Rail System Showing Pantograph and Catenary.

This device is evolved to provide a more compact and responsive single arm design at high speeds when the trains get faster in speed [1, 2]. The pantograph is spring loaded device which pushes a contact shoe up against the contact wire to collect the electric current needed for running the train. As the train moves, the contact shoe starts sliding over the wire and can set up acoustical standing waves in the wires which break the contact and degrade current collection. Therefore, the force applied by the pantograph to the catenary is regulated to avoid loss of contact due to excessive transient motion. The electric transmission system for modern electric rail systems consists of an upper load carrying wire (known as a catenary) from which a contact wire is suspended. The pantograph is connected between the contact wire and the electric contact. The mathematical model, equations of motion and equivalent block diagram are used to derive the closed-loop transfer function of the pantograph system which comes out to be [3]:

$$G_p(s) = \frac{121968.9(s+53.85)}{s^4 + 23.59\,s^3 + 9785\,s^2 + 81190\,s + 3.493\times10^6} \qquad (1)$$

2 Particle Swarm Optimization

In PSO, the 'swarm' is initialized with a population of random solutions. Each particle in the swarm is a different possible set of the unknown parameters to be optimized. Representing a point in the solution space, each particle adjusts its flying toward a potential area according to its own flying experience and shares social information among particles. The goal is to efficiently search the solution space by swarming the particles toward the best fitting solution encountered in previous iterations with the intent of encountering better solutions through the course of the process and eventually converging on a single minimum error solution. The position corresponding to the best fitness is known as $pbest$ and the overall best out of all the particles in the population is called $gbest$. The velocity update in a PSO consists of three parts; namely momentum, cognitive and social parts. The balance among these parts determines the performance of a PSO algorithm. The parameters c_1 and c_2 determine the relative pull of $pbest$ and $gbest$ and the parameters r_1 and r_2 help in stochastically varying these pulls. The modified velocity and position of each particle can be calculated using the current velocity and the distances from the $pbest_{j,g}$ to $gbest_g$ as shown in the following formulae [3].

$$v_{j,g}^{(t+1)} = w * v_{j,g}^{(t)} + c_1 * r_1(\ ) * (pbest_{j,g} - x_{j,g}^{(t)}) + c_2 * r_2(\ ) * (gbest_g - x_{j,g}^{(t)}) \qquad (2)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \qquad (3)$$

3 Performance Indices

A performance index is a quantitative measure of the performance of a system and is chosen so that emphasis is given to the important system specifications. To optimize the performance of a closed-loop control system, one can try to adjust the control system parameters to maximize or minimize some performance indices. This performance index enables one to specify a desired response towards which the system is optimized [5, 6]. A system is considered an optimum control system when the system parameters are adjusted so that the index reaches an extreme value, commonly a minimum value. The performance indices or the fitness functions for the proposed algorithms are:

(i) Integral of the square of the error, ISE

$$J_{ISE} = \int_0^{t_\infty} [y(t) - y_r(t)]^2 \, dt \qquad (4)$$

(ii) Integral of time multiplied by absolute error, ITAE

$$J_{ITAE} = \int_0^{t_\infty} t \left| y(t) - y_r(t) \right| dt \qquad (5)$$

(iii) Integral of time multiplied by the squared error, ITSE

$$J_{ITSE} = \int_0^{t_\infty} t[y(t) - y_r(t)]^2 \, dt \qquad (6)$$

Where $y(t)$ and $y_r(t)$ are the unit step responses of original and reduced order systems.

4 Results and Comparison

The second order reduced transfer functions $R_{pise}(s), R_{pitae}(s)$ and $R_{pitse}(s)$ of the original fourth order plant transfer function $G_p(s)$ (1), are obtained by using proposed algorithm applying different fitness functions ISE, ITAE and ITSE respectively. The step responses of the original $G_p(s)$ and all the reduced order plant transfer functions are compared in Fig.2.

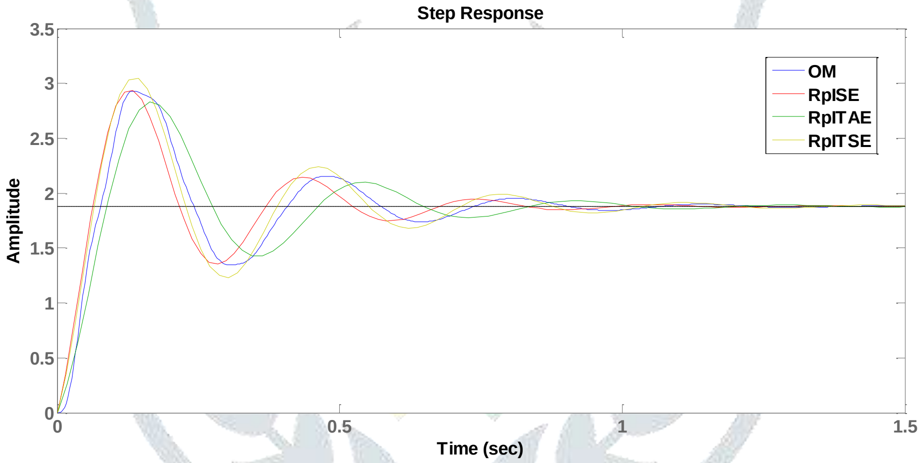

Fig.2. Comparison of Step Responses of the Original and the Reduced Order Plant Transfer Functions

All reduced transfer functions are shown in Table 1. The values of performance indices (fitness functions) and corresponding transfer functions of controllers i.e. $G_{cise}(s), G_{citae}(s)$ and $G_{citse}(s)$ obtained are also shown in table 1.

Table1. Reduced Order Transfer Functions for various Fitness Functions

Fitness functions	Reduced order models	Value of performance Indices	Controller
ISE	$R_{pise}(s) = \frac{19.34s + 830.7}{s^2 + 9.082s + 441.8}$	3.2×10^{-2}	$G_{cise}(s) = \frac{5.87s + 187.22}{s^2 + 16.088s + 547.82}$
ITAE	$R_{pitae}(s) = \frac{10.3s + 561.2}{s^2 + 7.865s + 298.4}$	2.41×10^{-5}	$G_{citae}(s) = \frac{7.29s + 189.6}{s^2 + 16.46s + 554.37}$
ITSE	$R_{pitse}(s) = \frac{18.07s + 730.8}{s^2 + 7.266s + 388.6}$	1.8×10^{-3}	$G_{citse}(s) = \frac{4.65s + 188.7}{s^2 + 16.26s + 551.85}$

The values of parameters e.g, swarm size, number of iterations, w, c_1 and c_2 used for implementation of the proposed algorithm are 25, 10, 0.4, 1.5 and 1.5 respectively.

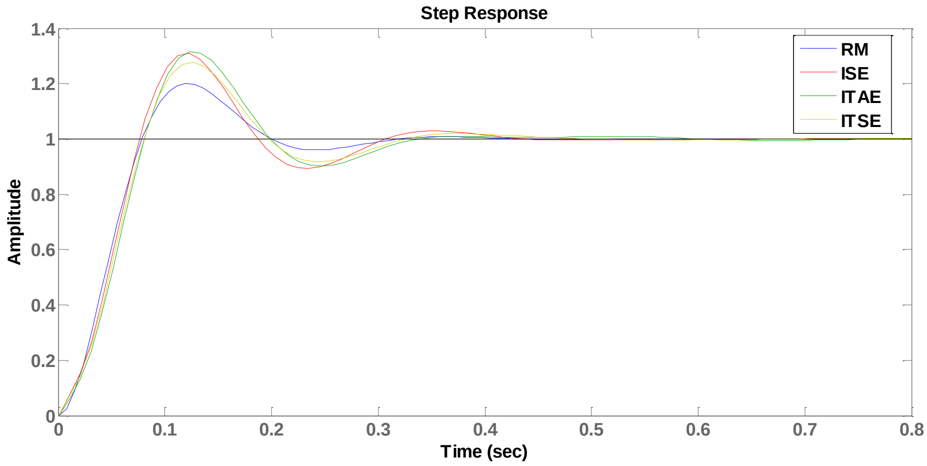

Fig.3. Comparison of Step Responses of the Original and the Reduced Order Closed- Loop Systems

Fig.3 shows the comparison of step responses of the reference model and closed loop transfer functions of the reduced models obtained by proposed algorithm. It is seen that all the responses are approximately matching both in steady state and transient stable regions.

Table 2. Comparison of Different Time Specifications of Step Responses

Model	Rise-Time (Sec)	Settling-Time (Sec)	% Overshoot	Peak-Time (Sec)
Reference Model	0.053	0.28	19.96	0.1192
Reduced Order Model (ISE)	0.055	0.38	30.93	0.1224
Reduced Order Model (ITAE)	0.057	0.31	31.46	0.1235
Reduced Order Model (ITSE)	0.058	0.30	27.78	0.1263

Table 2 shows the comparison of time durations of step responses of the reference model, closed-loop transfer function of the original plant and that of the reduced model. It is obvious from the results that the various specifications are quiet comparable to each other.

5. Conclusion

The importance of the evolutionary techniques (e.g. PSO, GA etc.) over the different conventional methods of reduction has been explained. In this paper, it is shown that the design of the controller for pantograph has become simpler using PSO by applying different fitness functions (e.g. ISE, ITSE, ITAE). The results obtained using the various performance indices are quite comparable as shown in the figure 3 and table 2. However for this particular system the algorithm developed by taking the ISE as fitness function consumes minimum time to get implemented. Further research in the field of control system is possible by implementing the other evolutionary techniques like Ant Colony optimization, fuzzy logic and ANN which will be one of the research areas of the authors in near future.

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