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Optimal fractional SSSC damping action for variable wind penetrations

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Abstract

An optimal fractional SSSC based control action has been proposed in this work for enhancing small signal stability of power system pertaining to intermittent variations in wind penetrations. The parameters of controllers are tuned by sailfish algorithm and ITAE based objective function has been chosen for minimization problem. A three machine system has been considered in this work with different operating conditions and step with random variations in wind penetrations have been executed with different machines and subject to which the system response and eigen values are analyzed. Based on system response it is observed that subject to intermittent variations in wind source the small signal stability is hampered due to increased power system oscillations and by properly tuning the fractional lead-lag control action based on static synchronous series compensator. These oscillations can be damped efficiently. The performance of proposed sailfish algorithm (SFA) tuned SSSC controlled action has been compared with PSO and DE algorithms subject to different case studies.

Subject Classification: *37N35.*

Keywords: *SSSC, Wind source, Fractional lead-lag controller, Sailfish algorithm.*

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1. Introduction

Based on several factors including depleting fossil fuels the renewal energy sources are going to be penetrated more and more in the coming future [1, 2]. But there are several aspects of these penetrations of renewal energy sources with existing power system. One of the aspects is the stability issue for power system for different disturbances including varying renewable integrations [3-6]. In this study, the wind penetrations have been examined with sudden and discrete variations with conventional power system and subject to this a SSSC based optimal controlled action is proposed. Different researches have been conducted depicting the effect of the wind source on the stability of power system and in some researches, it has been concluded that due to stochastic variations in wind penetrations, the angular frequency variations is becoming more challenging creating critical mode of oscillations[3,7]. So, damping of these power system oscillations is going to be a challenging issue for the system operators. Power system stabilizer (PSS) has been used for so many years to damp these oscillations. But there are certain drawbacks of PSS like leading power factor operations and interfering with voltage regulations, etc. FACTS based devices are gaining more attentions since past few years for damping of system oscillations. Out of these FACTS devices, series, shunt and series –shunt connected FACTS devices have been reported in many researches for providing efficient damping action. SSSC is a series connected FACTS device where the voltage source converter is connected in series with the transmission line at the point of common coupling. SSSC has multiple functions and out of which an important function is to provide additional damping torque to the system oscillations. Swarm and evolutionary algorithms are very much efficient for optimal gain selections [8-10]. So an important issue is selection of the parameters of SSSC based control action. By optimally choosing appropriate parameters for SSSC the controllability of the damping action can be much enhanced. Different metaheuristic techniques like PSO, DE have been applied here to tune the fractional lead–lag control action based on SSSC and sailfish algorithm as presented in [11] is proposed to tune the controller gains. The performance of sailfish algorithm has been compared with PSO and DE algorithms and it is found to provide much efficient damping action in contrast to PSO and DE.

2. System Under Study

A three-machine system with wind penetration has been considered here. The SSSC is installed between the machines at PCC as shown in Figure 1. Modulation index and phase angles of the converters are the parameters to be controlled for SSSC. In Figure 1 the transfer function model of wind sources is integrated with all generators [6]. In this model K_W and T_W are the gain and time constants of wind generation respectively. Fractional lead-lag controller is proposed for damping action as shown in Figure 2. Here K_P, T_1, T_2, p are the parameters of fractional lead-lag controller where K_p is the gain T_1 and T_2 are the time constants and p is the fraction parameter. The modeling of SSSC with power system is presented by following equations.

$$\Delta \dot{\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \tag{1}$$

$$\Delta \dot{\delta} = \omega_0 \Delta\omega \tag{2}$$

$$\dot{E}'_q = [(-E'_q + E_{fd}) + I_d(X_d - X'_d)] / T'_{d0} \tag{3}$$

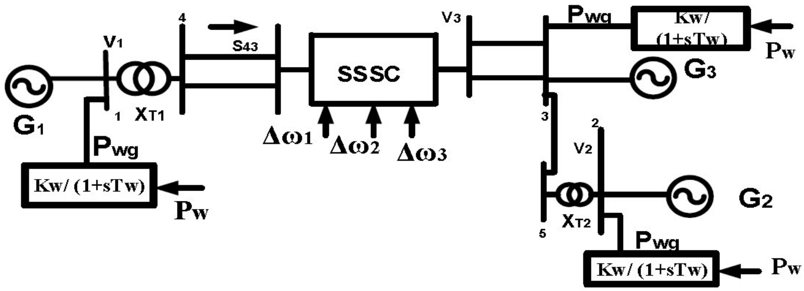

Figure 1

Multi-machine system with UPFC

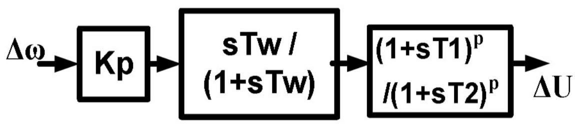

Figure 2

Fractional lead-lag controller

$$\Delta \dot{E}_{fd} = \frac{-\Delta E_{fd} + K_A(\Delta V_{ref} - \Delta V_t + V_s)}{T_A} \tag{4}$$

$$\dot{V}_{dc} = \frac{3m_E}{4C_{dc}}(I_{Eq}\sin\delta_E + I_{Ed}\cos\delta_E) + \frac{3m_B}{4C_{dc}}(I_{Bq}\sin\delta_B + I_{Bd}\cos\delta_B) \tag{5}$$

For the above equations,

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pm}\Delta m + K_{p\delta m}\Delta\psi + K_{pb}\Delta m_b + K_{pd}\Delta V_{dc}$$

$$\Delta E_q = K_3\Delta E'_q + K_4\Delta\delta + K_{qm}\Delta m + K_{q\delta m}\Delta\psi + K_{qd}\Delta V_{dc}$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vm}\Delta m + K_{v\delta e}\Delta\delta_E + K_{vdm}\Delta\psi + K_{vd}\Delta V_{dc}$$

The K_{pu}, K_{qu}, K_{vu} and K_{cu} are row vectors defined as:

$$K_{pu} = [K_{pm} \quad K_{p\delta m}] \tag{6}$$

$$K_{qu} = [K_{qm} \quad K_{q\delta m}] \tag{7}$$

$$K_{vu} = [K_{vm} \quad K_{v\delta m}] \tag{8}$$

$$K_{cu} = [K_{cm} \quad K_{c\delta m}] \tag{9}$$

The vector u is defined as:

$$u = [\Delta m \quad \Delta\psi]^T \tag{10}$$

3. Objective Function

Equation (11) shows the ITAE based objective function where speed variation is the input. K_P, T_1, T_2, p are the tune parameters of FSSSC where the gain K_p values is 1-100, T_1 and T_2 are the time constants values are 0-1 and fraction p value is 0-1.

$$J = \int_0^{tsim} t\left|\Delta\omega\right| dt \tag{11}$$

4. Sailfish Algorithm (SFA)

Sailfish Algorithm (SFA) is a new algorithm reported in [11] which is inspired by the nature and mimics the hunting nature strategy of the sailfish groups. SFA takes less time to solve optimization problem, it has the advantages that diversity of swarm, local solution avoided and convergence speed is too high. SFA equations are expressed as below.

$$SF_{position} = \begin{bmatrix} SF_{1,1} & SF_{1,2} & \dots & \dots & SF_{1,d} \\ SF_{2,1} & SF_{2,2} & \dots & \dots & SF_{2,d} \\ \vdots & \vdots & \dots & \dots & \vdots \\ \vdots & \vdots & \dots & \dots & \vdots \\ SF_{m,1} & SF_{m,2} & \dots & \dots & SF_{m,d} \end{bmatrix} \tag{12}$$

$$fitness\ value\ of\ sailfish = f(sailfish) = f(SF_1, SF_2, \cdots, SF_m) \tag{13}$$

$$SF_{fitness} = \begin{bmatrix} f(SF_{1,1} & SF_{1,2} & \dots & \dots & SF_{1,d}) \\ f(SF_{2,1} & SF_{2,2} & \dots & \dots & SF_{2,d}) \\ \vdots & \vdots & \dots & \dots & \vdots \\ \vdots & \vdots & \dots & \dots & \vdots \\ f(SF_{m,1} & SF_{m,2} & \dots & \dots & SF_{m,d}) \end{bmatrix} = \begin{bmatrix} F_{SF_1} \\ F_{SF_2} \\ \vdots \\ \vdots \\ F_{SF_m} \end{bmatrix} \tag{14}$$

$$S_{position} = \begin{bmatrix} S_{1,1} & S_{1,2} & \dots & \dots & S_{1,d} \\ S_{2,1} & S_{2,2} & \dots & \dots & S_{2,d} \\ \vdots & \vdots & \dots & \dots & \vdots \\ \vdots & \vdots & \dots & \dots & \vdots \\ S_{m,1} & S_{m,2} & \dots & \dots & S_{m,d} \end{bmatrix} \tag{15}$$

$$S_{fitness} = \begin{bmatrix} f(S_{1,1} & S_{1,2} & \dots & \dots & S_{1,d}) \\ f(S_{2,1} & S_{2,2} & \dots & \dots & S_{2,d}) \\ \vdots & \vdots & \dots & \dots & \vdots \\ \vdots & \vdots & \dots & \dots & \vdots \\ f(S_{m,1} & S_{m,2} & \dots & \dots & S_{m,d}) \end{bmatrix} = \begin{bmatrix} F_{S_1} \\ F_{S_2} \\ \vdots \\ \vdots \\ F_{S_m} \end{bmatrix} \tag{16}$$

$$X^i_{new\_SF} = X^i_{elite\_SF} - \lambda_i \times \left(rand(0,1) \times \left(\frac{X^i_{elite_{SF}} + X^i_{injured_S}}{2} \right) - X^i_{old_{SF}} \right) \tag{17}$$

Pseudo code of SFA

1. Random initialization of populations for sailfish and sardine.
2. Initializing A = 4, ε = 0.001.
3. Computing fitness values.
4. Appropriate sailfish and sardines are found out and they are treated as elite and injured.

While conditions for ending is not satisfied
for each member
compute λi
Then position of member is changed
end for
Compute attack power
If attack power < 0.5
Calculate α
Compute β
As per the value of α and β, a set of sardines is selected
Elite sardine position is updated
else
All sardine positions are updated
end if
All sardine fitness should be computed
If an appropriate solution for sardine population is needed
Change a sailfish with injured sardine
Remove the hunted sardine from all
Update the appropriate members
end if
end while
Return appropriate sailfish

5. Result and Discussion

The objective of present work is to create efficient damping torque in the power system to damp oscillations. For this ITAE based objective function has been applied for minimizing the angular frequency variations. Different case studies have been conducted in this work which is based on sudden and intermittent or discrete variations in wind penetrations. In case-I, wind penetrations are suddenly raised by 0.5p.u. and subject to this the oscillations have been analyzed with eigen values and system response. PSO, DE and Sailfish algorithms are employed to tune the parameters of fractional lead-lag control action based on SSSC. A three-machine system has been considered with different operating conditions taken from respective reference [6] and subject to step variations in the wind penetrations, the eigen values are also analyzed. The system response is presented in Figure 3, optimal gains in Table-1 and eigen values are presented in Table-2 for local oscillations subject to G1. It is found that the eigen values being shifted to negative half of complex plane much efficiently by tuning the parameters with sailfish algorithm. In case-II random variations in the wind penetration has been executed with the three machines as in pattern of Figure 5 and a system response have been analyzed. System responses for the generators G_1, G_2 and G_3 have been shown in the Figure 6. From case-I and case-II, it is observed that by sudden or random variations in the wind penetrations, the variations in angular frequency are much enhanced and by tuning the controller parameters of SSSC efficiently, these oscillations can be damped much efficiently. From this multimachine system result analysis subject to stochastic wind penetrations, it has been concluded that sailfish algorithm tuned fractional lead-lag control action is much efficient to create additional damping torque for angular frequency variations.

Table 1

Parameters of optimization

Gains	DE	PSO	SFA
K_B	52.97	80.71	95.36
T_{B1}	0.432	0.493	0.627
T_{B2}	0.957	0.446	0.736
p	0.201	0.479	0.261

Table 2

Eigen value for local oscillations of G1

DE	PSO	SFA
-98.5721, -0.2912 + 3.5673i, -0.2912 - 3.5673i, -2.1305, -1.1423, -0.0025, -0.1004, -0.6667	-98.5725, -0.8227 + 3.4573i, -0.8227 - 3.4573i, -2.1344, -1.4867, -0.0025, -0.1013, -0.6667	-98.5730, -1.5791+3.1407i, -1.5791 -3.1407i,-2.1424, -1.1471,-0.0025, -0.1025, -0.6667

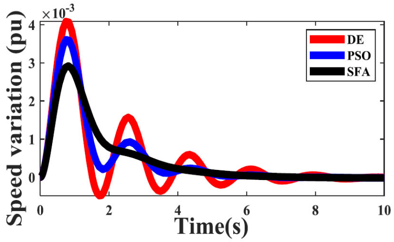

Figure 3

Speed variation for 0.5pu wind

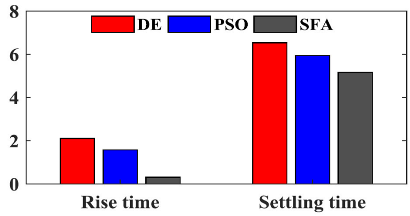

Figure 4

Comparison of settling time and rise time of G_1

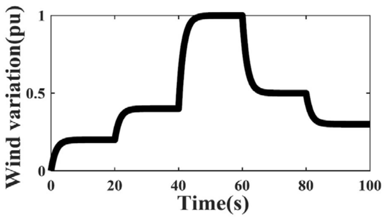

Figure 5

Random wind generation

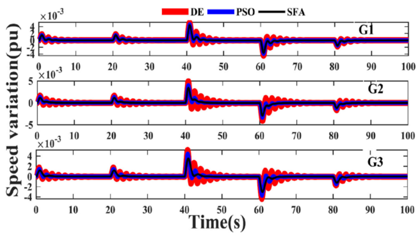

Figure 6

Speed variation in pu for random wind change

6. Conclusion

Different case studies have been conducted in this work with multimachine system considering four generators with different operating conditions with stochastic wind penetrations. It has been found that stochastically varying wind penetrations excite system oscillations giving rise to more variations in the angular frequencies and by efficiently tuning the controller parameters these variations can be much reduced. The SSSC based fractional lead-lag control action has been applied in this work whose parameters are tuned by sailfish algorithm. A sailfish algorithm has been also compared with PSO and DE algorithms and it is observed that the efficacy of the sailfish algorithm is much better as compared to PSO and DE algorithms. In terms of providing adequate damping to the oscillations in angular frequencies. This work can be further extended with different renewable energy resources and for large interconnected power system and this algorithm can also be modified in the future work so as to become compatible with an extended power system.

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