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Transient Stability of Power Systems with Different Configurations for Wind Power Integration

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Abstract - **Previous transient stability studies investigating the effects of wind power integration into a conventional power system assume the insertion point of the wind-generating units to be at the same bus and interconnection voltage as the synchronous generators they are substituting or complementing. While these assumptions offer some insights into the effects of the wind on the existing system, important points about the physical distance and interconnection voltage of wind farms with respect to the conventional power system are neglected. This paper analyzes the effects of integrating doubly-fed induction wind turbine generators through different transmission line configurations and at different buses. The IEEE 14-bus test system is used in order to compare results with previous works. Results show that connecting wind generators through transmission lines and to different buses introducesdelays in the speed dynamic responses of existing synchronous generators. These delays in turn affect the bus voltage oscillations. Results also show that there is no significant effect on the base cases when using different interconnection voltages to connect the wind. The results of this study can be used by power system operators when deciding how to connect wind farms to an existing power network when optimizing for stability response to a large fault. Overall, wind farms should be connected through additional transmission lines to buses near where synchronous generators are located and further away from loads and higher risk fault areas.**

I. Introduction

As power generated from wind has continued to grow over the last couple of decades, many studies have investigated the modeling of the different wind turbine generators and their effects on power system stability. Typically, these studies have focused heavily on the assumptions taken in the modeling of the wind turbine generator and its associated controls [1-4]. There has been substantially less focus placed on the assumptions taken in the modeling of the power system. While the existing works may offer some insights, the underlying assumptions may affect significantly the outcome of any analysis. In this paper, one of these assumptions is brought to light in an effort to encourage researchers to develop better power system models that truly represent the transmission configurations for integrating large wind farms into the grid. The common assumption that is challenged in this paper is the insertion of doubly-fed induction generators (DFIGs) at the original synchronous generator bus location when simulating the transient stability effects of wind power.

Large wind farms that are connected directly to the transmission system are typically located offshore or in remote areas due to their size and lack of aesthetic appeal. Also, the large wind farms are often not linked to the rest of the power system through the same interconnection voltage as the synchronous generators. In both of these cases, additional transmission lines and transformers are needed in order to properly integrate the wind farms into the power system. This paper analyzes the transient stability effects of these power systems when the different transmission configurations are taken into account. Based on the results, conclusions are made regarding the optimal way to connect doubly-fed induction wind turbine generators (DFIGs) to an existing power system for the purposes of providing enhanced transient stability in the presence of large disturbances.

Well-known transmission line, transformer, and generator models are summarized in Section II. The integration of these models into a complete power system model is provided in Section III. This section also provides an overview of transient stability analysis. In Section IV, the IEEE 14-bus test system and the various transmission line modifications of interest are presented. Simulation results comparing the transient stability effects of the modifications are also shown in Section IV. Concluding remarks are provided in Section V.

II. Line, Transformer, and Generator Model

This section summarizes the well-known models used to represent transmission lines and transformers for power system studies. Synchronous generators and DFIG generators used to represent wind turbines are also summarized. All of the individual components are combined into a complete power system model using a set of differential-algebraic equations, and this integration is discussed.

A. Transmission Line and Transformer Models

Here, we only consider short transmission lines. A transmission line is defined as short if it is less than 1500 km

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[5]. Short transmission lines can be represented using the a π lumped model of Figure 1.

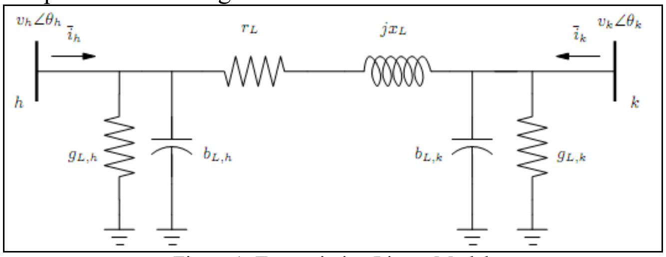

Figure 1: Transmission Line π Model

The labels, r_L and x_L represent the lumped series resistance and reactance respectively while $g_{L,h}$, $g_{L,k,}$ and $b_{L,h}$,$b_{L,k}$ represent conductances and susceptances. The subscripts h and k denote parameters associated with the sending-end and the receiving-end respectively.

The complex powers injected at each node are represented by

$$\bar{s}_h = \bar{v}_h \bar{i}_h^* \tag{1}$$

$$\bar{s}_k = \bar{v}_k \bar{i}_k^* \tag{2}$$

where the injected currents $\bar{i}_h$ and $\bar{i}_k$ can be expressed in terms of the node voltages and network admittance matrix $\bar{Y}$ as

$$\begin{bmatrix} \bar{i}_h \\ \bar{i}_k \end{bmatrix} = \begin{bmatrix} \bar{y}_L + \bar{y}_{L,h} & -\bar{y}_L \\ -\bar{y}_L & \bar{y}_L + \bar{y}_{L,k} \end{bmatrix} \begin{bmatrix} \bar{v}_h \\ \bar{v}_k \end{bmatrix}. \tag{3}$$

The admittances, represented by the $\bar{y}$, are related to the conductances and susceptances as follows:

$$\bar{y}_L = g_L + jb_L . \tag{4}$$

The admittances for each transmission line are aggregated into the network admittance matrix $\bar{Y}$ in (3). The network admittance matrix is crucial to the power flow solutions and it also contributes to the system's state matrix which is used for stability analysis.

On the other hand, transformers can be modeled as a transmission line with a series impedance and a shunt admittance at the sending-end bus that models iron losses and magnetizing susceptance. The main difference in modeling the transformer and transmission line is that transformers have a complex nominal tap ratio $me^{j\phi}$ that allows modifying the magnitude and phase angle of the bus voltage sending and receiving ends [5].

B. Synchronous Generator and DFIG Models

Synchronous machine models are used to represent conventional thermal plants. The most basic model is the classical model, which can be represented as a second order system with the following differential equations

$$\dot{\delta} = \Omega_b(\omega - 1) \tag{5}$$

$$\dot{\omega} = \frac{(p_m - p_e - D(\omega - 1))}{M} \tag{6}$$

where

δ : rotor speed

ω : rotor angle

Ω_b : base frequency

p_m, p_e : electrical power, mechanical power

D : damping coefficient

M : mechanical starting time ($M = 2H$)

H : inertia constant

The drawback of the classical 2nd order model is that it neglects all electromagnetic dynamics. Higher order models that include transient and subtransient phenomena are needed for stability analysis. In this paper, we use a 6th-order model to represent the synchronous machines. The 6th order model is described by (5) and (6) along with differential equations for transient voltages $\dot{e}'_q$ and $\dot{e}'_d$ and subtransient voltages $\dot{e}''_q$ and $\dot{e}''_d$. These variables represent the dynamics of the dc field winding and of the rotor core induced currents and the fast dynamics of damper windings respectively. Full derivation and details on this model can be found in [6-7]. Model comparisons, detailed modeling, and the explanation of assumptions for higher-order versus reduced-order models can be found in various references [2],[5],[6].

In addition to the six differential equations, the machine model also has six algebraic equations in the following variables: active power p, reactive power q, bus voltage magnitude v, bus voltage angle θ, mechanical power p_m and field voltage v_f. Complete details on the algebraic equations can be found in [5],[6].

The general structure of a DFIG wind turbine model and its associated controls is shown in Figure 2 [1].

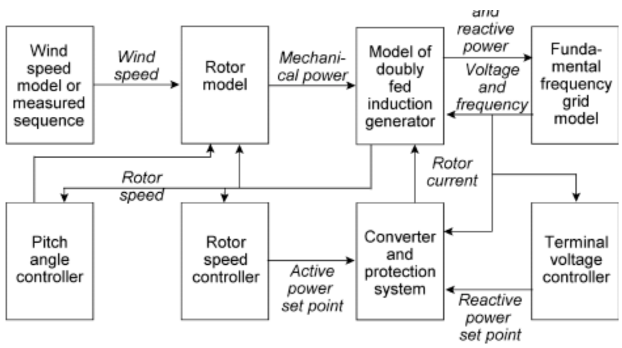

Figure 2: General DFIG Wind Turbine Model with Associated Controls

The equation of motion for the rotor modeled as a single shaft is described by the first-order differential equation

$$\dot{\omega}_m = \frac{\tau_m - \tau_e}{2H_m} \tag{7}$$

where ω_m is the rotational speed, τ_m and τ_e are the mechanical and electrical torques respectively, and H_m is the mechanical inertia constant.

The wind speed is an input to the rotor model. The rotor model assumes an algebraic relationship between the wind speed, v_w and the mechanical power extracted from the wind, p_w as described below [1].

$$p_w = \frac{\rho}{2} c_p(\lambda,\theta) A_r v_w^3 \tag{8}$$

where c_p is a performance coefficient function and A_r is the area swept by the rotor. Mechanical power is then related to mechanical torque by

$$\tau_m = \frac{p_w}{\omega_m}. \tag{9}$$

Since converter dynamics are fast with respect to electromechanical transients, their models can be highly simplified [1]. The converter is modeled as an ideal current source where the d and q-axis rotor currents, i_{qr} and i_{dr}, are state variables used for voltage and rotor speed control respectively. A pitch angle controller uses the actual value of the rotor speed to control the blade pitch angle.

III. SYSTEM MODEL AND TRANSIENT STABILITY ANALYSIS

This section discusses the integration of the individual device models discussed in Section II into a power system model. The methodology for performing transient stability analysis is also discussed.

A. Integrated Power System Model

The non-linear differential and algebraic equations that represent the individual device models can be combined to create a system model. The general equations are shown below [8]

$$\begin{bmatrix} \dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} f(x,y) \\ g(x,y) \end{bmatrix} \tag{10}$$

where x is the vector of state variables that typically include the machine model dynamics and controller dynamics and y is the vector of algebraic variables that typically include the algebraic equations associated with the machine models, transmission line models, and the power flow equations. The function f is a nonlinear vector function that represents the system differential equations, and g is a vector function that represents the system algebraic equations.

The complete Jacobian matrix of Equation (10) can be written as follows

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} f_x & f_y \\ g_x & g_y \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \tag{11}$$

where f_x and f_y are the Jacobian terms associated with the partial derivatives of the state-space equations with respect to the state and algebraic variables, while g_x and g_y represent the Jacobian terms associated with the partial derivatives of the algebraic equations with respect to the state and algebraic variables. Under the assumption that g_y is non-singular, Δy can be eliminated from (11) to obtain a more compact expression in terms of Δx as follows:

$$\Delta\dot{x} = \left(f_x - f_y g_y^{-1} g_x\right)\Delta x. \tag{12}$$

The term within the braces is usually referred to as the state matrix and it is denoted as A_s.

It thus follows that any modifications in the transmission lines configurations will affect the state matrix A_s. This is because the modified power system with additional transmission lines or the insertion of wind farms at different locations will yield different power flow equations that will change the algebraic equations that make up g. Additionally, the system of variables making up x will be different due to the modified number of transmission lines and transformers in the system. In summary, the proposed changes will modify f_y, g_x and g_y.

B. Transient Stability Analysis

Transient stability deals with the ability of a power system to maintain synchronism when subjected to a large or severe disturbance [9],[10]. Examples of a large disturbance include loss of generation, loss of a large load, or a transmission line fault. Transient stability analysis looks at the system response to these large disturbances through time domain simulations of the system's states and algebraic variables. Synchronous generator rotor angle and speed as well as bus voltages are some of the system variables typically affected by large disturbances.

In the event of a large disturbance, the non-linear differential algebraic equations representing the power system can not be linearized about an operating point since the perturbation can not be assumed to be sufficiently small. Instead, numerical integration methods for solving the high-order differential equations are needed. Many different techniques are available, and the most commonly used techniques derive from the explicit forward Euler's method.

The main objective of transient stability analysis is to determine whether or not the system is stable based on the system's time domain simulation response when the numerical integration is solved. If the time domain simulation diverges, then the system is unstable. Otherwise, the system is stable. The dynamic models associated with the machines that make up the f_x Jacobian are almost always stable on their own. For this reason, the product $f_y g_y^{-1} g_x$ is typically called the degradation matrix, D, since it degrades the stability of the f_x matrix [5]. Also, it is this degradation matrix that is modified when the power system configuration is changed. Thus, it is important to study the system's behavior under the new sets of conditions.

IV. CASE STUDY: IEEE 14-BUS SYSTEM

In this section, an overview of the IEEE 14-bus test system is provided. Then, different case studies are shown where modifications are made to the test system in order to analyze the effects of different transmission line configurations on the transient stability of the system in the presence of wind power penetration.

A. IEEE 14-Bus System

The IEEE 14-bus system of Figure 3 [5]. is a common benchmark used to evaluate the impact of various disturbances on power systems. In the system, buses 1 and 2 are synchronous generator buses that provide active power to the 11 loads in the system. Buses 1 and 2 have generators rated at 615 MW and 60MW respectively. Synchronous compensators are located at buses 3, 6, and 8, and they either generate or absorb reactive power based on the balancing needs of the system.

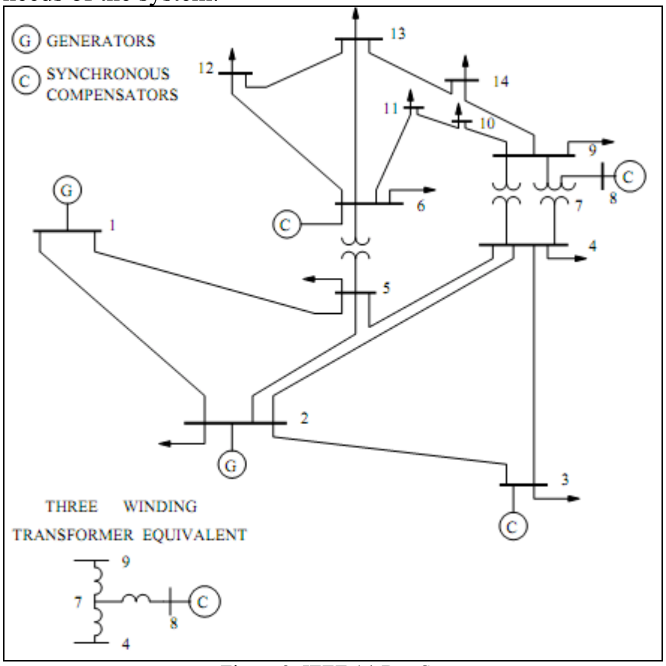

Figure 3: IEEE 14-Bus System

B. Case Studies

There are four different comparisons shown in this section. A diagram of the modifications for each of the comparisons is provided. Each comparison is followed up by analysis in the form of time domain simulations for the synchronous generator speed and voltage at bus 1. The focus is on bus 1 because this is where the majority of generated power occurs in the original test system, and this is where the largest rated synchronous generator is located. These factors make this bus most vulnerable to instabilities due to a transient fault. Additionally, simulations show that the synchronous machines at buses 1 and 2 oscillate in the same manner, so it would be somewhat redundant to show all of the simulations for the synchronous generator at bus 2.

In all cases, a three-phase transmission line fault is used as the disturbance. This is simulated through a line 2-4 outage occurring at $t = 1$ s that is cleared at $t = 1.2$ s. In all cases, we also assume there is deep penetration of wind. A wind generated power of 308MW is connected to bus 1. This represents approximately 50% of the total power generated at that bus. For each of the cases that include the integration of wind, the synchronous generator power at bus 1 is reduced to 307 MW. Generally, the main assumption challenged by the following cases is that large wind farms are connected to synchronous generator buses without the need for additional transmission lines or transformers to account for the distance or interconnection voltages between the different generators. Each case focuses on a specific issue in an attempt to reach a conclusion on the best way to connect wind farms to an existing power system when optimizing for transient stability.

1. *Case A – Effects of adding Wind to Bus 1 with and without Transmission Lines (TL).*

In this case, we are interested in analyzing the effects of adding wind to the system at bus 1 with and without additional transmission lines. Figure 4 shows the different configurations considered here. For all diagrams, "G" denotes a synchronous generator, "W" denotes a wind farm composed of DFIGs, and "T" denotes a transmission line system. When the interconnection voltages between any two buses are different, the transmission line system includes a transformer that either steps up or steps down the voltage. For the case considered here, a 69 kV interconnection is used for the wind generator. Since 69 kV is also the original voltage at bus 1, no transformer is needed.

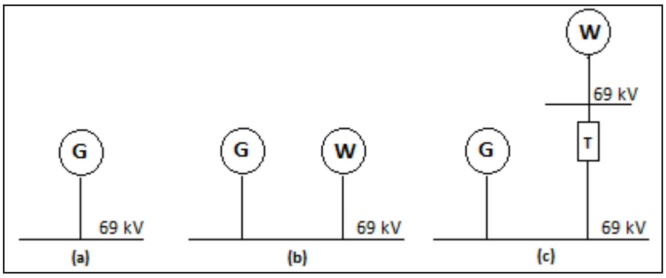

Figure 4: Case A – Effects of adding Wind with and without TL to Bus 1

Figures 5 and 6 show the time-domain responses for the different cases in Figure 4 when the system is subject a momentary disturbance. In all simulations below, the *x*-axis denotes time in units of seconds while the *y*-axis is denoted in per-unit (p.u.) voltage or speed. Figure 5 illustrates the effects of integrating wind power generator into a power system. The system becomes more oscillatory and settles to a different steady state value of 1 p.u. There is also an apparent shift or delay caused when adding the transmission line.

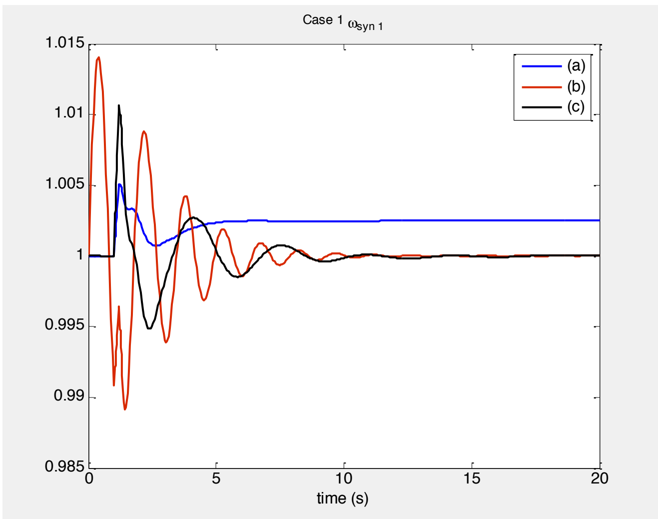

Figure 5: Comparing transient stability effects on ω_{syn1} for cases in Fig. 4

Figure 6 shows the time-evolution of the voltage at bus 1 for the three different scenarios. The outage at t = 1s causes a significant undershoot during the transient periods. The inclusion of transmission lines and wind generators led to slight improvement in the system's damping and a slight reduction in the peaks as compared to when the wind generator is connected directly to the same as bus as the synchronous generator.

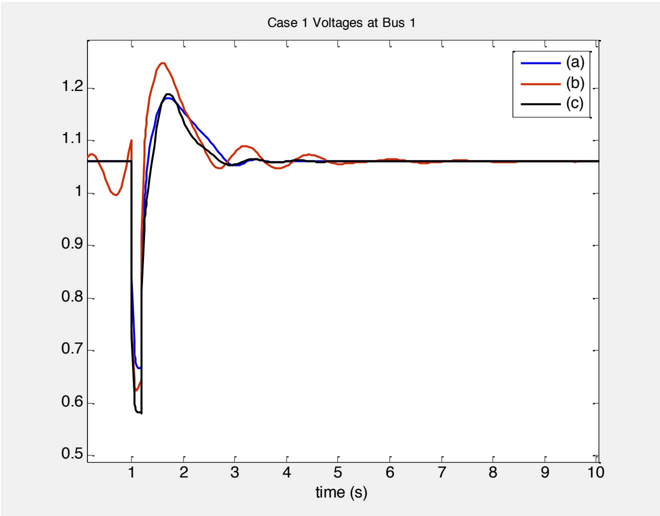

Figure 6: Comparing transient stability effects on V_{bus1} for cases in Fig. 4

2. *Case B – Effects of adding Wind through Different Interconnection Voltages*

In this case, we are interested in analyzing the effects of adding wind to the system at bus 1 through different interconnection voltages. It is important to investigate this because wind farms may be connected to an existing power system at a different voltage level as compared to those of the synchronous generators. Figure 7 shows the different configurations under study. Figure 7(a) is the base case where the wind generator is connected at same interconnection voltage as the synchronous generator. Hence, there is no need for voltage transformation. The other two cases have transformers for voltage step-up (Figure 7(b)) and for voltage step-down (Figure 7(c)).

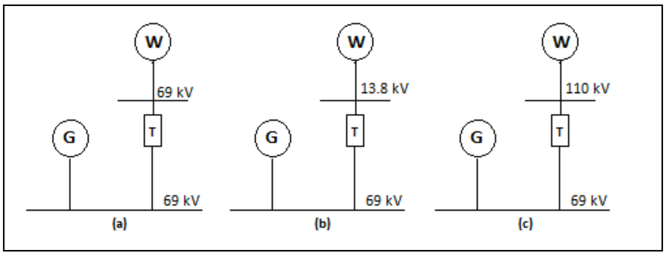

Figure 7: Case B – Effects of Adding Wind through Different Interconnection Voltages

The simulated results of Figures 8 and 9 show that voltage transformation has little or no effect on the transient behavior of the system.

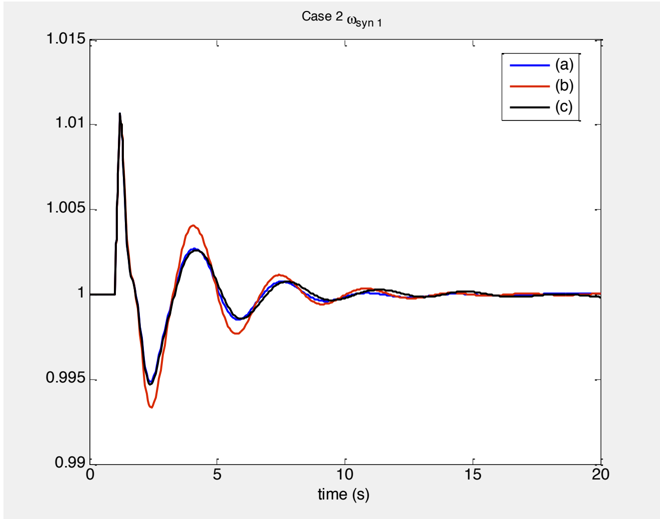

Figure 8: Comparing transient stability effects on ω_{syn1} for cases in Fig. 7

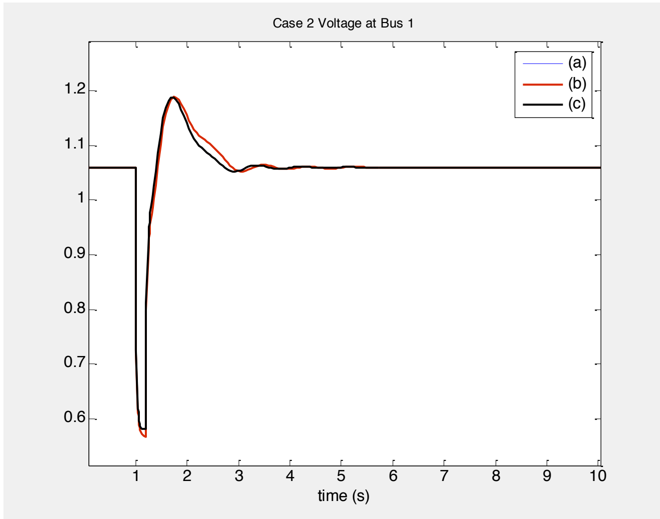

Figure 9: Comparing transient stability effects on V_{bus1} for cases in Fig. 7

3. *Case C – Effects of adding Wind to Different Buses*

Here, we are interested in connecting the wind to different power system buses. It is possible for wind farms to be located near other power system buses and away from the main point of conventional power generation. Figure 10 shows the different configurations where the wind generator is connected in step to bus 1, bus 8 and bus 14.

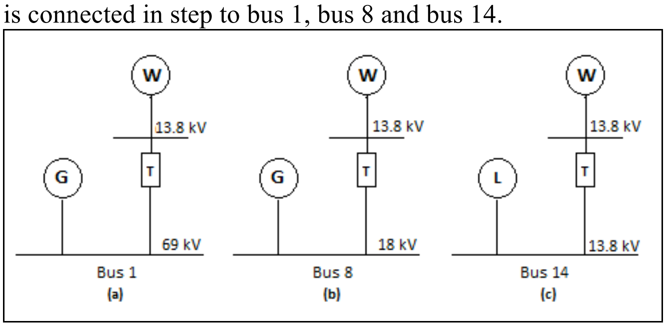

Figure 10: Case C – Effects of Adding Wind to Different Buses

Figure 11 shows that the bus location to which a wind generator is connected has significant effect on the frequency evolution of the system. Specifically, as the wind generator is moved farther away from bus 1, the more the phase-shift in the frequency oscillations. There is not much effect on the bus voltage in all scenarios as shown in Figure 12.

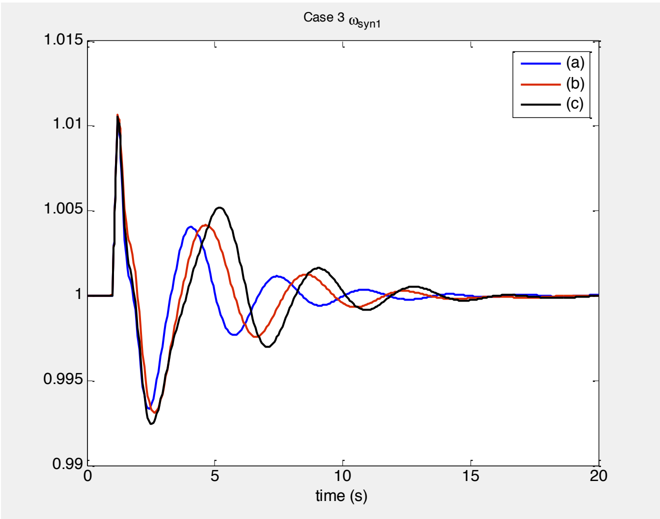

Figure 11: Comparing transient stability effects on ω_{syn1} for cases in Fig. 10

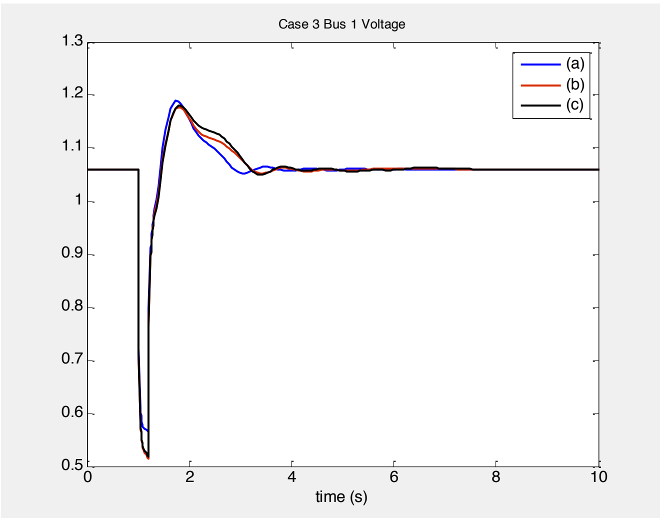

Figure 12: Comparing transient stability effects on V_{bus1} for cases in Fig. 10

4. *Case D – Effects of Adding Wind through Multiple TLs*

In this case, we are interested in seeing the effects when the wind generation is fed into more than one bus. An example considered here is shown in Figure 13.

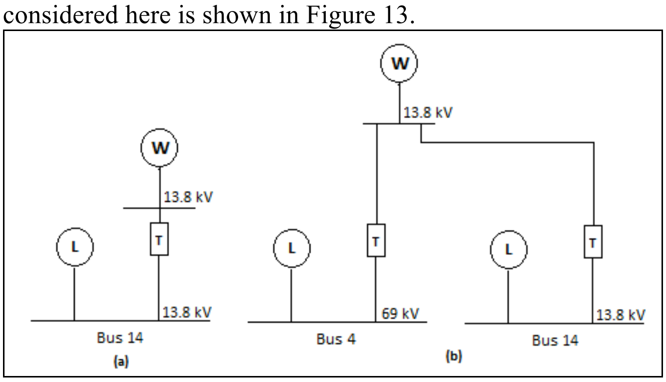

Figure 13: Case D – Effects of Adding Wind Through Multiple TLs

As shown in Figures 14 and 15, the idea of connecting the wind to multiple buses does not seem to have significant effect on the transient stability of the system.

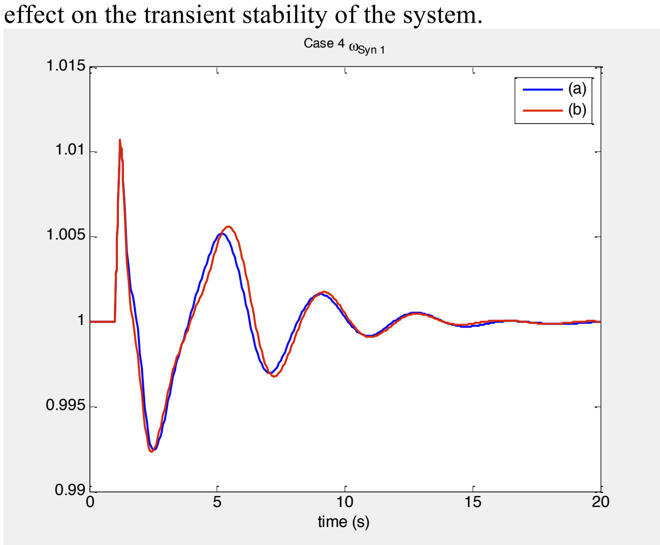

Figure 14: Comparing transient stability effects on ω_{syn1} for cases in Fig. 13

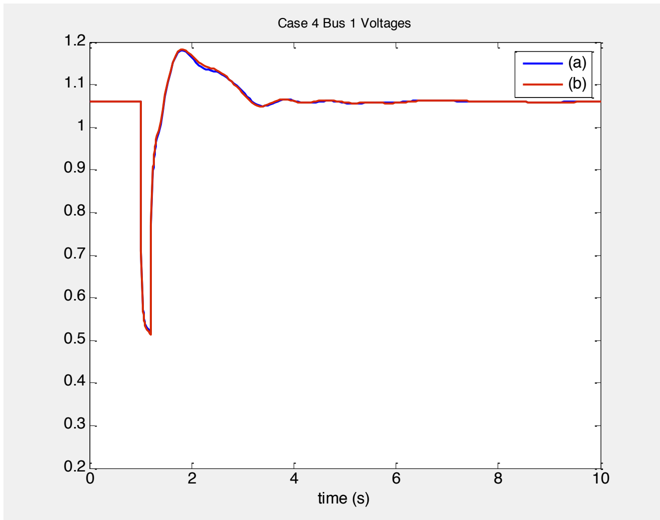

Figure 15: Comparing transient stability effects on V_{bus1} for cases in Fig. 13

5. *Further Discussion*

It should be noted that the effects of disturbance on a bus voltage depends on its proximity to the location of fault. As shown in Figure 16, the voltage at bus 4 is more negatively impacted as compared to buses (e.g. bus 1) farther away from the fault location.

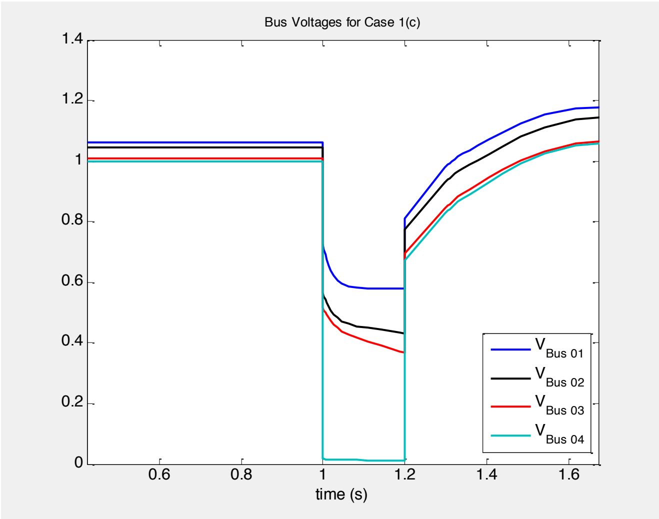

Figure 16: Comparing transient stability effects on different bus voltages for cases in Fig. 13

V. CONCLUSION

This paper has studied the transient stability effects on a conventional power system when large integration of wind power is connected through various transmission line configuration schemes. Based on the simulation results, connecting the wind power generating units through additional transmission lines both at Bus 1 and at other buses had a noticeable effect on the transient stability of the system (shown in Cases A and C), while varying the interconnection voltage of the wind power to the rest of the system had a negligible effect (shown in Cases B and D). This type of analysis can be used by power system operators when deciding how to best integrate a large wind farm into an already existing power network.

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