

## Article

# Power System Stability Enhancement Using a Novel Hybrid Algorithm Based on the Water Cycle Moth-Flame Optimization

Ikram Boucetta <sup>1,\*</sup> , Djemai Naimi <sup>2</sup>, Ahmed Salhi <sup>2</sup>, Saleh Abujarad <sup>3</sup>  and Laid Zellouma <sup>1</sup>

<sup>1</sup> Electrical Engineering Department, El-Oued University, El-Oued 39000, Algeria; laid-zellouma@univ-eloued.dz

<sup>2</sup> Electrical Engineering Department, University of Biskra, Biskra 07000, Algeria; d.naimi@univ-biskra.dz (D.N.); a\_salhi\_m@yahoo.fr (A.S.)

<sup>3</sup> Department of Electromechanical, Systems and Metal Engineering, Ghent University, Tech Lane Ghent Science Park—Campus Ardoyen, Technologiepark Zwijnaarde 131, B-9052 Ghent, Belgium; saleh.abujarad@ugent.be

\* Correspondence: boucetta-ikram@univ-eloued.dz; Tel.: +213-675540477

**Abstract:** Poor control of the power grid can lead to a total system collapse, causing significant economic losses and possible damage to security and social peace. Therefore, improving power system stability, particularly transient stability, has become one of the major research topics. This paper proposes a developed modeling approach that provides the optimal stabilizer parameters of the control devices, aiming at improving the electrical network stability by minimizing the angular speed deviation in the presence of a severe disturbance event using a novel hybrid algorithm called Water Cycle-Moth Flame Optimization (WCMFO). The main advantages of the proposed method are the speed of response and its efficient exploration and exploitation ability to attain the best solution quality. This is achieved by imposing a thermodynamic incident (an abrupt change in mechanical torque) on the well-known test model (SMIB), Single Machine Infinite Bus. To test the effectiveness of the proposed method, Power System Stabilizer (PSS), Proportional-Integral-Derivative (PID-based PSS), and Fractional Order-PID (FOPID-based PSS) are implemented to control and ensure the system's ability to return to a stable state in the presence of this fault. The achieved experimental outcomes have proven the superiority, and efficiency of the developed approach (WCMFO) in terms of damping the oscillations and reducing the overshoot, with an improvement of 44% over the Water Cycle Algorithm (WCA), Moth-Flame Optimization (MFO), and Artificial Ecosystem Optimization (AEO). It is envisaged that the proposed method could be very useful in the design of a practical high-performance power system stabilizer.

**Keywords:** power grid; transient stability; control devices; power system stabilizer; proportional-integral-derivative controller; Fractional Order-PID controller; Single Machine Infinite Bus; Water Cycle-Moth Flame Optimization; thermodynamic incident



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## 1. Introduction

In recent decades, rapid technological development and the increasing demand for electrical energy have made the power grid very complex [1].

Power systems are generally faced with the problem of sustaining voltage regulation and transient stability [2]. These power grids are vulnerable to various incidents such as short circuits, overloads, line breaks, sudden changes in mechanical torque, etc. One of the most dangerous incidents that the electrical network can face is the sudden disturbance that causes the total instability of the system. Control of stability, in particular transient stability in the presence of these faults, has recently become one of the most widely researched topics [3].

In the literature, various control system, and auxiliary devices have been developed to improve transient stability [4], for example, the Automatic Voltage Regulator (AVR),

the Power System Stabilizers (PSSs) [5], Fractional Order-PID (FOPID) [6], Proportional-Integral-Derivative (PID), and the Flexible AC Transmission Systems (FACTS) devices [7]. The PSSs, PID, and FOPID are the most commonly used devices in order to ensure the efficient operation of the electrical grid. Where the main aim of the stabilizers is to provide adequate torque on the mechanical part of the generator and to ensure better damping of the electrical system [8]. Unfortunately, it presents several difficulties when there is a certain non-linearity in the system caused by the inflexibility of the parameters' values [9].

Due to the recognized numerical methods constraints in solving complex optimization problems, many researchers have developed a new approach called meta-heuristic algorithms that are based on natural phenomena, to meet well-operating conditions and deal with a variety of optimization problems. Various research works have been elaborated to adjust stabilizers parameters using meta-heuristic algorithms in order to improve power system stability. Sheshnarayan et al. [10] used the Cuckoo Search Optimization technique to design a robust PID controller based-PSS. With the aim of improving the power system stability, an optimal design and tuning of the FOPID-based PSS using the Bat Algorithm were suggested by L. Chaib et al. [11]. Vijayakumar et al. [12] have proposed an Enhanced Genetic Algorithm to optimize the PID controller parameters. Boucetta et al. [13] used a new optimization method called the Water Cycle Algorithm to provide the optimal PSS parameters settings for improving the transient power system stability.

Recently, various hybrid approaches have been introduced to enhance the solution quality and the searchability of the basic meta-heuristic methods. In 2019, S. Khalilpourazari et al. introduced a novel hybrid algorithm called Water Cycle-Moth Flame Optimization (WCMFO) based on (WCA) and (MFO), to yield better performance of the exploration and exploitation phases of both algorithms to counter their respective weaknesses. Its ability to solve optimization problems was tested using 23 benchmark functions. The hybrid algorithm has proven its superior performance over the Artificial Bee Colony algorithm (ABC), Genetic Algorithm (GA), Cuckoo Search (CS), and Gravitational Search Algorithm (GSA) [14]. WCMFO has been used in several applications such as parameters determination of proton exchange membrane fuel cell stack electrical model [15], and optimal overcurrent relay coordination in Microgrid [16].

This paper contributes to the developing research area of power system stability enhancement. An efficient hybrid approach based on Water Cycle-Moth Flame optimization algorithm has been proposed to provide the optimal stabilizer settings of the control devices (PSS, PID-based PSS, FOPID-based PSS). The WCMFO's performance was compared with three other meta-heuristic techniques, Artificial Ecosystem Optimization (AEO), Water Cycle Algorithm (WCA), and Moth Flame Optimization (MFO) to confirm its effectiveness. The suggested approaches are examined and evaluated on a SMIB test system under different operating terms.

The major contribution pillars of the present research work are the following:

- i. The hybrid method WCMFO has been applied and adapted for the first time to optimize the settings of three different control systems (PSS; PSS-PID; PSS-FOPID) in order to improve the stability performance of the electrical grid.
- ii. The WCMFO outperforms the other meta-heuristic algorithms by obtaining significantly better solutions in reducing overshoot, damping oscillations, and settling time.
- iii. The presented model in this article provides a more realistic and accurate stabilization of power system without performing time-consuming simulations.
- iv. The developed model aims to improve the electrical network stability via the minimization of the angular speed deviation in the presence of a severe disturbance event.

The rest of the article is organized in the following way: Section 2 presents the power system modelling; the transient stability, the proposed stabilizers and the objective functions, which are the performance indices, are discussed briefly in Section 3; Section 4 aims at describing the suggested method; the results are presented and discussed in Section 5; the conclusion is stated in Section 6.

## 2. Power System Modeling

The system that was considered in this study is the linear model of the synchronous generator connected to an infinite bus via an electrical transmission line (SMIB) [2]. It consists of an exciter and a voltage regulator that controls the voltage ( $V_t$ ) across the synchronous generator. The infinite bus voltage ( $V_{in}$ ) is maintained at a constant nominal value. This system provides significant aspects of the multi-machine system behavior as it is easier to study, highly useful for illustrating the impact of various factors on the power system stability [10]. In this study, the SMIB model is used in order to examine the control devices in a virtual environment for real time simulation. Figure 1 presents a principal line diagram for the (SMIB) model connected with three different control devices which are PSS, PSS-PID, and PSS-FOPID. The power system data are given in Appendix A.

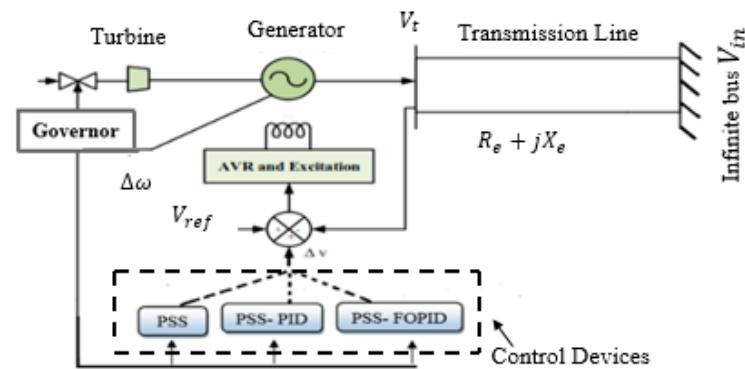


Figure 1. Schematic line diagram (SMIB) system [10].

## 3. Transient Stability and the Proposed Stabilizers

### 3.1. Transient Stability

#### 3.1.1. Definition

Transient stability is one of the major studying fields, it is defined as the capability of an energy system to regain a stable state in the presence of sudden and severe disturbances [4]. Where the main purpose of the transient stability study is to analyze the system response and to determine whether or not machines will return to synchronous frequency after being subjected to a sudden disturbance [7].

#### 3.1.2. Swing Equation

To ensure that a system is transiently stable in the presence of severe disturbances, the power system must provide an equilibrium between all torques applied to the rotor of the synchronous generator at any moment of the day, as its behavior described by the swing equation [17]. It is a non-linear differential equation of a 2nd-order. In many instances, the transient stability is determined during primary swing of the machine power angles after the disturbance, which usually lasts around one second [13]. The mechanical power output and the internal voltage of the generating units are constant. The swing equation is given by:

$$\frac{2H}{\omega_{syn}} \omega_{pu}(T) \left( \frac{d^2 \delta(T)}{dT^2} \right) = Q_{mpu}(T) - Q_{epu}(T) - \frac{D}{\omega_{syn}} \left( \frac{d\delta(T)}{dT} \right) \quad (1)$$

where  $T$  is time in seconds.

### 3.2. Description of the Proposed Stabilizers

The proposed stabilizers are intended to minimize the power system oscillations, overshoot, and settling time following a severe incident, for enhancing the power system stability.

### 3.2.1. Power System Stabilizer (PSS)

The main goal of a PSS is to provide appropriate torque on the rotor of the concerned machine to improve the performance of the electrical power system. PSS's input signal is typically the synchronous speed deviation  $\Delta\omega$  [2,8]. Equation (2) presents the PSS transfer function.

$$U(s) = k_{pss} \left( \frac{sT_w}{1+sT_w} \right) \left( \frac{1+sT_1}{1+sT_2} \right) \left( \frac{1+sT_3}{1+sT_4} \right) \Delta\omega(s) \quad (2)$$

### 3.2.2. PID Based PSS

PID-PSS ensures a robust control performance. It operates a function that provides an appropriate torque on the generator rotor by compensating the phase lag between the machine's electrical torque and the exciter input [7–20]. The transfer function of the PID\_PSS is given by Equation (3):

$$U(s) = \left[ K_{pss} \left( \frac{sT_w}{1+sT_w} \right) \left( \frac{1+sT_1}{1+sT_2} \right) \left( \frac{1+sT_3}{1+sT_4} \right) \right] \left[ K_P + \frac{K_i}{s} + K_d s \right] \Delta\omega(s) \quad (3)$$

### 3.2.3. FOPID Based PSS

The use of a (FOPID) in industries is attributed to the large benefits that can be used to solve many problems in power system [6]. The FOPID controller has the following parameters: the integral  $K_i$ , differential  $K_d$ , proportional  $K_p$  constants, fractional-order derivative  $\mu$ , and integral elements  $\lambda$  [21]. The following equation demonstrates the (FOPID) controller transfer function (TF):

$$G_c(s) = K_P + K_i s^{-\lambda} + K_d s^\mu \quad (4)$$

A robust and flexible hybrid stabilizer is a combination of a conventional PSS and (FOPID) controller that is considered to provide the optimum (PSS\_FOPID) [11]. The TF of the proposed controller to adjust the excitation voltage is defined by Equation (5):

$$U(s) = \left[ k_{pss} \left( \frac{sT_w}{1+sT_w} \right) \left( \frac{1+sT_1}{1+sT_2} \right) \left( \frac{1+sT_3}{1+sT_4} \right) \right] \left[ k_p + k_i s^{-\lambda} + k_d s^\mu \right] \Delta\omega(s) \quad (5)$$

### 3.2.4. Objective Function

The WCMFO method was employed for reducing the values obtained by the objective functions of the system to achieve the optimum stabilizer settings. We used performance indices (PI) in order to reduce the overshoots and the power system oscillations [11]:

Integral Absolute Error (IAE)

$$U(s) = \left[ k_{pss} \left( \frac{sT_w}{1+sT_w} \right) \left( \frac{1+sT_1}{1+sT_2} \right) \left( \frac{1+sT_3}{1+sT_4} \right) \right] \left[ k_p + k_i s^{-\lambda} + k_d s^\mu \right] \Delta\omega(s) \quad (6)$$

Integral Squared Error (ISE)

$$U(s) = \left[ k_{pss} \left( \frac{sT_w}{1+sT_w} \right) \left( \frac{1+sT_1}{1+sT_2} \right) \left( \frac{1+sT_3}{1+sT_4} \right) \right] \left[ k_p + k_i s^{-\lambda} + k_d s^\mu \right] \Delta\omega(s) \quad (7)$$

Integral of the Time-weighted Absolute Error (ITAE)

$$U(s) = \left[ k_{pss} \left( \frac{sT_w}{1+sT_w} \right) \left( \frac{1+sT_1}{1+sT_2} \right) \left( \frac{1+sT_3}{1+sT_4} \right) \right] \left[ k_p + k_i s^{-\lambda} + k_d s^\mu \right] \Delta\omega(s) \quad (8)$$

where *tsim* is the simulation time.

### 3.2.5. Fault Type Selection

The sudden change in mechanical torque (thermodynamic incident) has been considered one of the most severe incidents, such as short circuit, overload, loss of generator unit, or loss of a large load. This incident can lead to a progressive increase in the deviation between the rotor angles of the generators or a gradual decrease in the voltages of the network nodes, subsequently causing an avalanche of breakdowns and a disconnection of a large part of the power grid, and sometimes even to a total collapse (Blackout), as was the case in Algeria on 3 February 2003, where 38 states suddenly went into darkness for 19 h.

## 4. Hybrid WCMFO Algorithm

Recently, various hybrid techniques inspired by nature were introduced by researchers for enhancing the efficiency of the exploitation and exploration search space of existing algorithms. In 2012 H. Eskandar et al. introduced the Water Cycle Algorithm (WCA), which mimics the phenomenon of the water cycle in nature [18], it has a high capacity to explore the solution areas. On the other hand, the (WCA) is suffering from the absence of an adequate operator to ensure the exploitation phase. The Moth-Flame Optimization (MFO) was inspired by the moth's spiral movement by Mirjaalili which has been proposed in 2015 [19]. Despite the very well performance of MFO's spiral movement capacity in the exploitation phase, but it is still unable to explore the solution space efficiently because they are often trapped in local optima.

Thus, the combination of the advantages of the (WCA) and the (MFO) leads to a modern hybrid (WCMFO) algorithm proposed by Khalilpourazari et al. in 2019 [14], which can perform considerably in solving complex optimization problems. For the (WCMFO) algorithm, (WCA) has been considered as the basic algorithm. The MFO's spiral movement is used to update the streams and river's position, in order to enhance the exploitation area. In addition, streams are enabled to maintain their position using a random walk (Levy flight) to enhance randomization in the WCA. The global process of the suggested (WCMFO) algorithm is summarized in a flowchart shown in Figure 2.

### WCMFO's Mathematical Model

The mathematical model of the suggested hybrid WCMFO is presented in the following subsection [14].

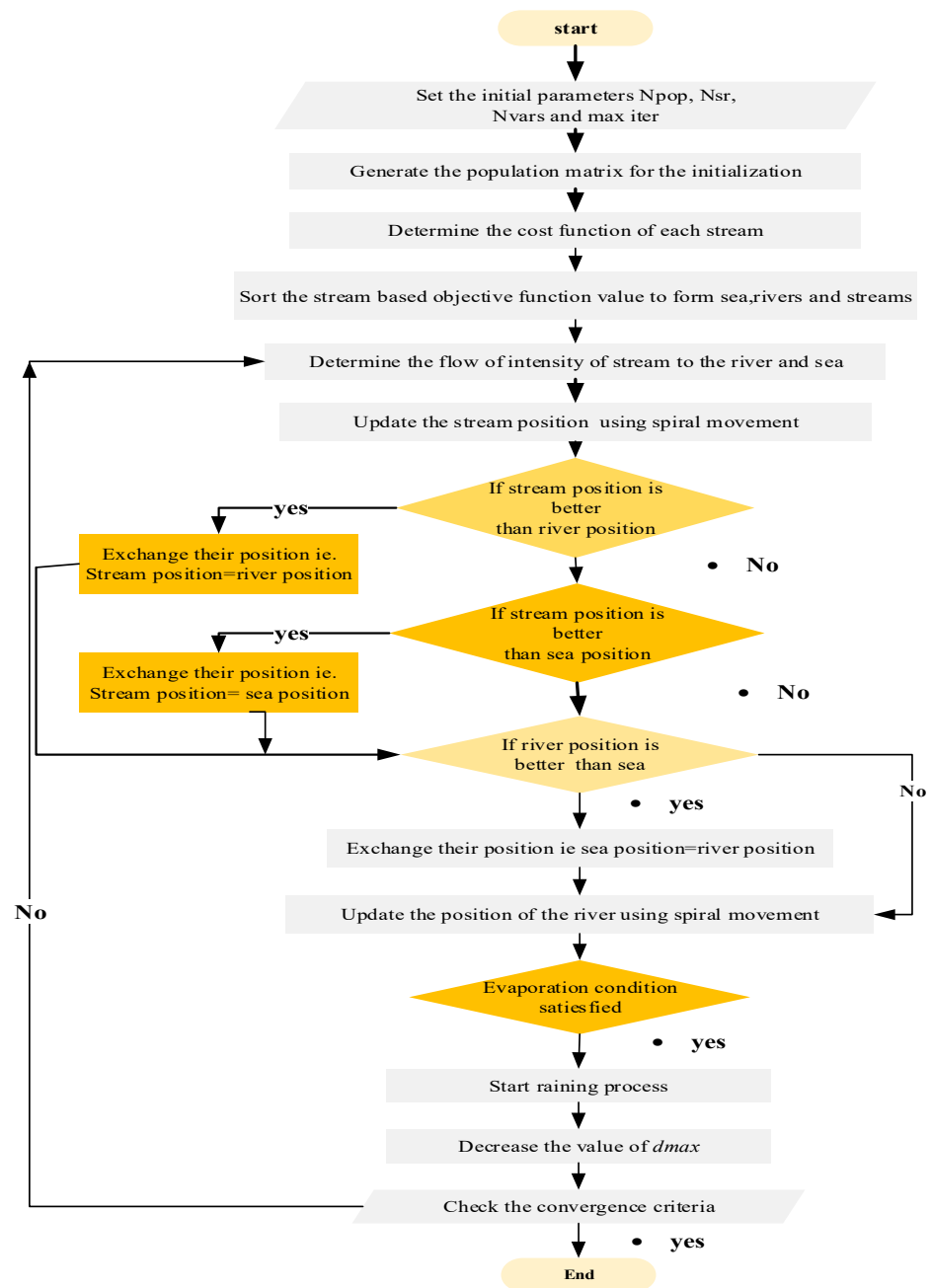
#### Step 1: Initialization

- Set the initial parameters  $N_{sr}$ ,  $N_{pop}$ , max-iter.
- Generate a random initial population using Equation (9) to generate the raindrops values for the population matrix given in Equation (10).

$N_{sr}$  = Number of River + 1, where 1 is the sea.

$$\text{Population of Raindrops} = LB + (UB - LB) \times \text{rand}(1, N_{var}) \quad (9)$$

$$\text{Population of raindrops : } \begin{bmatrix} \text{Raindrop1} \\ \text{Raindrop2} \\ \dots\dots\dots \\ \text{Raindrop } N_{pop} \end{bmatrix} = \begin{bmatrix} x_1^1 x_2^1 x_3^1 \dots\dots x_{N_{var}}^1 \\ x_1^2 x_2^2 x_3^2 \dots\dots x_{N_{var}}^2 \\ \dots\dots\dots \\ x_1^{N_{pop}} x_2^{N_{pop}} x_3^{N_{pop}} \dots\dots x_{N_{var}}^{N_{pop}} \end{bmatrix} \quad (10)$$



**Figure 2.** Hybrid WCMFO algorithm flowchart [15].

Step 2: Sea, rivers and stream creation.

- The cost functions for each flow in the initial population matrix is calculated using:

$$c_i = \text{cost}_i = f(X_1^i, X_2^i, \dots, X_{N_{sr}}^i) \quad (11)$$

where;  $i = 1, 2, 3, \dots, N_{pop}$ .

- The minimum value in raindrops is considered as a sea.

$$N_{Raindrops} = N_{pop} - N_{sr} \quad (12)$$

Step 3: Determination of the Intensity of rivers and sea by:

$$NS_n = \text{round} \left\{ \left| \frac{\cos t_n - \cos t_{Nsr}}{\sum_{n=1}^{Nsr} C_n} \right| \times N_{streams} \right\}, n = 1, 2, \dots, N_{sr} \quad (13)$$

$NS_n$ : Streams numbers which flow in rivers or sea.

Step 4: Exploitation phase

The MFO's exploitation phase is incorporated into the WCA in order to improve exploitation performance by following spiral Equation:

$$X_{stream}^{i+1} = \left| X_{stream}^{i+1} - sea \right| \times \cos(2\pi t) + sea \quad (14)$$

where: ' $t$ ' is a uniform random number  $[-1,1]$  in order to define the next closed position of stream to the sea.

Step 5: Evaporation condition and rain process

- Assess the evaporation state with:

$$\left| X_{Sea}^i - X_{River}^i \right| < d_{\max} \quad i = 1, 2, \dots, N_{sr} - 1 \quad (15)$$

$d_{\max}$ : is a value that adaptively decreases by:

$$d_{\max}^{i+1} = d_{\max}^i - \frac{d_{\max}^i}{\max \text{ iteration}} \quad (16)$$

- Rain process:

In the raining process, the new raindrops form streams in the different locations, for specifying the new locations of the newly formed streams, the following equation is used:

$$X_{stream}^{new} = LB + rand \times (UB - LB) \quad (17)$$

Equation (18) aims to encourage the generation of streams which directly flow to the sea in order to improve the exploration near sea (the optimum solution) in the feasible region for constrained problems.

$$X_{stream}^{new} = X_{sea} + \sqrt{\mu} \times randn(1, N_{var}) \quad (18)$$

$\mu$  is a factor that indicates the range of the search area near the sea. From a mathematical point of view, the term  $\sqrt{\mu}$  in Equation (18) represents the standard deviation and, accordingly,  $\mu$  defines the concept of variance. A suitable value for  $\mu$  is set to 0.1.

Step 6: Convergence criteria

For the suggested WCMFO algorithm the convergence is given by:

$$a = 1 + \text{current} - \text{iter} \cdot \left( \frac{-1}{\max.\text{iter.}} \right) \quad (19)$$

## 5. Results and Discussion

The current section focuses on assessing the power system stability by incorporating one of these distinct stabilizers, respectively (PSS, PID-PSS, and FOPID-PSS), into the well-known power test system (SMIB), in the case of a thermodynamic incident.

### 5.1. Analysis Strategy

The analysis of this study has been divided into two parts. The first part aims to demonstrate the effectiveness of the suggested (WCMFO) by using the (PI) including

IAE, ISE, and ITAE. The simulation results are compared with three other meta-heuristic optimization techniques as (WCA, MFO, AEO). The second part focuses on enhancing the efficiency of the power system stability. Three stabilizers (PSS, PSS-PID, PSS-FOPID) were considered in order to prove the efficiency of the WCMFO method under different operating conditions. The analysis of angular speed behavior has been used to assess the stability of the power grid. The stability benchmarks used to validate this study are:

- The overshoots
- Power system oscillations
- Settling time

## 5.2. Simulation Results

The efficiency of the suggested method has been assessed in the MATLAB/Simulink environment. Before performing the optimization process, certain settings should be defined in the proposed (WCMFO) to achieve better performance. The Table 1 presents the description of each system.

**Table 1.** Algorithm parameters.

| Parameters                              | PSS | PSS-PID | PSS-FOPID |
|-----------------------------------------|-----|---------|-----------|
| Number of Iteration                     | 50  | 50      | 50        |
| Number of Population (Nvars $\times$ 3) | 15  | 24      | 30        |
| Decision Variables (Nvars)              | 5   | 8       | 10        |

Table 2 illustrates the standard limits of the optimized settings. The time constant ( $T_w$ ) is assumed to be 10 s.

**Table 2.** A typical range of the stabilizer parameters.

| Stabilizers Parameters |     |      |      |      |      |       |       |       |       |           |
|------------------------|-----|------|------|------|------|-------|-------|-------|-------|-----------|
|                        | Kps | T1   | T2   | T3   | T4   | Kp    | Ki    | Kd    | $\mu$ | $\lambda$ |
| Min                    | 0.1 | 0.01 | 0.01 | 0.01 | 0.01 | 0.001 | 0.001 | 0.001 | 0.1   | 0.1       |
| Max                    | 5   | 2    | 2    | 2    | 2    | 1.2   | 1.2   | 1.2   | 0.9   | 0.9       |

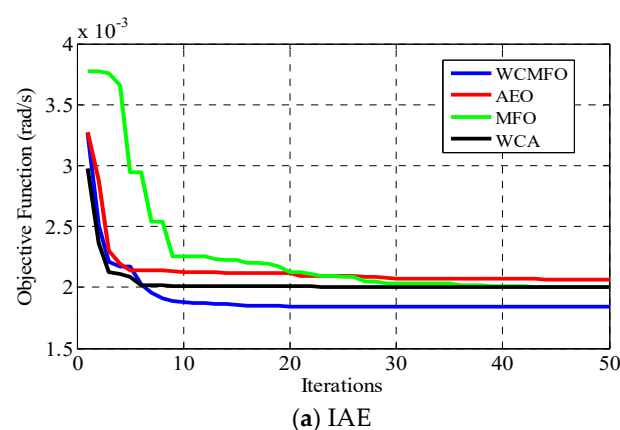
The final optimized settings achieved using WCMFO for each stabilizer are shown in Table 3. It should be noticed that the suggested algorithms are executed many times to select the optimal stabilizer settings.

**Table 3.** Optimal stabilizer parameters based on the proposed WCMFO.

| Stabilizers | Stabilizer Parameters |        |        |        |        |        |        |                    |                    |       |           |
|-------------|-----------------------|--------|--------|--------|--------|--------|--------|--------------------|--------------------|-------|-----------|
|             | PI                    | Kps    | T1     | T2     | T3     | T4     | Ki     | Kp                 | Kd                 | $\mu$ | $\lambda$ |
| PSS_FOPID   | IAE                   | 4.9987 | 0.0345 | 0.1957 | 2      | 0.618  | 1.2    | 1.2                | 1.2                | 0.1   | 0.8019    |
|             | ISE                   | 5      | 2      | 0.6882 | 1.9891 | 0.6883 | 1.2    | 1.1989             | 1.2                | 0.1   | 0.7926    |
|             | ITAE                  | 4.9896 | 0.01   | 0.7025 | 2      | 0.1554 | 1.1954 | 1.2                | 1.1987             | 0.1   | 0.8183    |
| PSS_PID     | IAE                   | 5      | 2      | 0.5901 | 2      | 0.1478 | 1.2    | $1 \times 10^{-3}$ | 0.001              |       |           |
|             | ISE                   | 5      | 2      | 0.6468 | 1.1145 | 0.6468 | 1.2    | 1.2                | $1 \times 10^{-3}$ |       |           |
|             | ITAE                  | 5      | 1.9332 | 0.6118 | 2      | 0.1447 | 1.2    | $1 \times 10^{-3}$ | $1 \times 10^{-3}$ |       |           |
| PSS         | IAE                   | 3.3204 | 1.0799 | 0.9917 | 1.5239 | 1.9805 |        |                    |                    |       |           |
|             | ISE                   | 5      | 0.2924 | 0.8689 | 1.997  | 0.822  |        |                    |                    |       |           |
|             | ITAE                  | 2.9575 | 1.9998 | 1.1218 | 0.9513 | 1.999  |        |                    |                    |       |           |

➤ *First Part*

The purpose of this section is to evaluate the efficiency of the proposed (WCMFO) using the (PI) including IAE, ISE and ITAE. The simulation outcomes are compared with three other meta-heuristic optimization techniques such as (WCA, MFO, AEO). The comparison of the convergence profiles of the proposed methods for each objective function is shown in Figures 3–5. The obtained results proved the robustness and speed of the (WCMFO) algorithm in resolving the transient stability problem. Furthermore, all figures obviously confirm that the suggested (WCMFO) algorithm outperforms the (WCA, MFO, AEO) in terms of solution quality and the minimum settling time for all performance indices analyzed as (IAE, ISE, ITAE).

**Figure 3.** Cont.

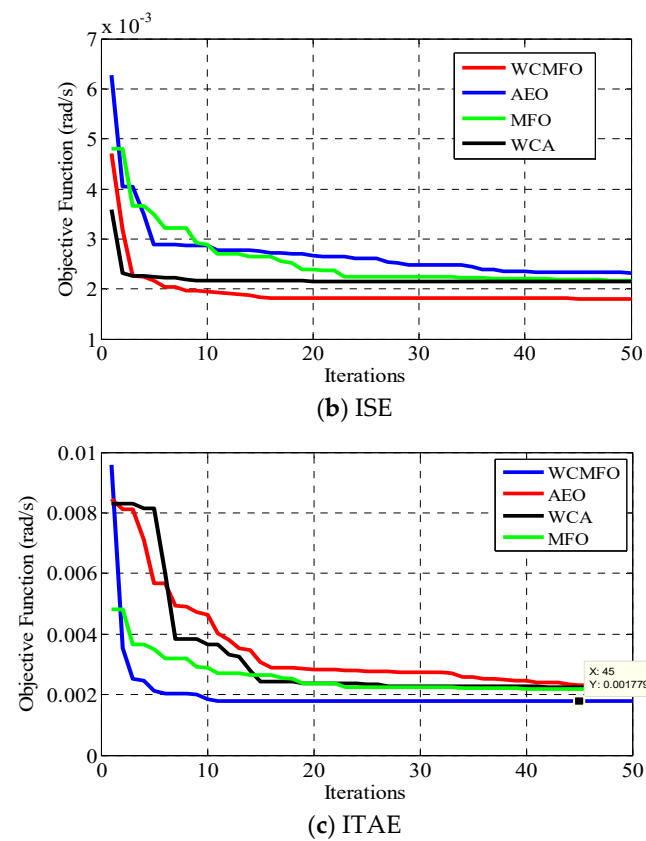


Figure 3. Convergence profile (a) IAE, (b) ISE, (c) ITAE using FOPID-PSS controller.

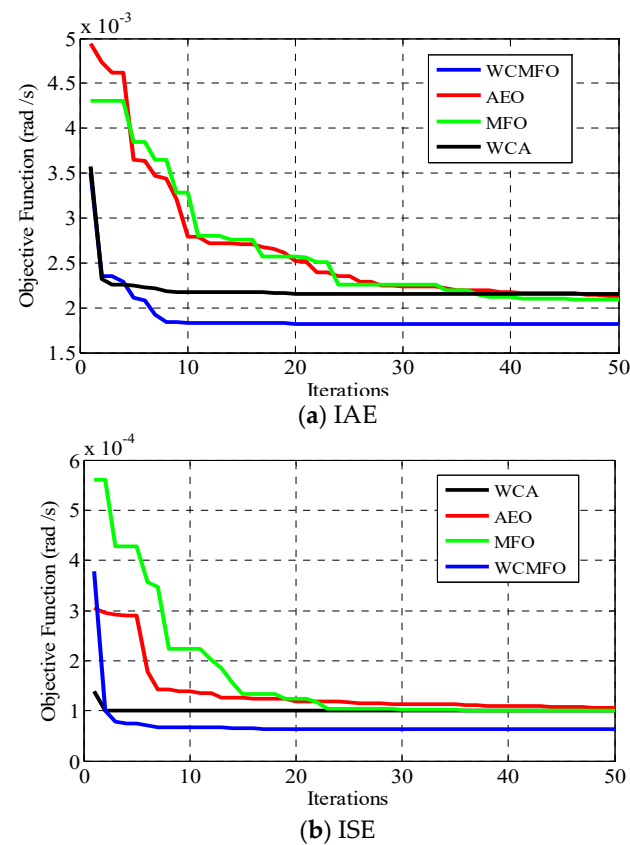
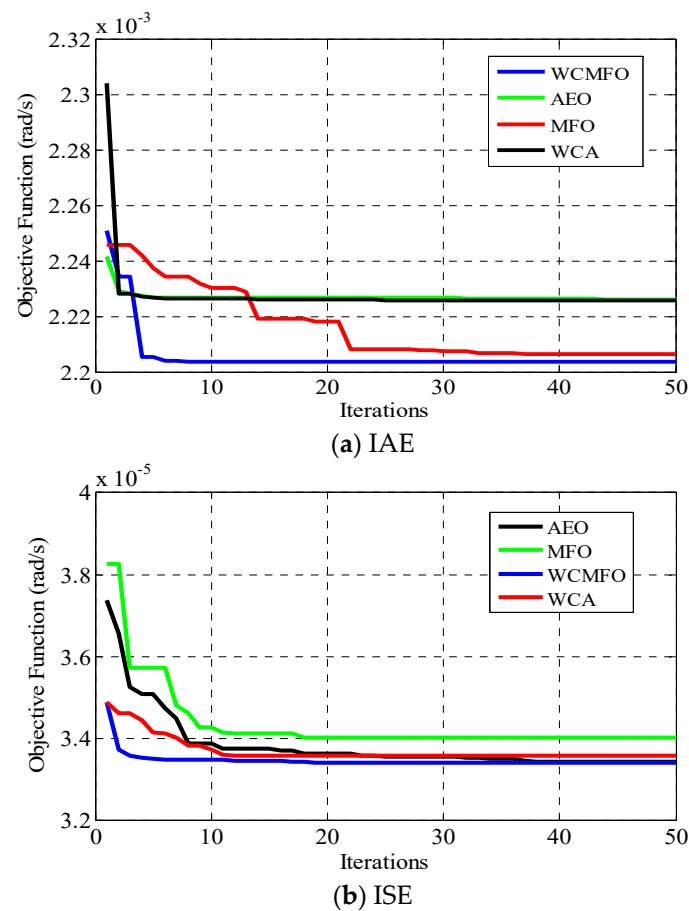


Figure 4. Convergence profile (a) IAE, (b) ISE using PID-PSS controller.



**Figure 5.** Convergence profile (a) IAE, (b) ISE using PSS controller.

Table 4, shows that the performance indices result achieved by the stabilizer (PSS-FOPID) based (WCMFO) is better than PSS and PSS-PID stabilizers under all operating conditions. (IAE, ISE, ITAE) have the minimum value with PSS-FOPID ( $0.00184$ ,  $2.84 \times 10^{-6}$ ,  $0.001763$  rad/s) due to their capacity and speed compared to the other stabilizers.

**Table 4.** Optimal objective function values.

|       |      | Objective Function Values (rad/s)       |                                         |                                         |
|-------|------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
|       | PI   | PSS_FOPID                               | PID_PSS                                 | PSS                                     |
| WCMFO | IAE  | <b>0.00184</b>                          | <b>0.001902</b>                         | <b>0.002203</b>                         |
|       | ISE  | <b><math>2.84 \times 10^{-6}</math></b> | <b><math>3.34 \times 10^{-5}</math></b> | <b><math>6.31 \times 10^{-5}</math></b> |
|       | ITAE | <b>0.001763</b>                         | <b>0.001828</b>                         | <b>0.002065</b>                         |
| WCA   | IAE  | 0.002004                                | 0.002154                                | 0.002329                                |
|       | ISE  | $3.28 \times 10^{-5}$                   | $3.36 \times 10^{-5}$                   | $1.00 \times 10^{-4}$                   |
|       | ITAE | 0.002154                                | 0.002269                                | 0.002154                                |
| MFO   | IAE  | 0.002033                                | 0.002094                                | 0.002208                                |
|       | ISE  | $3.29 \times 10^{-5}$                   | $4.41 \times 10^{-5}$                   | $1.04 \times 10^{-4}$                   |
|       | ITAE | 0.002109                                | 0.002176                                | 0.002103                                |
| AEO   | IAE  | 0.002105                                | 0.002144                                | 0.002327                                |
|       | ISE  | $3.51 \times 10^{-5}$                   | $3.37 \times 10^{-5}$                   | $1.05 \times 10^{-4}$                   |
|       | ITAE | 0.002313                                | 0.002341                                | 0.002204                                |

### ➤ Second Part

Three cases were carried out under the same conditions in which: the system is stable from 0 s to 0.5 s, after that a thermodynamic fault has been applied.

#### 5.2.1. Case 1: System Analysis without Stabilizer

A sudden disturbance on the variation of mechanical torque is introduced, then the system response is analyzed according to the angular speed variation evolution.

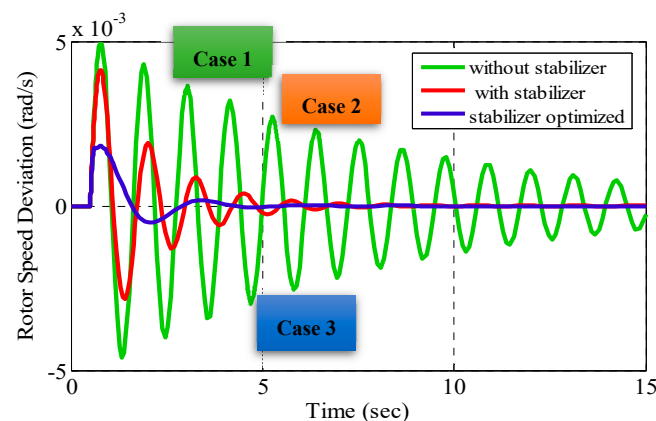
#### 5.2.2. Case 2: System Analysis with Stabilizer Integration

FOPID-PSS stabilizer is introduced into the SMIB test system as shown in Figure 1

#### 5.2.3. Case 3: Setting the Stabilizer Parameters

The optimal stabilization parameters of the (FOPID-PSS) are providing using the hybrid WCMFO algorithm.

In the last case, a significant improvement is noticed in the power system by minimizing the angular speed deviation. A considerable reduction of the overshoot (**from 0.00412 to 0.00181 (rad/s)** with an improvement of 44%), and damping of the oscillations, as shown in Figure 6.



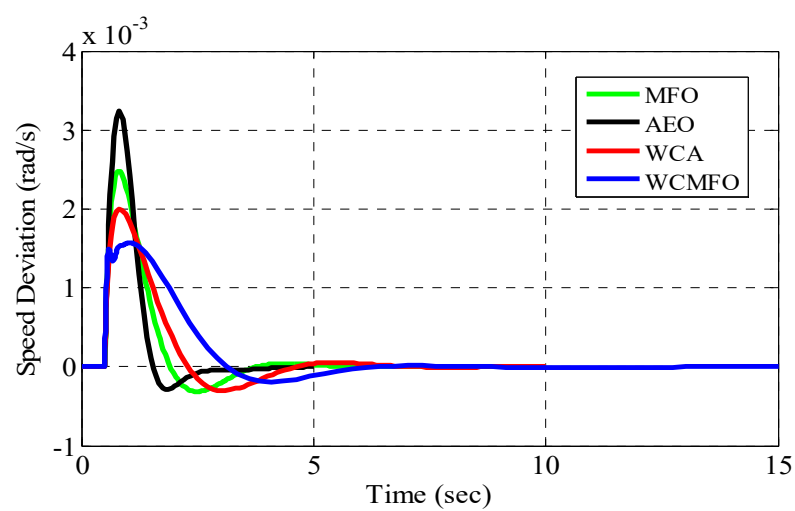
**Figure 6.** Angular speed deviation (with and without stabilizer).

It should be noted that during the simulation process, a difference was observed between the control devices in terms of response time and the number of runs to reach the appropriate solution. Regarding (FOPID-PSS) and (PID-PSS) the results obtained were very satisfactory in the first iterations and in a short time. On the other hand, to achieve adequate results with (PSS), the process needed to be run more than 30 times.

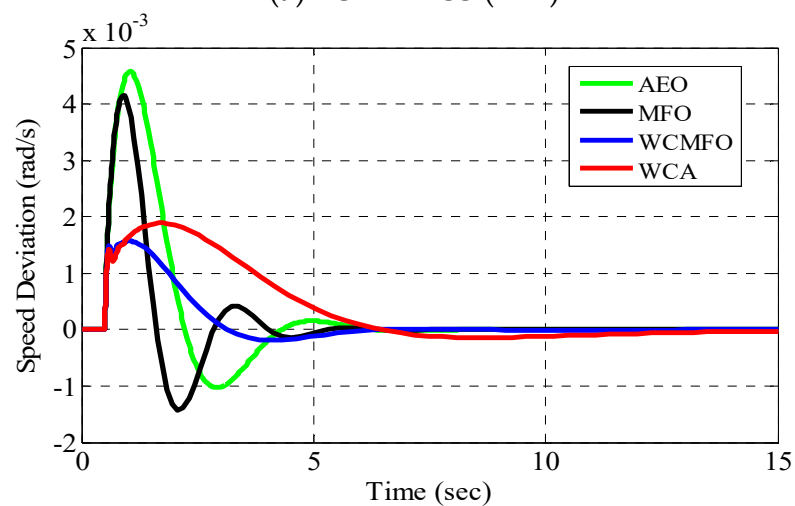
The previous results show that the suggested (WCMFO) has demonstrated superior performance in terms of damping the oscillations, settling time, and overshoots compared to the other algorithms as shown in Figure 7. In other meaning, the control system (PSS-FOPID) shows a considerable improvement in the power system stability, the oscillations are quickly damped, and the system reaches the steady-state faster than the other proposed stabilizers.

To provide a clear comparison and to assess the performance of each suggested technique. The angular speed deviation results for each stabilizer are used and shown in the histogram, Figure 8.

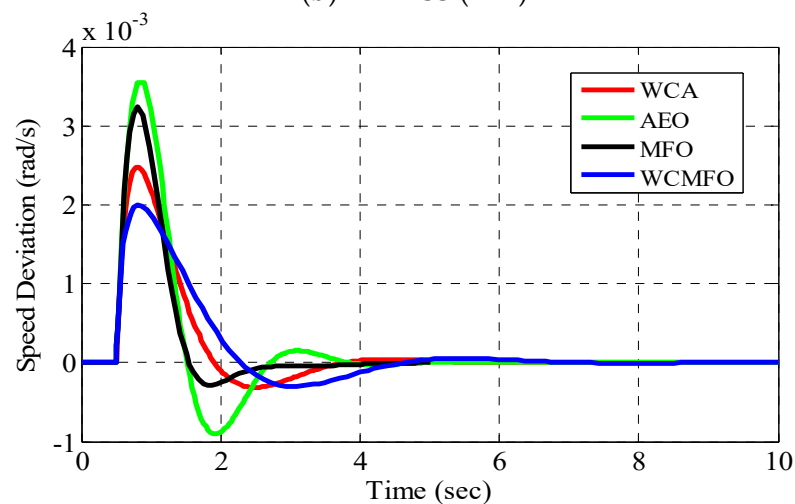
According to Figure 8, the results obtained from the histogram for each objective function obviously proved the effectiveness of the (WCMFO) in resolving the transient stability problem under this severe disturbance (thermodynamic fault).



(a) FOPID-PSS (IAE)

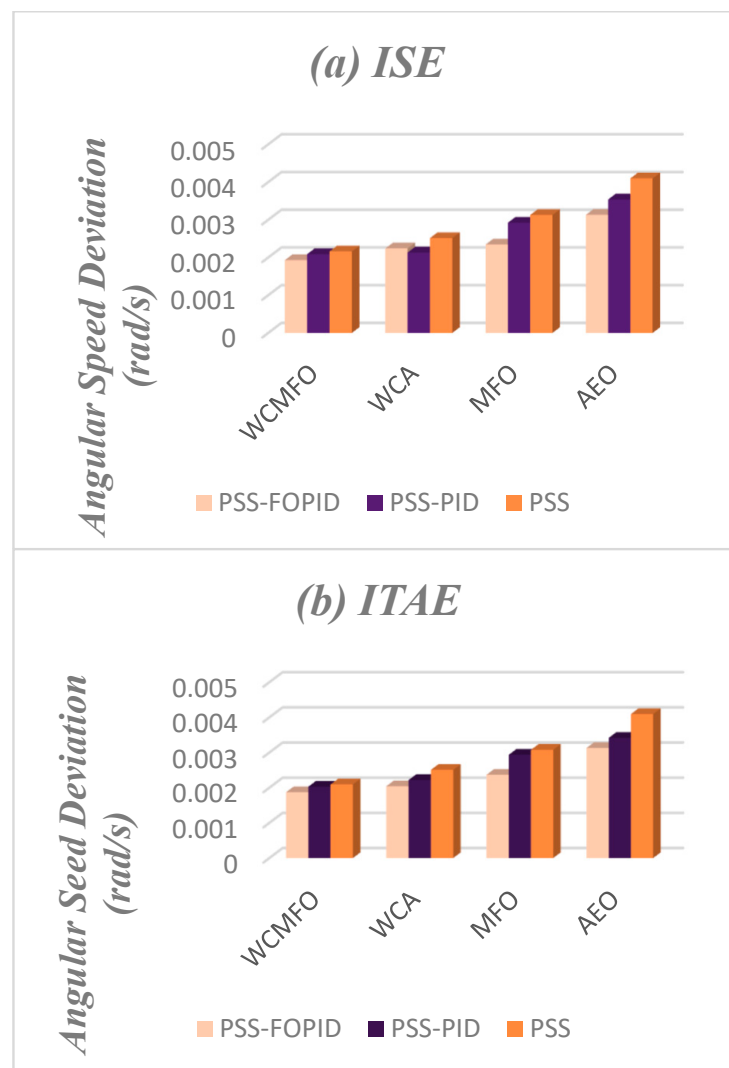


(b) PID-PSS (IAE)



(c) PSS (IAE).

**Figure 7.** Angular speed deviation (a–c).



**Figure 8.** Angular speed deviation values (a,b).

## 6. Conclusions

Transient stability is a serious and crucial problem in power system operations. Therefore, this paper presents a new hybrid approach called (WCMFO). The presented method has been applied and adapted for the first time to optimize the settings of three different control systems (PSS, PSS-PID, and PSS-FOPID), with the aim of improving the stability performance of the electrical grid considering a thermodynamic disturbance. The achieved outcomes revealed that the WCMFO outperforms the AEO, MFO, and WCA approaches, in terms of convergence ability, speed response, and minimum settling time for all performance indices analyzed (IAE, ISE, and ITAE).

The simulation results demonstrate that the control devices based on WCMFO provide a great control performance compared to the other techniques. It is also worth mentioning that the proposed WCMFO-based PSS-FOPID is a suitable controller for enhancing the power system, which proved the advantage of the WCMFO in selecting the optimal stabilizer settings under severe operating terms. The proposed algorithm has also confirmed its robustness and speed in solving the transient stability problem.

This algorithm was tested and validated on different test systems; the superior performance of this hybrid method is due to the fact that it combines of both based algorithms by introducing the MFO's spiral movement into the WCA to enhance its exploitation ability.

The presented results ensure the opportunity for our future research in this area: Incorporating the robust control system (PSS-FOPID) in a multi-machine power system,

using the WCMFO algorithm based on a multi-objective function to obtain the best stabilizer parameters. Imposing sudden disturbances (short-circuit, overload, and line breaks), in order to evaluate the ability and efficiency of the proposed control system (PSS-FOPID based WCMFO) to maintain the power system stability under various operating conditions.

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## Nomenclature

|                           |                                                                                                        |
|---------------------------|--------------------------------------------------------------------------------------------------------|
| $C_i$                     | Cost function                                                                                          |
| $D$                       | Represents a damping torque anytime the generator deviates from its synchronous speed.                 |
| $e(t)$                    | Error                                                                                                  |
| $H$                       | Normalized inertia constant                                                                            |
| $K_i$                     | The integral constant                                                                                  |
| $K_d$                     | The differential constant                                                                              |
| $K_p$                     | The proportional constant                                                                              |
| $K_{pss}$                 | Gain                                                                                                   |
| $LB$                      | Lower Bound                                                                                            |
| $max\_iter$               | Maximum number of iterations                                                                           |
| $N_{pop}$                 | Population size                                                                                        |
| $N_{sr}$                  | Number of rivers + the sea                                                                             |
| $N_{sn}$                  | Streams numbers which flow in rivers or sea                                                            |
| $N_{var}$                 | Number of decision variables                                                                           |
| $PI$                      | Performance Indices                                                                                    |
| $Q_{epu}$                 | Generated electric power added to electric losses in (p.u)                                             |
| $Q_{mpu}$                 | Difference between the mechanical power provided by the prime mover and the mechanical losses in (p.u) |
| $rand$                    | Random number                                                                                          |
| $t_{sim}$                 | The simulation time                                                                                    |
| $T$                       | Time in seconds                                                                                        |
| $T_w$                     | High-pass filter of time constant                                                                      |
| $T_1, T_2, T_3$ and $T_4$ | Lead-lag structured phase compensation blocks                                                          |
| $TF$                      | Transfer function                                                                                      |
| $UB$                      | Upper Bound                                                                                            |
| <b>Greek symbols</b>      |                                                                                                        |
| $\delta$                  | Rotor angle referred to the synchronous reference axis in (rad)                                        |
| $\mu$                     | Fractional-order derivative element                                                                    |
| $\lambda$                 | Fractional-order integral element                                                                      |
| $\Delta\omega$            | The synchronous speed deviation                                                                        |
| $\omega_{syn}$            | Synchronous radian frequency                                                                           |
| $\omega_{pu}$             | Frequency in (p.u)                                                                                     |

## Appendix A

| Parameters                             | Value (p.u)    |
|----------------------------------------|----------------|
| Line impedance $R_e + jX_e$            | $0.02 + j0.65$ |
| D-axis reactance, $X_d$                | 1.81           |
| Q-axis reactance, $X_q$                | 1.76           |
| Armature resistance, $R_a$             | 0.003          |
| Infinite bus Voltage, $V_{in}$         | 1              |
| Inertia constant, $H$                  | 3.5            |
| Rated speed, $\omega_0$                | 377            |
| Field circuit time constant, $T'_{d0}$ | 8 (s)          |
| Damping factor, $K_D$                  | 0              |
| Regulation gain, $K_A$                 | 200            |
| Exciter time constant, $T_E$           | 1              |
| Exciter gain, $K_E$                    | −0.05          |
| Time constant, $T_\omega$              | 10             |
| Nominal loads, $P_t$ $Q_t$             | 0.5, 0.3       |
| Frequency                              | 60 HZ          |

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