FPID controller design based different optimization Techniques for model order reduction of AVR

Nasir A. Al-Awad, Nora G. Rahman

Abstract— **Fractional+ Proportional + Integral + Derivative (FPID) controller configuration is proposed and executed on the decreased request of Automatic Voltage Regulator (AVR) framework utilizing soft-computing(Optimizations) systems, Invasive Weed Optimization (IWO), Differential Evolution (DE), Ant Colony Optimization(ACO), Sine Cosine algorithm (SCA). Minimization of a multi-target work controls these calculations' investigation until the procedure meets with an ideal arrangement. A recreation study is conveyed to analyze the presentation of every one of these methods for controller plan technique. The time-area ideal tuning of model order reduction of (AVR) frameworks were done utilizing Integrated Square Error (ISE), Integrated Time Square Error (ITSE), Integrated Absolute Error (IAE) and Integrated Time Absolute Error (ITAE) as the exhibition lists. The presentation of the FPID controller is approved with best heuristic strategies, (SCA). The aftereffects of FPID controller is additionally contrasted and traditional PID controller. The FPID controller showed strong execution in transient exhibitions, robust performance in transient performances, less settling time, maximum overshot and steady-state error. The FPID controller displays an ISO-damping property (flat reaction).**

***Keywords*—AVR, Model reduction, IWO, DE, ACO, SCA.**

I. INTRODUCTION

The higher request frameworks can be found in diverse enterprises like oil, bond, substance, pharmaceutical, flying machine framework, nuclear atomic plant, adaptable robot controller [1], quadrotor with a variable level of opportunity (DOF) [2], fuel injector and flash planning of vehicles, and so on [3]. Commonly, nonlinear frameworks are linearized at various working focuses, and end up being higher request frameworks [4, 5]. Additionally, at times during displaying of the framework, one may will in general get higher request framework utilizing first guideline strategy or limited component model [6, 7]. For the most part, these models are improper for some, applications like examination of framework, streamlining or control framework structure. In enormous scale frameworks, the framework multifaceted nature makes the calculation illogical inferable from memory and time restrictions just as the ill-conditioning [8]. Designing of the controller for this class of frameworks is constantly a difficult undertaking. If the order of the system is more than two, it is referred as higher order control system [9]. In [6] designed fractional order controller with a model reduction method for higher order systems using optimization method. In 1998, B. Bandyopadhyay et al. proposed a technique for designing a stabilizing controller for the stable higher order system via its reduced order model. The paper [10] proposed fuzzy self-tuning PID controller for higher order system.[11] proposed fuzzy PID controller for this category of systems. In most of these works, higher order systems are approximated to lower order system by means of model reduction methods like Pade approximation methods, Routh approximation techniques, model reduction by impulse/step error minimization, principal component analysis method [12], and balanced-truncation method [13]. These methods are preferred in the case of limited computational power, accuracy and storage capabilities. These reduced models need to prevent essential characteristics of the original system. However, it is not always possible to capture these characteristics. Hence, reduced order model is not appropriate for different applications if it is not capturing important characteristics. The disadvantage of some methods is that they do not guarantee stable reduced models even though the original system is stable.

As of late, Heuristic Algorithms (HA) upheld streamlining are developed as a useful asset for finding ideal answers for an assortment of designing advancement issues [14].

A tuning technique for the partial request framework dependent on investigative strategy was proposed by [15]. Parameters of the FPID controller were gotten by tackling conditions that were acquired from the ideal determinations. Consequences of this strategy were approved utilizing two models. The tuning strategy dependent on the details just as the proposed auto-tuning technique for FPID controller dependent on the hand-off test was depicted in [16] and [17]. It permits the prerequisites of power requirements for the FPID framework utilizing basic relations among its parameters.

The tuning of fractional order controllers dependent on numerical strategies has been proposed by numerous analysts. In view of a hereditary calculation [18, 19] were proposed tuning of FPID utilizing indispensable of time-weighted total mistake (ITAE) and control contribution as an exhibition file. The paper [19] additionally proposed tuning of FPID utilizing a versatile hereditary calculation for the dynamic attractive bearing framework. In light of the hereditary calculation [20], tuning rules have been created utilizing time area execution record. The upgraded particle

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swarm optimization (PSO) technique has likewise been utilized for structuring of partial request controllers [21, 22]. The FPID controllers were additionally structured by various techniques like an improved differential advancement enhancement approach by [23], electromagnetism like calculation [24] and MIGO (Ms constrained integral gain optimization) strategy by [25]. In this work, numerical based technique is utilized for structuring of FPID controller, as scientific models are accessible for higher request frameworks. The auto-tuning strategy for FPID controller was created dependent on transfer [23] and modulus, stage and stage slant of the procedure [26]. IMC based tuning for the FPID controller was proposed by few researchers [27].

II. MODEL REDUCTION OF AVR

(AVR) is a gadget intended to control voltage naturally, for example to take a fluctuating voltage level and change it into a steady voltage level, as the AVR model is unpredictable and in high order. There are numerous methods for improving it to the low order, and there are additionally numerous sorts of programmed voltage controllers [28].Fig. 1 show the block-diagram of AVR.

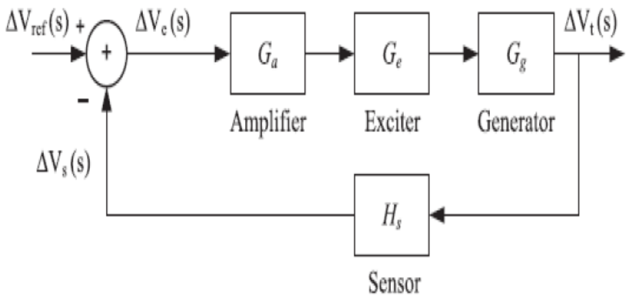

Fig.1 shows block-diagram of AVR system

Due to paper limitation, [29] gives more details and deriving the transfer functions for each component, the whole closed-loop transfer function is:-

$$\frac{V_t(s)}{V_{ref}(s)} = Go(s) = \frac{0.0599s^3 + 5.994s^2 + 8.252s + 825.2}{0.00573s^6 + 0.644s^5 + 7.686s^4 + 55.571s^3 + 465.86s^2 + 879.208s + 1086} \quad (1)$$

The transfer function of AVR as appear in “(1)” is sixth order , so we've tried to approximate it to second order.

There are many methods for model order reduction [30],but in this work Biogeography-based optimization (BBO) is used and this an evolutionary algorithm that optimizes a function by stochastically and iteratively improving candidate, for more details see ref.[31]. The parameters of BBO algorithm in this work are considered as follows:

1- Generation count limit =150
2- Population size=50
3- Mutation Probability = 0.06
4- Number of Elites = 2

Refer to “(1)” of original system and using all solution steps of (BBO) algorithm, by MATLAB program, it is found that the reduced transfer function is:-

$$G_r = \frac{0.0003217s + 2.401}{1.277s^2 + 2.386s + 3.171} \quad (2)$$

III. FPID CONTROLLER

Alain Oustaloup is initially presented the fractional-order Controllers (FOC). He urbanized the three different form of the CRONE controller with the end goal that first, second and third generation controllers were developed [32]. I. Podlubny exhibited the primary report on fractional order PID controller [33, 34]. He authored an idea of fractional order PI D controller which is the expansion of the old style PID controllers, where a PID controller structure with an integrator of order λ and a differentiator of order μ was presented [35]. The PI D controller is additional bendy and gives better prospects to adjust the dynamic properties of partial request frameworks conversely with the old style PID controller. The structure of FPID controller is in the parallel form:

$$C(s) = Kp + \frac{Ki}{s^{\lambda}} + Kds^{\mu} \quad (3)$$

IV. TUNING OF FPID CONTROLLER

The points of generally intrigued by FOPID controller is to evaluate the controller parameters such huge numbers of techniques are accomplished for instance self - tuning and auto-tuning which presented by [36],rule base technique [37] for which FOPID controller dependent on Ziegler Nichols-type rules, Analytical strategies [38]. at last numerical treatment for streamlining fractional order controllers has been presented by different researchers, in light of the genetic algorithm [39], based on particle swarm optimization (PSO) technique[40] has additionally been utilized for assessing the controllers parameters. The FPID controllers were likewise structured by various strategies like an improved differential development enhancement approach by [41].

In this work, numerical based strategy is utilized for planning of FPID controller, as scientific models are accessible for reduce AVR framework. The tuning strategies for FPID controller were created dependent on soft techniques algorithms and with different performance indices, Integral square error (ISE),Integral time square error(ITSE),Integral absolute error(IAE) and Integral time absolute error (ITAE).

A- IWO algorithm

(IWO) is a new computational method which is employed to resolve optimization problems of one-of-a-kind varies. Like most of the algorithms in the place of evolutionary computation, IWO has no need to the gradient of the function in its optimization process [42]. Fig.2 shows the flow-chart of IWO, Four distinct objective features are used to examine the controller's efficiency: ISE, ITSE, IAE and ITAE. Thus, in equations.(4)–(7) the objective features used in this research phase are provided:

$$ISE = \int_0^{\infty} e^2(t)d(t) \quad (4)$$

$$ITSE = \int_0^\infty t.e^2(t)d(t) \quad (5)$$

$$IAE = \int_0^\infty e\ (t)dt. \quad (6)$$

$$ITAE = \int_0^\infty t.e\ (t)dt. \quad (7)$$

Generally the parameters of the IWO algorithm are considered as follows in this work:
Smin=0, Smax=5, itermax=150, n=2, initial population size=2, maximum population size=10, initial value of standard deviation=0.5, the final value of standard deviation=0.001. Matlab package can be used to execute IWO procedures.

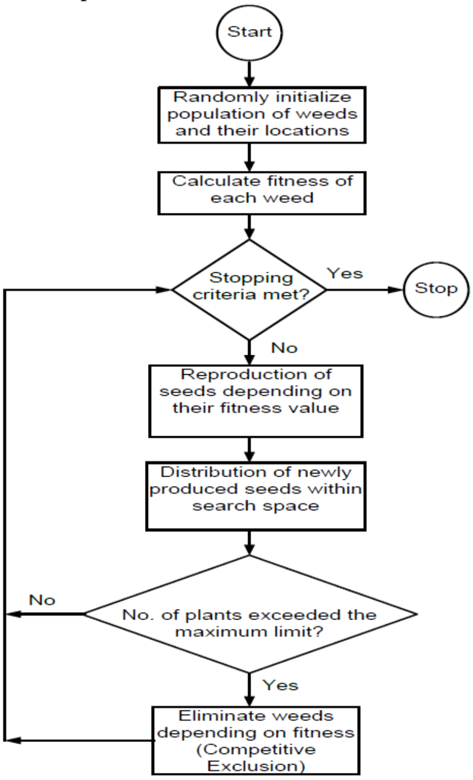

Fig.2 Flowchart of IWO

Firstly, the tuning is done to obtain the parameters of PID controller Kp, Ki and Kd by using MATLAB statement "pidtool" with some tuning, the values are:- Kp=2.9253, Ki=2.9774, and Kd=0.6473.

The designed FOPID controller is approximated by oustaloup filter. The fractional derivative and integrals of FOPID controller have been approximated by N=5 and filter frequency [Wl,Wh] =[0.001,1000].Table.1parameters values of FPID controller with different performance indices using IWO algorithm, while Table.2 shows transient parameters with different performance indices while fig.3 shows the transient response comparison of IWO-FPID with different performance indices.

Table 1. Parameters values of FPID controller with different performance indices using IWO algorithm

Performance index	Kp	Ki	λ	Kd	μ
ZN-PID	2.92	2.98	1	0.647	1
ISE	10	10	0.7893	10	1.412
ITSE	10	10	1.0010	6.477	1.020
IAE	9.623	10	1.0142	4.480	1.126
ITAE	5.136	8.666	1	3.336	0.875

Table 2. Transient parameters values of FPID controller with different performance indices using IWO algorithm

Performance index	Ts(sec)	Tr(sec)	Mp%	Tp	Ess
ZN-PID	6.6522	3.3707	0.6789	1.27	0
ISE	1.0031	6.7437	2.0701 e-7	3.43	0
ITSE	0	1.5706	0.2058	2.93	0
IAE	0.0026	0.8068	0.3043	2.11	0
ITAE	2.1734	0.8176	0.3259	0.709	0

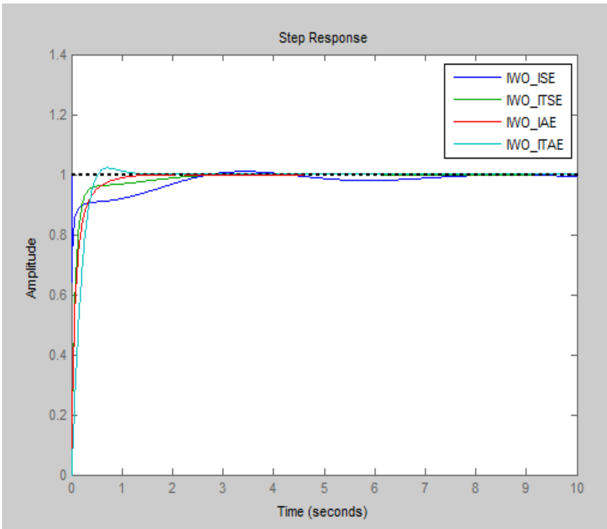

Fig.3 shows the transient response comparison of IWO- FPID with different performance indices

B- DE algorithm

DE algorithm is a population based algorithm like genetic algorithms using similar operators; crossover, mutation and selection. The main operation of DE is based on the differences of randomly sampled pairs of solutions in the population. The DE algorithm also uses a non-uniform crossover that can take child vector parameters from one parent more often than it does from others [43].
Fig.4 shows the flow-chart of DE, also, four distinct objective features are used to examine the controller's efficiency, equations(4)-(7).

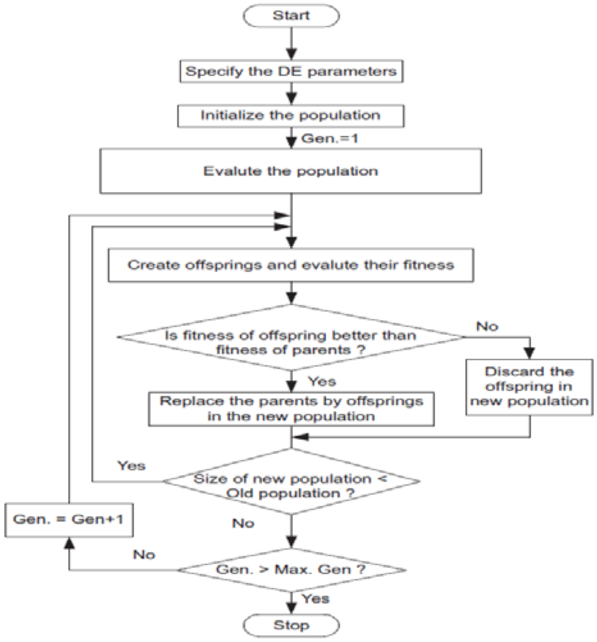

Fig.4 Flowchart of DE

Generally the parameters of the DE algorithm are considered as follows in this work:

Population size, pop size (NP)= 10, reduced bound scaling factor F1=0.2, upper bound F2=0.8, crossover likelihood Cr=0.2. The technique of mutation utilizes "DE / Rand/1" and 150 iterations maximum. If the ideal theoretical solution is discovered, the program will end. The lower bound of decision variables [00000] and the upper bound of decision variables [10 10 1.5 10 1.5]. Matlab package can be used to execute DE procedures. Table.3 indicates the FPID controller values depending on the performance indices, while Table.4 shows transient parameters with different performance indices. Fig.5 shows the transient response comparison of DE-FPID with different performance indices.

Table 3. Parameters values of FPID controller with the different performance indices using DE algorithm

Performance index	Kp	Ki	λ	Kd	μ
ZN-PID	2.92	2.98	1	0.647	1
ISE	10	10	10	0.789	1.4115
ITSE	10	9.7607	5.1492	1.009	1.0806
IAE	10	10	4.8438	1.010	1.1362
ITAE	7.387	10	3.9717	1	0.9917

Table 4. Transient parameters values of FPID controller with the different performance indices using DE algorithm

Performance index	Ts(sec)	Tr(sec)	Mp%	Tp	Ess
ZN-PID	6.6522	3.3707	0.6789	1.273	0
ISE	0.9898	22.932	3.9697e-04	3.466	0.99
ITSE	0.0495	1.0527	0.2594	3.330	0
IAE	0.0187	0.9345	0.3010	6.958	0
ITAE	0.0922	0.4976	0.2884	0.985	0

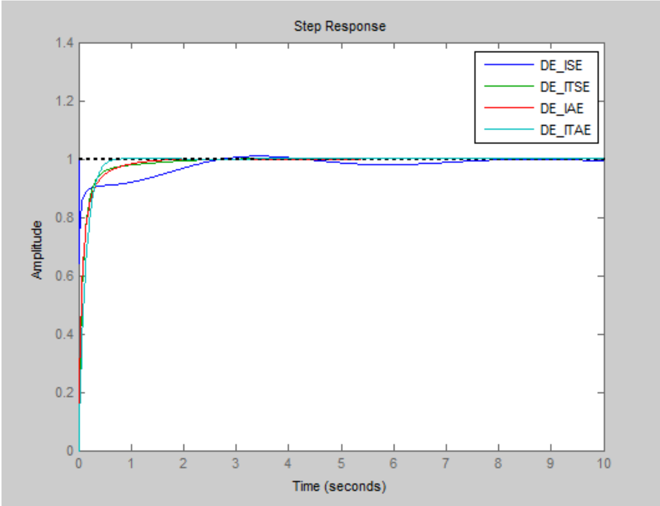

Fig. 5 Shows the transient response comparison of DE-FPID with different performance indices

C- ACO algorithm

(ACO) methodology is based on the ant's capability of finding the shortest path from the nest to a food source. An ant repeatedly hops from one location to another to ultimately reach the destination (food). ACO is a general term for ant-based algorithms used for solving optimization problems [44]. Fig.6 shows the flow-chart of ACO, also, four distinct objective features are used to examine the controller's efficiency, equations (4)-(7). Generally the parameters of the ACO algorithm are considered as follows in this work:

NumOfAnts=10,Pheromone=0.09,EvaporationParameter=0.65,PositivePheremon=0.2,NegativePheremone=0.1,MaxTour=150,MinValue=0,MaxValue=1,LB = [0 0 0 0 0];UB = [10 10 1.5 10 1.5].

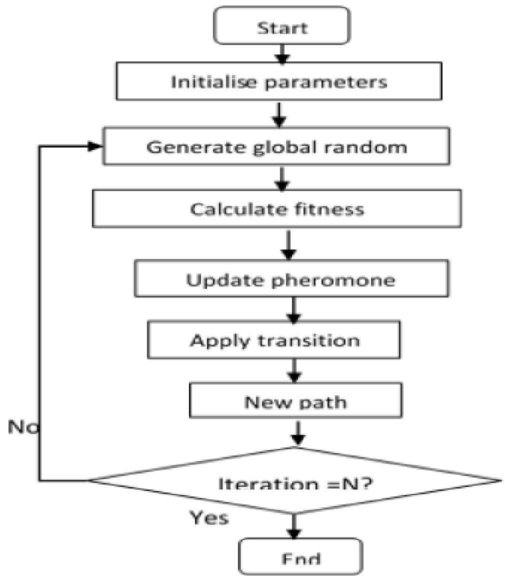

Fig.6 Flowchart of ACO

Table.5 indicates the FPID controller values depending on the performance indices, while Table.6 shows transient parameters with different performance indices. Fig.7 shows the transient response comparison of ACO-FPID with different performance indices.

Table 5. Parameters values of FPID controller with different performance indices using ACO algorithm

Performance index	Kp	Ki	λ	Kd	μ
ZN-PID	2.92	2.98	1	0.647	1
ISE	9.9800	9.5200	9.96	0.8250	1.386
ITSE	8.7	9.84	5.4	0.9990	1.023
IAE	10	9.8	4.5200	1.0110	1.152
ITAE	7.24	10	3.92	1.008	0.963

Table 6. Transient parameters values of FPID controller with different performance indices using ACO algorithm

Perfor-mance index	Ts (sec)	Tr(sec)	Mp%	Tp	Ess
ZN-PID	6.6522	3.3707	0.6789	1.2730	0
ISE	9.6986	0.2203	4.7448e-06	0	0
ITSE	0.1964	1.2550	1.3159e-07	2.9406	0
IAE	0.0218	0.8607	0.3155	6.1018	0
ITAE	0.5468	0.4493	0.2834	0.7316	0

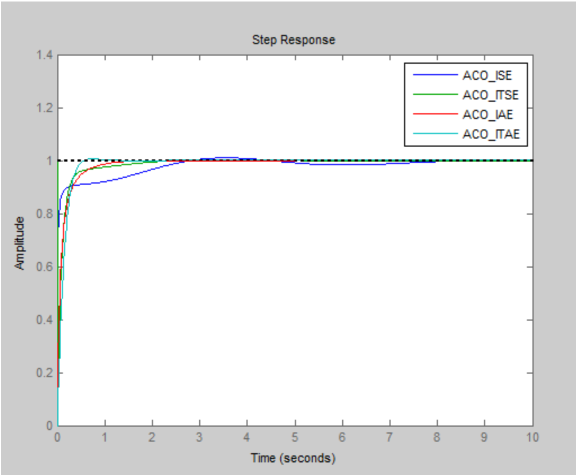

Fig. 7 shows the transient response comparison of ACO-FPID with different performance indices

D- SCA algorithm

is a new optimization technique for solving optimization problems. The SCA creates multiple initial random candidate solutions and requires them to fluctuate outwards or towards the best solution using a mathematical model based on sine and cosine functions. It uses the sine and cosine functions to explore and exploit the space between two solutions in the search space in order to find better solutions, several random and adaptive variables also are integrated to this algorithm to emphasize exploration and exploitation of the search space in different milestones of optimization [45]. Fig.8 shows the flow-chart of ACO, also, four distinct objective features are used to examine the controller's efficiency, equations (4)-(7). Generally the parameters of the ACO algorithm are considered as follows in this work:

Lb=[0 0 0 0 0], ub=[10 10 1.5 10 1.5], search agents number=10,maiximum iterations=150, Dim=number of variables=5.

Table 7. Parameters values of FPID controller with different performance indices using SCA algorithm

Performance index	Kp	Ki	λ	Kd	μ
ZN-PID	2.92	2.98	0.647	1	1
ISE	10	10	10	0.845915	1.42107
ITSE	9.62003	10	7.77615	1.04564	0.827074
IAE	7.6988	9.8833	4.5358	1	0.96059
ITAE	9.4023	9.7808	4.3588	1.0037	0.88293

Table 8. Transient parameters values of FPID controller with different performance indices using SCA algorithm

Performance index	Ts(sec)	Tr(sec)	Mp%	Tp	Ess
ZN-PID	6.6522	3.3707	0.6789	1.2730	0
ISE	1.9174	17.5373	2.5549e-04	3.4292	0
ITSE	1.8087	1.8569	0.1835	0.3582	0
IAE	0.1638	0.4577	0.2582	3.4270	0
ITAE	1.9187	1.5877	0.2761	0.6981	0

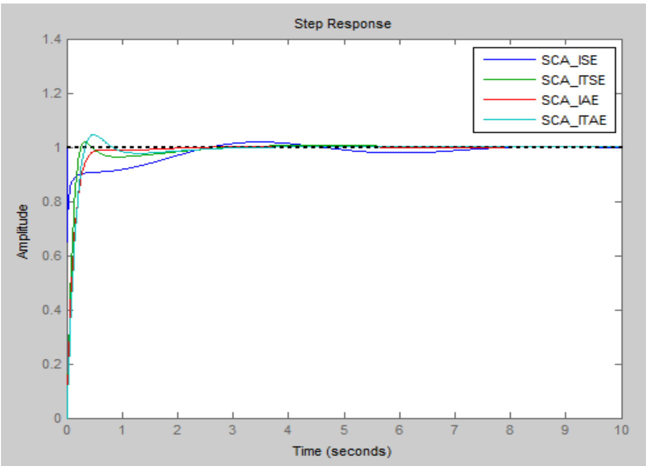

Fig. 8 shows the transient response comparison of SCA-FPID with different performance indices

V. Discussion

In this paper, simulation study is performed and implemented using Matlab R2010a software. Four objective functions are considered to guide the optimization search. In order to perform a fair estimation, all the considered optimization procedures are assigned with the similar preliminary algorithm parameters as specified, population size (N) is 10; maximum number of iteration is assigned as(150) and simulation time is allocated as (10sec).Firstly, FPID design procedure is executed with IWO using a three dimensional search (Kp, Ki, Kd, λ ,μ). Later, similar tuning procedure is repeated on the AVR system using other optimization methods, such as DE,ACO, and the obtained FPID values are presented in Tables 1,3,5,7.During the simulation study, it is assumed that, the system is free from external disturbances. Fig .3,5,7,8 presents the value of the terminal voltage with respect to the simulation time and the corresponding performance measure values are recorded in Tables 2,4,6,8. From these tables, it is noted that, the ISE,gives bad design requirements offers larger (Mp) and (Ts) values compared with alternatives(ITSE,IAE,ITAE).For(ITSE),it seen that(IWO) and(DE) are gives almost identical transient response parameters(Mp,Ts).see fig.9.

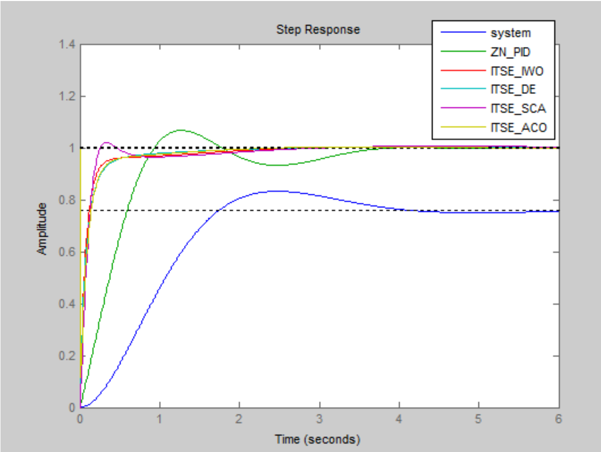

Fig. 9 shows the transient response comparison of ITSE-FPID with different optimization methods

While (IAE) performance index is better compared with others indices for all optimization methods, as seen from table 4 and fig.10.

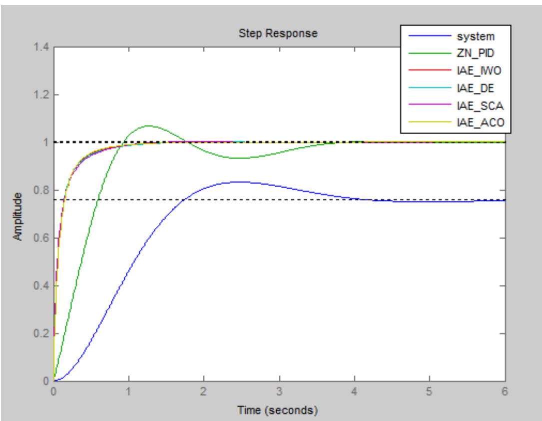

Fig. 10 shows the transient response comparison of IAE-FPID with different optimization methods

From this study, it is verified that, even though the number of controller parameters to be tuned is large, the FPID-DE structure with IAE offers better set point tracking response and good controller output compared with traditional PID and FPID controllers with different optimization methods.

VI. Conclusion

In this paper, traditional PID controller for model order reduction of AVR design is proposed and its performance is validated with IWO, DE, ACO and SCA optimization methods. The simulation study shows that, the controller parameters obtained with the considered DE algorithm and IAE performance index is better performance measure values compared with others methods with different indices. In this paper, we have given an idea of different optimization techniques which are used for tuning FPID controller parameters. From the comparison study with Z-N, IWO, DE and SCA, we can also conclude that the DE method can make the convergence speed for FPID parameters optimization problems faster with good global searching ability. All the conventional methods of controller tuning lead to a large Ts, Mp, Tr and Ess of the controlled system. Hence a Soft computing techniques is introduces into the control loop. Generally, IWO, DE, ACO and SCA based tuning methods have proved their excellence in giving better results by improving the steady state characteristics and performance indices, when compared with conventional methods, but still DE is the best one because the mutation operation simply changes aspects of the solution according to a statistical distribution which weights minor variations in the behavior of the offspring as highly probable and substantial variations as increasingly unlikely.

VII. Acknowledgment

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