Wide area controller design of STATCOM and PSS in Multimachine power system using BF-PSO Algorithm

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Abstract—In this paper, an optimal wide area controller is designed for a multi-machine power system together with a Static Compensator (STATCOM). Wide area control signals are used to provide auxiliary control to power system stabilizers (PSS) and STATCOM in order to achieve enhanced damping of system oscillations in power systems. A modified intelligent Particle Swarm Optimization (BF-PSO) has been used for optimal and coordinated selection of the STATCOM and Power System Stabilizers (PSS) of generators wide area damping controller parameters. Then, Simulation results are provided in a sample 4-machine 1-bus (Kundur) power system to indicate that the proposed wide area controller improves the damping of the rotor speed deviations of the generators during large scale disturbances. Simulation results have shown that the proposed coordinated wide area controller using modified BF-PSO can reach to optimal and coordinated selection of the STATCOM and PSS damping controller parameters accurately and has better performance in damping oscillations.

Keywords-component; wide area controller; STATCOM; PSS; PSO algorithm; coordinated design

I. INTRODUCTION

Power system oscillations at very low frequencies would continue for a while and then disappear, or continue to grow, causing system separation. When large power systems are interconnected relatively weak tie lines, low frequency oscillations are observed. These oscillations may sustain and grow to cause system separation if no adequate damping is available. These low frequency oscillations are due to the lack of damping of the mechanical mode of the interconnected system, and the desired additional damping can be provided by supplementary excitation control that commonly are known as the power system stabilizer (PSS) [1-3].

In the last decades, PSSs have been used by utilities in real power systems as they have proven to be the most cost-effective electromechanical damping control. Because PSS proper tuning and placement have the most important role on improving power system stability, previous studies have concentrated on methods that lead to the best dynamic performance of power system [1-5].

On the other hand, recent development of power electronics introduces the use of flexible ac transmission system (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the stability of a power system. Static synchronous compensator (STATCOM) is member of FACTS family that is connected in shunt with the system. Even though the primary purpose of STATCOM is to support bus voltage by injecting (or absorbing) reactive power, it is also capable of improving the power system stability [6]. It has been proved that shunt FACTS devices give maximum benefit from their stabilized voltage support when sited at the mid-point of the transmission line [6]. The first swing stability of the system is greatly influenced by choice of different models of the transmission line [7]. For long transmission lines, when the actual model of the line is considered, the results may deviate significantly from those found for the simplified model. With pre defined direction of real power flow, the shunt FACTS devices need to be placed slightly off-center towards the sending end for maximum benefit from the transient stability point of view.

Although the local control signals are easy to get, they are not as highly controllable and observable as wide area signals for the inter-area oscillation modes. Due to restriction of local measurements, these controllers based on local signals tend to be difficult to offer satisfactory performance under various system operating conditions.
The wide area measurement system (WAMS) in power systems can provide wide area signals that are used to enhance the damping of power systems. A supervisory level power system stabilizer (SPSS) using wide area measurement has been proposed [8] that included robust controller loops. A method based on linear matrix inequalities (LMI) was applied to the controller design. However, the effects of the communication delays on the performance of the SPSS were not analyzed. With the rapid advancement in wide area measurement systems technology, fast communication networks and powerful information technology, the widely dispersed signals of power systems can be centralized, processed and distributed even in real time, which makes the wide area signal a good alternative for control input [9]. A number of conventional techniques have been reported in the literature pertaining to design problems of conventional PSSs: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory. Unfortunately, the conventional techniques are time consuming as they are iterative and require heavy computation burden and slow convergence. In addition, the search process is susceptible to be trapped in local minima and the solution obtained may not be optimal [9].

The evolutionary methods constitute an approach to search for the optimum solutions via some form of directed random search process. A relevant characteristic of the evolutionary methods is that they search for solutions without previous problem knowledge. Recently, particle swarm optimization (PSO) appeared as a promising evolutionary technique for handling the optimization problems. PSO is a population-based stochastic optimization technique, inspired by social behavior of bird flocking or fish schooling.

This paper uses a modified BF-PSO technique to determine coordinated and optimal wide area controller parameters of STATCOM and PSSs for transient stability improvement. The parameters of both STATCOM and PSSs controllers are indicated simultaneously using the proposed BF-PSO algorithm and the damping of power system oscillations and improving the interactions between PSSs and STATCOM-based controllers are compared with non-coordinated design of them.

II. POWER SYSTEM AND STATCOM MODELING

A. Generator Modeling

In this study, the generator will be presented by the fifth-order ($5^{th}$) model comprising of the electromechanical swing equation and the generator internal voltage equation. The dynamic model for the $i^{th}$ machine in the power system including its exciter is expressed in terms of the differential equations given in the following equations [7]:

$$\frac{d\delta}{dt} = e_n e_h$$

(1)

$$\frac{d\omega}{dt} = -\frac{1}{2H_i}\left(P_m - P_e - D_e\omega\right)$$

(2)

$$\frac{de_{di}}{dt} = \left[-e_{di} - (x_{di} - x_{di}^{'})I_{di}\right]\frac{1}{T_{qoi}}$$

(3)

$$\frac{de_{qd}}{dt} = \left[\frac{E_{fdi} - e_{dif} - (x_{di} - x_{di}^{'})I_{di}}{T_{dqi}}\right]\frac{1}{T_{dqi}}$$

(4)

$$\frac{de_{rs}}{dt} = -\frac{1}{T_m}\left(E_{fr} - E_{gres}\right)\frac{K_{m}}{T_m}\left(V_o - V_{es}\right)$$

(5)

Where,

- $\delta$ Generator rotor angle
- $\omega_i$ Rotor speed of Generator $i$
- $\omega_m$ Base (synchronous) speed
- $P_m$ Mechanical power input
- $P_e$ Electrical power output
- $H_i, D_i$ Inertia constant, damping coefficient of generator
- $e_d, e_q$ Quadrature (q) and direct (d) axis internal voltage
- $E_{fr}$ Field voltage
- $x_d, x_d'$ Synchronous, transient direct (d) axis reactance
- $I_d$ d-component of armature current
- $T_s, K_A$ time constant, Exciter gain
- $V_i$ Generator terminal voltage
- $E_{fr}, V_o$ Nominal field, terminal voltage

B. STATCOM Modeling

The STATCOM is modeled as a voltage-sourced converter behind a step down transformer. The STATCOM generates a controllable AC-voltage source behind the leakage reactance. A block diagram of a STATCOM is shown in Fig. 1 [9].
The STATCOM consists of a step-down transformer (SDT) with an impedance of $Z_{SDT}$, a three-phase GTO-based voltage source converter (VSC) and a dc link capacitor $C_{DC}$. The SDT is connected to a bus in a power system. The voltage difference across $Z_{SDT}$ produces an active and reactive power exchange between the STATCOM and the power systems [1]. The VSC generates a controllable AC voltage given by:

$$V_0^r = km \times V_{dc} (\cos \phi + i \sin \phi)$$  

(6)

Where, $k$ is the ratio between the AC and DC voltage depending on the converter structure and $m$ is the modulation ratio defined by pulse width modulation (PWM). $V_{dc}$ is the DC voltage and $\phi$ is the phase defined by PWM.

The dynamic model of the STATCOM is described by:

$$\frac{dV_{dc}}{dt} = \frac{km}{C_{DC}} (I_d \cos \phi + I_q \sin \phi)$$  

(7)

Where, $I_d$ and $I_q$ are the currents in the STATCOM. $V_0^r$ and $V_{dc}$ can be controlled by $m$ and $\phi$. The active and reactive power exchange between the STATCOM and the power systems can be controlled by adjusting $V_0^r$.

III. COORDINATED WIDE AREA BASED CONTROLLER DESIGN

Wide Area Measurement systems are going to be used increasingly in power systems. Consequently, a wide area controller can be created using wide area signals provided by the WAMS. Additionally, the STATCOM has also been used in power systems. This section presents the coordinated wide area controllers design of the power system stabilizers and the STATCOM controller to improve the power system stability.

A. Power System Stabilizer (PSS) Controller

The IEEE Type-ST excitation system shown in Fig. 7 is considered. As shown in Fig. 7, a conventional lead-lag PSS is installed in the feedback loop to generate a stabilizing signal $u_{PSS}$.

B. STATCOM Controller System

Considering the STATCOM modeling mentioned in section II, the phase $\phi$ is adjusted by the capacitor voltage controller that is shown in Fig. 7 [3-4,5]. The input of the capacitor voltage controller is the capacitor voltage $V_{dc}$.

C. Wide Area Controller

A block diagram of a PSS and a wide area controller in the generator $i$ is shown in Fig. 8 [6].

$$G_{w}(s) = K_{w} \left( \frac{1 + \alpha_{w} T_{w} s}{1 + T_{w} s} \right)^{n} \quad n = 1, 2 \text{ or } 3$$  

(8)

$$G_{w}(j \omega) = |G_{w}(j \omega)| e^{j\phi_{lag}}$$  

(9)

Where, $K_{w}$ is the gain, $\alpha_{w}$ is a constant, $T_{w}$ is a time constant and $\phi_{lag}$ is the angle. One oscillation cycle is defined as $\tau^{\ominus}$. The wide area signal from a WAMS has a time delay due to the communication process and lags behind its original signal by the angle $\phi$-lag. The lead-lag compensation pair in ($\tau^{\ominus}$) compensates for the angle $\phi_{lag}$.

For this study, if the time delay causes a lag angle $\phi_{lag}$ in the range of $\phi^{\ominus}$ to $\Lambda^{\ominus}$, then the lead-lag compensation block is tuned to $K_{w}^{\ominus} \cdot \alpha_{w}$ and $\phi_{lag}^{\ominus} = 0$. If $\phi_{lag}$ is within the range of $\Lambda^{\ominus}$ to $\Lambda^{\ominus}$, then $K_{w}^{\ominus} < \cdot$ and $\phi_{lag} = (\phi_{lag} - 180)^{\ominus} < [\Lambda]$.

Considering the PSS, STATCOM and WACS controllers block diagram, the parameters which should be tuned are determined as follows:
for each PSS: \((K_{PSS}, T_s, T_r, T_a, T_i)\),
for each WACSs (considering a delay time): \((K_{wB}, \alpha_B)\)
for STATCOM: \((K_{DCB}, K_{ACB}, K_{ABC}, K_{ABC})\)

These parameters of the controllers are optimized simultaneously by using the proposed modified BF-PSO algorithm to minimize the fitness function. The (BF-PSO) combines both algorithms BF and PSO. This combination aims to make use of PSO ability to exchange social information and BF ability in finding a new solution by elimination and dispersal.

D. Particle Swarm Optimization (PSO)

The PSO algorithm, developed by Kennedy and Eberhart, models the behavior of a group of particles whose initial values are specified by a group of proposed random solutions [1].

PSO starts with initial swarm matrix but doesn’t have complementary operators such as jumping and merging. The rows in matrix are named particles (like chromosomes in genetic algorithm). They have variable values and are not binary. Every particle moves with particular speed on the cash area. Particles optimize their speeds and positions based on local and global optimized points and by using the equations mentioned below [1]:

\[
\begin{align*}
V_{new}^{m,n} &= V_{old}^{m,n} + \Gamma_1 \times r_1 \times (p_{local\ best}^{m,n} - P_{old}^{m,n}) + \\
& \quad \Gamma_2 \times r_2 \times (P_{global\ best}^{m,n} - P_{old}^{m,n}) + \\
& \quad V_{new}^{m,n}
\end{align*}
\]

Where,
- \(V_{m,n}\) velocity of particles
- \(P_{m,n}\) particle variables
- \(r_1, r_2\) random numbers
- \(\Gamma_1, \Gamma_2\) training factor
- \(p_{local\ best}^{m,n}\) best local solution
- \(P_{global\ best}^{m,n}\) best global solution

A particle decides where to move next, considering its own experience, which is the memory of its best past position, and the experience of the most successful particle in the swarm.

E. Bacterial Foraging Optimization (BF)

The BF algorithm was first presented by Pasino in [6]. The selection behavior of bacteria tends to eliminate poor foraging strategies and improve successful foraging strategies. After many generations a foraging animal takes actions to maximize the energy obtained per unit time spent foraging. This activity of foraging led the researchers to use it as optimization process. The foraging process consists of four stages: chemotaxis, swarming, reproduction, and elimination [17], and these are briefly explained hereafter.

1) Chemotaxis: This stage mimics the bacteria’s ability to climb to regions of nutrient concentration, avoiding noxious substances and searching for a way out of neutral media. The bacterium usually takes a tumble, followed by a tumble or a swim to carry out this search. For \(N_r\) number of chemotactic steps, the direction of movement after a tumble is given by:

\[
\theta^i(j+1,k,l) = \theta(j,k,l) + C(i) \times \phi(j)
\]

where \(C(i)\) is the step size taken in the direction of the tumble by the \(i\)th bacterium, \(j\) is the index for the chemotactic step taken, \(k\) is the index for the number of reproduction step, \(l\) is the index for the number of elimination–dispersal event, and \(\phi(j)\) is the unit length random direction taken at each step. In other published applications

2) Swarming: The bacteria in times of stresses release attractants to signal other bacteria to swarm together. It however also releases a repellent to signal others to be at a minimum distance from it. Thus, all of them have a cell to cell attraction via the attractant and cell to cell repulsion via the repellant. The following equation represents the swarming behavior in the bacterium foraging:

\[
J_{ce}(\theta, P(j,k,l)) = \sum_{i=1}^{s} \left[ -d_{\text{attract}} \exp(-\alpha_{\text{attract}} \sum_{m=1}^{P} (\theta_m - \theta_m^i)^2) \right] \\
+ \sum_{i=1}^{s} \left[ h_{\text{repellant}} \exp(-\alpha_{\text{repellant}} \sum_{m=1}^{P} (\theta_m - \theta_m^i)^2) \right] i = 1, S
\]

where
- \(d_{\text{attract}}\) depth of the attractant effect;
- \(\alpha_{\text{attract}}\) measure of the width of the attractant;
- \(h_{\text{repellant}} = d_{\text{attract}}\) height of the repellant effect;
- \(\alpha_{\text{attract}}\) measure of the width of the repellant
- \(P\) number of parameters to be optimized;
- \(S\) number of bacteria.

3) Reproduction: After all the \(N_r\) chemotactic steps have been covered, a reproduction step takes place. \(S_r (S_r = S/4)\) bacteria having a lower survival value (less healthy) die, and the remaining \(S_r\) is allowed to split into two, thus keeping the maintaining a constant population size.

4) Elimination and Dispersal: Environment changes for the bacteria all the time. Bacteria are either destroyed or moved to different parts of the intestine, resulting in positive and negative influences on their lives. In BF algorithm, the dispersal event takes place after a certain number of reproduction processes. First, a \(p_{ed}\) (the probability of elimination and dispersal) is chosen for each bacterium, and then based on the selected \(p_{ed}\) it moves to another position in
the environment. These events can effectively prevent trapping in local optimal points. Also, \( N_{el} \) is the number of elimination and dispersal [\(^{17}\)].

Also, \( N_{ed} \) is the number of elimination and dispersal [\(^{21}\)].

F. Bacterial Foraging Optimization Oriented by Particle Swarm Optimization (BF-PSO)

Considering (\(^{19}\)), each movement step of BFA algorithm is dependent on the random parameter of \( \phi(j) \), which slows down the searching process. For this purpose, by considering PSO

![Figure 6](image6.png)

Figure 6. Sample 1-machine 11-bus (Kundur) power system with STATCOM.

![Figure 7](image7.png)

Figure 7. Algorithm flowchart of BF-PSO.

A simple flowchart of the bacterial foraging oriented by particle swarm optimization algorithm shown in fig. 7.

G. Objective Function

The main objective function which has used in proposed Wide area controller design of STATCOM and PSS is expressed as follows [\(^{14}^{\text{of}}\)]:

\[
OF = \sum_{i=1}^{\text{num}} \left[ \left( o_{\text{sh},i} \times 10^8 \right)^2 + \left( u_{\text{sh},i} \times 10^8 \right)^2 + \left( t_{\text{st},i} \times 10^1 \right)^2 + \left( \frac{d}{dt} \Delta \omega_{r,i} \right) \times 10^8 \right]
\] (15)

Where, \( o_{i} \), \( u_{i,i} \), and \( t_{i} \) are overshoot, undershoot and settling time of the \( i \)th generator’s speed.

Now considering the limitations of designed controller parameters, the optimal values of them can be extracted.
IV. CASE STUDY AND SIMULATION RESULTS

A sample 4-machine 8-bus (Kundur) power system, shown in Fig. 3, is considered for the proposed wide area coordinated damping controller design. Each area consists of two generator units. The rating of each generator is $4 \cdot 10^6$ MVA and $8 \cdot 10^3$ kV. Each of the units is connected through transformers to the $8 \cdot 10^3$ kV transmission line. There is a power transfer of $6 \cdot 10^6$ MW from area 1 to area 2. Each synchronous generator of the multi-machine power system is simulated using a fifth-order ($s^5$) model and the STATCOM device is considered using a current injection model. The detailed bus data, line data, and the dynamic characteristics for the machines, exciters and loads including the STATCOM data are given in [7]. Also, the ranges of parameters’ limits considered for design procedure are given in [7].

The main parameters values of PSO and BF-PSO algorithms are shown in Table I. It should be noticed that the number of cost function evaluations for (BF-PSO) is $8 \cdot 10^7$ (S.NN Nm Ncd) while that of PSO is $8 \cdot 10^7$ (S.NN). Hence it is clear that the proposed (BF-PSO) produces better results with lower computation cost.

The power system is simulated for a $4 \cdot 10^{-3}$-sec Three-phase fault that happens at Bus number 8 in second 1. The speed deviation of generators for uncoordinated, PSO and BF-PSO based controller design are shown in Figs. A, B, C, D and E.

| Parameter | $S$ | $n$ | $N_1$ | $N_2$ | $N_{cd}$ | $c_{ij}$ | $P_d$ | $C_r$ | $C_r$ | $n_r$
|-----------|-----|-----|-------|-------|---------|---------|-------|-------|-------|--------
| BF-PSO    | 1   | 1   | 1     | 1     | 1        | 1        | 1     | 1     | 1     | n_r    |
| PSO       | 1   | 1   | 1     | 1     | 1        | 1        | 1     | 1     | 1     | n_r    |

As shown in Figs. A, B, C, D and E, the coordinated design of STATCOM and PSSs controllers using BF-PSO algorithm gives a better performance.

V. CONCLUSIONS

In this paper, a coordinated PSS and DSTATCOM wide area damping controller has been proposed and designed. Furthermore, a modified BP-PSO algorithm has been used for optimal and coordinated selection of the proposed controller. The proposed coordinated wide area controller has been simulated in a 4-machine 8-bus power system using BF-PSO algorithm and the results are compared with PSO and local area control. The simulation results confirmed that the proposed coordinated wide area controller with BF-PSO algorithm can achieve better dynamic response.

REFERENCES


