OPTIMAL DESIGN OF POWER SYSTEM STABILIZER USING DIFFERENTIAL EVOLUTION TECHNIQUE

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Abstract

The power system is characterized by oscillation in machine rotor angle and speed during and after the fault cases. Therefore, power system stabilizer (PSS) should be used for damping the power system oscillations. Modern optimization techniques have been applied to design (PSS) in recent years. In this paper, Differential Evolution technique (DE) is proposed as a modern technique to search for optimal controller parameters of PSS in Single Machine Infinite Bus (SMIB) system, by minimizing the deviation in the oscillatory rotor speed of the generator. This technique is applied at specific operating point and at multiple operating points. Simulink & MATLAB environment are used to find the optimal design which is compared to other techniques such as Genetic Algorithm (GA).

1. Introduction

The main reason for discriminate human and development from the middleages is the discovery of electricity, which is the basis of development and technical in this world. So, it makes sense to see that networks of electric power increased complexity evolution of mankind. This complexity requires more accurate and sophisticated techniques to maintain the stability and the reliability of the system used. One of the most important controllers is power system stabilizer (PSS). From here, increased interest in PSS over the years and development in the techniques use to obtain the preferred design to guarantee the highest levels of reliability in the event of any malfunction networks under any fault. In 1969, Demello and Concord provided a basis for the design of PSS, were the first to use the theory of phase compensation in the frequency domain to make a thorough analysis of a lead-lag compensator to provide an efficient excitation system for the synchronous machine in order to utilize the control signal in the excitation system. Since the seventies of the last century, different techniques were used to design the PSS to offer the greatest possible stability, and reliability of the system. However, the techniques of optimal and adaptive control were used to design PSS. During the last two decades, it seems that, the use of Artificial Intelligence Techniques such as Fuzzy...
Logic and Expert systems [8-12] is increased. Recently, the evolutionary algorithms (EAs) have taken a great attention. Where, these algorithms are used efficiently to solve nonlinear and multi-objective optimization problems such as Genetic algorithm (GA), Tabu search algorithm (TS), simulated annealing (SA), particle swarm optimization (PSO), and Differential Evolution technique (DE) [13-21].

Recently, DE is considered as one of the efficient techniques of Evolutionary algorithms. It has more advantages such as [22]:

- Fast and simple for application and modification.
- Effective global optimization capability.
- Parallel processing nature.
- Efficient algorithm without sorting or matrix multiplication.
- Self-referential mutation operation.
- Effective on integer, discrete and mixed parameter optimization.
- Ability to handle no differentiable, noisy, and/or time-dependent objective functions.
- Operates on flat surfaces.
- Ability to provide multiple solutions in a single run and effective in nonlinear constraint optimization problems with penalty functions.

For these reasons and other advantages, this technique is chosen in this paper. Where, DE is used to design the PSS in case of single operating point and multiple points which are compared, as well as comparing with the GA results.

2. Differential Evolution

In 1995, Price and Storn proposed new evolutionary algorithm called Differential Evolution technique (DE) [23]. The DE is powerful and simple stochastic search evolutionary algorithm for global optimization. The DE consists of four processes which can be defined as:

- Initialization,
- Mutation,
- Crossover,
- Selection.

The initial population is chosen randomly within the range of variable bounds. Mutation and crossover are used to generate trial vectors, and after that selection determine, the vectors that will continue to next generation. In Differential Evolution there are several strategies but this paper use (DE/rand/1/bin) scheme which is the most successful and widely used strategy.

2.1 Initialization

The initial population starts with chose number and assume population=NP and Generation = Gen, generated a new value for

\[ X_j \quad j = 1, 2, 3 \ldots \ldots D \]

Using equation:

\[ X_{ij}(0) = X_{ij}^{\text{min}} + \text{rand}(0,1)(X_{ij}^{\text{max}} - X_{ij}^{\text{min}}) \]

Where, \( i = 1, 2, \ldots, \text{NP} \quad j = 1, 2, \ldots, \text{D} \)

\( D \) = number of variables, \( \text{NP} \) = number of members in a population, \( \text{rand}(0,1) \) is uniformly distributed random number between (0,1). \( X_{ij}^{\text{max}}, X_{ij}^{\text{min}} \) are maximum and minimum bounds for \( X_j \) after creating the initial population it evolves through mutation, crossover and selection operation.

2.2 Mutation

For the mutation process \( X_{r1,g}, X_{r2,g} \) and \( X_{r3,g} \) are chosen randomly from current population and not coinciding the \( X_j \). For each target vector, a mutant vector \( U \) for each generation is created as follow:

\[ V_0 = X_{r1,g} + F(X_{r2,g} - X_{r3,g}) \]

Random chosen index \( r1, r2 \) and \( r3 \in \{1, 2, \ldots, \text{NP}\} \), \( F \in [0,2] \) random chosen factor.

2.3 Crossover

Crossover is used for increasing the diversity of population in particular. Target vector and mutated vector are merged to obtain a trial vector using the following equation:

\[ U_{ij,G} = \begin{cases} V_{ij,G} & \text{if} \ \text{rand}(0,1) \leq CR \\ X_{ij,G} & \text{else} \end{cases} \]

Where, \( CR \in [0, 1] \) and is selected randomly.

2.4 Selection
The trial vector \( U_{iG} \) is compared with the target vector \( X_{iG} \) and the best value of function is chosen for next generation as:

\[
X_{iG+1} = \begin{cases} 
U_{iG} & \text{if } F(U_{iG}) \leq F(X_{iG}) \\
X_{iG} & \text{otherwise}
\end{cases}
\]

After that, repeat this process for all population vectors (NP), the process of mutation, crossover and selection continue until the maximum number of DE iterations is reached.

The flow chart of DE technique is shown in Fig. 1.

3. System Modeling

Single machine against infinite bus system is chosen as a test system to design the PSS using DE technique. Single line diagram for the system is shown in Fig. 2. The system parameters are given in the Appendix.

The generator can be represented by 3rd orders model with three equations; two equations are differential equations for rotor electro-mechanical oscillation and one equation for internal voltage of generator.

\[
\dot{\delta} = \omega_b(\omega - 1) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1)
\]

\[
\dot{\omega} = \frac{1}{M}[T_m - T_e - D(\omega - 1)] \quad \ldots \ldots \ldots (2)
\]

\[
E_q = \frac{1}{T_{do}}[E_{id} - \dot{E}_q - (X_q - \dot{X}_d)i_d] \quad (3)
\]

Where,

\( \delta \) is the rotor angle,

\( \omega_b \) is the reference speed,

\( \omega \) is the rotor speed,

\( M \) is the rotor inertia constant,

\( T_m \) is the mechanical Torque of generator (input),

\( T_e \) is the electric Torque of generator (output),

\( D \) is the rotor damping coefficient,

\( \dot{E}_q \) is the generator internal voltage,

\( T_{do} \) is the time constant of open circuit excitation,

\( E_{fd} \) is the field voltage,

\( X_q \) is the d-axis of steady state reactance of generator,

\( \dot{X}_q \) is the d-axis of transient reactance of generator,

\( i_d \) is the d-axis of stator current.

The electrical torque of generator can be represented as:

\[
T_e = V_d i_d + V_q i_q \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)
\]

\[
V_t = \sqrt{V_d^2 + V_q^2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5)
\]

\[
V_d = I_q X_q \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (6)
\]

\[
V_q = E_q - X_q i_d \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (7)
\]

Where,

\( V_d, V_q \) are the d-q axis of terminal voltage.

\( i_q \) is the q-axis of stator current.

\( X_q \) is the q-axis reactance of the generator.
The main idea of the exciter is regulating the output voltage of generator by controlling the field current; the field voltage can be represented by the following equation:

$$E_{fa} = \frac{1}{T_a} \left[ K_a (V_{ref} - V_t + U_{pss}) - E_{fa} \right] \ldots (8)$$

The stabilizing signal, which is the output of the PSS is given by:

$$U_{pss} = \Delta \omega \cdot \frac{ST_\omega}{1 + ST_\omega} \cdot \frac{1 + ST_1}{1 + ST_2} \cdot K_{pss} \ldots (9)$$

Where,

- $K_{pss}$ is the stabilizer gain.
- $T_\omega$ is the wash out time constant.
- $(T_1$ and $T_2)$ are the time constants of the one-stage lead/lag phase compensator.

4. Problem Formulation

The parameters of PSS ($K_{pss}, T_\omega, T_1$ and $T_2$) need to be optimized in order to improve the system performance. The nonlinear model of the system introduced by Equations (1)-(9) is used in order to estimate the fitness function for the DE technique.

4.1 Objective function

The main objective of PSS is to damp the oscillations in rotor angle and speed. Therefore, single objective functions $j_1$ and $j_2$ can be used in the
optimization process. On the other hand, multi-objective function $j_3$ can be used by merging $j_1$ and $j_2$ with specific weighting factors a, b.

The objective functions are defined as follows:

$$j_1 = \int_0^{T_s} |\omega - 1| \cdot dt \quad \ldots \ldots \ldots (10)$$

$$j_2 = \int_0^{T_s} |\delta - \delta_0| \cdot dt \quad \ldots \ldots \ldots (11)$$

$$j_3 = a \cdot j_1 + b \cdot j_2 \quad \ldots \ldots \ldots (12)$$

Where,

$T_s$ is the simulation time,

$T_f$ is the fault instant,

The weighting factors are selected as: (a = 10 and b = 0.2).

The optimization problem can be formulated as:

Minimize $j_1, j_2, j_3 \quad \ldots \ldots \ldots \ldots (13)$

Subject to

$$K_{pss-min} \leq K_{pss} \leq K_{pss-max} \quad \ldots \ldots \ldots \ldots (14)$$

$$T_{1-min} \leq T_1 \leq T_{1-max} \quad \ldots \ldots \ldots \ldots (15)$$

$$T_{2-min} \leq T_2 \leq T_{2-max} \quad \ldots \ldots \ldots \ldots (16)$$

$$T_{\omega-min} \leq T_\omega \leq T_{\omega-max} \quad \ldots \ldots \ldots \ldots (17)$$

Typical ranges of the optimized parameters are [0.1-100] for $K_{pss}$, [0.1-1] for $T_1$, [0.05-2] for $T_2$ and [0.5-5] for $T_\omega$.

5. Results and discussions

The operating point of the system is not constant all the time. So, the effect of changing the operating point should be studied. The optimization process is applied at specific operating point (single point) as well as (multiple points) design. The system response should be justified at any operating point when the PSS parameters are designed at single-point or multiple-points.

Table 1 shows the PSS parameters which are optimized at single-point.

<table>
<thead>
<tr>
<th>Operating point</th>
<th>$P$</th>
<th>$Q$</th>
<th>$K_{pss}$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.075</td>
<td>100</td>
<td>0.599</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>0.15</td>
<td>100</td>
<td>0.5224</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>0.225</td>
<td>88.3576</td>
<td>0.3263</td>
<td>0.05</td>
<td>2.11</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>0.3</td>
<td>84.7785</td>
<td>0.2689</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>0.375</td>
<td>79.2025</td>
<td>0.2571</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>0.45</td>
<td>73.2865</td>
<td>0.25</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>0.525</td>
<td>68.718</td>
<td>0.2479</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
<td>0.6</td>
<td>66.8051</td>
<td>0.251</td>
<td>0.05</td>
<td>5</td>
</tr>
</tbody>
</table>

All of the above results are obtained using DE with the following parameters:

$G=200, NP=40, F=0.9, CR=0.5$

Figures 4, 5 show a comparison between the system (rotor speed and angle) when the parameters are optimized by DE and GA. These figures show the improvement of the system response using the DE compared with GA. The comparison is carried out at the operating point ($P=1$, $Q=0.015$).

![Fig. 4 Rotor speed](image-url)
Figures 6 and 7 show the rotor angle and rotor speed responses at the operating point (P=0.1, Q=0.075). The PSS parameters are designed using the single-point condition as well as the multiple-point condition.

Figures 8 and 9 show the rotor angle and rotor speed responses at the operating point (P=0.2, Q=0.15). The PSS parameters are designed using the single-point condition as well as the multiple-point condition.

The system response to short circuit near to the infinite bus is checked and compared for two cases, single point design and multiple point design. Figures 6-9 show a comparison between the system responses for the two cases. It is logic to have better response of the system when using the single-point design. Since, the PSS parameters are designed at the single-point. But, how the system response will be? If the PSS parameters are designed at specific point (P=1.0, Q=0.015 p.u) and the system operate at another point (P=0.1, Q=0.075 p.u). To get the answer of this question see Figs. 10 and 11, which show the rotor speed and angle response to 3-phase short circuit near the infinite bus.

It is clear from these figures that, the system response using multiple-points design is better than that of single-point design.
6. Conclusions

An improvement in the optimization process has been obtained using the proposed DE technique compared with the GA. The PSS parameters have been designed successfully by the proposed DE. Also, the single-point designed parameters and multiple-points designed parameters have been tested and compared, considering the change in the system loading conditions, however, the multiple-points design get more better response.

REFERENCES


Appendix

Generator Data:
M=9.26, D=0,
X_d = 0.976 , X_q = 0.55 ,
\( \hat{T}_d = 7.76 \), \( \hat{T}_q = 1.4 \),
\( \hat{X}_d = 0.19 \), \( \hat{X}_q = 0.7 \)

Exciter data:
K_a = 50, \( T_a = 0.05 \)

Line data:
R=0, X= 0.997

For GA the PSS parameters at P=1, Q=0.015

<table>
<thead>
<tr>
<th>( K_{PSS} )</th>
<th>( T_2 )</th>
<th>( T_1 )</th>
<th>( T_\omega )</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.8396</td>
<td>0.1581</td>
<td>0.0647</td>
<td>0.726</td>
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