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Artificial Neural Networks Controller for Power System Voltage Improvement

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***Abstract*— In this paper, power system voltage improvement using wind turbine is presented. Two controllers are used: a PI controller and Artificial Neural Networks (ANN) controller are investigated. The power flow exchanged between the wind turbine and the power system has been controlled in order to improve the bus voltage based on reactive power injection (or absorption) produced by variable speed wind turbine. The wind turbine is based on a doubly fed induction generator (DFIG) controlled by field-oriented control. Indirect control is used to control of the reactive power flow exchanged between the DFIG and the power system. The proposed controllers are tested on power system for large voltage disturbances.**

Keywords*— *Artificial Neural Networks controller, double fed induction generator (DFIG), Field-oriented control(FOC), PI controller , power system voltage improvement.

I. INTRODUCTION

Over the last years, there has been a strong penetration of renewal energy resources into the power system. Wind power is one of the fastest growing sustainable energy resources over the past decade. Wind energy generation has played and will continue to play a very important role in this area for the coming years. Wind is a sustainable energy source since it is renewable, widely distributed, and plentiful. In addition, it contributes to reducing the greenhouse gas emissions since it can be used as an alternative to fossil-fuel-based power generation. Wind turbines can be grid connected or independently operated from isolated locations. The two critical factors in finding the most suitable locations for wind turbines are wind speed and the quality of wind.

Wind energy has been used for hundreds of years for milling grains, pumping water, and sailing the seas. The use of windmills to generate electricity can be traced back to the late nineteenth century with the development of a DC windmill generator.

The evolution of wind power conversion technology has led to the development of different types of wind turbine configurations that make use of a variety of electric generators. The variable speed DFIG wind energy system is one of the main wind energy conversion systems configurations in today's wind power industry.

Doubly fed induction Generators (DFIG) based wind turbines have undoubtedly arisen as one of the leading technologies for wind turbine manufacturers, demonstrating that it is a cost effective, efficient, and reliable solution. A DFIG in a wind turbine has the ability to generate maximum power with varying rotational speed, to control active and reactive by integration of electronic power converters such as the back-to-back converter, low rotor power rating resulting in low cost converter components, etc. Owing to the decoupled active and reactive control possibilities [1,2], the main area of application for the DFIG is in variable-speed generating systems such as wind power and hydro power [1-4].

Although the multitude of strategies and means of protection, power systems are confronted by numerous constraints such as the increase in demand, disturbances, planning, interconnection and network complexity. It is imperative to provide detailed informations for each option. An important study that should be included in the design of electrical networks is controlling and improving the voltage stability, the main causes for occurrence of voltage instability are:

- Voltage sources are too far from load centers;
- Loss of a heavily loaded line (or generator)
- High Reactive Power Consumption at Heavy Loads;
- Poor coordination between multiple FACTS. [5-8].

Voltage is one of the most important parameters for the control of electric power systems. Many techniques have been used to control and improve the power system voltage such as:

- The On-Load tap changer (OLTC) transformers;
- Automatic voltage control;
- Synchronous condenser;
- Shunt compensation;
- Voltage control by FACTS devices;
- Distributed generation;

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- Excitation control;
- Induction regulators.

Voltage control and reactive-power management are two aspects of a single activity that both supports reliability and facilitates commercial transactions across transmission networks. Reactive power affects power system operation in numerous ways:

- Loads consume reactive power, so this must be provided by some source.
- The delivery system (transmission lines and transformers) consumes reactive power, so this must be provided by some source (even if the loads do not consume reactive power). Note however that all transmission lines do provide some reactive power from their shunt line charging which offsets their consumption of reactive power in their series line losses.
- The flow of reactive power from the supplies to the sinks causes additional heating of the lines and voltage drops in the network.
- The generation of reactive power can limit the generation of active power.

So, one primary dilemma with reactive power is that a sufficient quantity of it is needed to provide the loads and losses in the network, but having too much reactive power flowing around in the network causes excess heating and undesirable voltage drops. The normal answer to this dilemma is to provide reactive power sources exactly at the location where the reactive power is consumed

In order to improve the quality of energy and to reduce the economic and social costs of a Blackout, there have been a large number of approaches that propose new restoration techniques as alternatives to these commonly used restoration procedures [9-11]. The required computing time and the capability to find restoration plans under unexpected fault conditions are critical issues in power system restoration estimation. In this paper, an alternative of using artificial neural networks (ANNs) in power system voltage restoration is investigated.

This paper is organized as follows: The first part studies wind park model and the dynamics of the DFIG model establishing the Field-oriented control strategy (FOC) with PI current and power controllers [3-4]. The second part shows the modeling of power system and reactive wind controller. Improvement of power systems voltage using PI controller and Artificial Neural Networks (ANN) controllers are presented in third part with discussion and analysis are shown in the fourth part, which the equivalence modeling of a wind park involves combining all turbines with the same mechanical natural frequency into a single equivalent turbine.

II. AN OVERVIEW OF ANN APPLICATION

A neural network is an information processing system. It consists of a number of simple highly interconnected processors (units) known as neurons similar to biological cells of the brain. These neurons are interconnected by a large number of weighted links, over which signals can pass. Each neuron receives many signals over its incoming connections, and produces a single outgoing response. Such networks have exceptional pattern recognition and learning capabilities [16-18]. Recent applications of ANN have shown that they have considerable potential in overcoming the difficult tasks of data processing and interpretation. Four major steps are necessary in ANN application [12-14]:

- Data generation.
- Selection of inputs.
- Selection of ANN architecture.
- Training the ANN and testing [12-14].

III. WIND GENERATOR MODEL

The electrical power produced by wind turbine generators has been growing continuously. A wind turbine installation consists of a turbine tower, which carries the nacelle, and the turbine rotor, consisting of rotor blades and hub. The mathematical relation for the mechanical power extraction from the wind can be expressed as follows:

$$P_{aer} = \frac{1}{2} C_p(\lambda, \beta) \rho S v_{wind}^3 \tag{1}$$

Where:

$P_{aér}$ is the extracted power from the wind;

ρ : is the air density (kg/m^3).

S : is the turbine swept area (m^2).

v_{wind} : is the wind speed (m/s).

β : is the blade pitch angle (deg).

C_p : is the performance coefficient of the turbine, Cp is often given as a function of the tip speed ratio λ.

The expression of the power coefficient Cp is given by the following equation (Cp for turbine 3 MW [15]:

$$C_p(\lambda,\beta) = (0.35 - 0.0167 \cdot (\beta - 2)) \cdot \sin\left(\frac{\pi \cdot (\lambda + 0.1)}{14.34 - 0.3 * (\beta - 2)}\right) - (0.00184 \cdot (\lambda - 3) \cdot (\beta - 2)) \tag{2}$$

λ : is the ratio of blade tip speed to wind speed defined by:

$$\lambda = \frac{R\Omega}{V_{wind}} \tag{3}$$

Ω: the wind turbine rotational speed (rad /sec);

R: the wind turbine radius.

Figure 1 presents the evolution of the power coefficient for different pitch angles β (2,4,6,8,10,12), which the pitch angle control operates only when the value for wind speed is greater than the nominal wind speed.

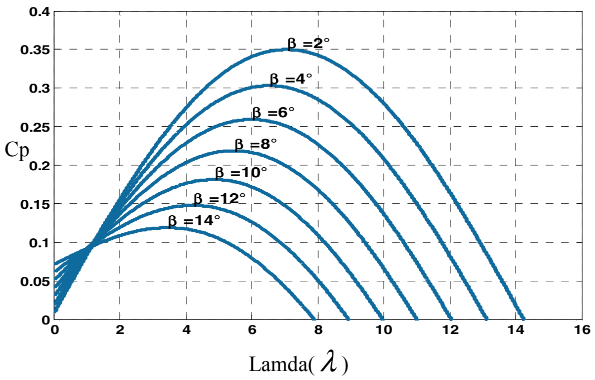

Fig 1: Power coefficient based on the ratio of speed

The aggregated wind farm model is based on the idea of adding the power of the individual wind turbine. The total mechanical power is:

$$P_m^e = \sum_{i=1}^{ng} P_i = \sum_{i=1}^{ng} \frac{1}{2} Cp_i(\lambda_i, \beta_i) \rho S_i v_{i\,wind}^3 \tag{4}$$

Where ng is the number of wind turbine in the wind farm.

IV. Double Fed Induction Generator Model

The Doubly-Fed Induction Generators utilize a wound rotor induction generator. The concept is based on two back-to-back voltage source converters connecting the grid and the rotor windings. The stator windings are connected directly to the grid [1-4]. A typical configuration of a DFIG is shown schematically in Fig. 2.

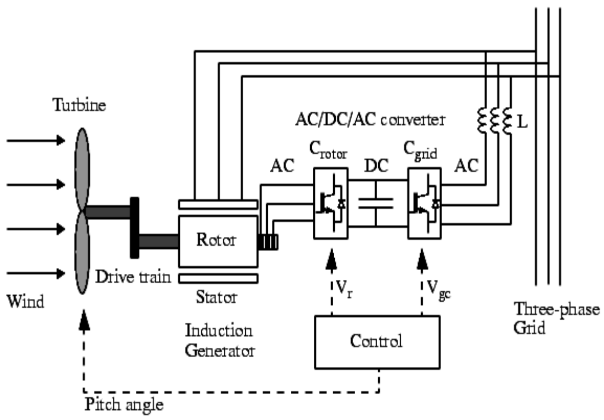

Fig. 2. The Wind Turbine and the DFIG System

The general model of the DFIG obtained using Park transformation is given by the following equations:

$$\begin{cases} v_{sd} = -R_s i_{sd} + \dfrac{d}{dt}\phi_{sd} - \omega_s \phi_{sq} \\ v_{sq} = -R_s i_{sq} + \dfrac{d}{dt}\phi_{sq} + \omega_s \phi_{sd} \\ v_{rd} = R_r i_{rd} + \dfrac{d}{dt}\phi_{rd} - \omega_r \phi_{rq} \\ v_{rq} = R_r i_{rq} + \dfrac{d}{dt}\phi_{rq} + \omega_r \phi_{rd} \end{cases} \tag{5}$$

Stator and rotor fluxes:

$$\begin{cases} \phi_{sd} = -L_s i_{sd} + M i_{rd} \\ \phi_{sq} = -L_s i_{sq} + M i_{rq} \\ \phi_{rd} = L_r i_{rd} - M i_{sd} \\ \phi_{rq} = L_r i_{rq} - M i_{sq} \end{cases} \tag{6}$$

The electromagnetic torque is done as:

$$C_{em} = \frac{pM}{L_s}\left(i_{rd}\phi_{sq} - i_{rq}\phi_{sd}\right) \tag{7}$$

The active and reactive power equations at the stator and windings are written as:

$$\begin{cases} P_s = -v_{sd} i_{sd} - v_{sq} i_{sq} \\ Q_s = -v_{sq} i_{sd} + v_{sd} i_{sq} \end{cases} \tag{8}$$

With:

$v_{sd}, v_{sq}, v_{rd}, v_{rq}$ stator and rotor voltage components.

$i_{sd}, i_{sq}, i_{rd}, i_{rq}$ stator and rotor current components.

$\phi_{sd}, \phi_{sq}, \phi_{rd}, \phi_{rq}$ stator and rotor flux components.

ω_s, ω_r stator and rotor pulsation.

R_s, R_r are stator and rotor resistances.

L_s, L_r are stator and rotor inductances.

M is mutual inductance.

The state model can then be written as:

$$\frac{d}{dt}[I] = [L]^{-1}\{[B][U] - [A][I]\} \tag{9}$$

With:

$$\begin{cases} [I] = \begin{bmatrix} i_{sd} & i_{sq} & i_{rd} & i_{rq} \end{bmatrix}' \\ [U] = \begin{bmatrix} v_{sd} & v_{sq} & v_{rd} & v_{rq} \end{bmatrix}' \end{cases} \tag{10}$$

$$[B] = diag[1 \quad 1 \quad 1 \quad 1] \tag{11}$$

$$[L] = \begin{bmatrix} -L_s & 0 & M & 0 \\ 0 & -L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} \tag{12}$$

$$[A] = \begin{bmatrix} -R_s & \omega_s L_s & 0 & -\omega_s M \\ -\omega_s L_s & -R_s & \omega_s M & 0 \\ 0 & \omega_r M & R_r & -\omega_r L_r \\ -\omega_r M & 0 & \omega_r L_r & R_r \end{bmatrix} \tag{13}$$

V. Field Oriented Control of DFIG

The control of the DFIG can establish an independent control of the active and reactive powers by the rotor voltages generated by an inverter [1-4]. The DFIG model can be described by the following state equations in the synchronous reference frame whose axis d is aligned with the stator flux vector.

$$\begin{cases} \phi_{sd}=\phi_s \\ \phi_{sq}=0 \end{cases} \quad (14)$$

By neglecting resistances of the stator phases the stator voltage will be expressed by:

$$\begin{cases} v_{sd}=0 \\ v_{sq}=v_s=\omega_s\phi_s \end{cases} \quad (15)$$

$$\begin{cases} \phi_s=-L_s i_{sd}+M i_{rd} \\ 0=-L_s i_{sq}+M i_{rq} \end{cases} \quad (16)$$

The arrangement of the equations gives the expressions of the voltages according to the rotor currents:

$$\begin{cases} i_{sd}=\dfrac{M}{L_s}i_{rd}-\dfrac{\phi_s}{L_s} \\ i_{sq}=\dfrac{M}{L_s}i_{rq} \end{cases} \quad (17)$$

We lead to an uncoupled power control; where, the transversal component of the rotor current controls the active power. The reactive power is imposed by the direct component i_{sd}.

$$\begin{cases} P_s=-v_s i_{sq}=-\dfrac{v_s M}{L_s}i_{rq} \\ Q_s=-v_s i_{sd}=-\dfrac{v_s M}{L_s}i_{rd}+\dfrac{v_s{}^2}{L_s\omega_s} \end{cases} \quad (18)$$

To properly control the machine, we will set the relationship between the rotor currents and voltages applied to the machine. Substituting in equation (17) currents by their value in equations (6) we obtain:

$$\begin{cases} \phi_{rd}=\left(L_r-\dfrac{M^2}{L_s}\right)i_{rd}+\dfrac{M}{L_s}\phi_s=\sigma L_r i_{rq}+\dfrac{M}{L_s}\phi \\ \phi_{rq}=\left(L_r-\dfrac{M^2}{L_s}\right)i_{rq}=\sigma L_r i_{rq} \end{cases} \quad (19)$$

And replacing the flux in the relation (5) we obtain:

$$\begin{cases} v_{rd}=R_r i_{rd}+\sigma L_r\dfrac{di_{rd}}{dt}-\sigma L_r\omega_r i_{rq} \\ v_{rq}=R_r i_{rq}+\sigma L_r\dfrac{di_{rq}}{dt}+\sigma L_r\omega_r i_{rd}+\dfrac{M}{L_s}\omega_r\phi_s \end{cases} \quad (20)$$

Where :

$\sigma=1-\dfrac{M^2}{L_s L_r}$ is leakage factor .

In steady state operation the voltage expressions are:

$$\begin{cases} v_{rd}=R_r i_{rd}+e_{rd} \\ v_{rq}=R_r i_{rq}+e_{rq}+e_\phi \end{cases} \quad (21)$$

With:

$$\begin{cases} e_{rd}=-\sigma L_r\omega_r i_{rq} \\ e_{rq}=\sigma L_r\omega_r i_{rd} \\ e_\phi=M/L_s\,\omega_r\phi_s \end{cases} \quad (22)$$

The inverter connected to the rotor of the DFIG must provide the necessary complement frequency in order to maintain constant the stator frequency despite the variation of the mechanical speed.

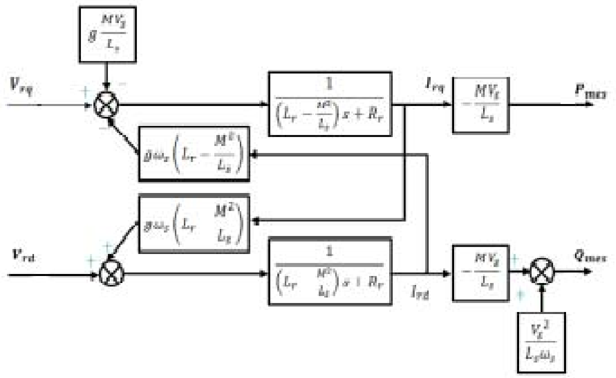

Fig. 3 Simplified Model of the DFIG

The model of the field oriented control of DFIG is shown by the figure 4:

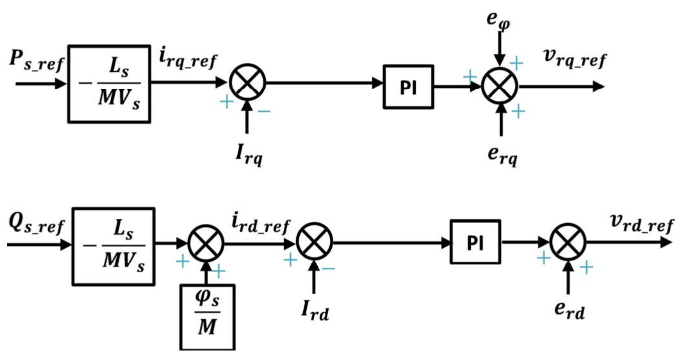

Fig. 4. Model of the field oriented control of DFIG

The independent control of active and reactive powers is shown in Figure.5 and 6, the both axes are controlled separately. This result is very interesting for wind energy applications to power system voltage improvement.

Figures 5 and 6 show the performance of the active and reactive power control.

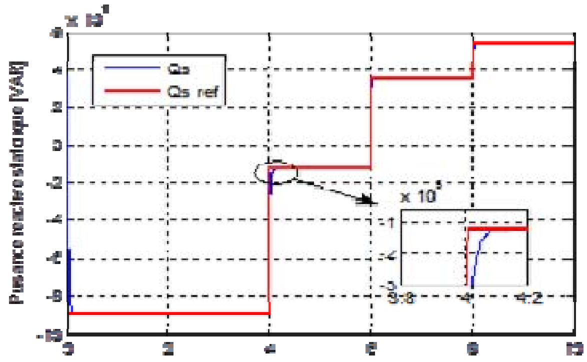

Fig. 5. Reactive power of DFIG using F.O.C

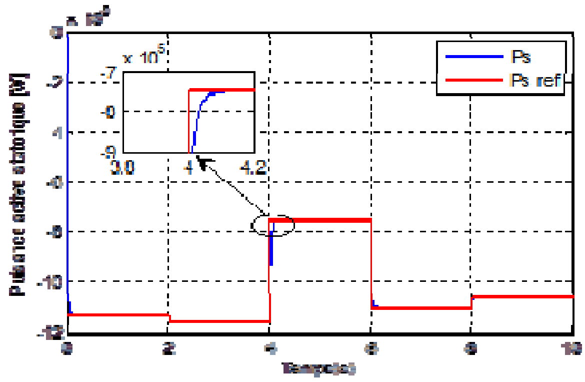

Fig. 6. Active power of DFIG using F.O.C

VI. Modeling of Power System

A single machine power system is used to demonstrate the fundamental concepts and principles of voltage control using wind turbine when its subjected to large disturbances:

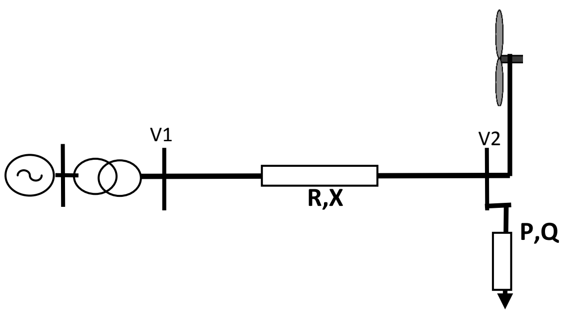

Fig. 7. A Single machine power system with wind generator

The wind power controller used for this purpose is given in figure.8, where k_{wind} and T_{wind} are the gain and time constant of the wind power controller respectively, in which the output power controller ($Q_{controller}$) will be used as specific or reference power to be produced by the DFIG.

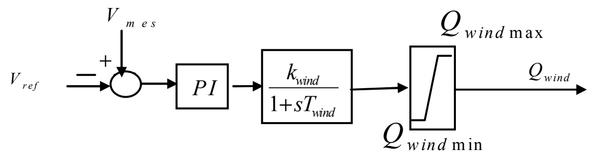

Fig. 8. Reactive wind power controller.

Where:

V_{ref}, V_{mes} are the reference and the measured voltage bus respectively.

The proposed power modulation Q_{wind} has been incorporated in the power system in which any deficit or excess of voltage is compensated by the DFIG.

$$\Delta V_{1-2} = \frac{PR + (Q - Q_{wind})X}{V} \qquad (23)$$

A. DFIG controlling using Neural Networks

The idea of this control consists a replacing the PI controller by artificial neural networks controller.

Figures 9 and 10 show the Neural Network controller used for reactive power control of DFIG , it consists of two hidden layers having a pureline and sigmoid activation function. The output layer consists of one output neuron having linear activation function. For training of the artificial neural networks, we have used backpropagation training algorithm,

The input signals chosen are the measured and reference voltage and the reactive power as output .These variables are determined from field oriented control.

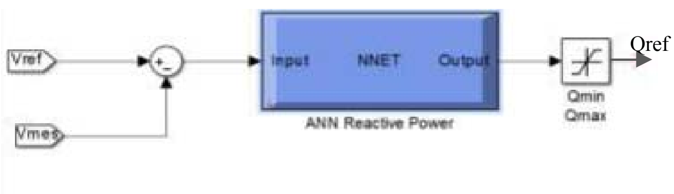

Fig. 9. ANN controller Simulink model for reactive power.

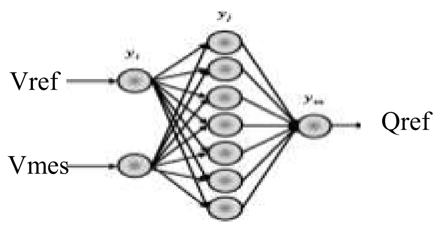

Fig. 10. ANN used for predicting reactive power

VII. RESULTS ANALYSIS

The efficiency of the proposed controller have been tested on a single machine test system connected to a wind farms as shown in Fig.7, a sudden variation of voltage of generator is applied at t=[3s-4s] (V_1= 1.1 V_{ref}) and at t=[5s-6s] (V_1= 0.9 V_{ref}) . Results are given in the following figures:

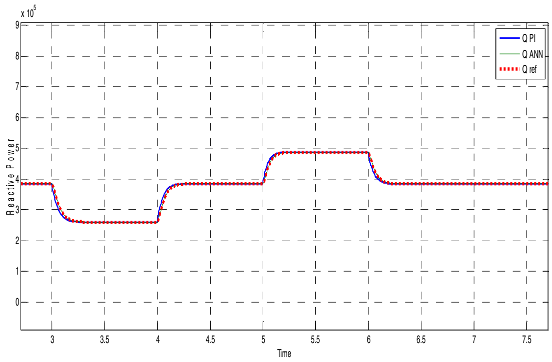

Fig. 11. Reactive power of wind turbine injected after disturbances

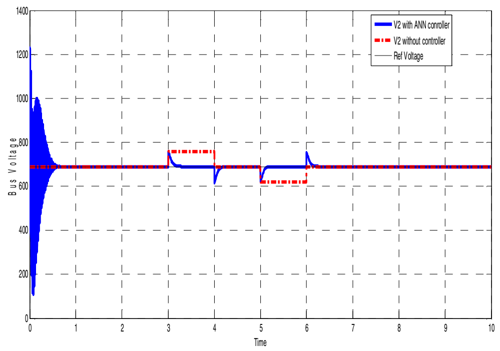

Fig. 12. Voltage control using reactive wind controller

VIII. CONCLUSION

This paper investigates the use of reactive power produced by wind turbine to improve the power quality. A PI and neural networks controllers have been successfully applied to improve power system voltage stability, which a new control strategy of reactive wind power has been successfully applied. The modeling of various components of power systems is discussed, which the wind turbine is based on a doubly-fed induction generator (DFIG), a field-oriented control is used to control of the power flow exchanged between the DFIG and the power system. The rapid controllability of injected reactive provided by wind turbines are used to control and improve of the power system voltage. Simulations performed on single machine test system indicate that the both proposed controllers ANN and PI controller can improve voltage stability. Results indicate that the reactive wind power control can significantly improve the system performance. Reactive power is a quantity that has become fundamental to the understanding and analysis of AC electric power systems.

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