Computational Intelligence Technique Based PI Controller using SVC

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Abstract: This paper presents Evolutionary Programming (EP) based optimization technique for estimating PI controller parameters of a Static Var Compensator (SVC) which controls a synchronous machine. SVC is one type of Flexible AC Transmission Systems (FACTS) devices, designed and implemented to improve the damping of a synchronous generator, as well as controlling the system voltage. Computational intelligence technique based PI controller using SVC is implemented in this study. The study involves the development of PI controller for SVC placement, while computational intelligence technique is used to optimize the values of proportional gain, \( K_P \) and interval gain, \( K_I \) parameters of PI controller. Validation with respect to eigenvalues determination and synchronizing and damping torque coefficients (\( K_S \) and \( K_D \)) value confirmed that the proposed technique is effective to improve the angle stability problem.

Key-Words: Transient stability, synchronizing torque coefficient, damping torque coefficient, evolutionary programming

1 Introduction
Static var compensator (SVC) is one of the FACTS technologies that are used widely for power transmission systems applications. The main application of SVC is to regulate the voltage of transmission systems. Over the last decades, many techniques have been proposed for the damping controllers for SVC to improve the damping of synchronous machines oscillations mode. Some techniques have been explored by means of the lead lag controllers [3], proportional-integral (PI) controllers [4] and proportional-integral-derivative (PID) controllers [5].

Recently, Evolutionary Programming (EP) has received much attention for global optimization problems. This evolutionary algorithm is heuristic population-based search method that used both random variation and selection. The search for an optimal solution is based on the natural process of biological evolution and is accomplished in a parallel method in the parameter search space. EP-based method has been applied in various researches in static and dynamic system stability [3],[6],[7].

This paper presents an efficient technique to determine the parameters of SVC damping controller in solving angle stability problems. PI controller has been chosen for the damping controller and its fixed-gains are determined using EP optimization technique. The method is based upon the population-based search methods that use both random variation and selection. The method is used to optimize parameters of PI controller. The goal is to stabilize the system in minimum time. In this paper, 3 conditions were considered: system with SVC and conventional PI controller, system with SVC and AIS based PI controller, and system with SVC and EP based PI controller.

2 The System Model
A single machine to infinite bus (SMIB) system model is considered in this study. The SVC is placed at the middle of the transmission line which is generally considered to be the ideal site. The following equations represent SMIB system with ignored SVC:

\[
\frac{\Delta \omega_r}{\Delta t} = \frac{\Delta T_m - K_1 \Delta \delta - K_4 \Delta \omega_r - K_2 \Delta \psi_{f\delta}}{2H} \quad (1)
\]

\[
\frac{\Delta \delta}{\Delta t} = \omega_0 \frac{\Delta \omega_r}{\Delta t} \quad (2)
\]

\[
\frac{\Delta \psi_{f\delta}}{\Delta t} = -\frac{K_3 K_4 \Delta \delta + \Delta \psi_{f\delta} - K_5 \Delta E_{f\delta}}{T_3} \quad (3)
\]

\[
\frac{\Delta E_{f\delta}}{\Delta t} = -\frac{K_4 K_5 \Delta \delta + K_5 K_6 \Delta \psi_{f\delta} + \Delta E_{f\delta}}{T_A} \quad (4)
\]

where \( T_m \) is a mechanical torque, \( H \) is the inertia constant, \( K_D \) is the damping torque coefficient, \( K_I \) and \( T_d \) are the circuit constant and time constant of the exciter oscillation system, respectively. \( \omega_0 \) is equal to \( 2\pi f_0 \). In this representation, the dynamic characteristics of the system are expressed in terms of \( K \) constants: \( K_I \),
The PI controller is designed to increase the damping torque of the SMIB system. The structure of PI controller is shown in Fig. 1. Value of proportional gain, $K_p$ and interval gain, $K_i$ parameters of PI controller should be kept within specified limits. In this paper, the EP algorithm is proposed for the optimal computation of the PI controller parameters.

$$\Delta \omega \rightarrow \frac{K_p + K_i}{s} \Delta \beta \left\{ \begin{array}{c} \min \\ \max \\ \min \end{array} \right\} \frac{K_v}{1 + sT_f} \Delta \sigma$$

Fig. 1. Structure of SVC-PI controller

The following state-space form is developed from SMIB system model:

$$\dot{X} = A \cdot X + B \cdot U$$

where

$$A = \begin{bmatrix} K_D & -K_1 & -K_2 & 0 & 0 & 0 \\ \frac{2H}{\omega_0} & -\frac{2H}{\omega_0} & -\frac{2H}{\omega_0} & 0 & 0 & 0 \\ 0 & -K_3K_4 & -\frac{1}{T_3} & K_3 & 0 & 0 \\ 0 & -K_3K_5 & -\frac{1}{T_3} & K_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_4} & K_4' \\ K_{pl} & -K_pK_1 & -K_pK_2 & 0 & 0 & 0 \end{bmatrix}$$

$$X = \begin{bmatrix} \Delta \omega_p \\ \Delta \delta \\ \Delta \psi_{pl} \\ \Delta E_{pl} \\ \Delta \sigma \\ \Delta \beta \end{bmatrix}$$

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$U = \begin{bmatrix} \Delta T_m \end{bmatrix}$$

$$K_{pl} = K_i - \frac{K_pK_D}{2H}$$

$$X$$ and $$U$$ are the state vector and input signal vectors, respectively. $$A$$ and $$B$$ are matrices of real constants with appropriate dimensions. The interaction among these variables is expressed in terms of the 7 constants $K_p$, $K_i$, $K_D$, $T_f$, $K_L$, $K_a$, and $K_e$. These constants with the exception of $K_a$, which are only a function of the ratio of impedance, are function of the operating real and reactive loading as well as the excitation levels in the generator. Detail calculation of parameters $K_p$, $K_i$, $K_D$, $T_f$, $K_L$, $K_a$, and $K_f$ can be found in [1]. The SMIB system parameters are as follows:

Generator parameters:

$$H = 2.0, T_{d0} = 8.0, X_d = 1.81, X_q = 1.76, X'_d = 0.30, R_a = 0.003, K_{ad} = K_{aq} = 0.8491, E_i = 1.0 \angle -36^\circ$$

Transmission line parameters:

$$R_e = 0.0, X_e = 0.65, X_L = 0.16$$

Exciter parameters:

$$K_f = 100, T_f = 0.05$$

SVC system parameters:

$$K_f = 10, T_f = 0.05$$

where $T_{d0}$ is the open circuit field time constant, $X_d$ and $X_q$ are the $d$-axis and $q$-axis reactance of the generator, respectively. $R_a$ and $X_d$ are the armature resistance and transient reactance of the generator, respectively. $K_f$ and $T_f$ are the circuit constant and time constant of the SVC system, respectively. $R_e$ and $X_e$ are the resistance and reactance of the transmission line, respectively. $X_e$ is the load reactance, $K_{ad}$ and $K_{aq}$ are the $d$-axis and $q$-axis of synchronizing torque coefficients, respectively. $E_i$ is the terminal voltage.

### 3 Computational Intelligence Technique

#### 3.1 Evolutionary Programming (EP)

The Evolutionary Programming (EP) is one of the evolutionary computing techniques which uses the models of biological evolutionary process to obtain the solution for complex engineering problems. The search for an optimal solution is based on the natural process of evolutionary biological evolution and is accomplished in a parallel method in the parameter search space. EP belongs to the generic fields of the simulated evolution and artificial life. It is robust, flexible and adaptable and it can yield global solutions to any problem, regardless any form of to the objective function.

In the EP algorithm, the population has $n$ candidate solutions with each candidate solution is an $m$-dimensional vector, where $m$ is the number of optimized parameters. The EP algorithm can be described as:

a) Step 1 (Initialization): Generation counter $i$ is set to 0, and generate $n$ random solutions $(x_k, k=1,...,n)$. The $k^{th}$ trial solution $x_k$ can be written as $x_k = [p_{k1},...,p_{km}]$, where the $i^{th}$ optimized parameter $p_{ki}$ is generated by random value in the range of $[p_{ki}^{\min}, p_{ki}^{\max}]$ with uniform probability. Each individual is evaluated using the objective function $J$. In this
initial population, minimum value of objective function \( J_{\text{min}} \) will be searched, the target is to find the best solution \( x_{\text{best}} \) with objective function \( J_{\text{best}} \).

b) Step 2 (Mutation): Each parent \( x_i \) produces one offspring \( x_{k+n} \). Each optimized parameter \( p_i \) is perturbed by a Gaussian random variable \( N(0, \sigma_i^2) \). The standard deviation \( \sigma_i \) specifies the range of the optimized parameter perturbation in the offspring. \( \sigma_i \) equation is as follows:

\[
\sigma_i = \beta \times \frac{J(x_i)}{J_{\text{max}}(x_i)} \times (p_{i}^{\text{max}} - p_{i}^{\text{min}}) \tag{11}
\]

where \( \beta \) is a scaling factor, and \( J(x_i) \) is the objective function of the trial solution \( x_i \). The value of optimized parameter will be set at certain limit if any value violates its specified range. The offspring \( x_{k+n} \) can be described as:

\[
x_{k+n} = x_k + [N(0, \sigma_1^2), ..., N(0, \sigma_n^2)] \tag{12}
\]

where \( k=1, ..., n \)

c) Step 3 (Statistics): The minimum objective function \( J_{\text{min}} \), the maximum objective function \( J_{\text{max}} \) and the average objective function \( J_{\text{ave}} \) of all individuals are calculated.

d) Step 4 (Update the best solution): If \( J_{\text{min}} \) is bigger than \( J_{\text{best}} \), go to Step 5, or else, update the best solution, \( x_{\text{best}} = x_{\text{best}} \). Set \( J_{\text{min}} \) as \( J_{\text{best}} \) and go to Step 5.

e) Step 5 (Combination): All members in the population \( x_i \) are combined with all members from the offspring \( x_{k+n} \) to become \( 2n \) candidates. These individuals are then ranked in descending order, based on their objective function as their weight.

f) Step 6 (Selection): The first \( n \) individuals with higher weights are selected along with their objective functions as parents of the next generation. The generation counter will be set to \( i+1 \) and algorithm will start again from Step 2.

g) Step 7 (Stopping criteria): The search process will be terminated if one of the followings is satisfied:

- It reaches the maximum number of generations
- The value of \( (J_{\text{max}} - J_{\text{min}}) \) is very close to 0.

### 3.2 Objective Function

The SVC controller is designed to minimize the power angle deviation after a disturbance and to accelerate the damping of the power system oscillations. In this work, the objective function can be formulated as the maximization of:

\[
J = \text{inv} \left( 1 + \sum_{t=1}^{T_{\text{sim}}} |\Delta \omega(t)| \right) \tag{13}
\]

where, \( \Delta \omega(t) \) is the change in rotor speed of the system at the \( t^{\text{th}} \) loading condition and \( T_{\text{sim}} \) is the time range of the simulation. Hence, the design problem can be formulated as:

Maximize \( J \)

Subject to

\[
K_p^{\text{max}} \leq K_p \leq K_p^{\text{min}}
\]

\[
K_i^{\text{max}} \leq K_i \leq K_i^{\text{min}}
\]

With the proposed approach, optimum proportional \( K_p \) and integral gain \( K_i \) settings of the PI controller were searched using EP and AIS for different operating points simultaneously.

### 4 Concept of Synchronizing & Damping Torque and Least Square (LS) Method

In this paper, an SMIB system model with SVC is placed in the middle of the transmission line is considered. The system comprises a steam generator connected via a tie line to a large system represented as infinite bus.

The change of electromagnetic torque \( \Delta T_e(t) \) can be broken down into two components namely the synchronizing torque \( K_S \) and damping torque \( K_D \). The synchronizing torque component is in phase and proportional with the change in rotor angle \( \Delta \delta(t) \) and the damping torque is in phase and proportional with the change in rotor speed \( \Delta \omega(t) \). The estimated torque \( \Delta T'_e(t) \) can be written as:

\[
\Delta T'_e(t) = K_S \Delta \delta(t) + K_D \Delta \omega(t) \tag{14}
\]

where:

- \( \Delta \delta(t) \) : Change in rotor angle
- \( \Delta \omega(t) \) : Change in rotor speed
- \( K_S \) : Synchronizing torque coefficients
- \( K_D \) : Damping torque coefficients

All the data of \( \Delta \delta(t) \), \( \Delta \omega(t) \) and \( \Delta T_e(t) \) can be obtained from either offline simulation or online measurements. Following a small disturbance, the time responses of these three items are recorded. The least square (LS) technique is then used to minimize the sum of the square of the differences between the electric torque \( \Delta T_e(t) \) and the estimated torque \( \Delta T'_e(t) \). The error of this torque is defined as:

\[
E(t) = \Delta T_e(t) - \Delta T'_e(t) \tag{15}
\]
The torque coefficients $K_S$ and $K_D$ are calculated to minimize the sum of the error squared over the interval of oscillation $t$, as given in equation (15), where $t=NT$ ($N$ is the number of samples and $T$ is the sampling period). For correct estimation of $K_S$ and $K_D$, the interval $t$ should be chosen adequately. The suitable value of $t$ which makes $K_S$ and $K_D$ constants during the oscillation period was found to be the entire period of oscillation. In matrix notation, the above problem can be described by an over-determined system of linear equations as follows:

$$
\Delta T_e(t) = \Delta \tilde{T}_e(t) + E(t) = Ax + E(t) \quad (16)
$$
$$
A = [\Delta \delta(t) \Delta \phi(t)] \quad (17)
$$
$$
x = [K_S \quad K_D]^T \quad (18)
$$

The estimated vector $x$ is optimized using EP optimization technique as explained in Section 3. The objective function can be formulated as the minimization of $E(t)$.

4 Results and Discussion

In order to show the advantages of modeling the SVC controller dynamics and tuning its parameters in the way presented in this paper, simulation studies of a SMIB power system with SVC are carried out. The MATLAB program simulation is conducted using all the 8 parameters: $K_1, K_2, K_3, T_3, K_4, K_5, K_6$ and $K_7$. In this simulation, value of proportional gain parameter, $K_P$ and interval gain parameter, $K_I$ of PI controller are optimized until maximum value of the objective function $J$ is defined with selected value of $K_P$ and $K_I$. A Simulink model of SMIB system with SVC is developed based on these 8 calculated parameters and 2 optimized parameters: $K_P$ and $K_I$ to produce 3 system responses (speed deviation, $\Delta \omega(t)$, angle deviation, $\Delta \delta(t)$ and torque deviation, $\Delta T_e(t)$). Based on these system responses, synchronizing torque coefficient $K_S$ and damping torque coefficient $K_D$ are then calculated using LS technique.

In this case, the performance of SVC with conventional based PI controller (CSVC) is compared to SVC with EP based PI controller (EP-SVC) and SVC with AIS based PI controller (AIS-SVC). Following three different loading conditions are simulated:

i. Case 1 ($P = -0.6 \text{ p.u.}, Q = 0.1 \text{ p.u.}$)
ii. Case 2 ($P = 0.15 \text{ p.u.}, Q = 0.2 \text{ p.u.}$)
iii. Case 3 ($P = -0.75 \text{ p.u.}, Q = 0.2 \text{ p.u.}$)

The response of speed deviation for Case 1 is shown in Figure 2(a). The system with CSVC is poorly damped and becomes stable for more than 5 seconds. Table 1 tabulates the results for comparative studies using CSVC, EP-SVC, and AIS-SVC. For EP-SVC and AIS-SVC, both systems become stable in almost 2 seconds. With the optimized PI parameters, the response of speed deviation for the proposed SVC is stable faster than the AIS-SVC.

The response for torque deviation for Case 1 is shown in Figure 2(b). Here, the proposed SVC shows better damping compared to CSVC and AIS-SVC. As compared to CSVC and AIS-SVC, the proposed EP-SVC has low oscillation and stable in shorter time.

![Fig. 2: Response for Case 1](image-url)

$K_S, K_D$ and eigenvalues for Case 1 are shown in Table 1. Optimized value of $K_S$ is smaller than the non-optimize one. The value of $K_D$ for EP-SVC is increased to 6.7562 compared to CSVC which is 0.0103. Value for AIS-SVC is also increased to 6.5690. It shows that the value of $K_D$ is increased for optimized SVC. The damping capability is also increased with SVC optimized in the system. All the results reveal that the
damping of the system with proposed SVC technique give better result compared to AIS-SVC and CSVC.

Table 1: Comparison of the CSVC, AIS-SVC and EP-SVC System for Case 1

<table>
<thead>
<tr>
<th>Type</th>
<th>$K_p$</th>
<th>$K_s$</th>
<th>Eigenvalues</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSVC</td>
<td>0.6135</td>
<td>0.0103</td>
<td>-19.7116</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-14.9720</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.6890 ± 9.5363i</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.0000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-4.3253</td>
</tr>
<tr>
<td>AIS-SVC</td>
<td>1.1121</td>
<td>0.3630</td>
<td>-21.8351</td>
</tr>
<tr>
<td>SVC</td>
<td>11.8906</td>
<td>6.5690</td>
<td>-11.7660</td>
</tr>
<tr>
<td></td>
<td>0.9642</td>
<td></td>
<td>-2.5044 ± 9.4981i</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-1.7771</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.0000</td>
</tr>
<tr>
<td>EP-SVC</td>
<td>1.3561</td>
<td>0.3656</td>
<td>-22.4014</td>
</tr>
<tr>
<td></td>
<td>0.9752</td>
<td></td>
<td>-9.7409</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>-2.2954</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>-0.0000</td>
</tr>
</tbody>
</table>

The response of speed deviation and torque deviation for Case 2 are shown in Figure 3(a) and 3(b), respectively. Both responses indicated that the proposed SVC technique give better result compared to AIS-SVC and CSVC. The response for the proposed EP-SVC is damping faster than the other two techniques.

Table 2: Comparison of the CSVC, AIS-SVC and EP-SVC System for Case 2

<table>
<thead>
<tr>
<th>Type</th>
<th>$K_p$</th>
<th>$K_s$</th>
<th>Eigenvalues</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSVC</td>
<td>0.8185</td>
<td>1.9349</td>
<td>-19.6417</td>
</tr>
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<td></td>
<td></td>
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<td>-13.7528</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.3526 ± 9.5734i</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-6.2806</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.0000</td>
</tr>
<tr>
<td>AIS-SVC</td>
<td>1.1020</td>
<td>0.1914</td>
<td>-22.1685</td>
</tr>
<tr>
<td>SVC</td>
<td>11.8891</td>
<td>2.9478</td>
<td>-2.9859 ± 9.3304i</td>
</tr>
<tr>
<td></td>
<td>0.9655</td>
<td></td>
<td>-9.4008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.0000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-2.8470</td>
</tr>
<tr>
<td>EP-SVC</td>
<td>1.3829</td>
<td>0.1890</td>
<td>-22.8824</td>
</tr>
<tr>
<td>SVC</td>
<td>11.5944</td>
<td>2.9634</td>
<td>-4.0561 ± 8.8510i</td>
</tr>
<tr>
<td></td>
<td>0.9762</td>
<td></td>
<td>-4.6928 ± 2.4801i</td>
</tr>
</tbody>
</table>

The response of speed deviation and torque deviation for Case 3 are shown in Figure 4(a) and 4(b), respectively. The responses observed in the both figures indicate that the proposed EP-SVC give better result as compared to AIS-SVC and CSVC. It is also shown that the EP-SVC technique cause the system reaches its stability faster than the others.
5 Conclusion

This paper has presented computational intelligence technique base PI controller. Two methods for optimizing $K_P$ and $K_I$ has been developed based on computation intelligence technique namely EP and AIS. Results obtained from the study indicated that EP outperformed AIS in terms of giving better $K_P$ and $K_I$ values which are responsible for stability point determination. EP also manages to perform much faster than AIS. It is also discovered that the installation of SVC into an SMIB system can help in improving angle stability. Incorporation of EP technique in optimizing the size of SVC has made the sufficiently compensated.

References:


