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Application of Adaptive Neuro-Fuzzy Inference System for Enhancing Controllability of A STATCOM in Power Systems

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Abstract— ***This paper using an Adaptive Neuro-Fuzzy Inference System (ANFIS) algorithm to improve the controllability of a static synchronous compensator (STATCOM). The power system is model as a Single Machine connected to Infinite Bus (SMIB) system with a Wind Power System (WPS). The comparison of the simulation results in time-domain based on a nonlinear system model subject to a three-phase short-circuit fault happened at the infinite bus is studied. It can be concluded that the performance of the waveforms with the designed ANFIS controller for a STATCOM is the best for improving the dynamic stability of the studied system.***

Index Terms— **Static Synchronous Compensator (STATCOM), Adaptive Neuro-Fuzzy Inference System (ANFIS), Wind Power System (WPS), Transient Stability, Voltage quality.**

I. INTRODUCTION

Flexible AC Transmission Systems (FACTS) devices have been proposed and implemented in power systems. In which, static synchronous compensator (STATCOM), has been used to enhance the power stability using fuzzy controller in the same system [1]. The applications of STATCOM to power system stability improvement were presented in [2]. A variable-blade pitch of a wind turbine and design of an output feedback linear quadratic controller for a STATCOM to perform mechanical power control and voltage control under different operating conditions were studied in [3]. Controller design and system modeling for quick load voltage regulation and suppression of voltage flicker using a STATCOM were explored in [4]. The application of a STATCOM to damp torsional oscillations of a series-capacitor compensated AC system were shown in [5].
Relating to wind generators, doubly fed induction generator (DFIG) is the most employed generator due to many merits of it such as, high efficiency compared to direct drive wind power system with a full-scale power converter, capability of decoupled control active and reactive power for better grid integration [6]. However, by connecting stator windings directly to the power grid, it is extremely sensitive to grid faults. To reduce affecting of the power grid to DFIG-based wind farm, in this paper, a STATCOM is proposed and the ANFIS algorithm is also suggested to contribute the damping to the studies system.

II. STUDIED SYSTEM CONFIGURATION

A. *System configuration*

Fig. 1 shows the configuration of the studied system containing a SMIB with a WPS and a STATCOM which are connected to a point of common coupling (PCC). The employed mathematical models of the studied system are described as below.

B. *Wind Power System Model* [6]

For modeling the WPS, an equivalent Doubly Fed Induction Generator (DFIG) driven by an equivalent wind turbine as shown in Fig. 2. In which, the stator windings of the DFIG are directly connected to the low-voltage side of the step-up transformer while the rotor windings of the DFIG are connected to the same low-voltage side through a rotor-side converter (RSC), a DC link, a grid-side converter (GSC), and a connection line.

For normal operation of a DFIG, the input AC-side voltages of the RSC and the GSC can be effectively controlled to achieve the aims of simultaneous output active-power and reactive-power control. The detailed operation of the RSC and GSC can be referred to [6].

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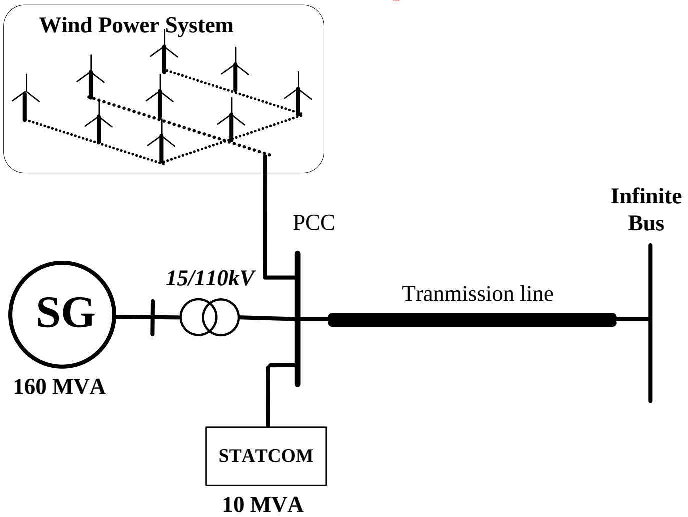

Fig. 1. System configuration

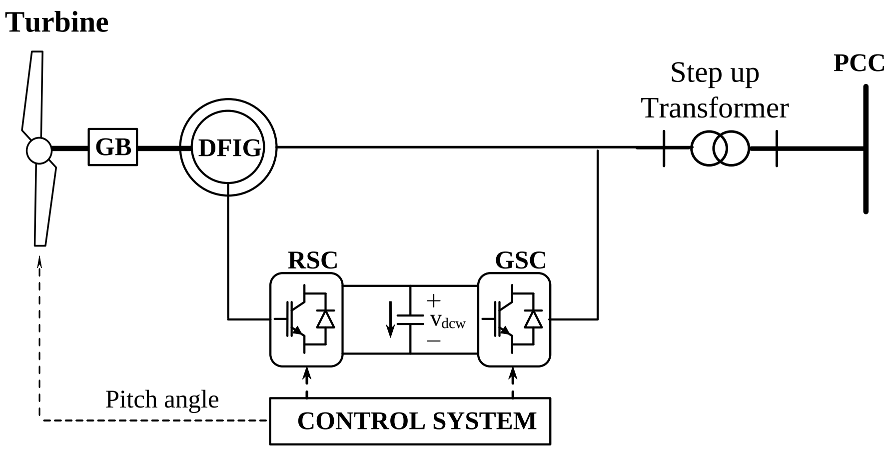

Fig. 2. Diagram of wind DFIG driven by a WT

C. SMIB system model [7]

In this research system, the power system is modeled as an equivalent SMIB system that is included a Synchronous Generator (SG) connected to an infinite bus through a transmission line. The block diagram model of the studied SG is shown in Fig. 3.

According to this model, four differential equations are rewritten as follows:

$$\tau'_{qo}\dot{E}'_d = -E'_d - (X_q - X'_q)I_q \quad (1)$$

$$\tau'_{do}\dot{E}'_q = -E'_q + E_{FD} + (X_d - X'_d)I_d \quad (2)$$

$$\tau_j\dot{\omega} = T_m - [I_d E'_d + I_q E'_q - (L'_q - L'_d)I_d I_q] - D\omega \quad (3)$$

$$\dot{\delta} = \omega - 1 \quad (4)$$

where E'_d (pu) is the d-axis internal transient stator voltage, E'_q (pu) is the q-axis internal transient stator voltage, E_{FD} (pu) is the field voltage, X_d is the d-axis synchronous reactance, X_q (pu) is the q-axis synchronous reactance, X'_d (pu) is the d-axis transient reactance, X'_q (pu) is the q-axis transient reactance, T_m (pu) is the mechanical torque input, τ_j is the inertia constant, D is the damping factor, τ'_{qo} (s) is the q-axis open-circuit time constant of the machine, τ'_{do} (s) is the d-axis open-circuit time constant of the machine, L'_d (pu)

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is the d-axis transient inductance, L_q' (pu) is the q-axis transient inductance, I_d (pu) is the d-axis stator current, I_q (pu) is the q-axis stator current, ω (rad/s) is angular velocity of rotor, and δ (rad) is rotor angle.
The Eq.(1)-(4) are used to design the ANFIS controller in section III and determine the outputs of SG.

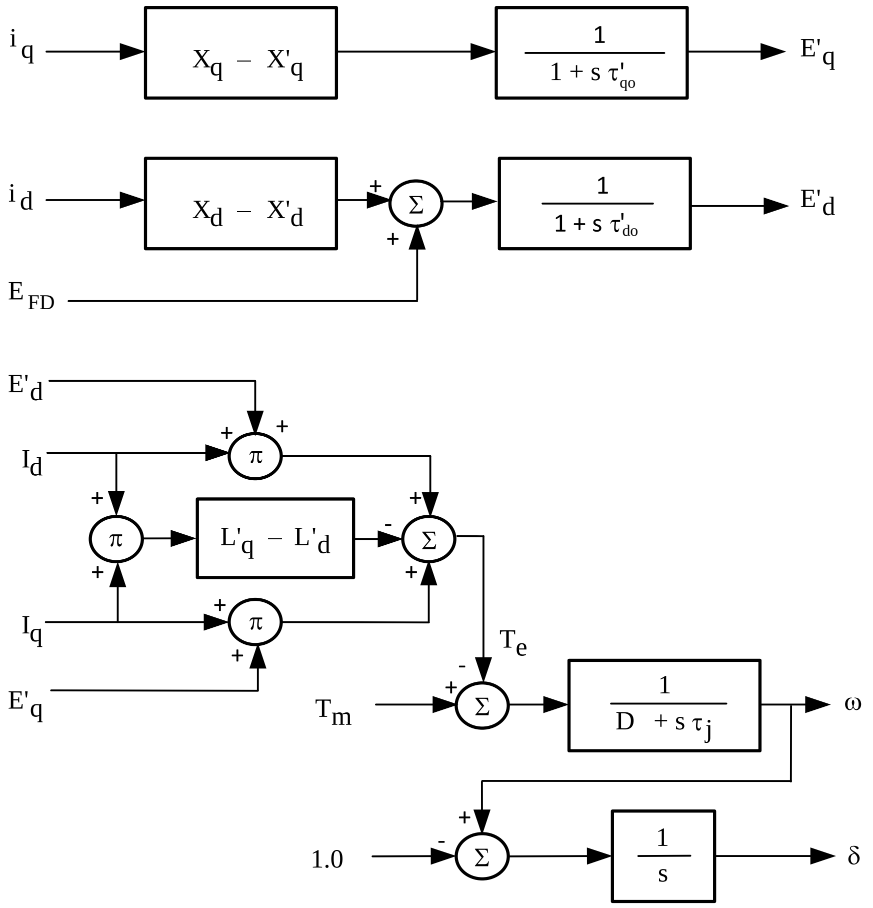

Fig. 3. Block diagram of the two-axis SG model.

D. STATCOM Model

A STATCOM is designed for regulating the voltage at its terminals by compensating the amount of reactive power in or out from the power system. When the system voltage is low, the STATCOM injects the reactive power to power system; when the voltage is high, it absorbs the reactive power. Besides, a STATCOM can be designed to act as an active filter to absorb system harmonics [11].
A STATCOM can improve power system performance in such areas as the followings [12]:

– The dynamic voltage control in transmission and distribution systems.
– The power-oscillation damping in power transmission systems.
– The transient stability.
– The voltage flicker control.

The control of a STATCOM is of not only the reactive power but also the active power in the connected line and requiring a DC energy source.
The output voltages of the proposed STATCOM in *dq*-axis can be written by [4].

$$v_{dsta} = V_{dcsta} \cdot km_{sta} \cdot \sin(\theta_{bus} + \alpha_{sta}) \quad (5)$$

$$v_{qsta} = V_{dcsta} \cdot km_{sta} \cdot \cos(\theta_{bus} + \alpha_{sta}) \quad (6)$$

where v_{qsta} and v_{dsta} are the pu *q*- and *d*-axis voltages at the output terminals of the STATCOM, respectively; km_{sta} and α_{sta} are the modulation index and phase angle of the STATCOM, respectively; θ_{bus} is the voltage phase angle of the common AC bus, and V_{dcsta} is the pu DC voltage of the DC capacitor C as shown in Fig. 4. The control scheme of the STATCOM can be referred to [9] and is shown in Fig. 5.

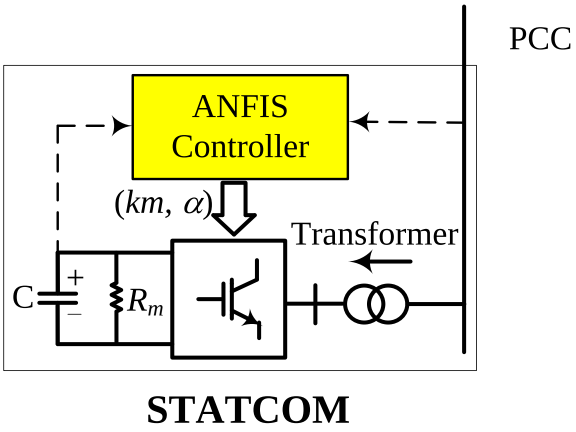

Fig. 4. ***STATCOM model***

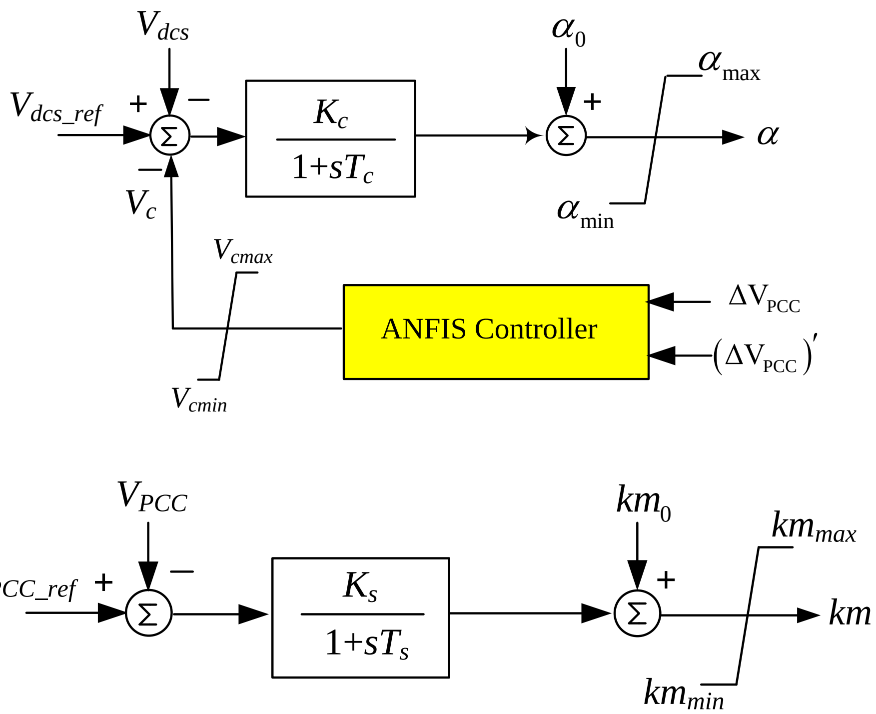

Fig. 5. Control scheme of STATCOM [9]

The pu DC voltage-current equation of the DC capacitor C can be described by

$$C(\dot{V}_{dcsta}) = \omega_b[I_{dcsta} - (V_{dcsta}/R_m)] \quad (7)$$

in which the DC current ca be calculated as

$$I_{dcsta} = i_{qsta}km\cos(\theta_{bus}+\alpha) + i_{dsta}km\sin(\theta_{bus}+\alpha) \quad (8)$$

where R_m is the pu equivalent resistance considering the equivalent electrical losses of the Statcom, and i_{qsta} and i_{dsta} are the pu q- and d-axis currents flowing into the terminals of the Statcom, respectively.

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III. ANFIS CONTROLLER DESIGN

This section employs the technique of ANFIS control theorem to add the damping at the yellow block shown in Fig. 5. The input signals are the voltage deviation at PCC (ΔV_{PCC}) and its derivative $d(\Delta V_{PCC})/dt$ which are fed to the ANFIS to generate the additional signal V_C in order to control the phase angle of the STATCOM.
The following fundamental design steps for designing an ANFIS are employed [10]:

– Data generation
– Rule extraction and membership functions
– Training and testing
– Results.

The using structure of ANFIS is the Sugeno-type with the structure rules are given as:

$$If\ (x_1 = A_i)\ and\ (x_2 = B_i)\ then\ (f_i = p_i x_1 + q_i x_2 + r_i) \quad (9)$$

where x_1 and x_2 are the inputs, and A_i, B_i are the fuzzy sets, f_i are the outputs within the fuzzy region specified by the fuzzy rule, and p_i, q_i and r_i are the designed parameters that are determined during the training process, and i is number of membership functions of each input.

In this paper, five linguistic variables for each input variable are used. These are NB (Negative Big), NS (Negative Small), ZR (Zero), PS (Positive Small), and PB (Positive Big). Seven linguistic variables for output variable are also defined, such as: IB (Increase Big), IM (Increase Medium), IS (Increase Small), KV (Keep Value), DS (Decrease Small), DM (Decrease Medium), and DB (Decrease Big).

This paper using the ANFIS toolbox in MATLAB with the type of membership function, the number of epochs, and the learning algorithm are chosen as Gauss, 20, and Hybrid, respectively. The surface rule for training ANFIS is shown in Fig. 6.

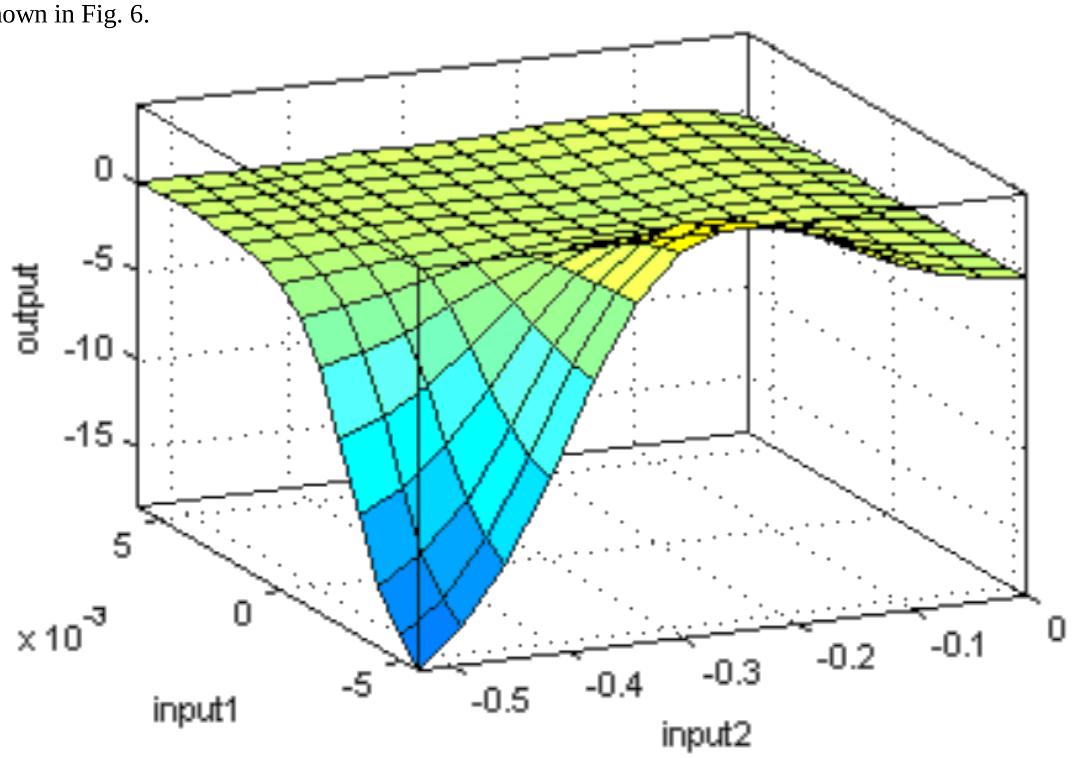
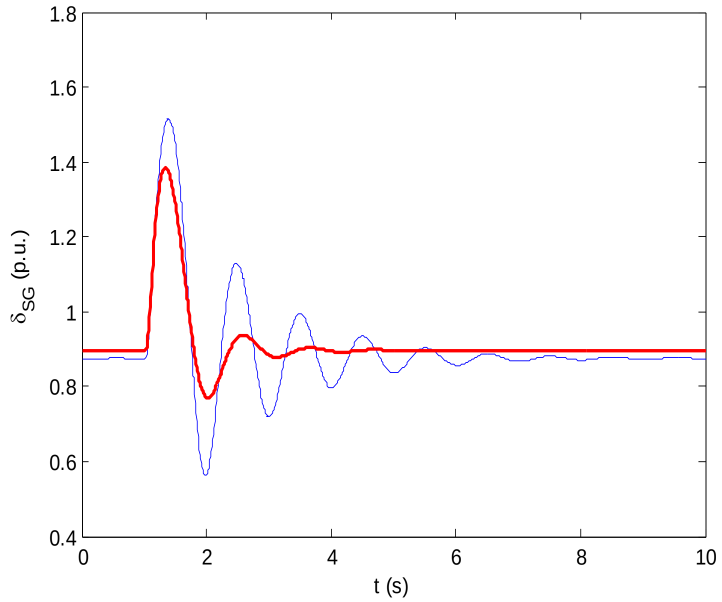


Fig. 6. Surface rule of the designed ANFIS.

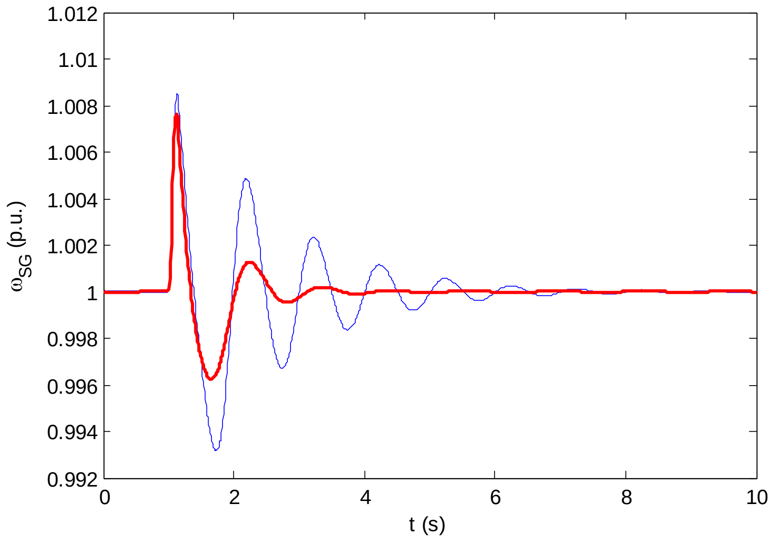
IV. SIMULATION RESULT

For showing the performance of the design ANFIS controller, this section uses the nonlinear system model to compare the damping characteristics contributed by the proposed STATCOM joined with the designed controller on transient stability improvement of the studied system under a three-phase short-circuit fault at the PCC.

With the three-phase short-circuit fault is suddenly applied to the grid at 1 second and is cleared at 1.1s (after 5 electrical cycles). The fault time is assumed to be the same time from real power grid operation. The cleared fault time depends on tripping time of the protection relay and contacts opening speed of the breaker. Fig. 7 presents simulation results of the proposed system with SIMULINK toolbox in MATLAB. In this figure, the comparative transient responses of the studied system in case of without controller (blue lines) and with ANFIS controller (red lines) are respectively plotted. In which, the rotor angle of the SG is shown in Fig. 7(a), the rotor speeds of SG is shown in Fig. 7(b), the active power of WPS is shown in Fig. 7(c), the voltage at PCC is also shown in Fig. 7(d). It is clearly observed from the comparative simulation results that proposed controller can offer better damping to the studied system.



(a) Rotor angle of SG



(b) Rotor speed of SG

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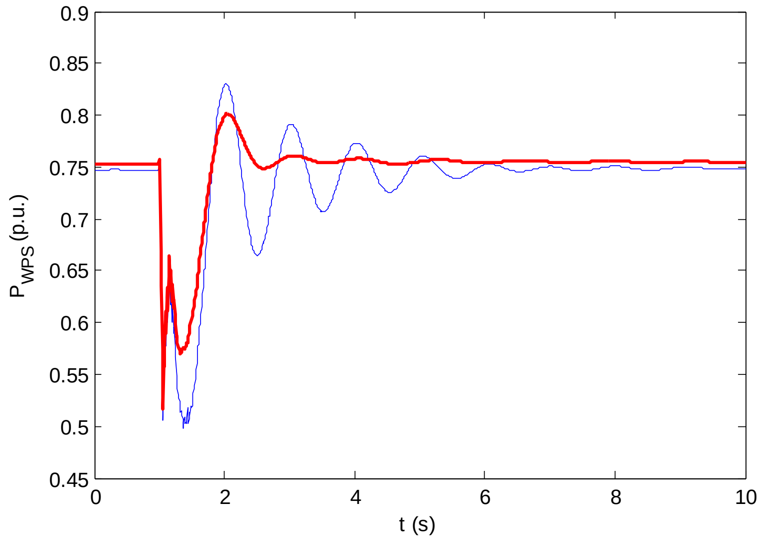
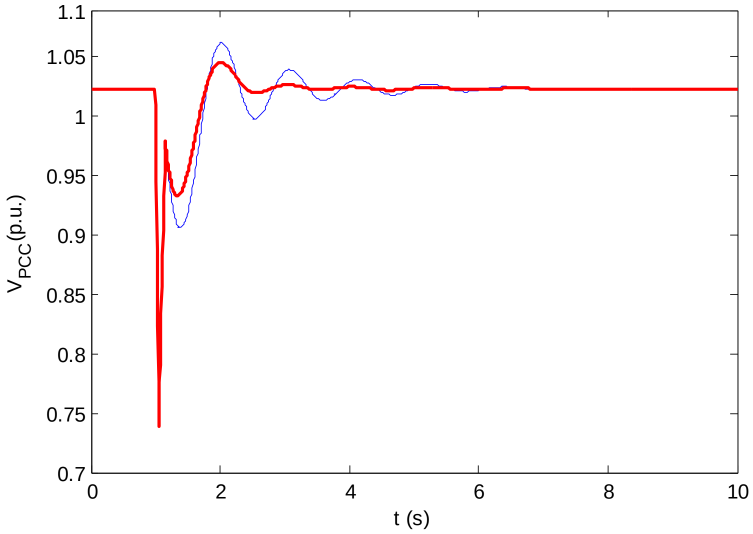


(c) Active power of WPS



(d) Voltage at PCC

Fig. 7. Comparative transient responses of the studied system under a three-phase short circuit fault at infinite bus in case of without controller (blue lines) and with ANFIS controller (red lines)

The simulation results also show that in the case of without controller, the waveforms of rotor angle, rotor speed, active power of the WPS and voltage at the PCC are recovered to the prefault steady-state operating conditions around 6 seconds with big oscillations. In the case of with the designed ANFIS controller, these waveforms are recovered to the prefault steady-state operating conditions around 3 seconds with small oscillations.
It shows that the proposed STATCOM with the designed ANFIS controller can supply proper reactive power to the system and offer better damping characteristics to quickly damp out the inherent oscillations of the studied system than the studied system without the controller for STATCOM under a three-phase short-circuit fault at the PCC bus of power grid.

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V. CONCLUSION

This paper has presented the stability improvement of a WPS integrated to power grid. The STATCOM is proposed and is connected to the PCC of the studied power system. To supply adequate reactive power to the system, an ANFIS controller for the STATCOM has been designed. It can be concluded from the simulation results that the proposed STATCOM joined with the designed controller has the better damping characteristics to improve the performance of the studied system under the most severe operating condition. With this simulation result, it can be used to design the ANFIS controller for STATCOM to improve transient stability of multi-machines power system, as well as use to design developed controllers for STATCOM to improve the voltage quality at the PCC, especially in locations connected to sensitive loads.

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