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Gradient based hybrid metaheuristics for robust tuning of power system stabilizers

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ABSTRACT

Power System Stabilizers are controllers installed on synchronous generators to damp power system oscillations through the excitation control. These controllers can have either a conventional fixed structure composed by stages of gain and phase compensation or a flexible modern structure composed by three bands that correspond to a specific frequency range (low, intermediate and high frequency) in which each band is composed by two branches that are based on differential filters (with a gain, lead-lag blocks and a hybrid block). Power system stabilizers design is a hard and time consuming task and an alternative for tuning controllers is by using optimization methods. This paper presents three hybrid metaheuristics for the robust and coordinated design of power system stabilizers. The tuning procedure is modeled as an optimization problem which aims at maximizing the damping ratio coefficients in closed-loop operation. Robustness requirement is met by using multiple operating scenarios in the design stage. For solving the optimization problem, three metaheuristics (Gravitational Search Algorithm, Bat Algorithm and Particle Swarm Optimization) are combined with the Steepest Descent Method for local search capability enhancement. The proposed hybrid algorithms are applied to benchmark systems for validation.

1. Introduction

Stability studies are often required to analyze the performance of Electrical Power Systems (EPS) when subject to increased load demands and contingencies. Voltage stability, Frequency stability and Rotor Angle stability (Transient and Small Signal) are important and complementary studies performed by engineers to ensure a reliable operation of EPS [1].

Small Signal Stability concerns low frequency electromechanical oscillations that arise from unbalanced torques (electrical and mechanical) at synchronous generators after perturbations (load and topology variations). These oscillations can limit the power interchange among areas and cause blackouts if they are not suitably damped [2]. According to the literature the main kinds of oscillations are: (*i*) Local (when a generator swings against the rest of the system at 1.0 to 2.0 Hz) and (*ii*) Interarea (when two coherent groups of generators swing against each other at 1 Hz or less) [3]. Besides these ones, another kind of oscillation is reported in [4]: it is associated to very slow oscillatory modes with frequency range of 0.01–0.05 Hz which are referred as global modes, found on isolated systems.

Since the seventies, Power System Stabilizers (PSS) have been used to reduce power system oscillations through the excitation control of synchronous generators. The main function of these controllers is to modulate the field voltage of generators to provide an additional damping torque (in phase with rotor speed deviations) [2].

The classical structure of PSS is composed by a gain stage and lead-lag blocks to provide the required compensation in the oscillation frequency and the most common control input signals reported in the literature are speed deviation and electrical power [2]. However speed deviation suffers from adverse torsional interactions and electrical power presents an excess of VAR modulation during mechanical power reference changes. In order to overcome these drawbacks, manufactures developed a digital PSS based on the integral acceleration power (referred as PSS2B) at the beginning of the nineties [5,6].

In general conventional power system stabilizers are allocated to damp local oscillations and through a properly tuning they can provide a suitable damping for inter-area modes associated

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Nomenclature

General

AVR	automatic voltage regulator
BAT	bat algorithm
EPS	electrical power systems
GHBAT	gradient based hybrid bat algorithm
GHGSA	gradient based hybrid gravitational search algorithm
GHPSO	gradient based hybrid particle swarm optimization
GSA	gravitational search algorithm
MB-PSS	multi-band power system stabilizer (pss4b)
PSO	particle swarm optimization
PSS	power system stabilizers
PSS4B	modern multi-band power system stabilizer

Control system

$(\xi_k)_j$	damping ratio associated with the *k-th* eigenvalue in the *j-th* operating condition
F_L, F_I, F_H	low, intermediate and high band central frequencies (Type PSS4B)
K_L, K_I, K_H	low, intermediate and high band gains (Type PSS4B)
T_w	washout time constant (conventional stabilizer)
ξ_{min}	lowest damping ratio taking all pre-specified operating conditions into account
$A_{Cj}, B_{Cj}, C_{Cj}, D_{Cj}$	state space matrices associated with the *j-th* operating condition in closed-loop operation (in upper case)
A_{Oj}, B_{Oj}, C_{Oj}, D_{Oj}	state space matrices associated with the *j-th* operating condition in open-loop operation
A_c, B_c, C_c, D_c	state space matrices associated with the control system
E_{FD}	field voltage (pu)
F_{Lp}, F_{Ip}, F_{Hp}	low, intermediate and high band central frequencies (Type PSS4B) where $p = 1 \ldots npss$
K_{H1}, K_{H2}	high band differential filter gains (Type PSS4B)
K_{H11}, K_{H17}	high band first lead-lag blocks coefficients (Type PSS4B)
K_{I1}, K_{I2}	intermediate band differential filter gains (Type PSS4B)
K_{I11}, K_{I17}	intermediate band first lead-lag blocks coefficients (Type PSS4B)
K_{L1}, K_{L2}	low band differential filter gains (Type PSS4B)
K_{L11}, K_{L17}	low band first lead-lag blocks coefficients (Type PSS4B)
K_{Lp}, K_{Ip}, K_{Hp}, K_{Gp}	low band, intermediate band, high band and series gains (Type PSS4B) where $p = 1 \ldots npss$
K_p	gain parameter (conventional stabilizer) where $p = 1 \ldots npss$
T_{H1}, T_{H2}, T_{H7}, T_{H8}	high band time constants (Type PSS4B)
T_{I1}, T_{I2}, T_{I7}, T_{I8}	intermediate band time constants (Type PSS4B)
T_{L1}, T_{L2}, T_{L7}, T_{L8}	low band time constants (Type PSS4B)
V_{Hmin}, V_{Hmax}	high band output limits (Type PSS4B)
V_{Imin}, V_{Imax}	intermediate band output limits (Type PSS4B)
V_{Lmin}, V_{Lmax}	low band output limits (Type PSS4B)
V_{PSSmin}, V_{PSSmax}	conventional stabilizers output limits
V_{STmin}, V_{STmax}	PSS4B output limits
α_p, ω_p	lead-lag compensator parameters (conventional stabilizer) where $p = 1 \ldots npss$
ΔP_e	generator's terminal electrical power
ΔV_{PSS}, V_{PSS}	stabilizers' output (conventional stabilizers)
$\Delta\omega$	generator's terminal speed deviation
nb	number of stages of a lead-lag compensator (conventional stabilizers)
$npss$	number of stabilizers
u	input variables vector
x	state variables vector
y	output variables vector
$\lambda = \sigma \pm j\omega_d$	complex eigenvalue with real (σ) and imaginary ($j\omega_d$) components
ξ	damping coefficient of any complex eigenvalue

Metaheuristics

G^t	gravitational constant at time t (GSA)
A_0, A_{min}	initial and final loudness value (Bat Algorithm)
A_i^t, r_i^t	loudness and emission pulse rate of the *i-th* individual in the *t-th* generation (Bat Algorithm)
F_i	fitness function associated with the *i-th* solution
F_{ij}^t	force acting on the *i-th* agent due to agent *j* in the *t-th* generation (GSA)
F_i^t	total force acting on the *i-th* agent in the *t-th* generation (GSA)
K_{best}	set of first agents with the best fitness value (GSA)
M_i^t	gravitational mass of the *i-th* agent in the *t-th* generation (GSA)
a_i^t	acceleration of the *i-th* agent in the *t-th* generation (GSA)
c_1, c_2	positive acceleration constants (PSO)
f_{ri}, A_i, r_i	frequency, loudness and emission pulse rate of *i-th* bat (Bat Algorithm)
$pbest_i$	best location in history associated with the *i-th* particle (PSO)
t_{max}	maximum number of generations
w_{max}, w_{min}	inertia weight bounds (PSO)
$worst^t$, $best^t$	worst and best solutions in the *t-th* generation (GSA)
w^t	inertia weight (PSO)
x^*	best solution found so far (Bat Algorithm)
x_i	solution i (agent or individual)
$x_{i\_d}^t$, $F_{ij\_d}^t$, $F_{i\_d}^t$	component on *d-th* direction of position and forces (GSA)
x_i^t, v_i^t	position and velocity of the *i-th* individual in the *t-th* generation
$gbest$	best location among all particles in history(PSO)

to generators on which they are fitted. The need for improving the damping in a wide range of oscillation modes (global, inter-area and local) led to the development of Multi-Band PSS (MB-PSS also known as PSS4B) [5–8]. PSS4B is based on the so-called flexible stabilizer structure [9] and it consists of three bands that correspond to a specific frequency range: low (typically 0.01–0.1 Hz for global modes), intermediate (0.1–1 Hz for inter-area) and high frequency (1–10 Hz for local modes). Each band is composed by two branches that are based on differential filters (with a gain, lead-lag blocks and a hybrid block). The input signals are derived from speed deviation (for low and intermediate frequency bands) and electrical power (for the high frequency band) [10,11].

The tuning procedure of several stabilizers in an EPS is a hard and a time consuming task due to two main reasons. The first one is associated to the robustness requirement consideration: a way to take the system's uncertainties (load and topology variations) into account is by considering several operating scenarios in the design stage, as described in [12]. The second one is associated to the required coordinated design to avoid undesirable interactions amongst the controllers: in this case all stabilizers must be simultaneously designed, as described in [13]. Although in practice the whole system does not stop so that these controllers are simultaneously tuned, it is worth mentioning a Brazilian case: in 1999 the north-south interconnection has given rise to a new