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Robust PID-PSS Design for Stability Improvment of Grid-Tied HydroTurbine Generator

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***Abstract*— Dynamic stability is considered a vital issue in modern power systems. In this work, a robust design is proposed for the stability improvement of grid-connected hydro-turbine generators using the adaptive concept-based Electro-Search optimizer (ESO). In this regard, we provide a dynamic stability analysis of a hydro-turbine generator located at the Aswan High Dam, where proportional integral-derivative power system stabilizer (PID-PSS) is examined for a single machine connected to the Egyptian power system (EPS). The PID controller is developed in the synchronized EPS to significantly mitigate low-frequency oscillations due to various expected faults and undesirable operating conditions. Comprehensive simulation analysis is performed using Matlab/Simulink considering the synchronous machine rotor speed, mechanical and electrical output powers, field and terminal voltages. The operative performance of the introduced adaptive PID-PSS based ESO is assessed against the conventional system (i.e. without PSS) and system with standard PID-PSS under normal operating conditions where the effect of a 3-φ short-circuit fault is subjected at the grid bus. The findings prove that the proposed adaptive strategy can effectively maintain the dynamic stability of the main grid against fluctuations.**

Keywords*— power system stabilizer, PID-PSS, low-frequency oscillations, hydro generators, power system stability, electro-search algorithm, adaptive control.

I. INTRODUCTION

Power system stability could be practically preserved by conserving both frequency and voltage in the system at the intended level in the event of a loss of generation, transmission line interruption throughout a fault, or a rise in electrical energy consumption. Specifically, low-frequency fluctuations are formed in the power system as a result of ill lines and a shortage of reactive power support in large-scale power systems. If enough damping is not supplied in the power grid, these oscillations can persist and develop, affecting the stability of the power system [1], [2]. In this regard, a power system stabilizer (PSS) is a type of power system stabilizer that is commonly utilized in power systems to enhance transient and dynamic stability [3], [4]. Inappropriate power system oscillations can be exacerbated by power system disruptions with renewable energy sources [3]–[8]. Accordingly, effective solutions are required to maintaining these characteristics in order to ensure the stability of the system [9].

In practical situations, PSSs have long been acknowledged as a viable option for dampening low-frequency oscillations caused by power system disruptions or variations, such as load fluctuations, generation changes, and various power system transitions [10]. The transmission network of general power systems is a very complicated, non-linear network with low allowable frequency oscillations ranging from 0 to 2 Hz [11]. The PSS's main idea is to improve the power system's angular stability, which is accomplished by adding a dampening signal to the oscillation of the generator's synchronous machine rotor excitation. To address this issue, conventional PSSs are employed. Nevertheless, the power system's complexity is increasing day by day as a result of the inclusion of solar and wind power and massively linked interconnections. As a result, design approaches must yield adequate PSS performance throughout a wide variety of operating circumstances. As a result, robust control approaches provide more options for controller design than the traditional approaches [12].

In terms of installed worldwide capacity, hydropower, solar technology, and wind turbines are the three most promising and utilized renewable energy sources (RES). To meet the ongoing rise in power demand, the Egyptian electricity sector is concentrating on expanding the RES penetrations, with a target to achieve 20% of the total energy required for electricity generation by 2022 and 42% by 2035 [13], [14]. Because of the intermittent and unpredictable nature of integrating RESs into electric grids, this approach will present numerous important problems, including power quality concerns, a lack of inertia, and frequency variations [15]–[19].

To ensure the stability of the power system, an adaptive proportional-integral-derivative (PID-PSS) controller design based ESO is introduced in this paper for a hydro-turbine generator (High Dam at Aswan, Egypt) connected to the EPS grid. Specifically, optimum gain settings of PID-PSS are optimally computed to mitigate various expected faults and undesirable operating conditions. An example for a single machine system (SM) is given to illustrate the effectiveness of the proposed controller, and simulation results are presented compared with the conventional system (no PSS) and system with classic PID-PSS. The proposed system is examined under two scenarios: (normal operation condition, and the effect of a 3- φ short circuit fault at the grid bus). The results show that the proposed adaptive PID-PSS is an effective solution to maintain the dynamic stability of the main grid.

The remainder of the paper is organized as follows: In Section II, we describe the EPS dynamic model and configuration. Section III introduces the general overview of oscillations that may appear in the power system. The Electro-search optimizer is described in Section IV. The proposed PID-PSS controller is presented in Section V. The dynamic response simulation and discussions via Matlab/Simulink are given in Section VI. Finally, Section VII concludes the work.

II. POWER SYSTEM MODEL CONFIGURATION

Egypt owns two hydropower stations with an overall installed capacity of 2.65 GW [20]. In this study, a High Dam in Aswan was taken into consideration. It consists of 24 turbines for electricity and irrigation each one equal 12 gates (turbines). Here, the proposed system consists of a single hydro-turbine generator with a power capacity equal to 200 MW is connected to the EPS grid via a step-up transformer connected as delta-star($\Delta \rightarrow Y$), step-down transformer for the distribution system, Ac bus with 3-fixed loads (3 MW at distribution side, and 15 MW at the grid side. Fig. 1 shows the one-line system layout of the SM connected to the studied EPS grid.

The behavior of power system dynamics is given by the following set of nonlinear equations, in addition, it can be demonstrated in state-space by the Heffron-Phillips model as described in [12], [21]:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E_q}' \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_o & 0 & 0 \\ -{}^{k_1}/_{M} & 0 & -{}^{k_2}/_{M} & 0 \\ -{}^{k_4}/_{T'_{do}} & 0 & -{}^{1}/_{k_3 T'_{do}} & {}^{1}/_{T'_{do}} \\ -{}^{k_E k_5}/_{T_E} & 0 & -{}^{k_E k_6}/_{T_E} & -{}^{1}/_{T_E} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ {}^{k_E}/_{T_E} \end{bmatrix} \Delta V_{ref} \tag{1}$$

which δ represents the angle of rotor, further, the ω, ω_o, M, and E'_q represent the angular and synchronous speed, inertia constant, and field flux emf in the transient state, respectively. Moreover, T'_{do} is considered the d-axis time constant of field circuit, E_{fd} represent the field voltage, as well as T_E and k_E are the time and gain constant of the voltage regulator, finally, V_{ref} represent the reference voltage. The k-constants of the model, i.e. from $k_1{:}\,k_6$ except k_3, are load-dependent.

III. OSCILLATIONS IN POWER SYSTEM

Electromechanical harmonic oscillations are considered an essential issue of a grid-connected electrical power structure. If these oscillations are not effectively managed, the power system will experience a partial or complete blackout. To ensure the secure and reliable operation of the power system, the stability target of the oscillations is a mandatory requirement. Hence, the oscillations frequency is ranged between 0.1 to 2 Hz and is classified according to the perturbation origin [22].

In recent years, several occurrences of unexpected oscillations have been reported, involving inter-area modes in power systems in both research and experimental [11], [23]. These fluctuations have become a significant issue [24]–[28]. As a result, there has been a surge in interest in these kinds, as well as approaches for constant monitoring and control choices to stabilize them.

IV. ELECTRO-SEARCH OPTIMIZER

ESO was presented primarily by [29] considering orbiting electron motions in the context of molecular space. More details about this method for power system application were presented in [18]. In this study, ESO is implemented as an adaptive controller such as [15], [18], [29]–[32]. It has many benefits such as plain coding, ease to use, less computational time. In general, its performance is remarkable and powerful, unaffected by the wide dimension issue, so it is a robust metaheuristics optimizer. The algorithmic details in the context of three stages are as follows:

Stage 1: Atom spreading

Stage 2: Transition for orbits

Stage 3: Relocating the nuclei

Based on the algorithmic steps, the ESO algorithm flowchart is shown in Fig. 2.

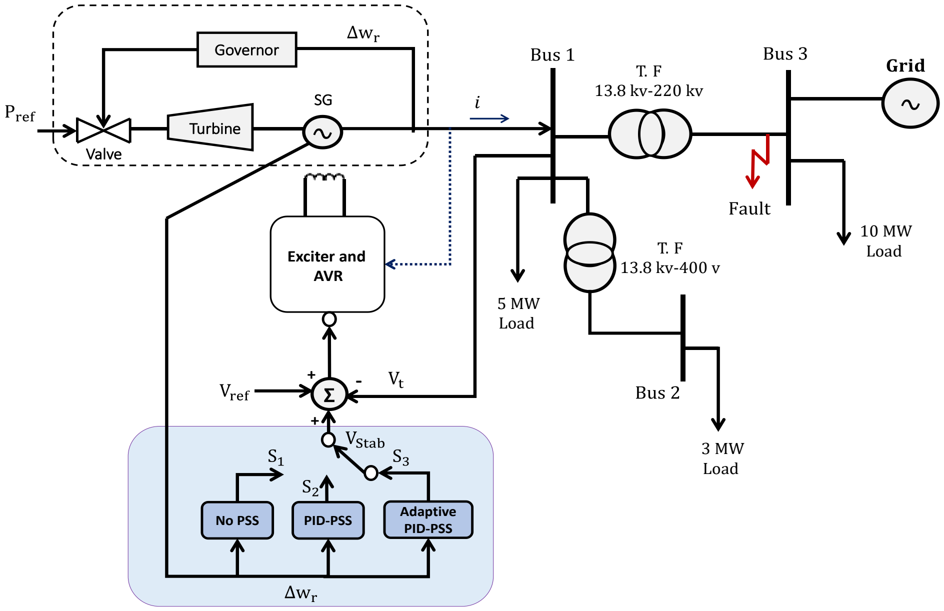


Fig. 1. One-line diagram of single machine hydro generator system based adaptive PID-PSS connected to grid.

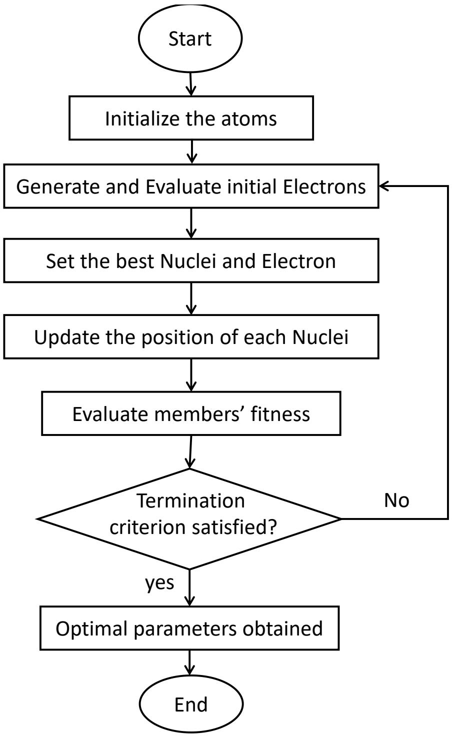


Fig. 2. Flowchart of ESO optimizer.

V. ADAPTIVE PID POWER SYSTEM STABILIZER MODEL

In this research, a linearized model of an SM tied to the grid, as displayed in Fig. 1, was considered for the stability analysis. A PSS is a device that enriches the performance of dynamic and transient stability of the power system. PSS acts as an additional supplementary device linked with the automatic voltage regulator (AVR) or the exciter to develop the stability constraints of this system [33].

Due to simple implementation and robust performance, the PID controller is suggested to be a tuning-based PSS and widely used as feedback control [34]. The configuration of the controller, i.e., PSS deemed in this work, is exhibited in Fig. 3. It involves a washout block as well as a PID controller tied in series with it. Where, T_w represents a time constant, in addition, K_P, K_i and K_D represent the proportional, integral, and derivative controller gains, respectively, and calculated in this study adaptively using ESO optimizer. The value of the washout block can be range between 1 to 20 seconds. The use of a proportional controller has the benefits of eliminating the rising time and steady-state inaccuracy. However, it will eventually increase overshoot. As a result, the system structure became insecure.

The PID stabilizer input signal is represented by the rotor speed, i.e., ΔW_r as shown in Fig. 3. Limits on power system stabilizer output are set to minimize the fluctuation degree of generator terminal voltage through transient situations. Positive and negative limitations of 0.15 p.u. and -0.15 p.u., respectively, are used to assure the stabilizer's greatest contribution.

The configuration of the synchronized damping controller for a closed-loop structure system and mathematical representations model of PID as well as PSS controller is given below:

$$U_{PID} = K_P + \frac{K_i}{s} + K_D.s \tag{2}$$

$$V_{stab} = K_{PSS}\frac{T_w s}{(1+T_w s)}\Delta W_r(s) \tag{3}$$

Where, K_{PSS} symbolizes stabilizer gain as well as T_w is labeled as the time constant of signal wash out.

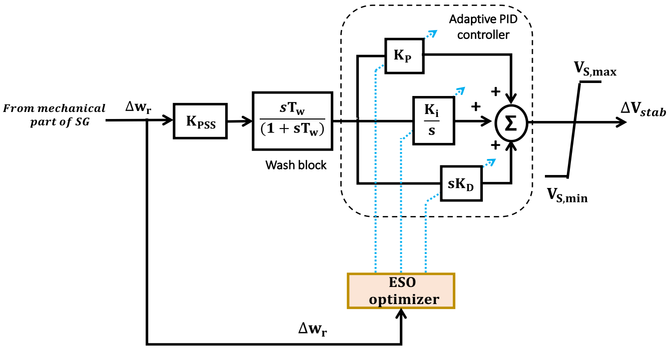


Fig. 3. Block diagram of adaptive PID-PSS using ESO optimizer.

The suggested ESO algorithm was used for the PID design-based PSS, it fed only from the speed deviation signal as a guide to tune the PID controller gains as shown in Fig. 3. The desired objective function (H_f) is a function of the on-time value of ΔWr, and it is based on the Integral Square Error (ISE) which is considered as a cost function and is given by:

$$H_f = \int_0^{\infty} (\Delta W_r)^2\, dt \tag{4}$$

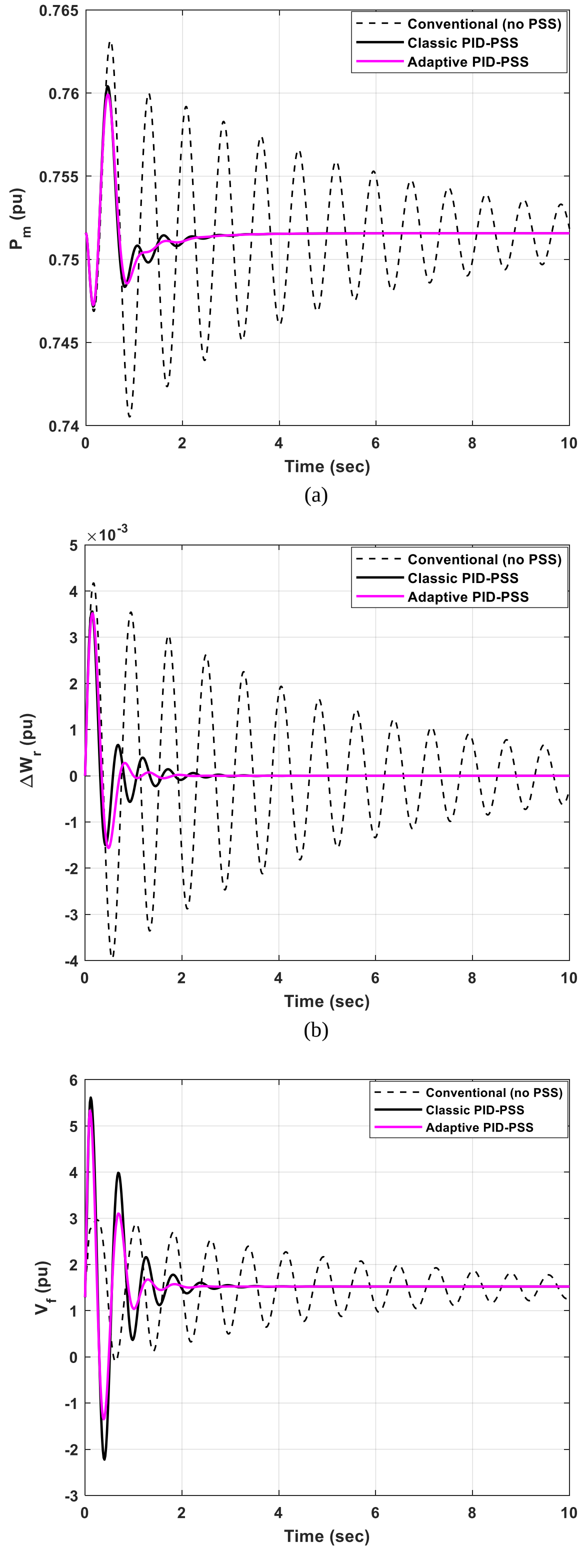
Where ΔWr represents the rotor speed deviation of the generator.

VI. VALIDATION AND SIMULATION

The efficacy of synchronized damping controllers was examined and contrasted under 3- φ short-circuit fault conditions at the grid side through the Simulink library. The findings of the Hydro turbine generator in case of the proposed adaptive control strategy, conventional system (no PSS), and system with the PID-PSS are evaluated by Simulink library setting beneath numerous fault conditions with the help of fixed 3 MW load tied to it as well as 15 MW load connected at bus 3. The 200 MW hydro generator is tied through a step-up transformer (13.8 → 220) KV to the EPS, and also linked via a step-down transformer ($\Delta\rightarrow Y$) (13.8 → 0.4) KV as shown in Fig. 1. The terminal and field voltages, rotor speed, and output electric powerP_e, mechanical output powerP_m, are stated by proposed two scenarios.

A. *Scenario 1: system examine under its normal operation (no faults)*

In Figs. 4 and 5, the parameters of the proposed system consist of rotor angle, followed by rotor angle deviation, as well as field voltage were analyzed in its normal operating condition (not faults). It is observed that without the PSS (the traditional one), the system takes more than 10 seconds to restore stability, but with the adaptive PID-PSS based ESO, it takes just 1 second. Furthermore, because the major goal of PSS is to offer additional damping in the system to minimize electromagnetic oscillations, the overshoot is decreased, indicating that the machine can quickly achieve a stable condition. Consequently, the adaptive concept with PSS plays a big role to improve the overall system response through the simulation period.

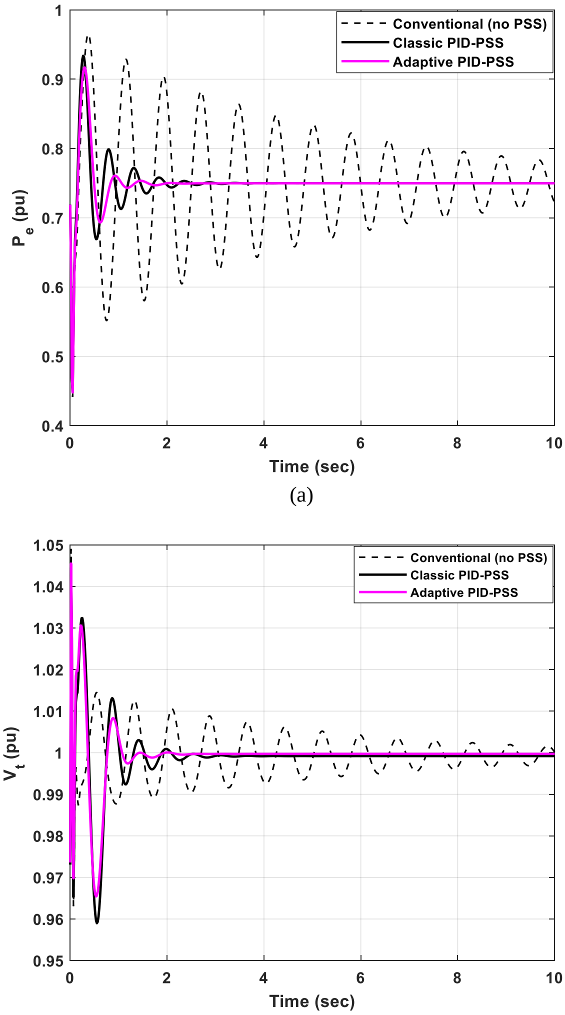


(a)

(b)

(c)

Fig. 4. System dynamic responses in case of normal operations without any faults: (a) P_m, (b) ΔW_r, and (c) V_f.



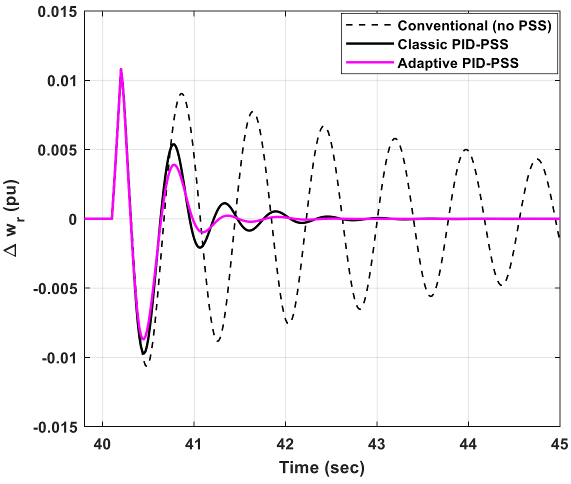
(a)

(b)

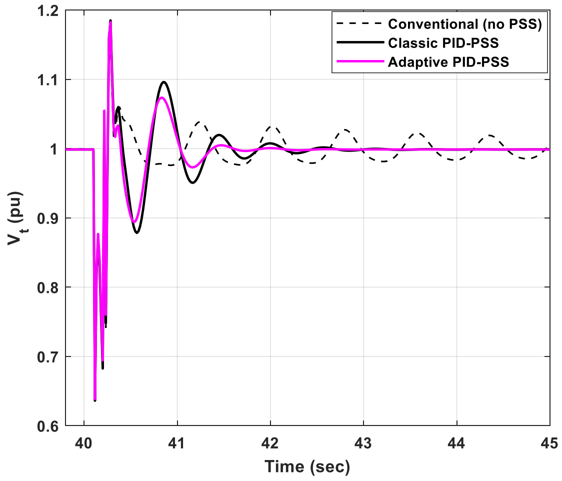
Fig. 5. System dynamic responses in case of normal operations without any faults: (a) P_e, and (b) V_t.

B. Scenario 2: under the effect of a 3- φ short-circuit fault at the grid side

In this case, the system performance is examined under the effect of a 3-φ fault subjected at the grid bus 3. The fault starting at 40.1 s and persisted in the system for 0.1 s. The synchronous system behavior under the 3-φ fault condition is displayed in Fig. 6. It can be noted that the system is stabilized after the fault is eliminated by 1 second, and the settling time of the system was mimicked with the suggested adaptive PID-PSS based ESO as compared to the conventional system and classic one. Finally, Integrating the PID-PSS controller provides a cost-effective solution for electromechanical oscillation damping while also improving the overall system dynamic stability.



(a)



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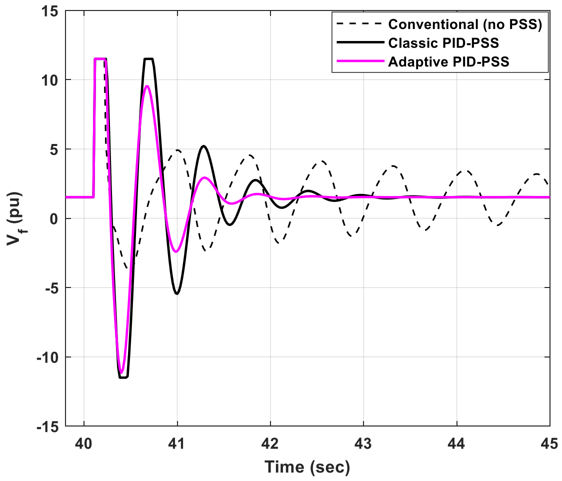
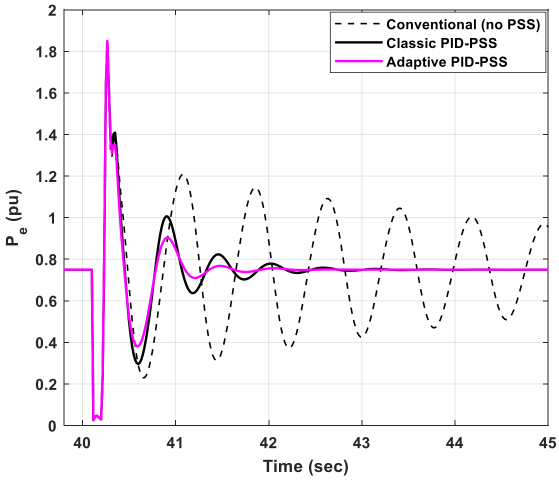


(c)



(d)

Fig. 6. System dynamic responses in case of a 3-φ short-circuit fault at the grid : (a) ΔW_r, b) V_f, (c) V_t, and (d) P_e.

VII. CONCLUSION

A hydro-turbine generator with a 200 MW output power that was established in High Dam, Aswan, Egypt has been taken as a case study in this paper. The main objective is to examine the power system operation with/without fault scenarios and how the expected low-frequency oscillation can be effectively damped between generators utilized in the power system out. To cover these issues, in this paper, we proposed the adaptive concept for PID-PSS using ESO optimizer to greatly enhance the dynamic stability of general power systems interconnected to hydro-turbine generators. Accordingly, we tested the stability of a given system for a single hydro turbine-generator connected to the grid via a step-up transformer and connected to a low voltage system via a step-down transformer $(\Delta \rightarrow Y)$. A comparison between the conventional system (no PSS), with standard PID-PSS, and the proposed adaptive PID-PSS based ESO has been demonstrated under the effect of a 3-φ short circuit fault subjected at the grid bus and also validated with its normal operation. The dynamic performance of the suggested adaptive controller has been evaluated to the conventional system without PSS and classic PID-PSS to demonstrate its superiority in suppressing the undesirable oscillations caused by sudden failure and rapid changes in the system condition. The effectiveness of the introduced PID-PSS in an adaptive manner is proven compared to the conventional and classic ones. Accordingly, we can claim that the introduced adaptive strategy for (PID-PSS) with the help of optimizers can maintain the dynamic stability of the main grid.

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