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Optimal GA-based PI control of SVC compensator improving voltage stability

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Abstract - *In this paper, a genetic algorithm is used for the optimization and tuning of PI controller parameters in order to improve the performance of SVC compensator in both dynamic and static response. The efficiency of the proposed method has been studied successfully using a transmission line model with SVC compensator controller by PI regulator. Comparative study results between the conventional PI controller and that developed using genetic algorithm confirm that the proposed method can effectively improve simultaneously static and dynamic performances: steady state error '0.002 V instead of 0.2 V', response time '2 ms instead of 25 ms' and overshoot '0.84 V instead of 80.2 V'.*

Résumé - *Dans cet article, un algorithme génétique est utilisé pour l'optimisation et le réglage des paramètres du contrôleur PI afin d'améliorer les performances du compensateur SVC dans la réponse dynamique et statique. L'efficacité de la méthode proposée a été étudiée avec succès à l'aide d'un modèle de ligne de transmission avec régulateur de compensation SVC par régulateur PI. Les résultats comparatifs de l'étude entre le contrôleur PI conventionnel et ceux obtenus à l'aide d'un algorithme génétique confirment que la méthode proposée peut efficacement améliorer simultanément les performances statiques et dynamiques: erreur d'état stationnaire '0.002 V au lieu de 0.2 V' - Temps de réponse '2 ms au lieu de 25 ms' et dépassement '0.84 V au lieu de 80.2 V'.*

Keywords: Voltage stability - Facts - Reactive power - SVC Compensator - Genetic Algorithm - PI control - Optimization.

1. INTRODUCTION

Every day, electrical systems operating conditions are in most cases very close to its maximum capacity due to the increase in power demand. These operating conditions have led to many problems that have arisen concerning voltage stability within the last several years, resulting in voltage collapse {France 1987, 1978 and 1976; Japan 1987 and 1970, etc...}, and voltage stability incidents {Brittany and Tokyo 1987; Sweden 1983; Belgium 1982; etc...} [1, 2]. Therefore, diverse types of compensators have been proposed to reduce harmonics and to enhance the power factor in order to ameliorate the power transmission efficiency of electrical power systems [3-5].

Flexible AC Transmission System (Facts) controller is considered as one aspect of the power electronics revolution going on increasingly in electric power systems [6]. It refer to a host of controllers such as:

- Thyristor Controlled Series Capacitor (TCSC) [7];
- Static Var Compensator (SVC) [8];

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- Voltage Source Converters (VSC) [9];
- Static Phase Shifting Transformer (SPST) [10];
- Static Synchronous Series Compensator (SSSC) [11];
- Static synchronous Compensator (STATCOM) [12];
- Unified Power Flow Controller (UPFC) [13];
- Interline Power Flow Controller (IPFC) [14].

Facts has the principal role to enhance controllability and power transfer capability in AC systems. Facts involves conversion and/or switching power electronics in the range of a few tens to a few hundred megawatts [15].

Among Facts controllers, SVC is a variable impedance device where the current is controlled through a reactor using back to back connected thyristor valves. it has been used for reactive power compensation since the mid 1970's, firstly for arc furnace flicker compensation and then in power transmission systems [16-17].

The application of SVC was initially used for load compensation of fast changing loads such as steel mills and arc furnaces. Their application for transmission line compensators begun in the late seventies with the aim of: **i-** controlling dynamic over voltage; **ii-** damping sub-synchronous frequency oscillations; **iii-** damping low frequency oscillations due to swing modes; **iv-** increasing power transfer in long lines; and **v-** improving stability with fast acting voltage regulation [18].

In this paper, a genetic algorithm is used for the optimization and tuning of PI controller parameters in order to improve the performance of SVC compensator in dynamic and static response. The efficiency of the proposed method has been studied successfully using a transmission line model with SVC compensator controller by PI regulator.

Comparative results between the conventional PI controller and that developed using genetic algorithm confirm that the proposed method can effectively improve simultaneously: accuracy, rapidity, ripple and overshoot.

The rest of this paper is organized as follows: Section **2** describes the SVC compensator used for this study. While Section **3**, considered as the main heart of this study, introducing the proposed GA-based PI controller approach as well as its implementation using Matlab environment. Discussions and main obtained results using the conventional PI and the proposed GA-based PI controllers are provided in Section **4**. Finally, Section **5** drawn some final conclusions and directions for future work.

2. SVC COMPENSATEUR

From an operational point of view, the SVC behaves like a shunt-connected variable reactance, which either generates or absorbs reactive power in order to regulate the voltage magnitude at the point of connection to the AC network.

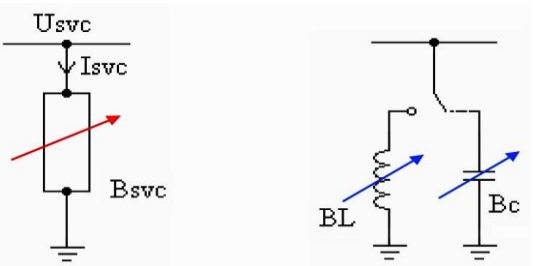

Fig. 1: SVC compensator [19]

It is used extensively to provide fast reactive power and voltage regulation support [11]. A schematic representation of the SVC is shown in figure 1.

The SVC compensator is modelled by a variable shunt admittance y_{svc} defined by:

$$y_{svc} = j\,B_{svc} \tag{1}$$

B_{svc} can be capacitive or inductive, or a mixture of both to provide or absorb reactive power Q_{svc}. The SVC values are expressed in the form of reactive power Q_{svc} absorbed at a nominal voltage V_n. The reactive power Q_{svc} is expressed by:

$$Q_{svc} = -V_n^2\,B_{svc} \tag{2}$$

The SVC provides reactive power to the system when it is capacitive. While it consumes reactive power when it is inductive (figure 2).

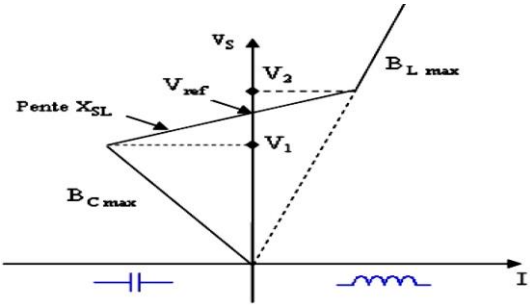

Fig. 2: SVC I/V Characteristic [19]

The SVC can operate in two different modes: **i-** the voltage control mode where the regulated voltage is within limits, and **ii-** the reactive power control where the SVC susceptance is kept constant.

The control of the SVC device can be done according to the following scheme [19].

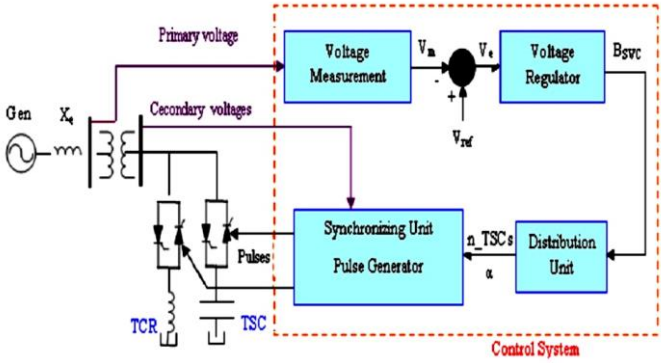

Fig. 3: SVC control scheme[16]

3. GA-BASED CONTROL OF SVC COMPENSATOR

3.1 Genetic algorithm

In nature, adaptation can be seen as a form of optimization. In nature optimization problems, the target is always moving, in the sense that all species are subject to simultaneous evolution and to concurrent changes in the environment. In engineering problems, the desired goal is normally fixed and specified in advance. One of the central concepts in this theory, is the notion of a population, where a group of individuals of the same species can mate and have offspring depending on their relative success surviving and reproducing [20].

In order to apply a GA to solve engineering optimization problems, the variables must be encoded in strings of digits referred to as chromosomes. The digits constituting the chromosome are referred to as genes. Thus, the genes encode the information stored in the chromosome, and there exists different encoding schemes. In the original GAs, introduced by Holland in the 1970s, a binary encoding scheme was employed in which the genes take the values 0 or 1 [21].

Once algorithm is initialized, a population of N chromosomes is generated by assigning random values, normally with equal probability for the two alleles 0 and 1, to the genes. The chromosomes thus formed constitute the first generation.

After initialization, each of the N chromosomes is decoded to form the corresponding problem's variables used to evaluate and assign a fitness value used for selecting individuals for reproduction using three popular operators [20, 22, 23]:

- **Selection**- The procedure of decoding the chromosome, evaluating the corresponding individual and assigning a fitness measure is repeated until all N individuals have been evaluated. The next step is to form the second generation. First of all, there must be a process of selection in which the most fit individuals are selected as progenitors;
- **Crossover**- After selection, new individuals are formed through reproduction. In sexual reproduction, the genetic material of two individuals is combined using a process referred to as crossover, which consists of cutting the chromosomes at a randomly selected crossover point and then assembling the first part of the first chromosome with the second part of the second chromosome, and vice versa.
- **Mutation**- The next step in the formation of new individuals is mutation. In GAs, once the new chromosomes have been generated through crossover, they are subjected to mutations in the form of random variation (bit flipping) of some, randomly selected, genes. Typically, mutations are carried out on a gene-by-gene basis in which the probability of mutation of any given gene equals a pre-specified mutation probability.

The flowchart of a simple GA is shown in figure 4.

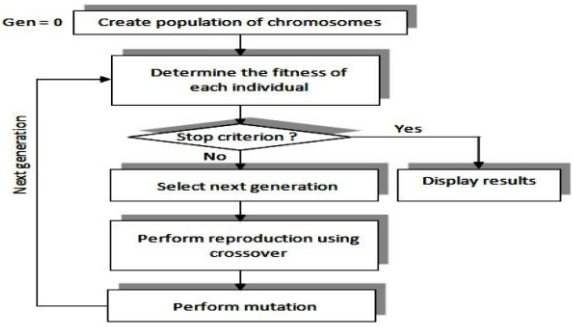

Fig. 4: Simple GA block diagram

3.2 GA-based SVC control implementation

Tuning PI controller parameters is a particularly challenging type of dynamic problems where the determination of parameters may require the optimization of a multi-objective function.

The objective is typically to minimize overshoot, response and settling times as well as ripple in steady-state response of the system. In this study, we tried to solve this problem by the application of genetic algorithm search having great potential for non-linear systems. The GAs are well-suited for this task by keeping a population of solutions instead of just one solution.

- **Encoding**- The PI controller gains K_p and K_i are encoded into binary strings constituing the chromosomes. The length of each chromosime is set to 32 bits (16 bits for K_p +16 bits for K_i).
- **Selection**- In this study, we use the roulette wheel selection method.
- **Crossover**- For this work, we apply a single point crossover using crossover probability P_c equal to 0.7.
- **Mutation**- For the mutation, the probability is set to 0.02 ($P_m = 0.02$).
- **Fitness function**- The fitness of each chromosome is evaluated using the below defined objective function [24-26]:

$$F = \alpha \times \text{overshoot} + \beta \times \text{ISE} \tag{3}$$

where $\alpha = \beta = 0.5$

$$\text{overshoot} = \max(P_{out}) - P_{ref} \tag{4}$$

and

$$\text{ISE} = \int_0^{\tau} ((P_{ref} - P_{out})^2 \, dt) \tag{5}$$

4. RESULTS AND DISCUSSION

The entire system including the transmission line, the SVC compensator as well as the PI controller are simulated using the Matlab/Simulink environment investigating different configurations:

- without SVC compensator;
- with SVC compensator controlled by non-optimized PI
- with SVC compensator controlled by GA-based optimized PI.

The transmission line used in our tests has the following characteristics:

- U_1 = 690 kV
- The resistance of the line equal to $R = 0.12\ \Omega/\text{km}$.
- The reactance of the line is equal to $X = j\,0.042\ \Omega/\text{km}$.

The model of the line including Facts device and its control is given in figure 5.

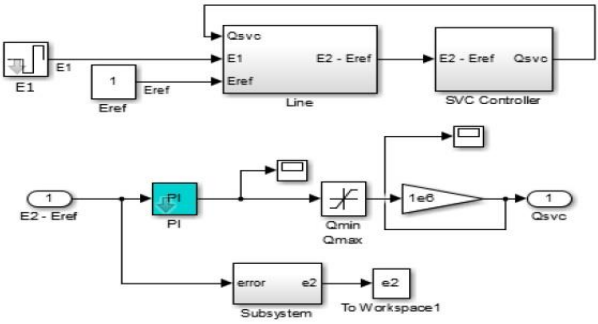

Fig. 5: Simulink model

The use of a simple transmission line is used to confirm the efficiency of genetic algorithm to search space and optimize PI parameters which is the main goal of this study.

4.1 Without SVC compensator

In this first case, we simulate the system without SVC compensation. From figures 6 and 7, it's clear that without SVC, E_2 did not follow the reference E_{ref} (we can not eliminate the error between E_2 and E_{ref}).

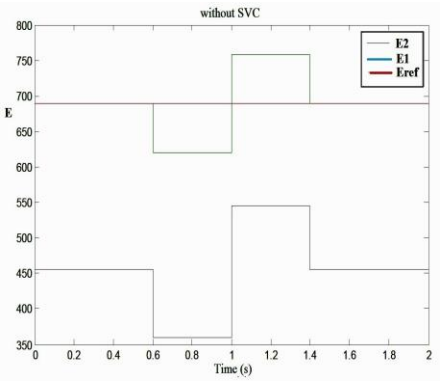

Fig. 6: Without SVC: Transmission voltages E_1, E_2 and E_{ref}

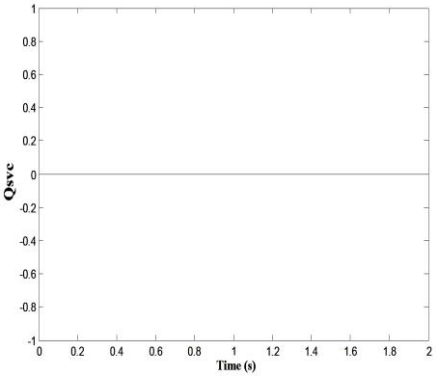

Fig. 7: Without SVC: Reactive power Q_{svc}

4.2 With SVC and with non-optimized PI

In this case, we have conducted several experiments: with a fixed K_p (0.001) and K_i variable and another with fixed K_i (0.001) and variable K_p .

4.2.1 Fixed K_p (0.001) and variable K_i

The parameters of the PI controller are given in **Table 1**.

Table 1: PI controller parameters

K_p	K_i		
0.001	0.001	0.01	1

Figures 8 and 9 show the obtained results.

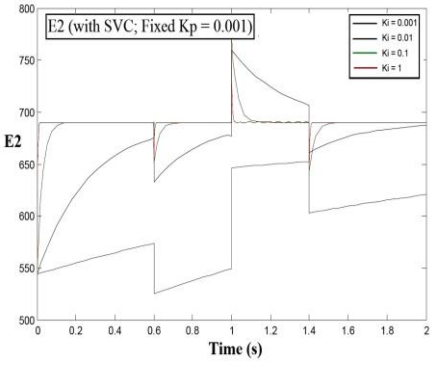

Fig. 8: With SVC (K_p= 0.001 and K_i variable): Transmission voltages E_1, E_2 and E_{ref}

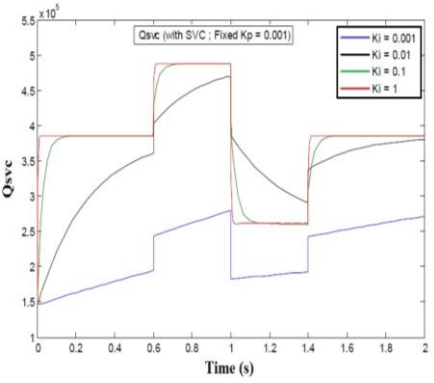

Fig. 9: With SVC (K_p=0.001 and K_i variable): Reactive power Q_{SVC}

We can see that using SVC controlled by non-optimized PI controller for which we have set $K_p = 0.001$ and increasing K_i from 0.001 to 1, we reduced the error between E_2 and E_{ref} and response time as a cost of increased overshoot.

4.2.2 Fixed K_i (0.001) and variable K_p

The parameters of the PI controller are given in **Table 2**.

Table 2: PI controller parameters

K_i	K_p		
0.001	0.001	0.01	1

Figures 10 and 11 show the obtained results.

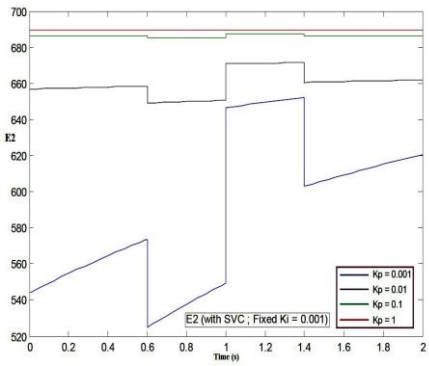

Fig. 10: With SVC (K_i=0.001 and K_i variable): Transmission voltages E_1, E_2 and E_{ref}

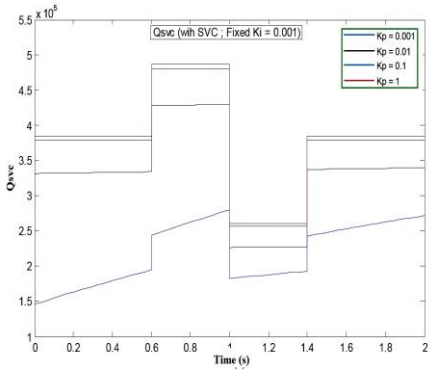

Fig. 11: With SVC (K_i=0.001 and K_i variable): Reactive power Q_{SVC}

We can see that using SVC controlled by non-optimized PI controller for which we have set $K_i = 0.001$ and increasing K_p from 0.001 to 1, we reduced the error between E_2 and E_{ref} and response time as a cost of increased oscillations (instability).

4.3 With SVC and with GA-based optimized PI

From previous results, it's clear that without SVC or with SVC and without optimized PI, we need to optimize the PI gains which have a direct impact on the SVC performances in dynamic as well as static regimes. To do this, we use GA to optimize the PI parameters with the following setting parameters:

Table 3: GA setting parameters

Parameter	P_c	P_m	P_{op} size	Nb iter
Value	0.7	0.2	100	160

The optimization process reducing the cost function is shown in figure 12.

After 160 generations, we get: $K_p = 0.2680$ and $K_i = 999.4416$. We use these parameters for the rest of simulations.

Figures below show the obtained results.

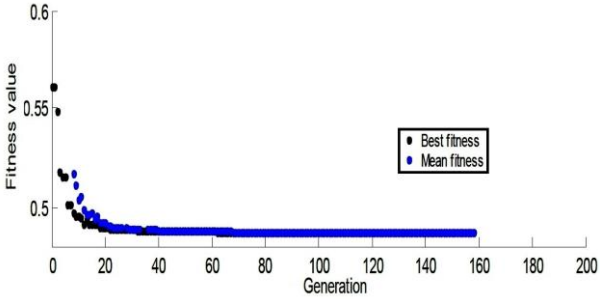

Fig. 12. Cost reduction

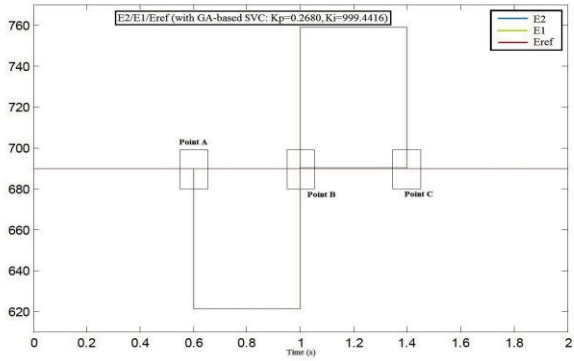

Fig. 13: With SVC with GA-based optimized PI
Transmission voltages E_1, E_2 and E_{ref}

Figures 14 to 16 below show the zoomed-in points A, B and C giving the static and dynamic performances of the proposed GA-based tuned PI controller used to drive the SVC reactive power Q_{SVC} in order to ensure a voltage stability.

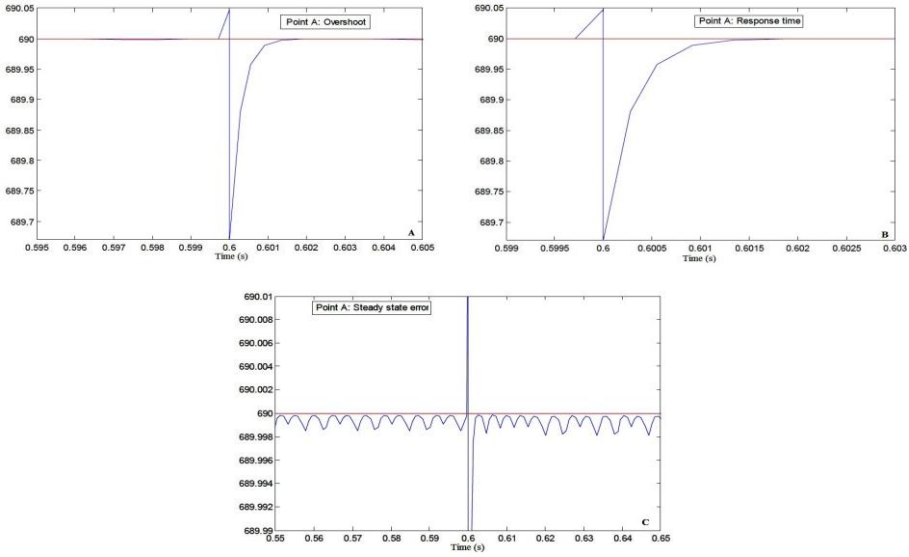

Fig. 14: **Point A**: **a-** Overshoot, **b-** Response time, **c-** Steady state error

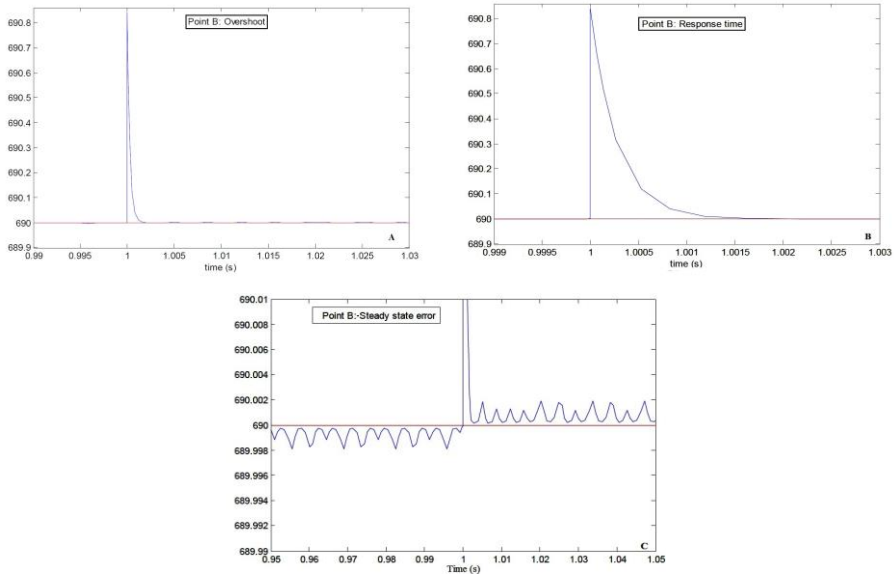

Fig. 15: **Point B**: **a-** Overshoot, **b-** Response time, **c-** Steady state error

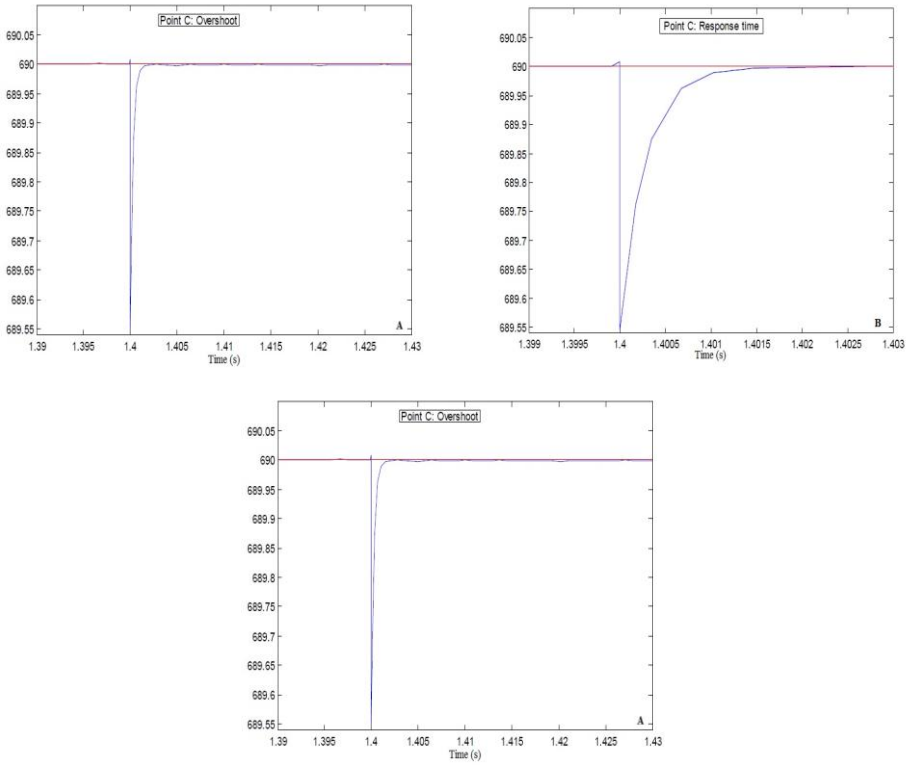

Fig. 16: **Point C**: **a-** Overshoot, **b-** Response time, **c-** Steady state error

Fig. 17 show SVC reactive power Q_{SVC} compensation provided by the GA-based optimized PI controller.

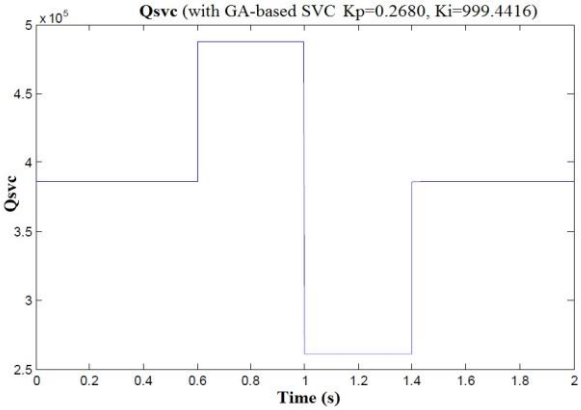

Fig. 17: With SVC with GA-based optimized PI: Reactive power Q_{SVC}

From figures 13 to 17, we can see that GA-base optimized PI improves significantly the SVC performances compared to the previous ones.

Table 4 summarizes the main improvements,

Table 4: Simulation results

Stability	Without SVC	Conv. SVC		GA based SVC
		K_p=0.001,K_1=1	K_p=1,K_1=0.001	K_p=0.2680 K_1=999.4416
Error	234.78	< 0.2	< 0.2	**< 0.002**
Res.time	–	~25 ms	~25 ms	**< 2 m/s**
Overshoot	-	~80.2 ms	~80.23 ms	**< 0.84**

5. CONCLUSION

Facts has the principal role to enhance controllability and power transfer capability in AC systems. Among Facts controllers, SVC is a variable impedance device used for reactive power compensation improving stability with fast acting voltage regulation. In this paper, a genetic algorithm is used for the optimization and tuning of PI controller parameters in order to improve the performance of SVC compensator in dynamic and static response. The efficiency of the proposed method has been studied successfully using a transmission line model with SVC compensator controller by PI regulator.

Comparative results between the conventional PI controller and that developed using genetic algorithm confirm that the proposed method can effectively improve simultaneously static and dynamic performances: steady state error {0.002 V instead of 0.2 V}, response time {2 ms instead of 25 ms} and overshoot {0.84 V instead of 80.2 V}.

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