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Design of DE Optimized SSSC-based FACTS controller

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Abstract. Power-system stability improvement by a static synchronous series compensator (SSSC)-based controller is studied in this paper. Conventionally, the lead-lag structure was used to modulate the injected voltage. But, in this paper PI, PID, PIDD structures are proposed to modulate the injected voltage. The design problem of the proposed controller is formulated as an optimization problem and Differential Evolution Algorithm is used to find out the optimal controller parameters. Different disturbances are applied to the single-machine infinite bus system and multi-machine infinite bus system and the performances of the conventional structure and the proposed structure are evaluated and compared. Only remote signals with required time delays are taken into account in this paper. The simulation results are presented and compared with a modern heuristic optimization technique under various loading conditions and disturbances to show the effectiveness of the proposed approach.

Keywords: FACTS, Static Synchronous Series Compensator, Differential Evolution Algorithm, Genetic Algorithm, PID Controller, Lead-Lag Structure.

1 Introduction

Recent developments in power electronics introduced Flexible AC Transmission Systems i.e. FACTS. It has a property of higher controllability in power systems by means of power electronics devices [1]. These devices include Thristor Controlled Series Compensator (TCSC), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC) and more. SSSC being a series device has the capability to increase or decrease the overall reactive voltage drop across the line, thereby controlling the power flow. Because the voltage that is injected by the VSC within the SSSC is not related to the line current and can be controlled independently, the SSSC is effective for both low and high load conditions as in [2,3,4].The applications of SSSC ranges from power oscillation damping to frequency stabilization in power systems that can be found in several references [5,6].

Despite much advancement, the lead-lag structure based controller and proportional-integral-derivative (PID) based controllers remain an engineer's choice for many industrial applications. These controllers are preferred because of their structural simplicity, favorable ratio between performance and cost and reliability.

Along with these, it also offers simplified dynamic modeling, lower user-skill requirements, and minimal development effort, which are issues of substantial importance to engineering practice as given in [7]. In this paper, both lead-lag and PID structures are considered along with PI and PIDD structures to modulate the SSSC injected voltage. Only remote signals are considered as input to the proposed controllers.

Conventional techniques such as eigenvalue assignment, mathematical programming and linear matrix inequalities have already been used in FACTS-based damping controller design. But, these methods are time consuming as they require heavy computation and has slow convergence rate. But, recently, Artificial intelligence-based approaches that are less time consuming are applied in this area. These methods include genetic algorithm [8,9,10], particle swarm optimization [11] and differential evolution searches for the optimal solutions via some form of directed random search process.

DE algorithm is a stochastic optimization method minimizing an objective function that can model the problem's objectives while incorporating constraints. This evolution strategy called DE has been recently proposed by Storn [12]. The algorithm mainly has three advantages; finding the true global minimum regardless of the initial parameter values, fast convergence, and using a few control parameters. DE is simple, fast and easy to use. It is quite effective in nonlinear constraint optimization including penalty functions and is useful for optimizing multi-modal search spaces as given in [13]. It has been applied to several engineering problems in different areas [14,15,16,17].

2 System Model

A single machine infinite-bus system with SSSC is shown in fig.1. The system comprises a synchronous generator connected to an infinite-bus through a step-up transformer and a SSSC is placed in between two double circuit transmission line. The generator is a subsystem which contains hydraulic turbine & governor (HTG) and excitation system. A non-linear hydraulic turbine model, a PID governor system and a servomotor constitutes the HTG system whereas the excitation system consists of a voltage regulator and DC exciter.

The SSSC consists of a converter that is connected in series with the transmission line. It operates without an external energy source as a series compensator whose output voltage is in quadratic with and controllable independently of the line current. The voltage injected (Vq) by the **SSSC** is (almost) in quadrature with the transmission line current such that it emulates the behavior of a series inductor or capacitor.

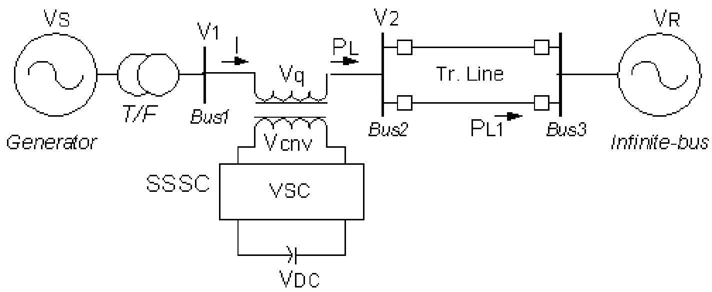

Fig. 1 Single-machine infinite-bus power system with SSSC

3 The Proposed Approach

3.1 Structure of SSSC-based Damping Controller

A combination of Proportional (P), Integral (I) or Derivative (D) is used as a SSSC based controller to modulate the SSSC injected voltage Vq. The PID controller structure is given in fig.2. This representation is similar to the strucuture used in MATLAB environment.

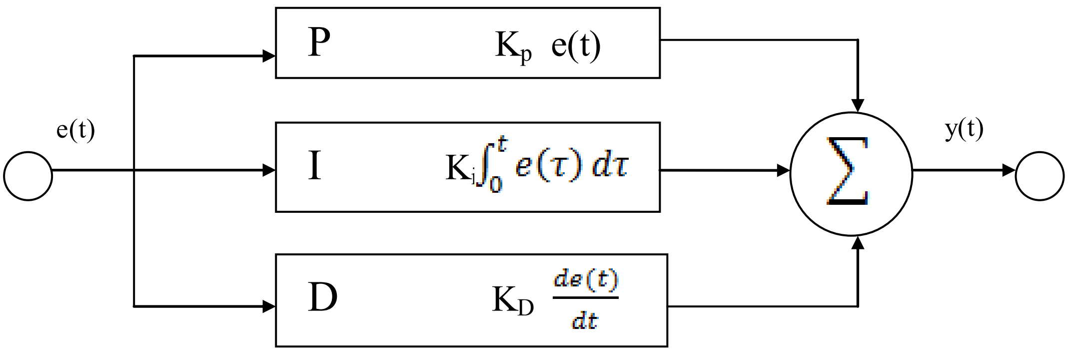

Fig-2 The structure of the PID controller

The Laplace transform form of the PID regulator is:-

$$G(s) = Kp + \frac{Ki}{} + Kds$$

The proportional mode adjusts the output signal in direct proportion to the controller input. An additional integral mode corrects for any offset that may occur between the desired value and the process output automatically over time. The derivative action should always improve the dynamic response. It depends on the slope of the error. If the error is constant, the derivative action has no effect.

Another structure used in this paper to modulate the SSSC injected voltage is the lead-lag structure as shown in fig.3. Input signal to the structure is speed deviation and its output is the injected voltage. This structure consists of a gain block, washout block and two stage lead-lag block. The two stage lead-lag block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The washout block acts as a high pass filter to allow signals associated with oscillations to pass as it is. The delay block produces a delay according to the type of input signal. In case of remote signal, both sensor time constant and the signal transmission delays are included whereas for local signal input, only sensor time constant is considered.

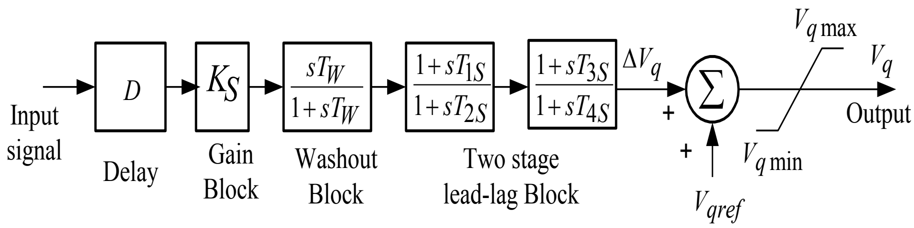

Fig. 3. Structure of proposed SSSC-based damping controller

This paper compares the performance of GA-based lead lag structure with DE-based PI, PID and PIDD structure. Time constants T_{1S}, T_{2S} and T_{3S}, T_{4S} are optimized by using GA technique whereas constants such as K_p, K_I , K_D are found out using DE algorithm.

3.2 Problem Formulation

In the present study, the values of K_p and K_i are to be determined. During steady state conditions ΔVq and Vqref is constant. During dynamic conditions the series injected voltage Vq is modulated to damp system oscillations. The effective Vq in dynamic conditions is:-

$$V_q = V_{qref} + \Delta V_q.$$

SSSC-based controllers are required to damp power system oscillations after the system is subjected to large disturbances. The objective function is to minimize the deviation in rotor speed , line power and power angle in which the oscillations are reflected. Here, the objective function is considered to be an integral time absolute error of the speed deviations and is expressed as:-

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| \cdot t \cdot dt$$

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4 Differential Evolution Algorithm

The DE algorithm is a population based algorithm like genetic algorithms using the similar operators; crossover, mutation and selection. The main difference in constructing better solutions is that genetic algorithms rely on crossover while DE relies on mutation operation. This main operation is based on the differences of randomly sampled pairs of solutions in the population.

The algorithm uses mutation operation as a search mechanism and selection operation to direct the search toward the prospective regions in the search space. 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. By using the components of the existing population members to construct trial vectors, the recombination (crossover) operator efficiently shuffles information about successful combinations, enabling the search for a better solution space.

An optimization task consisting of D parameters can be represented by a D-dimensional vector. In DE, a population of NP solution vectors is randomly created at the start. This population is successfully improved by applying mutation, crossover and selection operators [9].

The main steps of the DE algorithm is given below:

Initialization
Evaluation
Repeat
Mutation
Recombination
Evaluation
Selection
Until *(termination criteria are met)*

4.1 Initialization

For each parameter j with lower bound X_j^L and upper bound X_j^U, initial parameter values are usually randomly selected uniformly in the interval $[X_j^L, X_j^U]$.

4.2 Mutation

For a given parameter vector $X_{i,G}$, three vectors ($X_{r1,G}$ $X_{r2,G}$ $X_{r3,G}$) are randomly selected such that the *indices i, r1, r2* and *r3* are distinct. A donor vector $V_{i,G+1}$ is created by adding the weighted difference between the two vectors to the third vector as:

$$V_{i,G+1} = X_{r1,G} + F.(X_{r2,G} - X_{r3,G}) \qquad \text{Where } F \text{ is a constant from } (0,2)$$

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4.3 Crossover

Three parents are selected for crossover and the child is a perturbation of one of them. The trial vector $U_{i,G+1}$ is developed from the elements of the target vector ($X_{i,G}$) and the elements of the donor vector ($X_{i,G}$).Elements of the donor vector enter the trial vector with probability *CR* as:

$$U_{j,i,G+1} = \begin{cases} V_{j,i,G+1} & if \quad rand_{j,i} \leq CR \quad or \quad j = I_{rand} \\ X_{j,i,G+1} & if \quad rand_{j,i} > CR \quad or \quad j \neq I_{rand} \end{cases}$$

With $rand_{j,i} \sim U(0,1)$, I_{rand} is a random integer from (1,2,….D) where *D* is the solution's dimension i.e number of control variables. I_{rand} ensures that $V_{i,G+1} \neq X_{i,G}$.

4.4 Selection

The target vector $X_{i,G}$ is compared with the trial vector $V_{i,G+1}$ and the one with the better fitness value is admitted to the next generation. The selection operation in DE can be represented by the following equation:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} & if \ f(U_{i,G+1}) < f(X_{i,G}) \\ X_{i,G} & otherwise. \end{cases}$$

where $i \in [1, N_P]$.

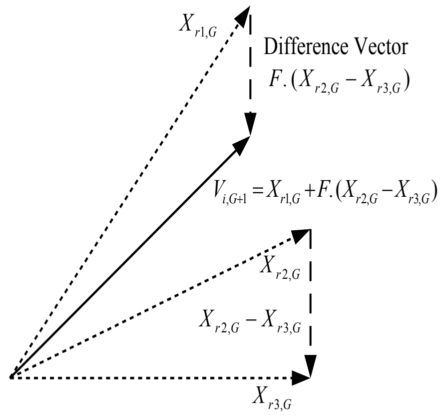

Fig. 4 shows the vector addition and subtraction necessary to generate a new candidate solution.

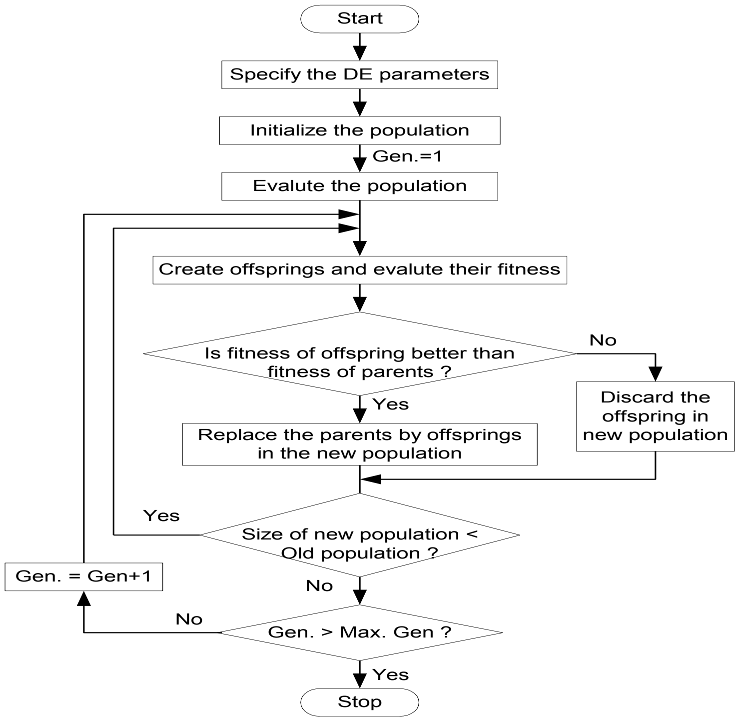

Fig. 5 Flow chart of proposed DE optimization approach

5 Results and discussions

The model of the system given in fig1. has been developed in Sim Power System blockset in MATLAB environment. The system consists of a of 2100 MVA, 13.8 kV, 60Hz hydraulic generating unit, connected to a 300 km long double-circuit transmission line through a 3-phase 13.8/500 kV step-up transformer and a 100 MVA SSSC. The DE is used to optimize the parameters of the controller.

DE step, size function , cross-over probability, the number of population, initialization, termination and evaluation function are the six issues to be determined by DE. Population size of 20 is considered. The cross-over probability is generally taken in the range 0.5 to1.The step size(F) is considered to be 0.8. Simulations were conducted in MATLAB 7.8.0 environment. This

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optimization was repeated 20 times and the best result among them is chosen for the controller. The best obtained result is given in Table 1.

Table 1. Optimal values of the parameters of the controller in different loading conditions.

LOADING CONDITION	PI	PID	PIDD
NOMINAL	$K_P = 72.9294$ $K_I = 0.0100$	$K_P = 65.6148$ $K_I = 0.0100$ $K_d = 1$	$K_P = 100.00$, $K_I = 0.2931$ $K_d = 0.0100$
LIGHT	$K_P = 100.00$ $K_I = 0.8597$	$K_P = 100.00$ $K_I = 1.3034$ $K_d = 1$	$K_P = 100.00$ $K_I = 1.8564$ $K_d = 0.0708$
HEAVY	$K_P = 78.4280$ $K_I = 0.9695$	$K_P = 74.9405$ $K_I = 0.7341$ $K_d = 0.9326$	$K_P = 100.00$ $K_I = 1.3654$ $K_d = 0.0598$

Case 1: Nominal loading (P_e=0.8 pu)

The robustness of the proposed controllers is tested under light loading condition. . A 3-phase self clearing fault of 100 ms duration is applied at the middle of one transmission line connecting bus 2 and bus 3, at *t* = 1.0 s. The speed response, power and the injected voltage plots are given in fig 6, fig 7and fig 8. It is observed that the PID controller gives the best result in this loading condition.

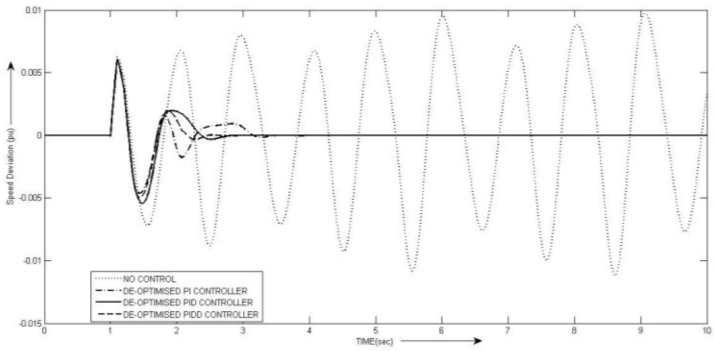

Fig. 6. . Comparison of different structures for speed deviation response for 100 ms 3-ph fault in transmission line with nominal loading

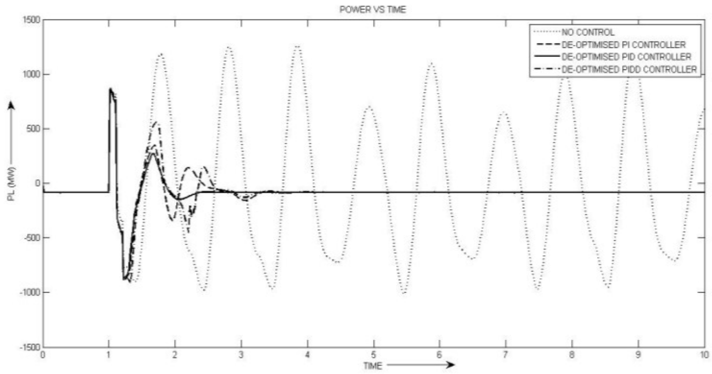

Fig. 7. Comparison of different structures for tie-line power flow response for 100 ms 3-ph fault in transmission line with nominal loading.

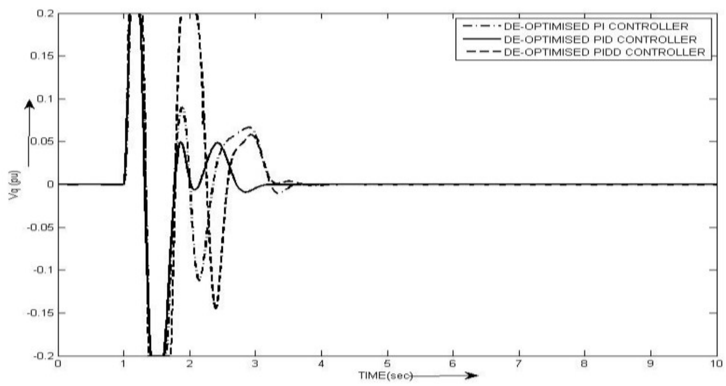

Fig.8. Comparison of different structures for SSSC injected voltage variation for 3-phase fault disturbance.

Case 2: Light loading (P_e=0.45 pu)

The robustness of the proposed controllers is tested under light loading condition. A 3-phase fault is applied at Bus 3 at t=1.0 sec. The fault is cleared in 1-cycle and the original system is restored after the fault clearance. It is observed that the DE-Optimised PI controller gives the best as compared to others. The speed response , power and the injected voltage plots are fig 9, fig 10, fig 11.

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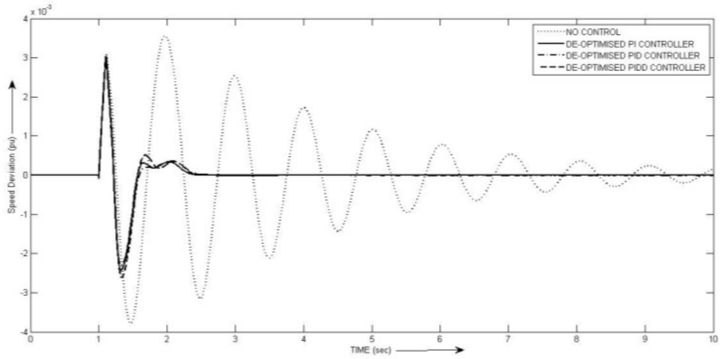

Fig. 9. Comparison of different structures for speed deviation response for 100 ms 3-ph fault in transmission line with light loading.

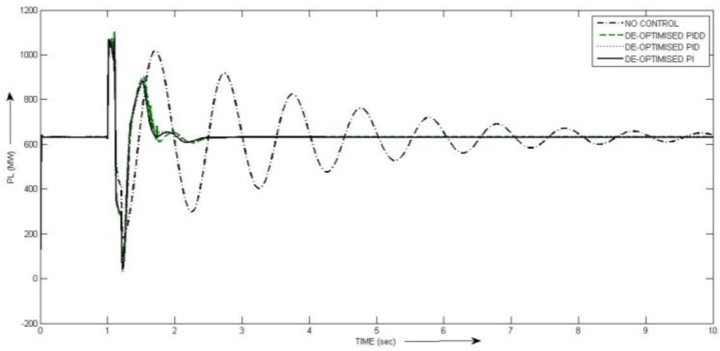

Fig. 10. Comparison of different structures for tie-line power flow response for 100 ms 3-ph fault in transmission line with light loading.

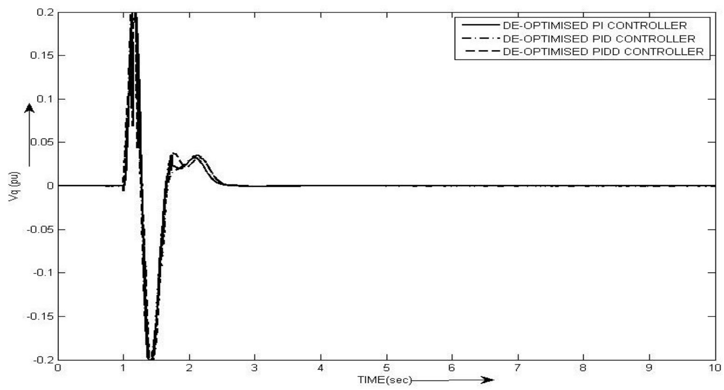

Fig.11. Comparison of different structures for SSSC injected voltage variation for 3-phase fault disturbance.

Case-3: Heavy loading (P_e = 1pu)

The robustness of the proposed controller is tested under heavy loading condition .This is done by disconnecting the load near bus 1 at t=1.0 s for 100 ms and by changing the generator to heavy loading condition. The speed response, power and the injected voltage plots are given in fig 12,fig 13 and fig 14. It is observed that PID controller gives the best result in this loading condition.

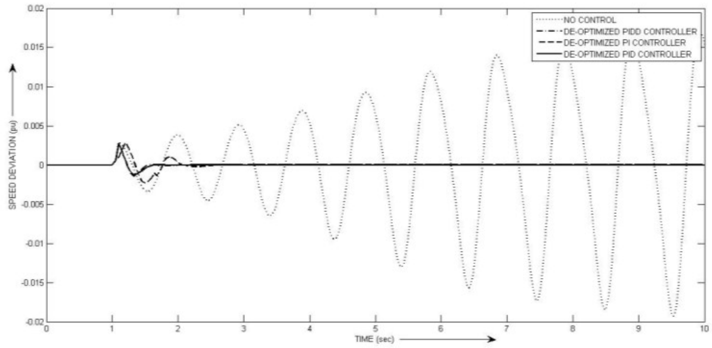

Fig.12. Comparison of different structures for speed deviation response for 100 ms 3-ph fault in transmission line with heavy loading.

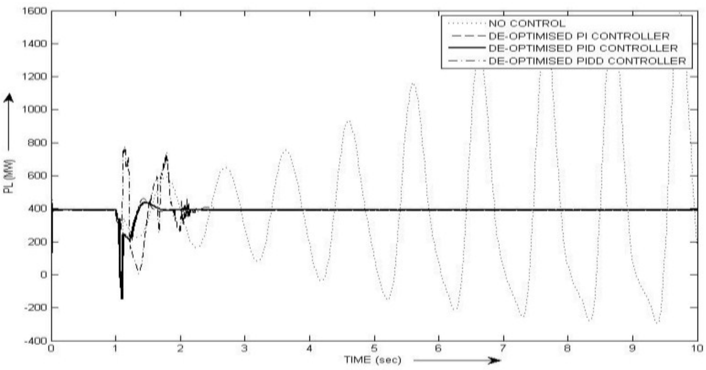

Fig. 13. Comparison of different structures for tie-line power flow response for 100 ms 3-ph fault in transmission line with heavy loading.

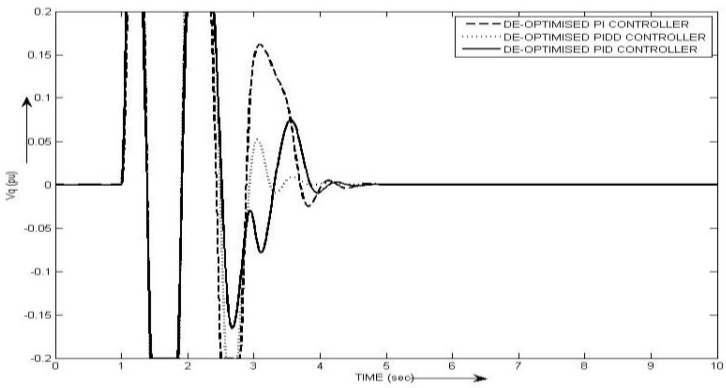

Fig.14. Comparison of different structures for SSSC injected voltage variation in heavy loading condition.

Case-4: Comparison with GA

In every loading condition, the best controller among PI/PID/PIDD controllers is found out. The result of the best controller is compared with the GA-based lead lag structure. The Optimal parameters of the lead-lag structure are liseted in table 2.

Table 2. Optimal values of the parameters of GA-based Lead-Lag Structure in different loading conditions.

LOADING CONDITION	PARAMETERS
NOMINAL	K_{PSSC} = 54.4917, T_{iSSSC1}=0.7802 T_{dSSSC1}=0.3673, T_{iSSSC2}=0.3051, T_{dSSSC2}=0.3909
LIGHT	K_{PSSC} = 85.4080, T_{iSSSC1}=0.5178 T_{dSSSC1}=0.2563, T_{iSSSC2}=0.3457, T_{dSSSC2}=0.4926
HEAVY	K_{PSSC} = 83.1218, T_{iSSSC1}=0.7413 T_{dSSSC1}=0.6494, T_{iSSSC2}=0.6308, T_{dSSSC2}=0.6228

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ISSN : 2277-7040 Volume 2 Issue 4 (March 2012)
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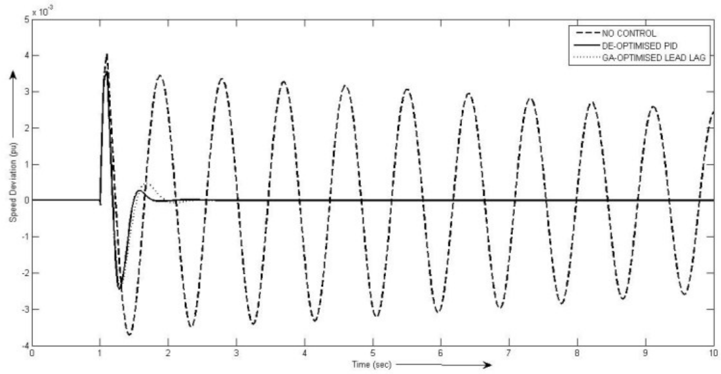

Fig.15. Speed deviation response for 100 ms 3-ph fault in transmission line with nominal loading.

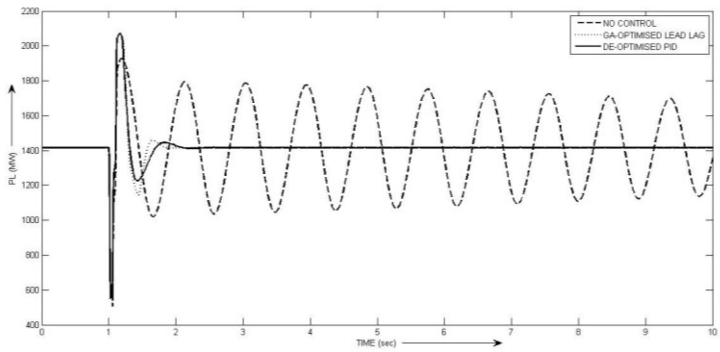

Fig. 16. For tie-line power flow response for 100 ms 3-ph fault in transmission line with nominal loading.

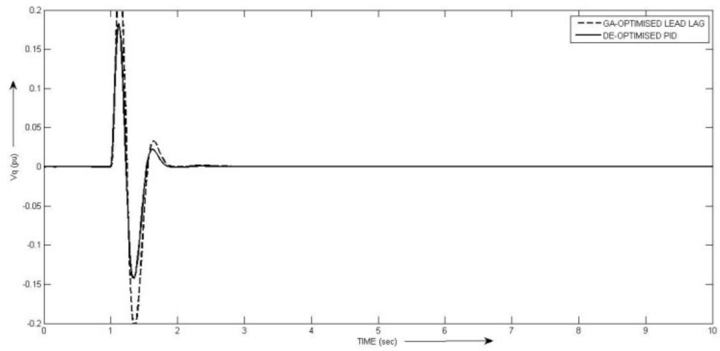

Fig.17. SSSC injected voltage variation in nominal loading condition.

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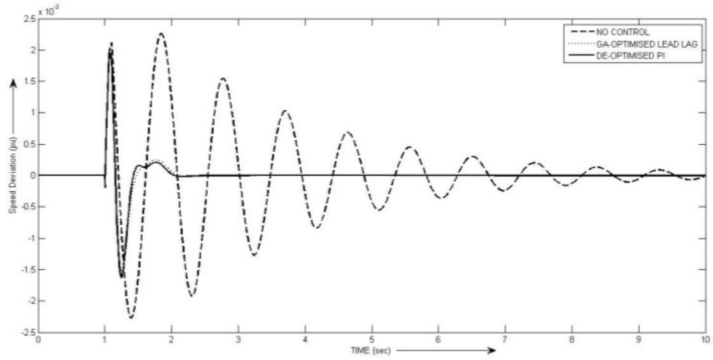

Fig.18. Speed deviation response for 100 ms 3-ph fault in transmission line with light loading.

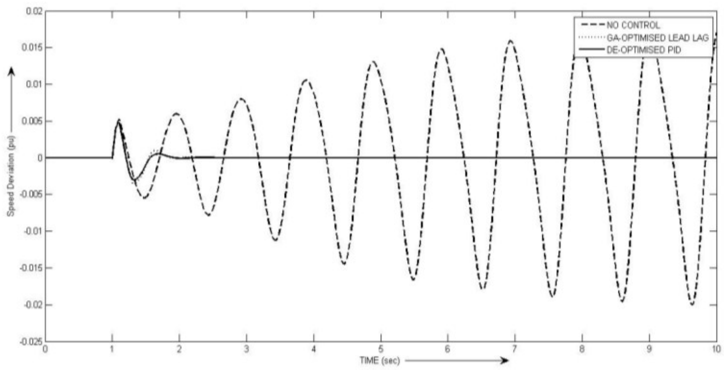

Fig.19. Speed deviation response for 100 ms 3-ph fault in transmission line with light loading.

6 Conclusion

Power system stability enhancement is improvement using SSSC-based damping Controller is studied. Different Controller structures are considered for the damping controller. The optimal parameters of the controller are searched by the Differential Evolution Algorithm. The controller is tested under different loading conditions and the results of the controllers are compared. It is found that PI gives best result in light loading conditions whereas PID controller gives the best result in nominal and heavy loading condition. The results of the best controller is compared with results of GA-based controller and it is found that DE –optimized controller gives better result.

6 Appendix

System data: All data are in pu unless specified otherwise. The data is taken from [18,19].

(i) Single-machine infinite-bus power system

Generator:
S_B = 2100 MVA, H =3.7 s, V_B = 13.8 kV, f = 60 Hz, R_S = 2.8544 e -3, X_d =1.305, $X_d^{'}$ = 0.296, $X_d^{''}$ = 0.252, X_q = 0.474, $X_q^{'}$ = 0.243, $X_q^{''}$ = 0.18, T_d = 1.01 s, $T_d^{'}$ = 0.053 s, $T_{qo}^{''}$ = 0.1 s.,
Load at Bus2: 250MW
Transformer: 2100 MVA, 13.8/500 kV, 60 Hz, R_1 = R_2 = 0.002, L_1 = 0, L_2 =0.12, D_1/Y_g connection, R_m = 500, L_m = 500
Transmission line: 3-Ph, 60 Hz, Length = 300 km each, R_1 = 0.02546 Ω/ km, R_0 = 0.3864 Ω/ km, L_1 = 0.9337e-3 H/km, L_0 = 4.1264e-3 H/ km, C_1 = 12.74e-9 F/ km, C_0 = 7.751e-9 F/ km
Hydraulic turbine and governor: K_a = 3.33, T_a = 0.07, G_{min} = 0.01, G_{max} = 0.97518, V_{gmin} = - 0.1 pu/s, V_{gmax} = 0.1 pu/s, R_p = 0.05, K_p = 1.163, K_i = 0.105, K_d = 0, T_d = 0.01 s, β =0, T_w = 2.67 s
Excitation system: T_{LP} = 0.02 s, K_a =200, Ta = 0.001 s, K_e =1, T_e =0, T_b = 0, Tc =0, K_f = 0.001, Tf = 0.1 s, E_{fmin} = 0, E_{fmax} = 7, K_p = 0
SSSC: Converter rating: S_{nom} = 100 MVA, System nominal voltage: V_{nom} = 500 kV, Frequency: f = 60 Hz, Maximum rate of change of reference voltage (V_{qref}) = 3 pu/s, Converter impedances: R = 0.00533, L = 0.16, DC link nominal voltage: V_{DC} = 40 kV, DC link equivalent capacitance C_{DC} = 375 x 10 $^{-6}$ F, Injected Voltage regulator gains: K_P = 0.00375, K_i = 0.1875, DC Voltage regulator gains: K_P =0.1 x 10 $^{-3}$, K_i = 20 x 10 $^{-3}$, Injected voltage magnitude limit: V_q = ± 0.2

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