WATER CYCLE ALGORITHM BASED POWER SYSTEM STABILIZER ROBUST DESIGN FOR POWER SYSTEMS

Navid Ghaffarzadeh *

Power System Stabilizers (PSSs) are used to enhance damping of power system oscillations. This paper presents a new fast algorithm to develop PSS. According to this regard, Water Cycle Algorithm (WCA) is used to detect optimum Power System Stabilizer parameters. For this purpose, the design problem of PSS is formulated as an optimization problem and WCA by forming three subsidiary objective functions is employed to search for optimal power system stabilizer's parameters to minimize the maximum overshoot and settling time together. In order to show the efficiency of the proposed algorithm, a comparison between WCA and without PSS condition has been done, and the results of proposed algorithm show that it detects optimum parameters in reasonable computation time to increase the power system stability.

K e y w o r d s: power system stabilizer (PSS), water cycle algorithm (WCA), power system stability, optimum parameters

1 INTRODUCTION

With development of power systems, connecting them to each other is inevitable but it will lead to create oscillations over the frequency range from 0.2 to 3 Hz in the systems [1]. If these low frequency oscillations are occurred in power systems and adequate damping devices are not provided, this may cause system instability and even loss of synchronism [2–4].

In order to damping oscillations, the generators should be equipped with power system stabilizers (PSSs) that provide supplementary feedback signals to do stabilizing Power systems. Two main approaches have been introduced in the literature that stabilize a power system over a wide range of operation conditions; adaptive control and robust control. Each of these methods has advantages and disadvantages that have been verified in [5]. In the recent years, several conventional techniques such as the eigenvalue assignment, gradient procedure for optimization, mathematical programming, and also the modern control theory, have been proposed in the literature pertaining to design problems of conventional power system stabilizers [2]. In [6] Power system Stabilizer (PSS) design is done with output feedback, but these controllers, need to centralized estimators and controllers. Fuzzy logic methods and artificial neural networks is used to design power system stabilizer (PSS) in [7–9]. Recently, various optimization techniques such as genetic algorithm [10, 11], evolutionary programming algorithm [12], steel plating process [4], and particle swarm optimization (PSO) technique [1, 2, 4, 5, 13–15] have been used for this purpose, but some of them have limits in optimizing, for example

genetic algorithm highly depends on the choice range of each parameter to be optimized [10].

In this paper water cycle algorithm is used to optimal design power system stabilizer (PSS). The idea of this algorithm is received from natural water cycle which is began by initialing of variables as Raindrops, then by forming the river and sea, evaporation is done and cycle is continued again until the best possible answer which is value of sea is fined. One advantage of this algorithm is in raining stage which in the probability of trapping in local maximum or minimum points is lost.

In most works, for designing the PSS, four or five variables is used which reduce efficiency and speed, but in this paper, only three parameters are considered as variables to design PSS, so the efficiency and speed for finding optimal PSS parameters is increased. Finally, this paper is organized as follows.

2 SYSTEM UNDER STUDY

2.1 Power System Model

The operations of generator, load, controllers and connecting them properly can be modeled with a set of differential- algebraic equations based on Heffron-Philips model. The system under study is shown in Fig. 1 and consisted of a single machine infinite bus system. In [16] model of a synchronous generator has been represented that consists of a winding on the q axis with field circuit. Also in [16] as well as [5] the dynamic model of the single machine connected to an infinite bus system is considered

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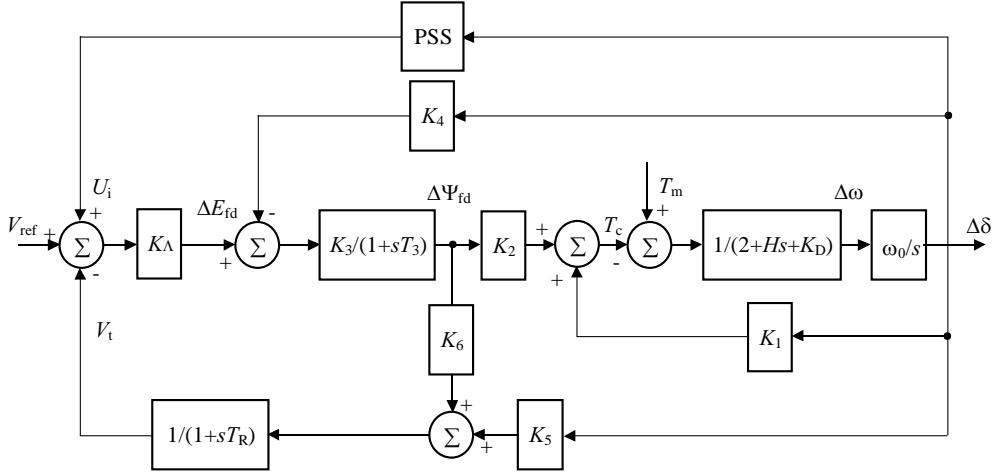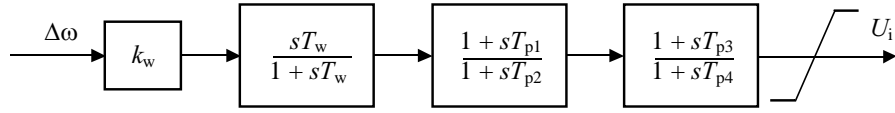
Fig. 1. The system under study

Fig. 2. The structure of power system stabilizer (PSS)

and its equations can be summarized as

$$\Delta\dot{\delta} = \omega_0 \Delta\omega\,,$$

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$$\Delta\dot{\omega} = \frac{T_m - T_e}{2H}\,,$$

$$T_e = K_2 \Delta\varphi_{fd}\,,$$

$$\Delta\varphi_{fd} = (\Delta E_{fd} - K_4 \Delta\delta)\frac{K_3}{1 + ST_R}\,, \tag{1}$$

$$\Delta E_{fd} = (-V_t + U_i)K_A\,,$$

$$V_t = (K_5 \Delta\delta + K_6 \Delta\varphi_{fd})\frac{1}{1 + ST_R}\,,$$

where are

δ : angle between quadrature axis and infinite bus bar.

ω_0 : $2\pi f$, $f = 60$ Hz.

ω : rotor speed.

T_m : mechanical torque.

T_e : electrical torque.

H : inertia coefficient.

$E_{f,d}$: generator field voltage.

K_A, T_R: exciter gain and time constant.

V_{ref} : reference voltage.

V_t : terminal voltage.

K_1 to K_6 are constant parameters that they are dependent on the machine parameters and the operating conditions. Generally K_1, K_2, K_3 and K_6 are positive. K_4 is mostly positive except for cases where line impedance is high. K_5 is positive for low to medium line impedances and low to medium loading. K_5 is usually negative for medium to high line impedances and heavy

loading. The K-parameters of the machine expressed in terms of P and Q can be discussed as [16] by equations (2) and (3).

$$K_1 = R_3 \frac{P^2}{P^2 + (Q+R)^2} + Q + R_1\,,$$

$$K_2 = R_4 \frac{P}{\sqrt{P^2 + (Q+R_1)^2}}\,,$$

$$K_3 = \frac{x'_d + x_e}{x_d + x_e}\,,$$

$$K_4 = R_5 \frac{P}{\sqrt{P^2 + (Q+R_1)^2}}\,, \tag{2}$$

$$K_5 = R_4 x_e \frac{P}{V_t^2 + Qx_e}\Big[R_6 \frac{Q+R_1}{P^2 + (Q+R_1)^2}\Big]\,,$$

$$K_6 = R_7 \frac{\sqrt{P^2 + (Q+R_1)^2}}{V_t^2 + Qx_e}\Big[x_e + \frac{R_1 x_q(Q+R_1)}{P^2 + (Q+R_1)^2}\Big]\,.$$

$$R_1 = \frac{V_t^2}{x_e + x_1}\,, \quad R_2 = K_3\,,$$

$$R_3 = R_1 \frac{x_q - x'_d}{x_e + x'_d}\,, \quad R_4 = \frac{V_t}{x_e + x'_d}\,,$$

$$R_5 = \frac{x_d - x'_d}{x_e + x'_d}\,, \quad R_6 = R_1 \frac{x_q(x_q - x'_d)}{x_e + x_q}\,, \tag{3}$$

$$R_7 = \frac{x_e}{x_e + x'_d}\,,$$

where are

$K_1, \ldots, K_6$: the K-parameters of the synchronous generator.

X_q : quadrature-axis synchronous reactance.

X'_d, x_d : generator direct-axis transient reactance, and direct-axis synchronous reactance respectively.

x_e : line reactance.

P, Q : real and reactive power loading respectively.

2.2 PSS Structure

PSS is used to compensate the phase lag between the exciter input and the machine electrical torque by producing a proper torque on the rotor of the machine. A widely used conventional lead-lag PSS, is considered in this study. In this structure, Power System Stabilizer (PSS) consists of a gain block with gain k_w, a signal washout block and two-stage phase compensation blocks. This structure is shown in Fig. 2, and follows from the equation

$$U_i = k_w \frac{sT_w}{1+sT_w} \frac{1+sT_{p1}}{1+sT_{p2}} \frac{1+sT_{p3}}{1+sT_{p4}} \Delta\omega. \quad (4)$$

As is shown in Fig. 2, the stabilizer includes a high pass filter where k_w and T_{p1}, and T_{p3} are Power System Stabilizer adjustable parameters, and T_w, T_{p2}, and TY_{p4} are considered constants $T_{p2} = T_{p4} = 0.05$, $T_w = 10$.

3 OVERVIWE OF WATER CYCLE ALGORITHM

Water cycle algorithm (WCA) is a novel optimization method for solving constrained engineering optimization problems that proposed in 2012 [17]. In this algorithm sea is best value and stream or river as initial population, adjoined to sea (best value) at last.

Water Cycle Algorithm (WCA) has ability to find maximum or minimum value of function with high speed and accuracy, so in this paper, this algorithm is applied to determine the optimum Power System Stabilizer (PSS) parameters in which power system oscillation is minimum. In fact, problem is to design the parameters of the power system stabilizer.

In a problem with N_{var} variables, each raindrop is a $1 \times N_{var}$ array and each array is a solution for problem. These arrays are put in a matrix

$$\text{Raindrop}_i = X_i = [x_1, x_2, \ldots, x_{Nvar}],$$

$$\text{Population raindrops} = \begin{bmatrix} \text{raindrop}_1 \\ \ldots \\ \text{raindrop}_i \\ \ldots \\ \text{raindrop}_{Npop} \end{bmatrix} \quad (5)$$

so N_{pop} is number of raindrops and population raindrops are initial population. Then cost of each raindrop is calculated by cost function.

3.1 Stream (or river) flow to river (or sea)

All streams and rivers join to the sea at last by expressions

$$\text{Position}_{\text{stream}}^{\text{new}} = \text{Position}_{\text{stream}} +$$
$$\text{rand} \times C \times (\text{Position}_{\text{river}} - \text{Position}_{\text{stream}}), \quad (6)$$

$$\text{Position}_{\text{river}}^{\text{new}} = \text{Position}_{\text{river}} +$$
$$\text{rand} \times C \times (\text{Positin}_{\text{sea}} - \text{Position}_{\text{river}}) \quad (7)$$

where C is a number between 1 and 2. rand is a uniformly distributed random number between 0 and 1. If the solution is given by a stream is better than its connecting river, the positions of river and stream are exchanged (*ie* stream becomes river and river becomes stream). Such exchange can similarly happen for rivers and sea.

3.2 Evaporation and Raining

In order to avoid getting trapped in local optima evaporation and raining process is proposed [17]. This is specific prominence for Water Cycle Algorithm (WCA) to comparison other optimization algorithms. Evaporation process end if

$$|\text{Position}_{\text{sea}} - \text{Position}_{\text{river}}| < \text{d}_{\max}, \quad (8)$$

$\text{d}_{\max}$ is a number near to 0. The value of $\text{d}_{\max}$ automatically decreases as

$$\text{d}_{\max}^{\text{new}} = \text{d}_{\max} - (\text{d}_{\max}/\text{maxiteration}). \quad (9)$$

After evaporation process, raining process begins.

In the raining process, the new raindrops are flowing to streams in the different locations. Eq (10) is used for new location of streams.

$$\text{Position}_{\text{stream}}^{\text{new}} = \text{Position}_{\text{sea}} + \sqrt{U} \times \text{randn}(1, N_{var}) \quad (10)$$

where U determines rate of search near to the sea. randn is the normally distributed random number.

3.3 End of loop

In this paper, maximum number of iterations (maxiteration) is used as a criterion for end of main loop which at the end loop, the optimal parameters are received.

Water Cycle Algorithm (WCA) parameters has been brought in Tab. 1.

Table 1. Water cycle algorithm (WCA) parameters

Parameters	Value
N_{var}	3
N_{pop}	30
C	2
U	0.1
$\text{d}_{\max}$	0.001
Maxiteration	50

Table 2. Water cycle algorithm (WCA) outputs

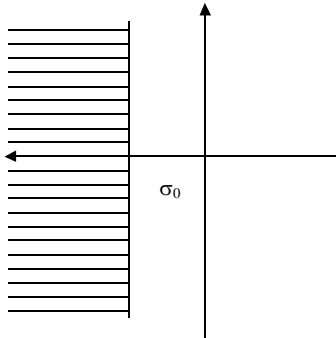| Operation Condition	a			b			c		
	T_{p1}	T_{p3}	k_w	T_{p1}	T_{p3}	k_w	T_{p1}	T_{p3}	k_w
J_1	0.1049	0.0976	44.37	0.1105	0.0997	40.44	0.0801	0.0809	52.08
J_2	0.1915	0.1874	47.25	0.1917	0.193	79.04	0.1709	0.1884	76.11
J_3	0.1327	0.0819	43.65	0.1259	0.0896	46.19	0.1028	0.1394	40.57

Fig. 3. J_1 operation region
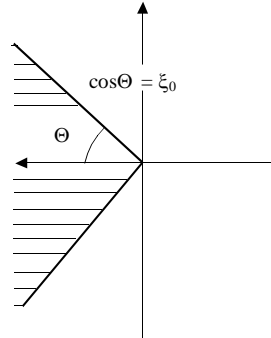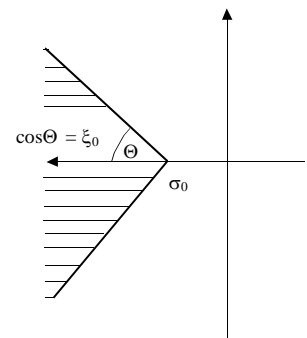

Fig. 4. J_2 operation region

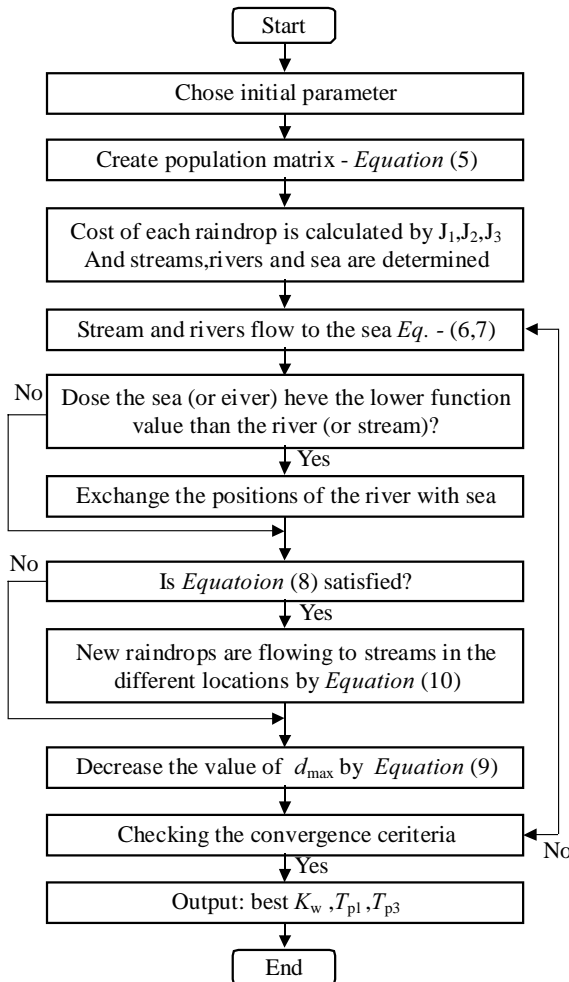**Fig. 5.** J_3 operation region

Fig. 6. Flowchart of proposed algorithm

4 OPTIMIZATION PROBLEM FORMULATION

In this present study, washout time T_w, T_{p2} and T_{p4} are considered constants, and k_w, T_{p1}, and T_{p3} should be determined. Consider, that the aim of main objective is to design Power System Stabilizer (PSS) which minimizes the power system oscillations in reasonable computation time.

In this paper, we consider three subsidiary objectives to determine the various parameters of Power System Stabilizer (PSS). The first objective is to determine the relative stability of the system. So the eigenvalues of system in order to access desirable level of damping ratio (σ_0) should be transferred to the left of $s = \sigma_0$, that is demonstrated in Fig. 3:

$$J_1 = \sum_{\sigma_i > \sigma_0} (\sigma_i - \sigma_0)^2 \qquad (11)$$

where σ_i is damping ratio, $\sigma_0 = 1.5$ is considered, and J_1 is the first subsidiary objective function.

The second subsidiary objective is to limit the overshoot of transferred eigenvalues to the specific area connector as Fig. 4. This causes to access desirable damping coefficient (ξ_0):

$$J_2 = \sum_{\xi_i > \xi_0} (\xi_i - \xi_0)^2 \qquad (12)$$

where ξ_i is damping coefficient, $\xi_0 = 0.2$ is considered, and J_2 is the second subsidiary objective function.

The third subsidiary objective is conflation two prior subsidiary objectives and can be expressed by the Figure 5 and following form

$$J_3 = \alpha J_1 + \beta J_2 \qquad (13)$$

where $\alpha = 1$ and $\beta = 10$ are considered, and J_1, J_2 and J_3 are first, second, and third subsidiary objective functions, respectively. Minimizing J_i $(i = 1, 2, 3)$ subject to

$$k_{w,\min} < k_w < k_{w,\max},$$
$$T_{P1,\min} < T_{P1} < T_{P1,\max},$$
$$T_{P3,\min} < T_{P3} < T_{P3,\max}.$$

Table 3. Details of these three operation conditions

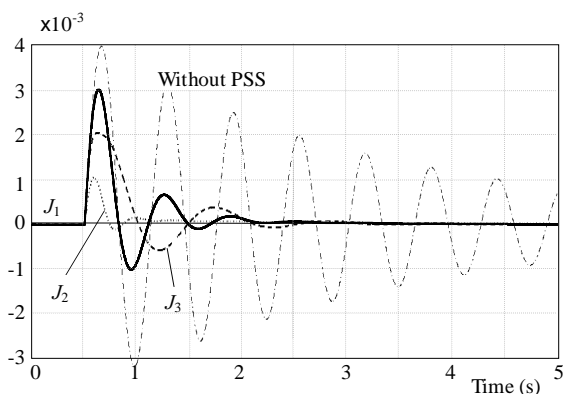| Operation Condition	a		b		c	
	Overshoot	Settling time(s)	Overshoot	Settling time(s)	Overshoot	Settling time(s)
J_1	2.55×10^{-3}	3.51	1.36×10^{-3}	3.46	1.32×10^{-3}	3.31
J_2	0.89×10^{-3}	4.16	0.34×10^{-3}	4.17	0.233×10^{-3}	4.52
J_3	1.73×10^{-3}	3.60	0.41×10^{-3}	3.68	0.301×10^{-3}	3.48

Fig. 7. Objective functions J_i $(i = 1, 2, 3)$ under light loading
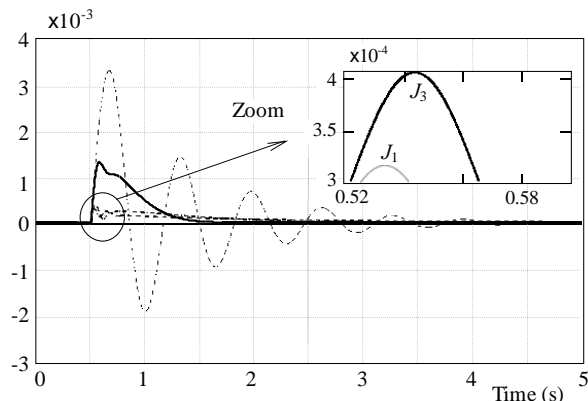

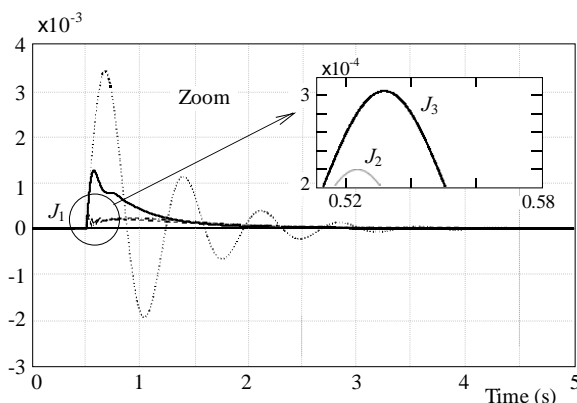**Fig. 8.** Objective functions J_i $(i = 1, 2, 3)$ under nominal loading

Fig. 9. Objective functions J_i $(i = 1, 2, 3)$ under heaving loading

The flowchart of Water Cycle Algorithm (WCA) with considering above objectives for detecting optimum Power System Stabilizer (PSS) parameters is shown in Fig. 6.

5 SIMULATION RESULTS

In order to assessment and detecting the efficiency and accuracy of the proposed controller, a Heffron-Phillip model is developed for Single machine infinite bus system using MATLAB/SIMULINK. This system is simulated under different operating conditions and severe disturbances. The severe disturbance is applied at $t = 0.5$ s, and its amplitude is 0.2 pu. Three operation conditions are considered:

a) Light loading
b) Nominal loading
c) Heavy loading

By applying Water Cycle Algorithm (WCA) according Tab. 1 to this system, the Power System Stabilizer (PSS) parameters in three operation conditions are received as Tab. 2.

Figure 7 shows J_i $(i = 1, 2, 3)$ which are objective functions under light loading. As is shown in this figure for light loading the J_2 has the least overshoot among other function, but J_1 has the least settling time. For nominal loading, as is shown in Fig. 8, J_2 has the least overshoot among other function, but J_1 has the least settling time. This condition is confirmed for heaving loading which is shown in Fig. 9. Details of these three operation conditions is summarized in Tab. 3.

To showing the efficiency and accuracy of this proposed controller, its results in three conditions (light, nominal and heaving loading) are compared while the PSS is lack in the system, and are shown in Figs. 7,8,9. This demonstrates that the overshoot, undershoot, settling time and speed deviations of machine are greatly reduced by applying the proposed WCA based tuned PSS.

To explain performance of the proposed method, one performance index Figure of Demerit (FD) based on the system operation is expressed as [18]

$$FD = (1000 \times OS)^2 + (1000 \times US)^2 + T_S^2 \qquad (14)$$

where Overshoot (OS), Undershoot (US) and settling time of rotor angle deviation in machine (T_S) are used

to evaluation the FD. So that, the best system response is reached when the FD index value is the lowest. Numerical results confirm with considering FD index, the objective function J_3 has the best operation as shown in Tab. 4.

Table 4. Numerical result of FD index

Operation Condition	a	b	c
	FD index value		
J_1	19.54	13.82	12.72
J_2	18.10	17.5	20.48
J_3	16.18	13.71	12.20

6 CONCLUSION

In this paper, the Water Cycle Algorithm (WCA) has been proposed to optimally turn the PSS parameters and by reduction of oscillations, improve power system stability. To optimize the PSS parameters, three objective functions have been considered which finally caused to reduce overshoot and settling times in different operation conditions. The simulation results shown that the first objective function J_1, reduced settling time, second objective function J_2 reduced overshoot and third objective function J_3 that is conflation of J_1 and J_2 properly improve overshoot and settling time. Using FD index in proposed WCA based tuned PSS revealed that, the overshoot, undershoot, settling time and speed deviations of the machine are greatly reduced under severe disturbance conditions. Also comparing between these results and results of without PSS condition, confirm that WCA is successful in detecting the optimal PSS parameters.

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