SMALL SIGNAL STABILITY ENHANCEMENT USING SUPPLEMENTARY SIGNALS FROM PMU

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REZUMAT. Această lucrare propune o abordare metaeuristică pentru setarea optimală a stabilizatoarelor de putere (PSS) în scopul îmbunătățirii stabilității sistemelor electroenergetice prin amortizarea suplimentară a oscilațiilor de putere folosind semnale de la Dispozitive de măsură fazoriale (DMF). Aşadar, problema destul de dificilă a proiectării PSS este transformată într-o problemă de optimizare care este rezolvată cu ajutorul algoritmului roiului de particule. Pentru atribuirea unui grad de performanță particulelor, se adoptă o funcție multiobiectiv care are la bază valorile proprii ale sistemului. Performanțele metodei propuse vor fi demonstrate prin intermediul analizei modale şi a simulărilor în domeniul timp.

Cuvinte cheie: PSO, măsurari fazoriale sincronizate, valori proprii.

ABSTRACT. This paper proposes a metaheuristic approach for optimal setting of power system stabilizers (PSS) in order to increase the power system stability by supplementary damping of the system oscillations using PMU signals. The complicated task of optimally determining PSS parameters is , thus, transformed into an optimization problem solved using Particle Swarm Optimization algorithm (PSO). For evaluating the particles, an eigenvalue –based multiobjective function is employed based on the system eigenvalues. The performances of the proposed approach are demonstrated throughout modal analisys and time domain simulations.

Keywords: PSO, PMU, eigenvalues.

1. INTRODUCTION

Power system stability has been an important concern for secure system operation even from the early beginnings of the first power systems. Over the years, the power systems were forced to operate more and more close to their operating limits because of the steady increase in network and electric power demand. Hence, power system stability became a vital problem not only for the operation of existent power systems, but also for the safe operation, and for the development of the Smart Grid concept.

The basic concept of power system stability is described as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. This definition offers a simple and sufficient understanding of the concept [1, 2].

An alternative solution towards the power oscillations issue is the development of devices such as Flexible Alternative Current Transmission Systems (FACTS) and PSSs installed in key points of the network. Nevertheless, the most convenient way of damping oscillations is the use of PSS as a supplementary control device to the excitation system of the synchronous machine. It generates an electric torque component through the generator excitation system proportional to the rotor speed deviation enhancing the transfer capability of the power system . The PSS structure as well as its influence towards the system stability is explained in greater detail in [3]. The most important aspects for designing such a controller are the proper choosing of stabilizer's feedback signals, the optimal parameter setting and the proper selection of controller's location.

In literature, the problem of optimal setting of PSS was intensively analyzed. Although different techniques such as Pole-Placement, Linear Matrix Inequalities, Linear Quadratic Regulator Formulation [4] were successfully used for PSS design, recently the optimization techniques such as Tabu Search, Genetic Algorithms (GA), Simulated Annealing or PSO gain more and more attention. This is due to the fact that conventional techniques are confronted with heavy computational burden and the possibility of getting trapped in local optimum [5]. On the other hand, the optimization techniques are characterized by their simple implementation and they don't require previous problem knowledge [6].

In [7], the PSS was optimally design using GA approach on a single machine infinite bus system (SMIB). As an objective function, it was used the damping ratio of the system eigenvalues in order to evaluate the chromosomes throughout the searching process. The time-domain simulation demonstrated the applicability of the GA on PSS design.

2. CLASSICAL POWER SYSTEM STABILIZER (CPSS)

In early 1960s, with the growth of the power systems, engineers used Automatic Voltage Regulators (AVRs) as close-loop feedback control in order to enhance the power system stability [1]. With the development of new technologies, for achieving a reliable and economically viable way of operating the power systems, new controllers were developed. Such a device is the PSS, which is used to add damping to electromechanical oscillations.

The purpose of PSSs is to introduce additional signal to provide damping to the generator rotor oscillations. This is achieved by modifying the generator excitation so as to develop a component of electrical torque in phase with rotor speed deviation making PSSs very efficient during line outage and large power transfer. In other words, the major objective of PSS is to increase the system capacity to transfer power in a safer and more stable manner. The CPSS is widely used in existing Power Systems and has made a contribution in enhancing Power System Transient. However, its performances become suboptimal under wide variations in system parameters and load conditions [4].

The common input signals used for the PSS are generator shaft speed, electrical power, accelerating power or terminal bus frequency [1], but the choice of a stabilizing signal is influenced by many factors such as its availability and the fact that certain signals have different advantages and disadvantages over the others. In Fig. 1 is represented the basic structure of CPSS.

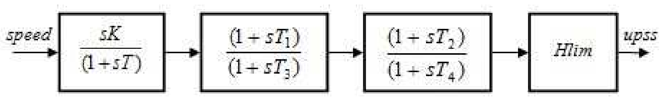

Fig. 1. Basic structure of power system stabilizer

where,

speed	-	the input signal;
u_{pss}	-	the PSS gain;
K	-	the output signal;
T	-	washout filter time constant;
T_1, T_2, T_3, T_4	-	the phase compensation time constants.

3. PARTICLE SWARM OPTIMIZATION ALGORITHM

PSO algorithm is an optimization method inspired by the natural movement and intelligence of bird flocks and fish schooling. It was introduced by Eberhart and Kennedy in 1995 to graphically simulate the graceful and unpredictable choreography of a swarm [8]. The concept behind of the PSO consists in moving a pre-defined number of particles trough-out the searching space in order to find the best solution. As in real life, the movement pattern of the simulated particles is given by the social interaction between the individuals from the population.

In Fig. 2 are represented the main steps for implementing the PSO algorithm. For a mathematical expresion of the flock, the particles are modeled as vectors in a multidimensional search space. First, the searching process starts by randomly generating a predefined number of particles which forms the population, and the velocity of the particles.

To evaluate the particles throughout the searching process, the particles are evaluated according to an objective function. In this way, the personal best of each particle so far, as well as the global best of the entire population are determined. With this information, the velocity of every individual is computed taking into account its previous velocity, personal best and global best (1). The new positions of the individuals are then updated by adding the computed velocities to the actual position according to (2).

$$v_i^{k+1} = wv_i^k + c_1 \cdot \text{rand} \cdot \left(\text{pbest}_i - s_i^k\right) + c_2 \cdot \text{rand} \cdot \left(\text{gbest} - s_i^k\right) \quad (1)$$

where:

v_i^k	-	Velocity of the i^{th} particle at iteration k
w	-	Inertia coefficient
c_1, c_2	-	Weighting coefficients
pbest_i	-	Personal best of the i^{th} particle
gbest	-	Global best of the population
s_i^k	-	Position of the i^{th} particle at iteration k

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (2)$$

where:

s_i^{k+1}	-	The position of the particle at iteration k+1
v_i^{k+1}	-	Velocity of the particle at iteration k+1

The searching process is finished when the computational limits are exceeded or until a relatively unchanged position has been encountered.

An important fact of the PSO is that the ratios of the three elements that influence the particle velocity in the optimization process must be first optimized to assign equilibrium between the local search and the global search.

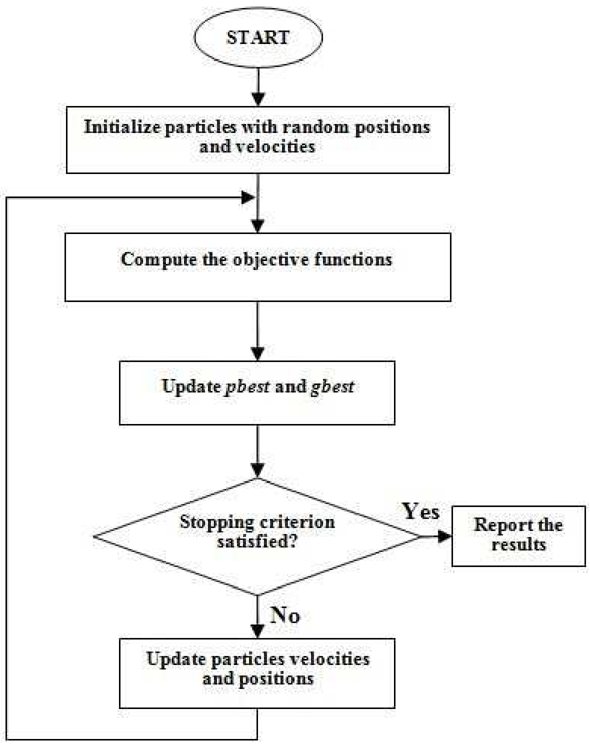

Fig. 2. PSO flow chart

4. PROBLEM STATEMENT

A. Power System Model

The aim of this paper is the optimal tuning of the multi-input PSS (MIPSS) in a multi-machine power system using PSO algorithm. The multimachine test system under study is the well known 10 machine – 39 buss test system widely used in power system stability studies (Fig.4). Every generator from the system is defined as a 6 order model and is equipped with standard IEEE1S AVR and TGOV1 governor.

B. MIPSS structure

The proposed PSS structure uses signals from key points of the network in order to damp out the power oscillations. The remote signals used by the PSS are the buss frequency and active power from tie lines measured and transmited throughout PMU infrastructure.

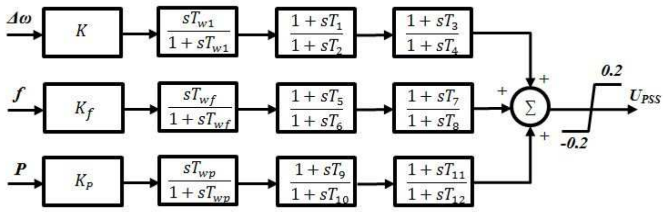

Fig. 3. Proposed MIPSS

As it can be seen from Fig. 3., the MIPSS has three inputs: the local speed based signal, the remote frequency signal and the remote active power signal respectively. Every signal has one gain block, one washout filter and two lead – lag stages, therefore, in the case of using only one PSS, a particle will be define by a vector consisting of 15 elements.

C. The objective function

To assign a certain degree of performance to the particles, they are evaluated according to an multi-objective function that takes into account the real part of the the eigenvalue as well as it's damping ratio. Using equation (3), the corresponding system eigenvalues are translated in a prescribed area of the complex *s*-plane defined by σ_0 and ξ_0.

$$J = \sum_{\sigma_0 \geq \sigma_i} (\sigma_0 - \sigma_i)^2 + \alpha \cdot \sum_{\varepsilon_i \leq \varepsilon_0} (\varepsilon_0 - \varepsilon_i)^2 \quad (3)$$

where,

σ_i - real part of the ith eigenvalue;

ζ_i - damping ratio of the ith eigenvalue;

σ_0 - Threshold;

ζ_0 - Threshold;

α - scalling factor.

Thus, the optimization problem is to minimize J under the following constraints:

$$\begin{array}{ccccc}
K_{min} & \leq & K & \leq & K_{max} \\
Kf_{min} & \leq & Kf & \leq & Kf_{max} \\
Kp_{min} & \leq & Kp & \leq & Kp_{max} \\
T_{min} & \leq & T_1 & \leq & T_{max} \\
T_{min} & \leq & T_2 & \leq & T_{max} \\
T_{min} & \leq & T_3 & \leq & T_{max} \\
T_{min} & \leq & T_4 & \leq & T_{max} \\
T_{min} & \leq & T_5 & \leq & T_{max} \\
T_{min} & \leq & T_6 & \leq & T_{max} \\
T_{min} & \leq & T_7 & \leq & T_{max} \\
T_{min} & \leq & T_8 & \leq & T_{max} \\
T_{min} & \leq & T_9 & \leq & T_{max} \\
T_{min} & \leq & T_{10} & \leq & T_{max} \\
T_{min} & \leq & T_{11} & \leq & T_{max} \\
T_{min} & \leq & T_{12} & \leq & T_{max}
\end{array}$$

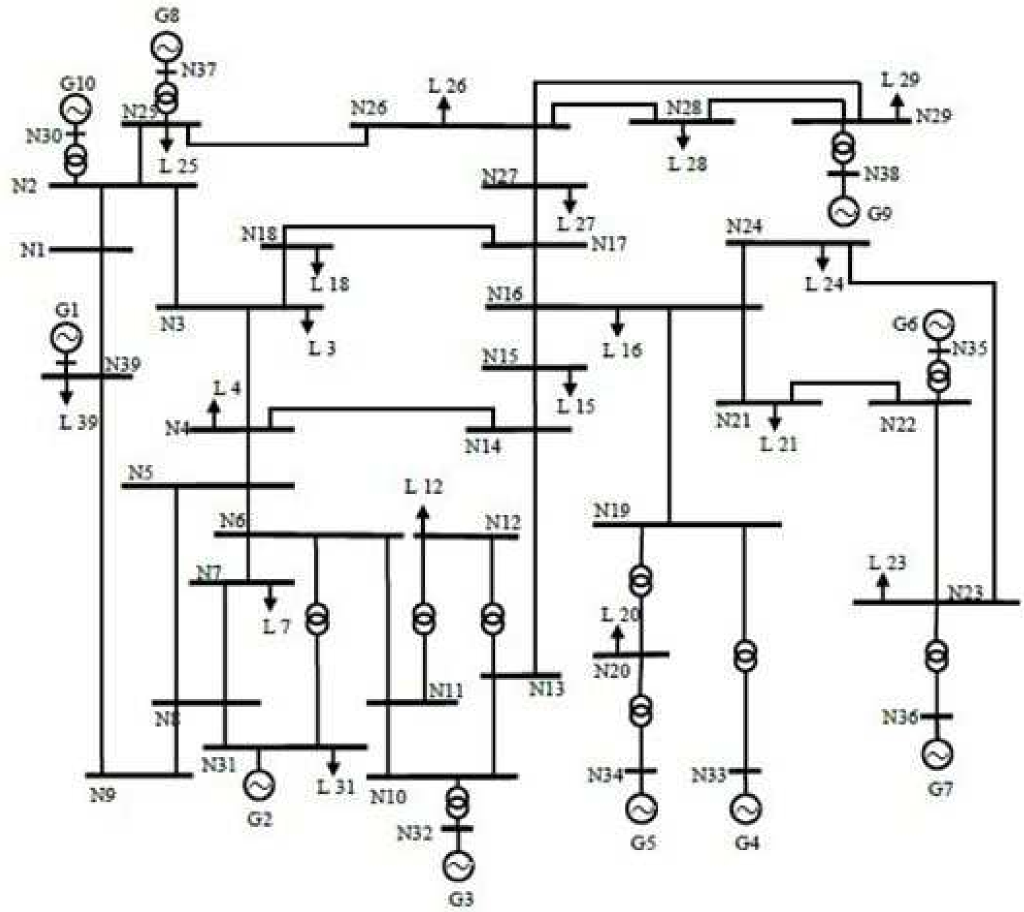

Fig. 5 10 generator – 39 bus system

Table 1

System eygenvalues

	Eigenvalue	**Damping factor**	**Frequency of oscillation [Hz]**
m1	**-0.112 ± j·2.889**	**0.038**	**0.459**
m2	**-0.131 ± j·3.405**	**0.038**	**0.542**
m3	**-0.190 ± j·4.383**	**0.043**	**0.697**
m4	**-0.238 ± j·3.817**	**0.062**	**0.607**
m5	**-0.292 ± j·5.209**	**0.056**	**0.829**
m6	-0.274 ± j·4.389	0.062	0.698
m7	-0.467 ± j·5.172	0.090	0.823

Table 2

Participation factor

	m1	***m2***	***m3***	***m4***	***m5***
G1	0.002	0.007	0.001	0.001	0.001
G2	0.054	0.573	0.031	0.001	0.008
G3	0.097	**1**	0.065	0.003	0.004
G4	0.088	0.101	0.004	0.636	0.002
G5	0.087	0.121	0.009	**1**	0.002
G6	0.144	0.196	0.006	0.559	0.003
G7	0.104	0.160	0.009	0.01	0.032
G8	0.034	0.001	**1**	0.001	0.180
G9	**1**	0.001	0.107	0.001	0.004
G10	0.001	0.009	0.182	0.001	**0.984**

4. PROPOSED APPROACH

According to the modal analisys applied to the power system in the case of AVR's and governors, there are nine eigenvalues associated to the rotor speed deviation which are caracterised by a oscilation frequency under 1 Hz. Also, it can be observed from Table 1, that there are three eigenvalues that have a damping factor which is under the maximum limit considered in practice (0,05). Therefore, action must be taken in order to damp out these oscillations. The solution proposed in this study case is to use both CPSS and MIPSS to enhance those oscillation modes caracterised by poor damping.

After computing the system eigenvalues and the participation factors (PFs) (Table 2) there are three steps that must be taken into account to implement the optimization strategy:

- identify the critical modes that are caracterised by poor damping (in this study we have taken five modes – bold faced in Table 1)
- find the optimal location of the PSS in order to damp the desired oscilation modes bassed on the participation factor of each generator to every oscillation mode;
- the parameters are optimally determined using the proposed method.

Taken into consideration the above mention steps, it has been concluded that the PSS are installed at the generators which have the maximum participation factor to a specific mode of oscillation. Based on this presumption, the PSS will be installed at the generators G_3, G_5, G_7, G_8, G_9.

In order to start the optimization process, first some PSO settings must be assumed:

- it is considered a population of 50 particles with 50 generations;
- the parameters σ_0 and ε_0, which define a specific area in the complex *s* plane where system eigenvalues are driven, are considered $\sigma_0 =-1$ and $\varepsilon_0=0.3$;
- the weights c_1, c_2 and w_1 were optimaly calibrated to assign equilibrium between the local search and the global search (c_1=0.5, c_1=0.2 and $w_1=[0.7...0.3]$).
- the weighting factor from the multiobjective function α was optimaly chosen by multiple runs on different values, to be equal to 10.

After running the optimization procedure for the five PSSs, the system eigenvalues are obtained as shown in Table 3.

It can be observed that in the presence of the five PSSs with the parameters optimised throughout the proposed method, all oscillation modes have been emproved.

The next step of the analisys is to enhance one oscillatori mode first by using an optimized CPSS, and afterwards an optimized MIPSS. From Table 3 it can be seen that the mode *m5* is caracterised by the lowest damping factor, therefore the PSS installed at G_8 will be reoptimised, using MIPSS that uses signals from remote location of the network. As to the remote signal that must be chosen for the MIPSS, this was the frequency signal from the bus where G_{10} is installed in the sistem (N30), because this generator participates the most to the oscillatory mode *m5*. The second remote signal of the MIPSS was chosen as the active power flow from the line between generators G_{10} and G_8.

After runing the optimization procedure for both CPSS and MIPSS, we can draw the following conclusions (Tabel 4):

Table 3

- System eigenvalues with CPSS at G_3, G_5, G_7, G_8, G_9

	Eigenvalue	**Damping factor**
m1	-0.268 ± j·2.893 /	0.092
m2	-0.293 ± j·3.385 /	0.086
m3	-0.345 ± j·4.448 /	0.077
m4	-0.335± j·4.385 /	0.076
m5	**-0.333 ± j·5.214 /**	**0.063**

Table 4

System eygenvalues in the case of CPSS at G_8 and MIPSS at G_8

	Eigenvalue	**Damping factor**
m1	-0.274 ± j·2.897/ 0.094	-0.280 ± j·2.91/ 0.095
m2	-0.293 ± j·3.38 / 0.086	-0.293 ± j·3.3 / 0.086
m3	-0.337 ± j·4.388 / 0.076	-0.336 ± j·4.3 / 0.075
m4	-0.568 ± j·4.485 / 0.125	-0.768 ± j·4.14/ 0.182
m5	**-0.384 ± j·5.17 / 0.074**	**-0.404 ± j·5 / 0.079**

- by using remote signals from key points of the network, the mode *m5* has been improved, from a damping factor of 0.074 to 0.079
- the modes *m4* and *m1* were also improved from 0.125 to 0.182 for mode *m4* and from 0.094 to 0.095 for mode *m1*, respectively.

To demonstrare the efectiveness of the proposed approach, some events were considered in order to excite a desired oscillation mode, as follow:

a) at simulation time *t=1 s*, an increase with 1% in the mecanichal torque of generator G_8, and a decrease with 1% in the mechanical torque of generator G_{10} are considered. This event will excite mode *m5*.

b) at simulation time *t=1 s*, an increase with 1% in the mecanichal torque of generator G_8, and a decrease with 1% in the mechanical torque of generator G_9 are considered. This event will excite mode *m4*.

According to time domain simulations, it is obvious the influence of the remote signal in damping the desired mode. As it can be seen from Fig. 4, the power oscillation is damped out the most in the case of MIPSS that uses remote signals. Also, the oscillation have been improved in terms of setling time and overshot.

In Fig. 5 can be observed the the power oscillation is very well damped out. This can be explaned from modal analisys point of view, where the oscillation mode has been significantly improved in the case of MIPSS, having a damping factor of 0.182 unlike in the case of CPSS, where the damping ratio is 0.125.

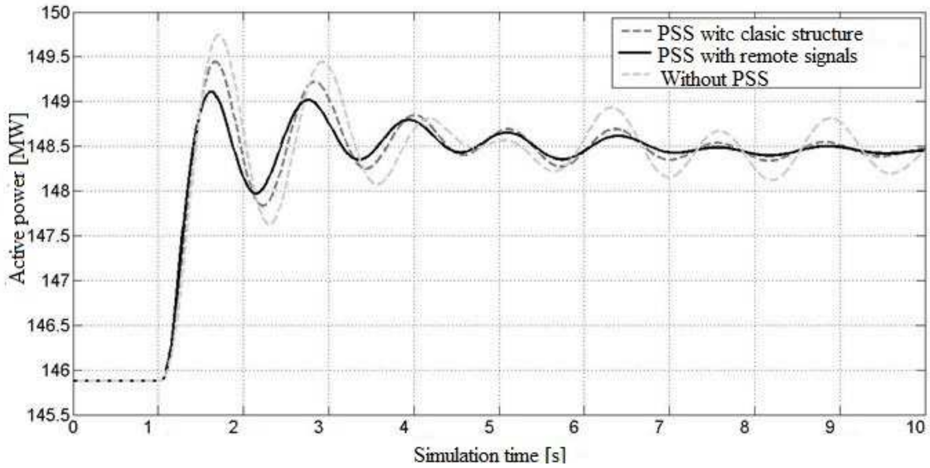

Fig. 4 The active power on the line between N25-N2 considering event *a* in the case of the sistem without PSS, in the case of CPSS at G_8, G_5, G_7, G_8, G_9 and in the case of CPSS at G_3, G_5, G_7, G_9 and MIPSS at G_8.

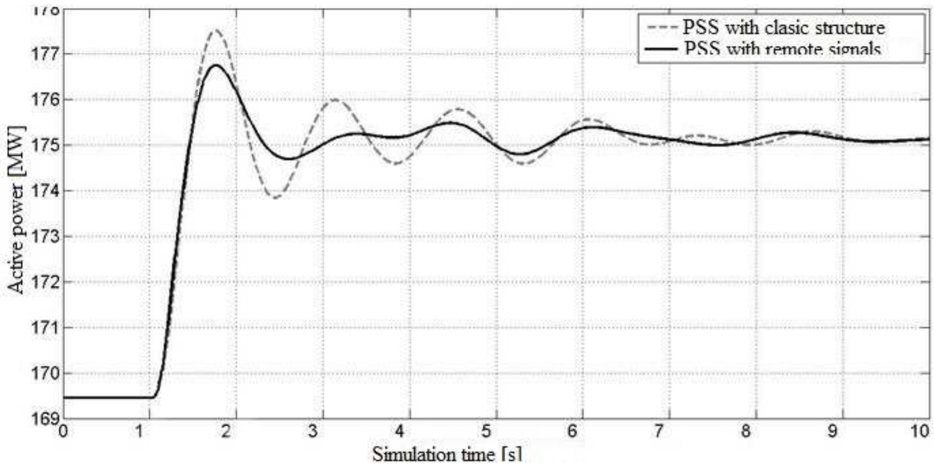

Fig. 5 The active power on line between N25-N26 considering event *b* in the case of retuned CPSS at G_8 and retuned MIPSS at G_8, respectively.

6. CONCLUSION

In this paper a metaeuristic approach was considered in optimal tunning of power system stabilizer using remote signals. For evaluating the particle throughout the searching space, an eigenvalue based multi objective function it is used. The supplementary input signal used in this study as an input to the PSS structure were bus frequency and tie line actiwe power.

The superiority of MIPSS was demonstrated in a complex power system comprising 10 generators and 39 buses throughout modal analisys and time domain simulation.

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