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EFFECTS OF GENERATOR PARAMETERS AND TRANSFORMER DISPOSAL ON DYNAMICS OF A HIGH-PENETRATION NO-STORAGE WIND-DIESEL SYSTEM

Chi-Hsiang Lin

Key words: dynamics, transformer, wind turbine generator, wind-diesel generation system, electromagnetic torque.

ABSTRACT

In this paper, dynamics of a high-penetration, no-storage wind-diesel (HPNSWD) system subjected to line faults are studied. It is found that the effect of induction generator electrical parameters on generator electromagnetic torque, system frequency and generator terminal voltage is significant, especially for the rotor resistance, which is able to significantly affect all the three target performances. Therefore, it will be the most effective way to improve the system dynamics by controlling the rotor resistance. It is also found that the system dynamics would be significantly improved by disposing a distribution transformer. However, the effectiveness depends on the installation position. A distribution transformer installed at the generator side will just reduce the generator terminal voltage and electromagnetic torque disturbance. If it is installed at the load side, all of the three system performances can be significantly improved.

I. INTRODUCTION

The wind turbine generation technology has been sophisticatedly developing recently. Many approaches using control and power electronic techniques have been proposed to achieve the maximal power tracking, the var compensation, the improvement of power factor, the reliability promotion (Amenedo et al., 2002; Chompoo-inwai et al., 2005; Hansen et al., 2007; Qiao et al., 2008; Su et al., 2012), and the enhancement of wind turbine tower (Chien, 2008).

The application of wind energy in autonomous power sys-

tems, which usually operate with diesel units, is found to be a good way to reduce the cost of the kWh produced (Karaki et al., 2000; Lu and Chang, 2013). So, over the past few years there has been a considerable effort to develop wind-diesel systems with higher fuel savings. Due to the high no-load fuel consumption and recommended minimum loading of diesel generators, the most effective savings are achieved when the diesel engines can be shut down. This leads to that the high-penetration; no-storage wind-diesel (HPNSWD) systems become a favorable approach for adding wind energy to remote diesel generator system (Jeffries et al., 1996; Papathanassiou and Papadopoulos, 2001).

However, in the so called high-penetration wind-diesel systems, the dynamics of the wind turbine generators differ notably from those connected to a very large grid. There are problems concerning dynamic responses subjecting to disturbances like random nature of wind variation, wind gust, sudden disconnection of wind turbine, and network disturbances (Sharma et al., 2000; Muljadi and Mckenna, 2002; Holdsworth et al., 2003; Chompoo-inwai et al., 2005; Bleijs, 2007). In fact, the operation of wind turbines in remote areas has proved that there are still operational problems in cases when the wind penetration is escalated and different disturbances occur. These problems are mostly due to the weakness of the electrical grid in the point where the wind turbines are connected, and would affect the system voltage and frequency (Moreno et al., 2002; Moreno et al., 2003).

In order to ensure that the wind turbines will not affect the system's power quality problems like variations in the frequency and the voltage, it is recommended that there is a limit to the installing wind capacity. However, in small autonomous power system this demand cannot be satisfied in cases when high wind penetration is required. So, it is always an important issue as how to promote the system voltage and frequency dynamics for HPNSWD systems.

Furthermore, power fluctuations can be problematic if the wind energy conversion system is feeding a weak grid or a stand-alone load. Power fluctuations would induce electromagnetic torque disturbances on the generator, which would

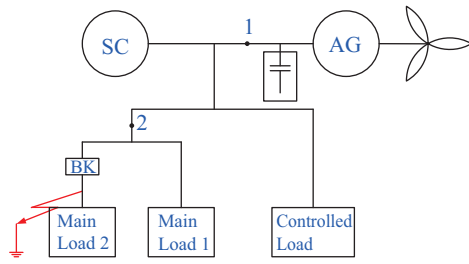


Fig. 1. Wind turbine system studied.

in turn induce torsional torque on the gear box and shafts (Muyeen et al., 2006; Peeters et al., 2006; Muyeen et al., 2007; Lin, 2008; Lin, 2010). If the torque peaks in the gear box and shafts are reduced, the wind turbine can operate with maximum aerodynamic efficiency. So it is also important to decrease the generator electromagnetic torque for HPNSW systems.

Since the three system performances (generator electromagnetic torque, system frequency and generator terminal voltage) are so important for an autonomous wind-diesel system, we focus our studies on analyzing the effects of induction generator winding parameters and distribution transformers disposal on them.

II. SYSTEM STUDIED

The system studied is the HPNSWD system developed by Hydro-Quebec, which aimed at using at the remote areas. The system scheme is shown in Fig. 1 (Gagnon et al., 2002). It is adopted in the system a synchronous generator driven by a diesel engine and an induction generator driven by a wind turbine. Power generated by the generators supplies two main loads, 100 kW in each, and a controlled load. When the wind speed is low, both the synchronous generator and induction generator supply power to meet the demand. When the wind speed is high enough that the power generated by the wind turbine generator exceeds the demand, the diesel engine generator can be shut down. Under this condition, the wind turbine generator supplies power to load on its own. The synchronous generator turns to be the synchronous condenser, which is responsible for regulating the system voltage by controlling the excitation.

1. Frequency Control

The system frequency is controlled by the controlled load, which consists of eight sets of three-phase resistors controlled by GTOs. The controlled load is able to consume real power from 0 kW to 446.25 kW with an interval of 1.75 kW. For minimizing the voltage disturbance, zero voltage switching is adopted.

2. Wind Turbine Characteristics

The wind turbine characteristics are shown in Fig. 2. Based on the characteristics, the unit is operable when the wind

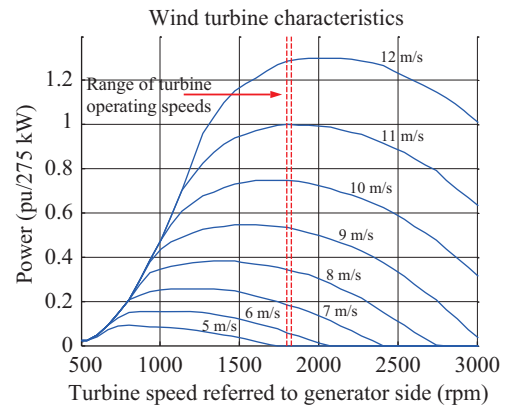


Fig. 2. Wind turbine Characteristics.

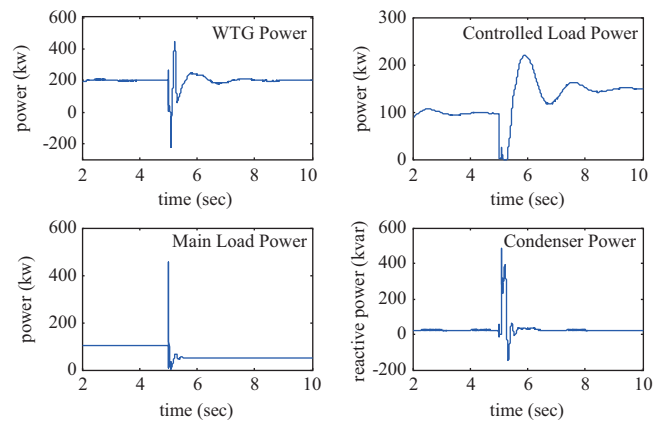


Fig. 3. Simulation results of real and reactive powers.

speed is between 6 m/s-12 m/s. For the wind speed is between 9 m/s-12 m/s, the wind turbine generator itself can meet power demand. If there are any excessive powers, they will be consumed by the controlled load in order to keep the system frequency stability.

3. System Responses to Faults

The system dynamic responses to network faults can be obtained by simulations using the Matlab/Simpower program. The results will be used as basis for comparisons later.

Wind speed is assumed to be 10 m/s for the simulations. It takes about 2 seconds for achieving the steady state. Under the steady state, the generator rotor speed is about 1.01 pu, a little above the synchronous speed. Output power of the wind turbine is 200 kW, of which 100 kW is supplying to the main loads and the other 100 kW is consumed by the controlled load for keeping system frequency at 60 Hz. For the synchronous condenser, it offers 10 kvar of reactive power for keeping the system voltage.

At $t = 5.0$ sec, it is assumed that one of the main loads occurs a three-phase-to-ground fault. At $t = 5.1$ sec (about 6 cycles later the fault), breakers trip and clear the fault. The simulation results are shown in Fig. 3. As can be seen, power oscillations take place in the wind turbine generator power.

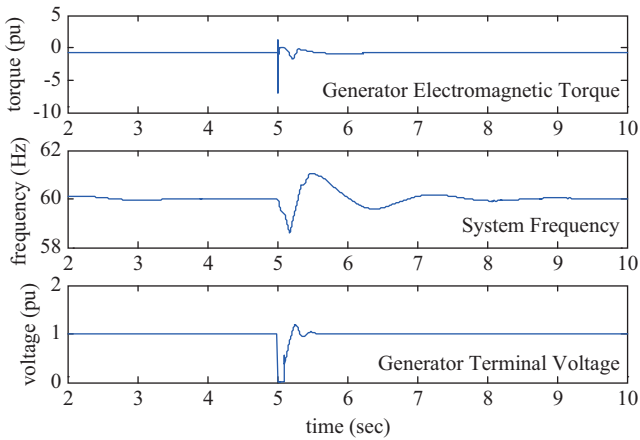


Fig. 4. Responses of the three target parameters.

The maximal peak-to-peak value reaches 600 kW. Severe disturbances of over 400 kW are induced in the main loads power due to the line fault and clearing. The controlled load regulates and absorbs up to 200 kW power or so. The reactive power provided by synchronous condenser also oscillates, with over 600 kvar peak-to-peak value. At $t = 9.0$ sec, the system recovered. The output power of wind turbine generator at steady state is 200 kW, of which 50 kW is supplying to the main loads and the other 150 kW to the controlled load.

The result of three target system performance parameters is shown in Fig. 4. From the top to bottom, they are generator electromagnetic torque, system frequency and generator terminal voltage respectively. As can be seen, severe disturbances occurred in the generator electromagnetic torque following faulting and clearing. The torque variation ($\Delta\tau_{EM}$), which is defined as the difference between the maximal and minimal values, reaches up to 8 pu. The system frequency also suffered fluctuation. It fell down to below 59 Hz following fault, and rise up to over 61 Hz following fault clearing. The frequency variation (Δf), which is defined as the different between maximal and minimal values, reaches up to 2.5 Hz. For the generator terminal voltage, it dropped to 0 at the fault time. When recovery, it overshoot and the peak voltage is 1.2 pu. The voltage variation (ΔV_{WT}), which is defined as the difference between the maximal and minimal values, is 1.2 pu.

III. STUDIES OF INDUCTION GENERATOR PARAMETERS

For investigating the factors that are able to affect the target system performance, we focused on the five generator windings parameters: stator resistance, stator leakage inductance, magnetization inductance, rotor resistance and rotor leakage inductance. Three simulation cases are conducted. One is the normal condition (case 1); the other two correspond to changes in parameter values: decreasing (case 2) and increasing (case 3). The ratings of induction generator are 275 kVA and 480V, and winding parameters are

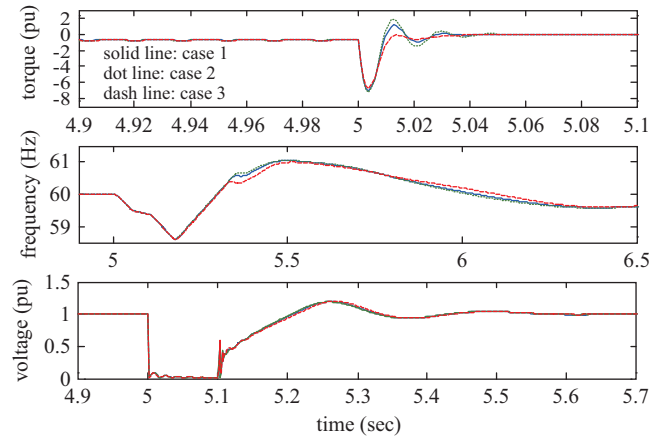


Fig. 5. Effect of stator resistance.

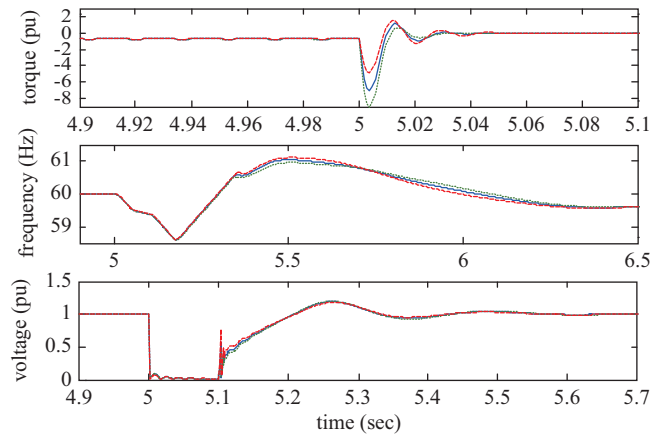


Fig. 6. Effect of stator inductance.

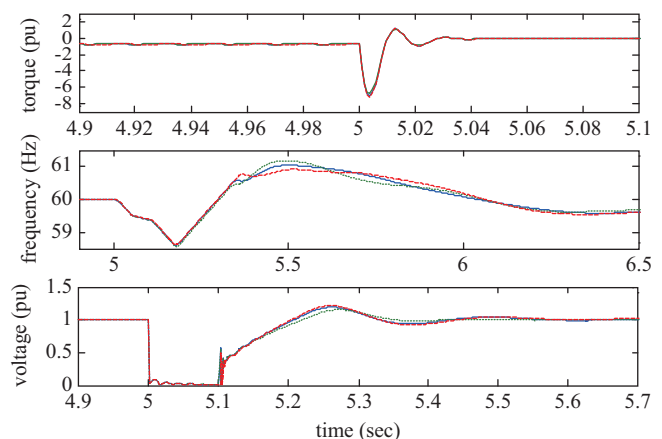


Fig. 7. Effect of magnetization inductance.

$$R_s = 0.016 \text{ pu}; L_{ls} = 0.06 \text{ pu}; L_m = 3.5 \text{ pu}; R_r = 0.015 \text{ pu}; \\ L_{lr} = 0.06 \text{ pu}$$

In Figs. 5 to 9, simulation results are shown. As can be seen, there are significant effects of stator resistance on generator

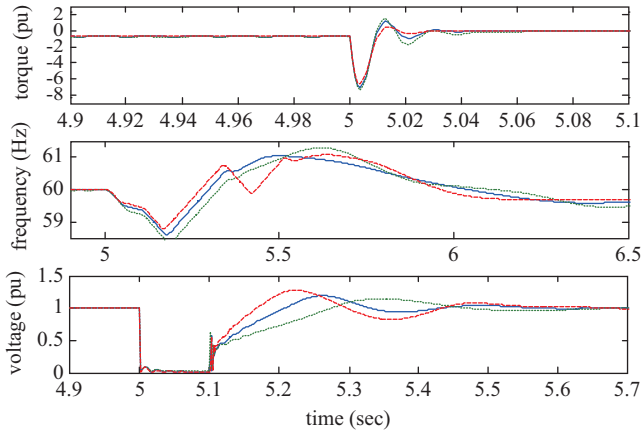


Fig. 8. Effect of rotor resistance.

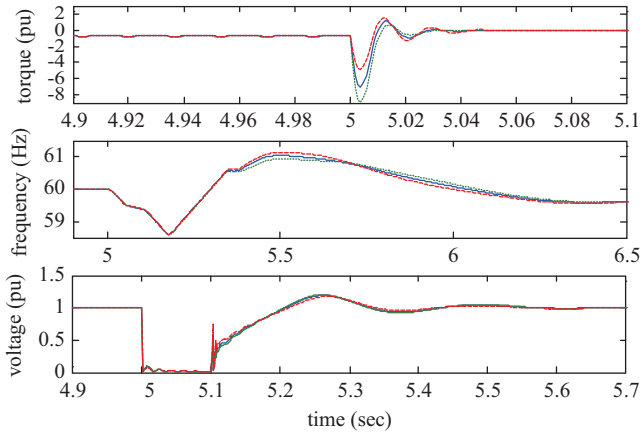


Fig. 9. Effect of rotor inductance.

electromagnetic torque. The larger the value is, the smaller the disturbance will be. However, there are not any effects of stator resistance on system frequency and generator terminal voltage.

The effects of stator leakage inductance are almost the same as those of stator resistance, except there is a little effect on system frequency. The larger the inductance is, the larger the frequency variation will be.

The magnetization inductance somewhat affects both system frequency and generator terminal voltage, but it would not affect generator electromagnetic torque. Increasing in inductance value will decrease the system frequency variation, yet will increase the generator terminal voltage fluctuation.

The most noteworthy is the rotor resistance simulation result. Rotor resistance is found to be able to significantly affect all the three target performances. Increasing in resistance value will reduce generator electromagnetic torque disturbance and system frequency variation, yet the generator terminal voltage fluctuation will be increased.

The effect of rotor leakage inductance on generator electromagnetic torque disturbance is also significant. Increasing in inductance value will alleviate the disturbance. It also

Table 1. Effect of generator parameters.

	R_s	L_{ls}	L_m	R_r	L_{lr}
$\Delta\tau_{EM}$	S	S	N	S	S
Δf	N	L	L	S	L
ΔV_{WT}	N	N	L	S	N

Note: S: significant effect.

L: a little effect.

N: negligible effect.

somewhat affects system frequency. The larger the inductance value is, the larger the frequency variation will be. Not any effect is found on the generator terminal voltage, though.

In Table 1, it is listed the affecting degree of the 5 generator parameters on the 3 target system performance. As can be seen, rotor parameters seem to be more influential than stator parameters. All of the generator parameters, except the magnetization inductance, significantly affect the generator electromagnetic torque disturbance. Rotor resistance has the most significant effect on the system frequency. It also is the only one parameter that has significant effect on the generator terminal voltage. To sum up, controlling the rotor parameters is better than the stator parameters for improving the system dynamics. Especially for the control of rotor resistance, which will be the best way to improve all the three system performance.

IV. STUDIES OF TRANSFORMERS DISPOSAL

According to the above studies, it can be known the significance of generator parameters on affecting the system performance. However, generator parameters can only be changed at the design and manufacture stages, or by the active control approaches which use power electronic techniques. Both are expensive and complicated. Therefore, it is proposed a relatively cheap and simple approach as a substitute, which corresponds to the disposal of a passive distribution transformer in the system.

The transformer adopted has a turn ratio of 1:1, of which the ratings are 300 kVA and 480V/480V, and winding parameters are $r_1 = r_2 = 0.002$ pu; $L_1 = L_2 = 0.08$ pu. For proving the feasibility, three cases are studied and the results are compared.

Case 1: No transformer is installed

Case 2: The transformer is installed at the wind turbine side (location 1 in Fig. 1)

Case 3: The transformer is installed at the main load side (location 2 in Fig. 1)

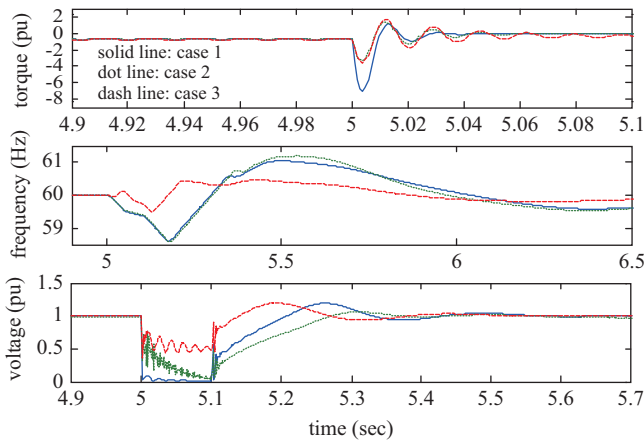
In Fig. 10, it is shown the simulation results of the three cases. For the case 2, $\Delta\tau_{EM}$ significantly decreases from 8.0 pu to about 5.0 pu (-35%), and ΔV_{WT} somewhat decreases from 1.2 pu to 1.0 pu (-17%). As to Δf , there are not any notable

Table 2. Results of the single-phase-to-ground fault.

case	$\Delta\tau_{EM}$ (pu)	% reduction
1	1.8	-
2	1.3	28
3	0.9	50
case	Δf (Hz)	% reduction
1	1.2	-
2	1.2	0
3	0.9	25
case	ΔV_{WT} (pu)	% reduction
1	0.24	-
2	0.22	8
3	0.13	46

Table 3. Results of the double-phase-to-ground fault.

case	$\Delta\tau_{EM}$ (pu)	% reduction
1	9.5, 15.0, 14.0	-
2	5.5, 9.0, 8.0	42, 40, 43
3	4.0, 8.0, 7.0	58, 47, 50
case	Δf (Hz)	% reduction
1	2.0, 2.5, 2.5	-
2	2.0, 2.5, 2.5	0, 0, 0
3	0.7, 0.9, 0.7	65, 64, 72
case	ΔV_{WT} (pu)	% reduction
1	1.5, 2.0, 1.9	-
2	1.2, 1.6, 1.4	20, 23, 27
3	0.7, 0.9, 0.9	56, 56, 55

**Fig. 10. Three performance parameters for the cases 1-3.**

change. For the case 3, $\Delta\tau_{EM}$ significantly decreases to 5.0 pu (-35%) and ΔV_{WT} significantly decreases to 0.85 pu (-29%). In addition, the most noteworthy is that Δf significantly decreases from 2.5 Hz to 1.0 Hz (-60%). Obviously, the system dynamics have been significantly improved by installing the transformer, and the preferable installation position of the transformer is at the main load side.

V. STUDIES OF FAULT TYPES

The studies above are only for the three-phase-to-ground fault. In order to verify the feasibility, it is necessary to further study both the single-phase-to-ground and double-phase-to-ground faults. The conditions for the simulation analysis remain the same as mentioned previously, except the fault type has changed.

1. Results of the Single-Phase-to-Ground Fault

The simulation results for the effect of single-phase-to-ground fault are tabulated in Table 2. Since the results for each phase are almost the same, only one of the values is shown. As can be seen, there will be about 28% and 50% improvement in $\Delta\tau_{EM}$, respectively, if the transformer is installed at the wind

Table 4. Effect of fault time on Δf (Hz).

fault time (s)	Case 1	Case 3	% reduction
4.6	4.0	1.8	55
4.7	5.0	1.5	70
4.8	2.0	1.2	40
4.9	3.2	1.0	69
5.0	2.5	1.0	30

turbine and main load sides. For Δf , nothing has improved if the transformer is installed at the wind turbine side. However, there will be 25% improvement if it is installed at the main load side. For ΔV_{WT} , there will be 8% and 46% improvement, respectively, if the transformer is installed at the wind turbine and main load sides.

2. Results of the Double-Phase-to-Ground Fault

For the double-phase-to-ground fault, the simulation results are tabulated in Table 3. Three values are shown, which correspond to the A-to-B-to-ground, B-to-C-to-ground, C-to-A-to-ground faults respectively. For $\Delta\tau_{EM}$, in average, there will be over 40% and 50% improvement, respectively, if the transformer is installed at the wind turbine and main load sides. For Δf , in average, there will be over 60% improvement if the transformer is installed at the main load side. For ΔV_{WT} , in average, there will be over 20% and over 55% improvement, respectively, if the transformer is installed at the wind turbine and main load sides.

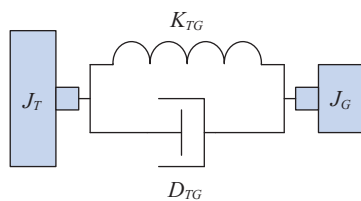
VI. EFFECTS OF FAULT AND CLEARING TIME

The disturbance induced by network faults is related to not only the fault types, but also the fault and clearing time. So, it is also necessary to verify the feasibility of the proposed approach under different fault and clearing conditions.

Only the effects on Δf , as shown in Table 4, are presented due to limitation of paper length. It can be seen that there are significant variations in Δf subjecting to different fault time. If the fault occurs at $t = 4.7$ sec, the Δf may reach as high as

Table 5. Effect of clearing time on Δf (Hz).

clearing time (cycle)	Case 1	Case 3	% reduction
5	2.3	0.9	61
6	2.5	1.0	60
7	2.7	1.0	63
8	2.7	1.0	63
9	2.9	1.0	66



$$J_T = 150 \text{ kgm}^2$$

$$J_G = 30 \text{ kgm}^2$$

$$K_{TG} = 2320 \text{ Nm/rad}$$

$$D_{TG} = 206 \text{ Nms/rad}$$

Fig. 11. Power train model of wind turbine units.

5 Hz. If the fault time changes to $t = 4.8$ sec, only 2 Hz is induced in Δf .

The effectiveness of installing transformer at the main load side in improving Δf is also different under the different fault time. If the fault occurs at $t = 4.7$ sec, there will be 70% improvement. However, only 40% improvement can be achieved for the fault time changing to $t = 4.8$ sec.

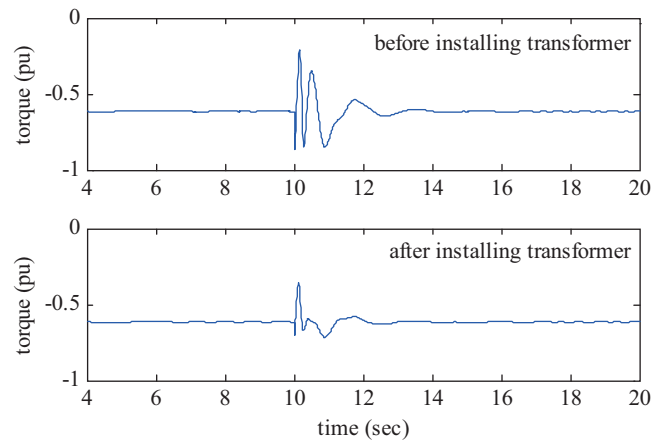
In the same manner, the effects of fault clearing time are studied. The results are listed in Table 5. As can be seen, there will be 2.9 Hz and 2.3 Hz if it is 9 cycles and 5 cycles of clearing time respectively. Also, the effectiveness of installing transformer at the main load side is somewhat different for the different clearing time. However, there are over 60% improvements in average.

VII. STUDIES OF TORSIONAL VIBRATIONS

It has been known and widely discussed in literatures that the disturbance of generator electromagnetic torque would induce torsional vibrations on the main shaft of wind turbine unit (Jeffries et al., 1996; Todorov et al., 2009; Wamkeue et al., 2012). Now that the proposed approach of installing a transformer at the main load side has been proved to be effective on reducing $\Delta \tau_{EM}$, it is interesting to further analyze its effectiveness on reducing shaft torsional torque.

For the simulation of wind turbine shaft torsional vibrations, power train is simplified to a two-mass model, as shown in Fig. 11. The J_G and J_T , respectively, represent the generator rotor inertia and the total inertia of shaft, hub and blades combination. The K_{TG} and D_{TG} represent shaft stiffness and damping respectively.

A comparison between before and after the installation of a

**Fig. 12. Simulation results of the main shaft torque before and after installing transformer.**

transformer at the main load side has been made. The simulation conditions remain the same as mentioned previously, except the switching timing is somewhat changed. A three-phase-to-ground fault is applied at $t = 10.0$ sec. The fault is cleared 6 cycles later.

The time domain simulation results are shown in Fig. 12. The upper and lower, respectively, are shaft torques before and after installing transformer. As can be found, the torsional vibration frequency is about 1.5 Hz. Before installing transformer, the torque difference between maximal and minimal values is 0.7 pu or so. It reduces to 0.3 pu after installing transformer. That is an improvement of over 50%. It can be expected that there would be significant alleviation on shaft damage.

VIII. CONCLUSIONS

It is found that there is significant effect of the induction generator parameters and the transformer disposal on dynamics of a HPNSWD system. For the induction generator parameters, the most effective way to improve the system dynamics is controlling the rotor resistance. For the transformer disposal, the best installation position is at the load side. The results will be helpful for the design of a HPNSWD system, and also for the improvement of system performance.

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