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MITIGATING SUBSYNCHRONOUS RESONANCE IN HYBRID SYSTEM WITH STEAM AND WIND TURBINE BY UPFC

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Abstract- With increasing the usage of wind power turbines in power systems, impact of wind generator on sub-synchronous resonance (SSR) is going to more important. Sub-synchronous resonance (SSR) is a significant problem in a series compensated power systems. The IEEE second benchmark model on SSR is taken with integrating aggregated synchronous generator-based wind turbine to carry out the studies. In this paper for damping the SSR in hybrid energy production system comprise wind and steam turbine a unified power flow controller (UPFC) has been used. To provide an optimal control on pitch angle in high speed of wind, fuzzy logic damping controller (FLDC) has been used. Supplementary shunt controller for UPFC has been also designed and ANFIS controller is added to this controller to mitigate the SSR.

Keywords: Wind Turbine, Steam Turbine, Subsynchronous Resonance, SSR, Unified Power Flow Controller (UPFC), Fuzzy Logic Damping Controller (FLDC), ANFIS.

I. INTRODUCTION

Wind power is the most fast growing technology for renewable power generation systems [1, 2]. Therefore with the fast growth of installed capacity of wind farms, the large wind turbine generators (WTGs) are widely used into electric power grids. The produced power by wind farm should be transmitted through the transmission system that can sustain large power flow.

Series capacitive compensation is a very economical technique to enhance the system stability and power transfer capability especially where large amounts of power must be transmitted through long transmission lines. However, this also leads to occurring the phenomenon of subsynchronous resonance (SSR) [3, 4]. It means that the interaction between the electrical oscillation modes of the series compensated network and the mechanical oscillation modes of the turbine-generator group may produce oscillating torsional torques [5].

SSR is a well-understood phenomenon that can be damped by flexible ac transmission system (FACTS) devices [6]. In recent years, there are many researches which have been done in order to damp the SSR. A method to damp the SSR by STATCOM in IEEE First Benchmark Model (FBM) system is presented by Mohamed S. El-Moursi et al [7]. Lingling Fan et al are Modeled DFIG-Based Wind Farms for SSR Analysis [8]. Impacts of large-scale wind power integration on subsynchronous resonance have been analyzed by Tang Yi, and Yu Rui-Qian [9].

This paper focuses on a unified power flow controller (UPFC) based on a supplementary shunt controller for damping SSR. In this paper wind and steam turbine have been used as a hybrid energy production system. The IEEE second benchmark model on SSR is taken with integrating aggregated synchronous generator-based wind turbine to carry out the studies. This paper shows that the UPFC with ANFIS controller in supplementary shunt controller is able to mitigate SSR.

II. SYSTEM CONFIGURATION

The configuration of the study system has been shown in (Figure 1). This figure shows the IEEE Second Benchmark Model (SBM) combined with UPFC in bus 1 which is principally used for SSR studies [10]. The system consists of steam and wind turbines with synchronous generator supplying power to an infinite bus per two parallel transmission lines which one of them is compensated by a series capacitor. A 600 MVA steam turbine-generator and 60 MVA wind turbines (which consist of 40 turbines and each turbine generate 1.5 MVA) are connected to an infinite bus, and the rated line voltage is 500 KV, while the rated frequency is 60 Hz. The shaft system comprise of four masses: a high pressure turbine (HP), low pressure turbine (LP), the generator (G), rotating Exciter (EX). Elastic shaft linked all masses together mechanically.

III. SUBSYNCHRONOUS RESONANCE

Ordinarily, SSR occurs in series compensated transmission lines. The power system compensated by a series capacitor has a sub-synchronous natural frequency (f_e) which is given by:

$$f_e = f_0\sqrt{X_c / X_l} \tag{1}$$

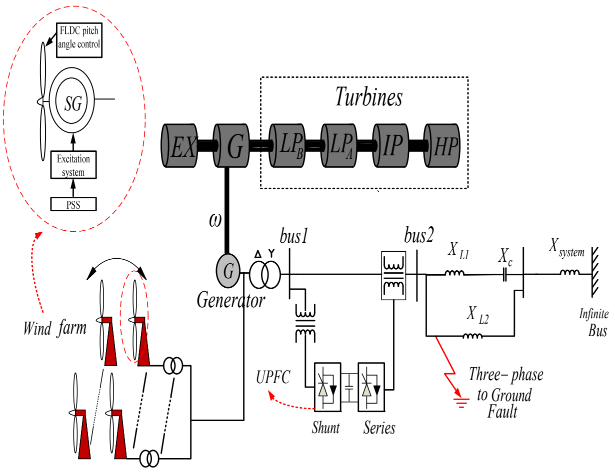


Figure 1. IEEE SSR second benchmark model supplied by the UPFC

If $f_r = f_0 - f_e$ is close to one of the torsional frequencies of the rotor shaft, the torsional oscillations will be excited and this condition lead to undesirable phenomenon namely SSR [3]. SSR is divided into two significant parts: Self-excitation (called as steady state SSR) and transient torques (called as transient SSR). Self-excitation is partitioned into two major parts: Induction Generator Effect (IGE), and torsional interaction (TI). The IGE is not probable in series compensated power system. But, the TI and transient SSR are usally occur in series compensated power systems [11, 12].

IV. MODELING OF WIND TURBINE

A fixed wind speed turbine system established on a synchronous generator (SG) has been analyzed in this work; wind speed is 13.5 m/s and the base speed is 11 m/s. the power extracted from the wind is determined by the following equations.

$$PW = C_p \frac{1}{2} \rho A V w^3 \qquad (2)$$

$$C_p = 0.5[\frac{116}{\lambda_i} - 0.4\theta_p - 5]e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \qquad (3)$$

$$\lambda = \frac{\omega R}{v\omega} \qquad (4)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta_p} - \frac{0.035}{\theta_p{}^3 + 1} \qquad (5)$$

where θ_p is the angle between the plane of rotation and the blade cross-section chord [13, 14]. Figure 3 shows the model of the wind turbine equipped by FLDC of pitch angle. The produced power of wind generator is directly related to the wind speed. Since most wind power production is produced at high speed, a half of the energy produced by wind turbines is produced in only 15% of working time. As a result, wind power plants are not sustainable like fuel energy production. The wind power generators installations must use a system to support the power generator for the time that wind turbine produces energy is low. In this paper wind and steam turbine have used as a hybrid energy production system.

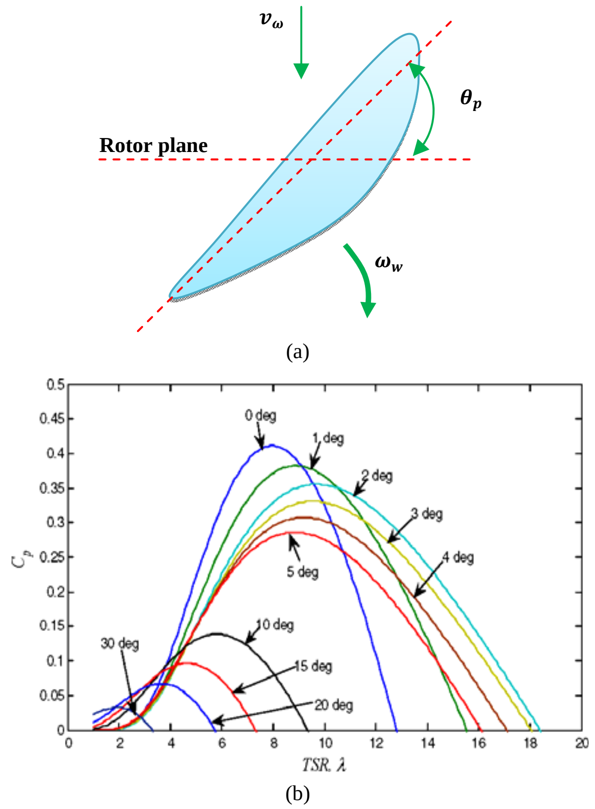


Figure 2. (a) Blade pitch angle θ_p, (b) Power coefficient versus blade pitch angle

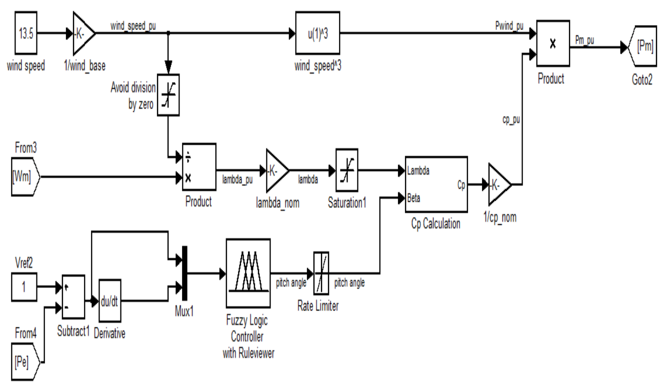


Figure 3. Wind Turbine modeled with Simulink

V. MODELLING OF UNIFIED POWER FLOW CONTROLLER (UPFC)

There are many FACTs devices that can be able to mitigate SSR, like: SVC, TCSC, STATCOM, etc. In this paper a unified power flow controller UPFC has been utilized for damping SSR. The structure of UPFC basically includes two voltage source inverters (VSIs) connected back-to-back with an interconnecting dc storage capacitor. One of them is connected to the system by a shunt transformer and another is connected to the transmission line by a series transformer [15]. The basic UPFC structure has been shown in Figure 4. Figure 5 shows the proposed method of auxiliary FLDC shunt controller.

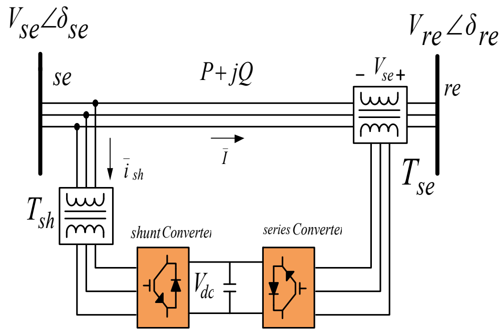


Figure 4. Structure of an UPFC between buses 1 and 2

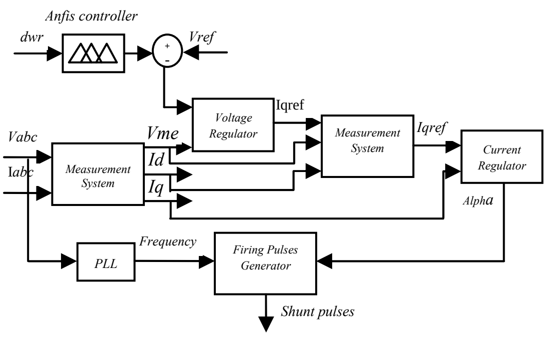


Figure 5. Schematic of auxiliary ANFIS shunt controller

VI. DESIGN OF FUZZY LOGIC DAMPING CONTROLLER (FLDC) AND ANFIS CONTROLLER

In recent years, Fuzzy Logic Damping Controllers (FLDCs) have been appeared as an effective tool to stabilize the power network [16, 17]. The main significant advantage of FLDCs toward conventional damping controllers (CDCs) can be cited as: FLDCs do not require an exact mathematical model; they can act with inaccurate inputs, control nonlinearity, and are more robust and effective than the CDCs in the power system [17]. In this paper for mitigating SSR, ANFIS controller has been applied to the UPFC shunt controller and FLDC has been applied to pitch angle controller of wind turbine.

Power deviation (ΔP) and its derivatives $(\partial \Delta P / \partial t)$ have used as the fuzzy controllers inputs and pitch angle (θ_p) is the output of fuzzy controller. Figure 6 shows the membership functions for the FLDC of pitch angle controller.

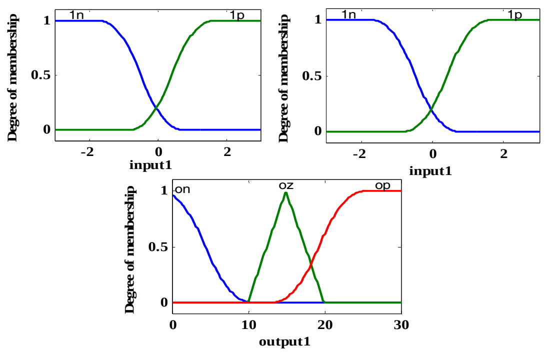


Figure 6. Membership functions for the FLDC of pitch angle controller

The control rules of the fuzzy controllers are showed below. The fuzzy sets have been determined as N: negative, Z: zero, P: Positive, respectively.

1. If (ΔP is P) and ($\partial \Delta P / \partial t$ is P) then (θ_P is N)
2. If (ΔP is P) and ($\partial \Delta P / \partial t$ is N) then (θ_P is Z)
3. If (ΔP is N) and ($\partial \Delta P / \partial t$ is P) then (θ_P is Z)
4. If (ΔP is N) and ($\partial \Delta P / \partial t$ is N) then (θ_P is P)

The ANFIS controller was first introduced by J. Jang in 1993 [18]. The ANFIS uses a hybrid learning algorithm to recognize consequent parameters of Sugeno-type fuzzy inference systems. For UPFC shunt controller rotor speed deviation $(\Delta\omega)$ considered as an ANFIS input and the output is reference voltage. Figure 7 shows membership functions for the ANFIS of UPFC shunt controller.

1. If ($\Delta\omega$ is P) then (V_{ref} is 1-1.29075)
2. If ($\Delta\omega$ is Z) then (V_{ref} is 1-0.03385)
3. If ($\Delta\omega$ is N) then (V_{ref} is 1-(-1.17375))

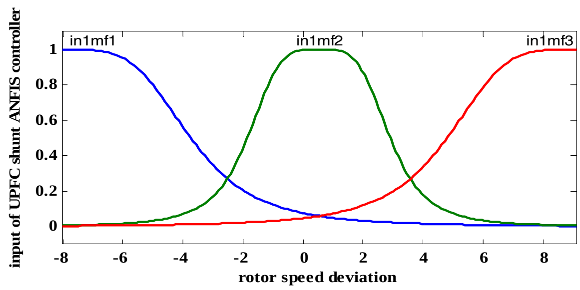


Figure 7. Membership functions for the ANFIS of UPFC shunt controller

VII. RESULTS AND SIMULINK IN MATLAB

For proving the effectiveness of the proposed control method to mitigate the SSR phenomenon, the IEEE Second Benchmark combined with the UPFC is modeled in MATLAB/Simulink. Two cases for studying are considered.

Firstly, the power system without any damping controllers and secondly with ANFIS controller is simulated. When the fault is cleared, large oscillations will be occurred between different parts of the turbine-generator shaft; Figure 8 shows such condition.

According to Figure 8 the UPFC without supplementary ANFIS controller cannot be able to mitigate SSR. SSR oscillations in wind turbine have shown in Figure 9. The Figure 9 shows the oscillations in wind turbine due to SSR phenomenon without UPFC.

In this section, a novel ANFIS controller has been added to the UPFC for observing specification variation of the system. Rotor speed, rotor speed deviation and torques of generator are shown in (Figure 10).

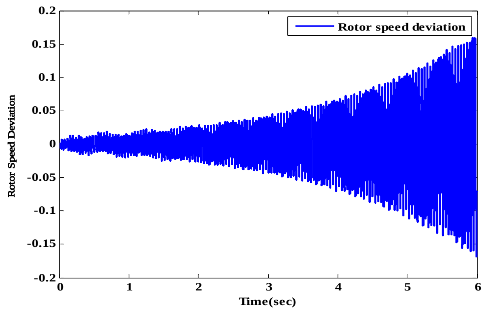
Figure 11 shows that the UPFC with supplementary controller in shunt with ANFIS can be able to mitigate SSR. With optimal pitch angle control by using FLDC in high wind speed, mechanic and electric power were closed to together. By this work wind generator produced power in near the 1pu.

VIII. CONCLUSIONS

With increasing use of wind power in power systems, impact of wind generator on subsynchronous resonance (SSR) is going to more important. Subsynchronous resonance (SSR) is a significant problem in a series compensated power systems.

This paper proposed a method for damping the SSR by UPFC. The IEEE second benchmark system equipped by steam and wind turbine as a hybrid energy production system was studied. As shown The UPFC without supplementary damping controller cannot be able to damp the oscillations of SSR phenomenon.

With applied ANFIS controller to shunt controller of UPFC and applied FLDC for controlling pitch angle of wind turbine, UPFC mitigated the SSR and mechanic and electric power of wind generator were closed to together. By this work wind generator produced power in near the 1pu.



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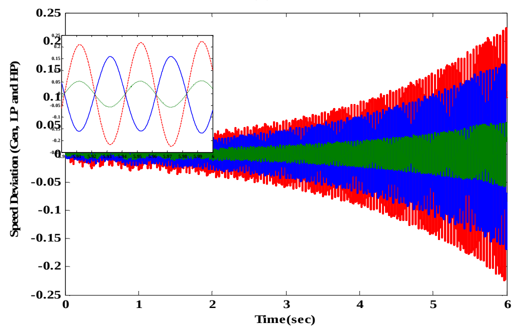

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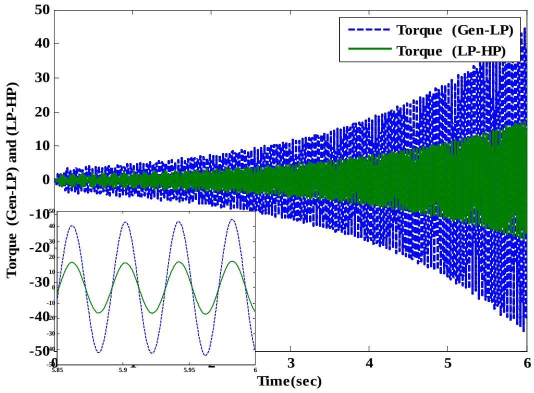
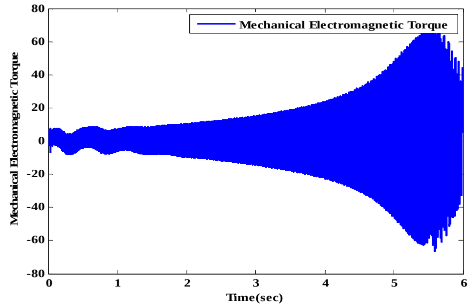


(c)

Figure 8. Simulation results for un-damped mode: (a) rotor speed deviation, (b) speed deviation between generator, Low pressure and high pressure turbine, (c) torque between generator, Low pressure and high pressure turbines



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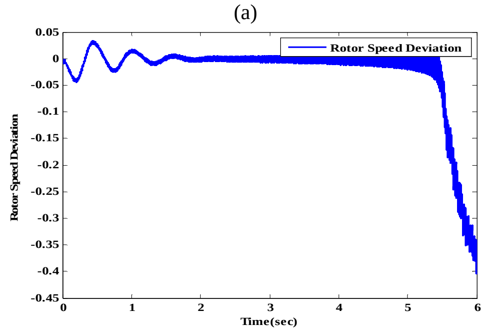

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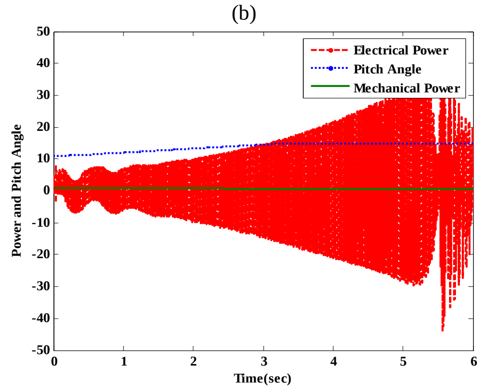

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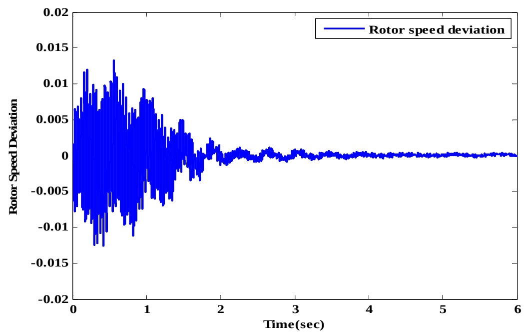
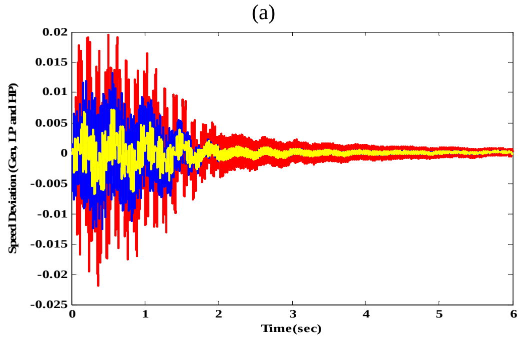
Figure 9. Simulation results for un-damped mode: (a) mechanical electromagnetic torque, (b) rotor speed deviation in wind turbine, (c) mechanical and electrical power and pitch angle



(a)



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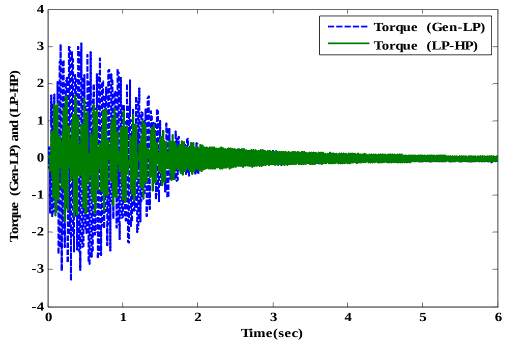
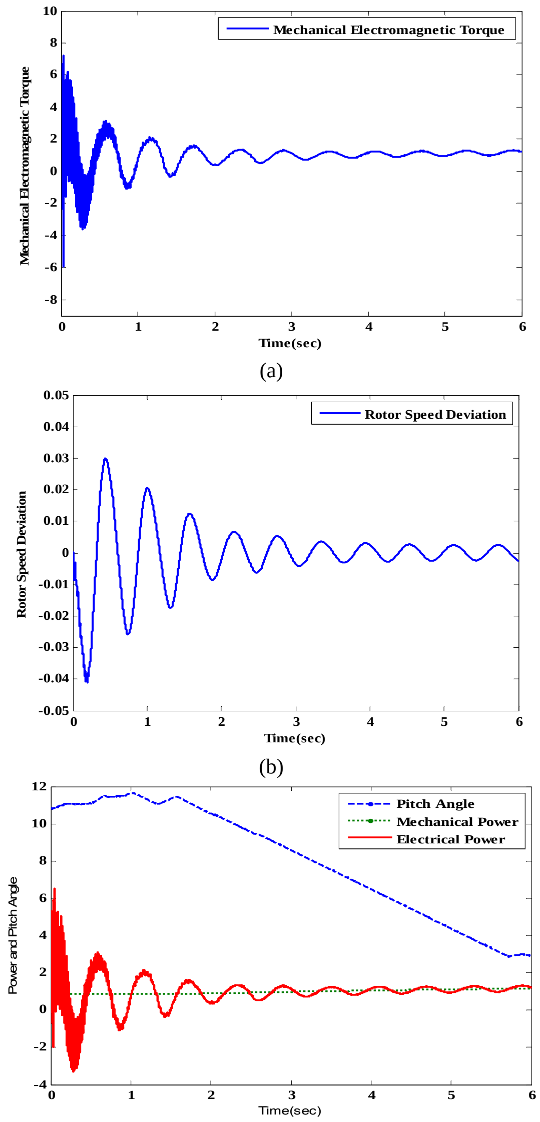


(c)

Figure 10. Simulation results with damping SSR by UPFC with ANFIS controller: (a) rotor speed deviation, (b) speed deviation between generator, Low pressure and high pressure turbine, (c) torque between generator, Low pressure and high pressure turbines



(c)

Figure 11. Simulation results for results with damping SSR by UPFC with ANFIS controller and FLDC for pitch angle controlling: (a) mechanical electromagnetic torque, (b) rotor speed deviation in wind turbine, (c) mechanical and electrical power and pitch angle

NOMENCLATURES

f_e : Electrical frequency of the power system

f_0 : Synchronous frequency of the power system

X_c : Reactance of series capacitor

X_l : Leakage reactance of compensated line

C_p : Power coefficient

A : Area swept by the rotor $A = \pi R^2$, R the radius of the blade [m]

v_w : Wind speed

ω_w : Angular velocity of rotor [rad/s]

v_ω : Wind speed upstream of the rotor [m/s]

R : Rotor radius [m]

θ_p : Pitch angle [°]

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