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Hybrid transient stability analysis of power systems having large penetration of doubly fed induction generator based wind energy conversion system

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Wind power has emerged as one of the most popular forms of renewable energy by virtue of its free availability. The larger proliferation of wind generators presents significant challenges to the stable operation of today's power systems. Due to the advantages of Doubly-Fed Induction Generators (DFIG) over other wind generators, the majority of wind farms are using variable speed wind turbines equipped with DFIG. In this paper, the impacts of grid- connected large DFIG based wind farms on power system Transient Stability (TS) is studied. The well-known Western System Coordinated Council (WSCC) 3-machine, 9-bus system is used as the test system to carry out the said analysis. The test system - with DFIG based wind farm integrated into it, is modeled and analyzed in a simulation environment.

Keywords: *DFIG; hybrid transient stability analysis; wind turbine; corrected transient kinetic energy (CTKE).*

1.0 INTRODUCTION

With increasing thrust on environmental sustainability and limited reserve of fossil fuels, renewable energy sources emerged as the natural alternative to fuel economic growth across the globe. Wind energy, as one of the freely available renewable electricity sources, is gaining increasing significance throughout the world. The components of a typical Wind Energy Conversion System (WECS) include:

1) Wind turbine 2) Generation and 3) Inter connection apparatus and control system. Wind turbines can be designed for constant-speed or variable speed operation, based on which the WECS can be classified as 1) Fixed speed and 2) Variable speed. Ref [1] presents an account of the various types of WECS.

Fixed speed wind turbines with induction generator have been widely used because of being reliable, durable and simple. Also the cost of its electrical elements is low. There are less contributions in improving system dynamic behavior due to the risks of uncontrollable reactive power consumption, mechanical stress and restrained power quality. Especially, because of its constant speed operation, all fluctuations within the wind speed are similarly transmitted as fluctuations within the mechanical torque after which as fluctuations in the electrical power on the grid [2]. With development in power electronic converters nowadays, the variable-speed wind turbine, has developed as the leading kind among the different newly installed wind generators. It has to be mentioned that the DFIG based variable speed wind energy conversion system is currently the most popular one because of its light weight, higher energy yield/cost, capability of controlling reactive power and the reason that the converter

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rating of approximately 20%-30% of the full machine power is needed [3,4].

It is known that the electrical behavior of DFIGs which are integrated with the system using power electronic converters [5] is quite different from the conventional synchronous generators. Power engineers have to confront a series of challenges due to the integration of huge wind- based electricity with the existing power systems. One of the critical problems engineers need to face is the effect of wind power penetration on the dynamic behavior of the system, e.g. the impact on TS. Wind generators- like the DFIG based ones - are integrated into the main grid through power-electronic-based inverters, which decouple the DFIG from the main grid all through disturbances. Subsequently, those generators generally supply no inertial support all through power system transients. Therefore, the inertial support from the rotating mass – which is typical of any synchronous generator - is missing in the case of Wind turbines interfaced through PE devices. Therefore, the effect of DFIG on TS [6] of the power system is worth investigating.

The studies carried out so far to investigate the effect of the presence of DFIG on TS of the system [7-10] has been done using Time Domain Solution (TDS) Method [11]. The existing Transient Stability Analysis (TSA) methods could be classified as: TDS Method, Direct Method and Hybrid Method.

TDS approach is the most typically used approach to solve the set of nonlinear equations describing the system dynamic equations, with a view to find out the TS [11]. The TDS is the most exact method to assess the TS. Regardless of its advantages, the TDS technique has shortcomings. Firstly, it is inherently time-consuming due to the step by step integration method involved in solving the differential equations. Secondly, it simply yields a yes or no kind of answer on the issue of stability, with no indication on the degree of stability. The equal area criteria [13] can be applied for the judgment of the TS, but this method has some modeling restrictions.

The direct method of TSA primarily based on the Transient Energy Function (TEF), named Direct TEF [12] hereafter, gives a second tool to the utility engineers for dynamic risk assessment. One of the advantages of the direct technique is its capability of yielding a stability index, y Margin (TSM), which measures the relative stability of the machine under observation. The transient energy margin permits rapid derivation of TS tive methods. Determination of the critical transient energy value is vital to the use of direct methods. This in turn requires identifying the controlling UEP (Unstable Equilibrium Point). However, Direct Methods suffer from some inherent shortcomings viz., pability because the transient energy functions are available only for limited types of power system models.

A Hybrid method is presented in [14] to evaluate the TS of a system. The term Hybrid comes from the fact that it combines both the time domain technique and the TEF evaluation in solving stability problems and producing a stability index similar to the transient energy margin in the Direct - TEF method [15]. Beyond the fault clearing, a time- domain simulation is initially done and using the concept of potential energy boundary surface (PEBS) crossing [16] a TSM, called hybrid TSM, is calculated.

In this paper, the impacts of grid-connected large doubly-fed induction generator based wind farms on power system TS is studied and TSA is carried out using Hybrid Method. Simulation studies are carried out in ETAP 12.6.0 to show

and compare the transient performance of the WSCC 3- machine, 9-bus system [17] with and without wind power integration during a severe grid fault. This paper is organized as follows: Section 2 presents the problem formulation; Section 3 presents Power system model; Section 4 presents Solution methodology; Simulation results are discussed in Section 5. Conclusions are drawn in Section

2.0 PROBLEM FORMULATION

From the Commencement of fault, the generators present in the system may be divided into two groups viz. Critical generators and Non Critical Generators depending on their dynamic behaviour. Those generators which are responsible for the loss of synchronism are classified as Critical Generators and the rest as Non-Critical Generators. Information related to the multi-machine system dynamics is obtained using time-domain-simulation. Depending on the criteria outlined in [18], the machines are grouped into critical and non-critical machines. The relative motion between the critical (represented by suffix *cr*) and non- critical generator (represented by suffix *sys*) groups can be described by the following equation:

$$M_{eq}\dot{\omega} = \frac{M_{eq}}{M_{cr}}\sum_{i=1}^{n_{cr}}(P_{mi}-P_{ei}) - \frac{M_{eq}}{M_{sys}}\sum_{i=1}^{n_{sys}}(P_{mi}-P_{ei}) = P_a \quad ...(1)$$

where, $\omega = \omega_{cr} - \omega_{sys}$

$$\omega_{cr} = \sum_{i=1}^{n_{cr}} M_i \tilde{\omega}_i \Big/ M_{cr} \quad , M_{cr} = \sum_{i=1}^{n_{cr}} M_i$$

$$\omega_{sys} = \sum_{i=1}^{n_{sys}} M_i \tilde{\omega}_i \Big/ M_{sys} \quad , M_{sys} = \sum_{i=1}^{n_{sys}} M_i$$

$$M_{eq} = M_{cr} M_{sys} \Big/ (M_{cr} + M_{sys})$$

Where:

Mi: Inertia constant of machine i;

ωi: Speed of machine i with respect to COI; Pmi: Mechanical power input of machine i; Pei: Electrical power output of machine i

As shown above, ω is the speed difference between two sets of advanced and non-advanced generators.

Corrected Transient Kinetic Energy (CTKE) [19] is the kinetic energy resulted from the speed difference.

Thus, $CTKE = \frac{1}{2} M_{eq}\omega^2$ ...(2)

A power system is stable if it absorbs the CTKE and convert it to the potential energy. TSM is the distance between the first CTKE peak and the critical first swing CTKE peak [20].Calculation of the TSM is done as per the method described in [20].

3.0 POWER SYSTEM MODEL

To investigate the effect of wind power integration on the TS of power systems, WSCC 3-machine, 9-bus system [17] shown in Figure 1 is used. The base values for power and frequency are taken as 100 MVA and 60 Hz respectively. In this study, the Synchronous Generator (SG) G3 (bus 3) is replaced by a large wind farm. It includes over 57 individual Wind Turbine Generator's (WTG). Each individual wind turbine is equipped with a DFIG that represents a 1.5 MW WTG system.

4.0 SOLUTION METHODOLOGY

The Hybrid method of TSA aims to produce TSM by combining both the TDS and TEF evaluation. Initially, the TS analysis is performed using TDS method to determine the critical clearing time of the considered test system which is subjected to a disturbance. To analyze the state of the system, the swing curves are plotted for different fault clearing times. The speed values of generators are read as an input data to the MATLAB program to evaluate the CTKE using Eq. (2) and the TSM is calculated based on the CTKE calculations.

5.0 SIMULATION RESULTS

TSA is carried out to observe and compare the transient performance of the test system. Figure 1. shows the one-line diagram of the test system (viz. the WSCC 3 machine, 9 bus system) with wind power integration using ETAP

12.6.0[21]. The disturbance initiating the transient is a three- phase fault occurring near bus 7 at the end of the transmission line 5–7. The fault is cleared by tripping the line 5–7 from the system.

Therefore after the fault, the system changes to a new operating conditions. The following two case studies were carried out.

A.WSCC 9-Bus System without Wind Power Integration

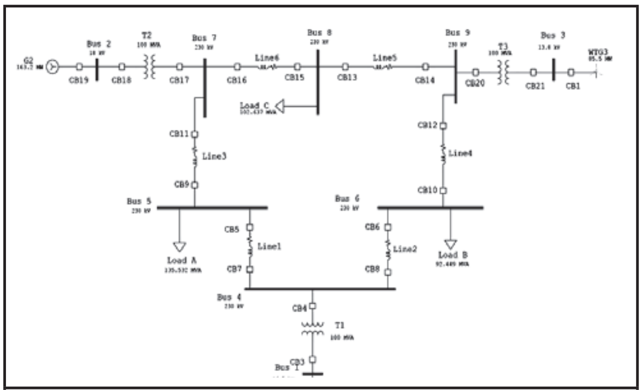

FIG.1. SINGLE LINE DIAGRAM OF THE TEST SYSTEM

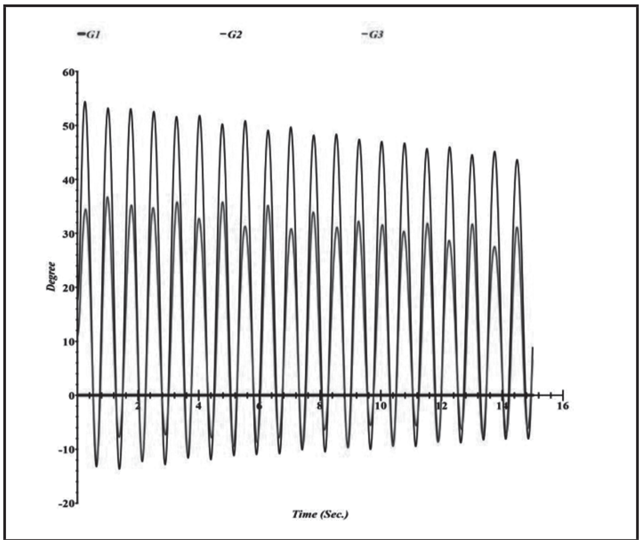

FIG.2. SYSTEM RESPONSE OF THE 9-BUS SYSTEM WITHOUT WIND POWER: RELATIVE POWER ANGLE OF G1, G2 AND G3 FOR THE SYSTEM WITH FCT=0.1S.

In this case, the system in Figure 2 has no wind power generator, i.e., G3 is an SG. Figure 2-4 demonstrate the transient responses of the relative power angle of G1, G2 and G3.System responses are given for different values of fault clearing time (FCT).

Figure 2 demonstrates relative power angle for the system with FCT=0.1s. The results demonstrate that the power system remains stable in this case.

Figure 3 demonstrates relative power angle for the system with FCT=0.222s. The results demonstrate that the power system remains marginally stable in this case.

Figure 4 demonstrates relative power angle for the system with FCT=0.223s. The results demonstrate that the power system becomes unstable following the disturbance.

The critical clearing time (CCT) is found to be 0.222s for the power system without DFIG.

B. WSCC 9-Bus System with Wind Power Integration

Figure 1. shows the one line diagram of Western System Coordinated Council (WSCC) 3 machine, 9- bus system [17] with a large wind farm. The SG G3 in the WSCC 3-machine, 9-bus system is replaced with a DFIG based wind farm, as shown in Figure 1. The same fault i.e., a 3 phase fault occurring near bus 7 on the transmission line 5-7 is applied to analyze the transient performance of the system with wind power integration.

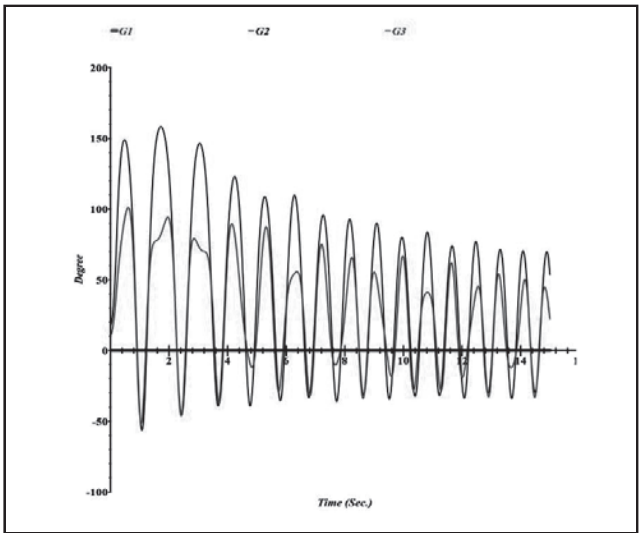

FIG.3. SYSTEM RESPONSE OF THE 9-BUS SYSTEM WITHOUT WIND POWER: RELATIVE POWER ANGLE OF G1, G2 AND G3 FOR THE SYSTEM WITH FCT=0.222S.

Figure 5-7 demonstrates the system responses of the relative power angle of G1 and G2.System responses are given for different values of FCT.

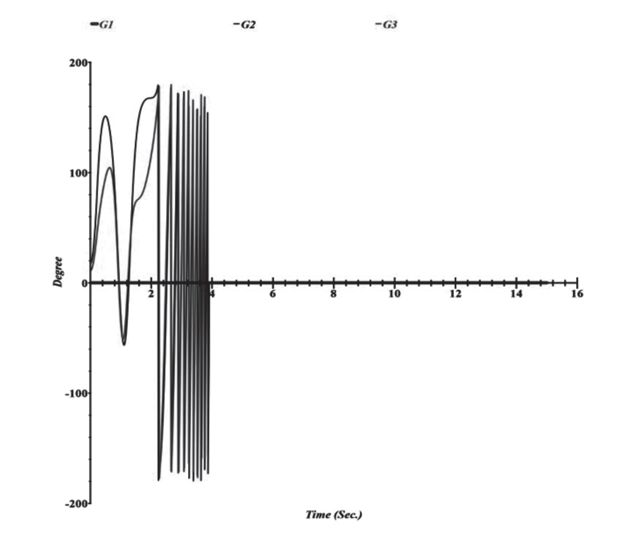

FIG.4. SYSTEM RESPONSE OF THE 9-BUS SYSTEM WITHOUT WIND POWER: RELATIVE POWER ANGLE OF G1, G2 AND G3 FOR THE SYSTEM WITH FCT=0.223S.

Figure 5 demonstrates the relative power angle for the system with FCT=0.1s. The results demonstrate that the power system remains stable in this case.

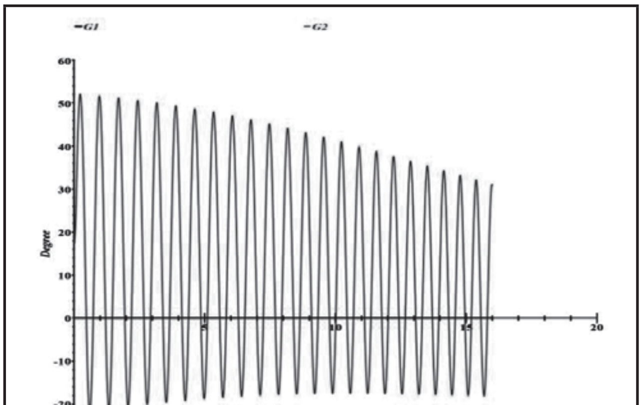

FIG.5. SYSTEM RESPONSE OF THE 9-BUS SYSTEM WITH WIND POWER: RELATIVE POWER ANGLE OF G1 AND G2 FOR THE SYSTEM WITH FCT=0.1S.

Figure 6 demonstrates the relative power angle for the system with FCT=0.2s. The results demonstrate that the power system remains marginally stable in this case.

Figure 7 demonstrates the relative power angle for the system with FCT=0.208s. The results demonstrate that the power system remains unstable in this case.

The CCT is found to be 0.2s for the power system with DFIG. When compared to the system with the only SG, CCT has decreased in this case, thereby rendering the system more vulnerable to stability issues following a disturbance.

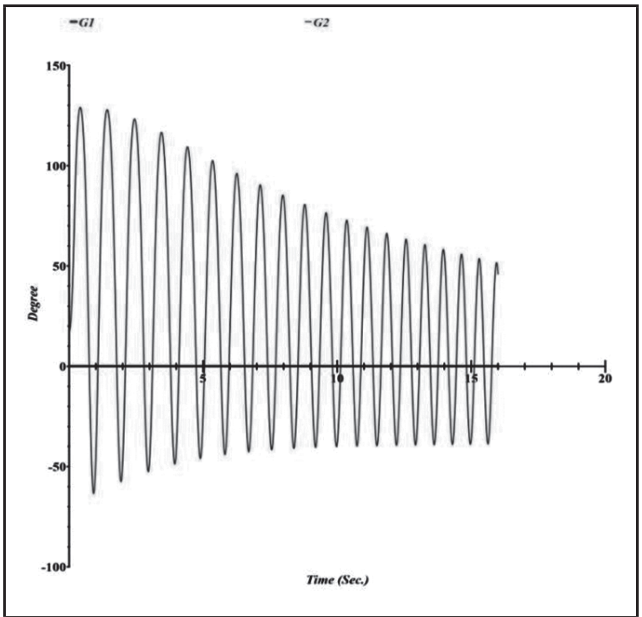

FIG.6. SYSTEM RESPONSE OF THE 9-BUS SYSTEM WITH WIND POWER: RELATIVE POWER ANGLE OF G1 AND G2 FOR THE SYSTEM WITH FCT=0.2S.

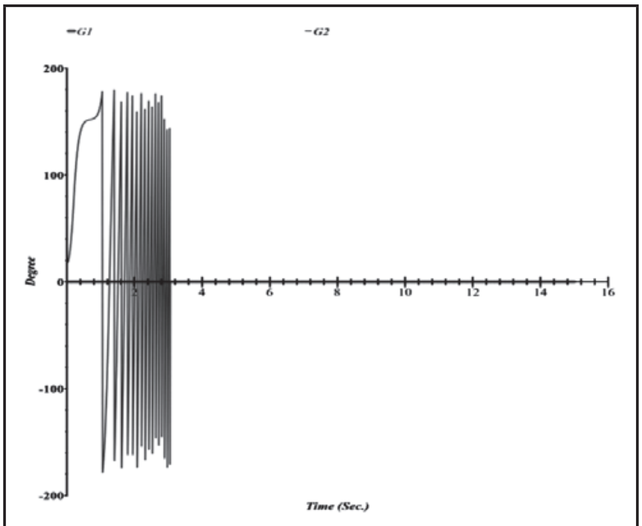

FIG.7. SYSTEM RESPONSE OF THE 9-BUS SYSTEM WITH WIND POWER: RELATIVE POWER ANGLE OF G1 AND G2 FOR THE SYSTEM WITH FCT=0.208S.

To observe the transient energy margin of the 9-bus system without wind power integration, the CTKE for the different clearing times is obtained in

Tables 1 and 2. A comparative analysis of Table 1 and Table 2 reveals that the critical clearing time reduces with the introduction of the DFIG in the system.

TABLE 1		
CORRECTED TRANSIENT KINETIC ENERGY S WITH DFIG		
Fault Clearing Time (s)	CTKE (pu)	TSM (pu)
0.0031	0.0166538	0.0008436
0.1	0.0170739	0.0004235
0.111	0.0170548	0.0004426
0.151	0.017289	0.0002084
0.181	0.0174173	0.0000801
0.2	0.0174974	0

It is also observed that with an increase in the clearing time, the TSM reduces indicating lesser stability margin for the post-fault operating point.

The TSM sensitivities (change in TSM w.r.t unit change in power output of the generator / power demand of the loads) may be ascertained for easy calculation of TSM values at different operating points. This would help the System Operator (SO) to ascertain the effect of addition of the DFIG on the stability of the system.

6.0 CONCLUSION

This paper investigates the effect of grid connected DFIG based WECS on power system TS. Simulation studies are carried out in ETAP 12.6.0 [21] to demonstrate the transient response of WSCC 3- machine, 9-bus system with wind power integration during a severe grid fault. The Hybrid method of TSA is presented in this paper. It has the advantages of both the TDS simulation method and the direct method of TS analysis. Just like the direct method, Hybrid method has the capability of producing a transient stability index called the TSM.

Results indicate that addition of DFIG reduces the CCT of the system thereby rendering the system susceptible to instability, following a disturbance. The TSM calculation carried out helps in ascertaining the effect of addition of DFIG's on the system stability thereby allowing the SO to take appropriate decision.

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