Investigation of Turbine Generator Shaft Torsional Interaction with Self-commutated Converter

Masayuki Watanabe, Hiroyuki Iki, Yoshihisa Uriu, Yasunori Mitani, and Yoshihide Kado

Abstract-- **This paper presents a simple diagnostic tool for the sub-synchronous torsional interaction between a turbine generator and self-commutated converters with large capacity connected to an industrial power system to avoid the damage of the rotor shaft between the turbine and generator. The resonance condition of the torsional vibration and the impact to the generator rotor shaft are investigated by the analysis on measurement data in the field and power system simulations.**

***Keywords*: Sub-synchronous torsional interaction, torsional vibration, self-commutated converter, turbine generator, interharmonics.**

I. Introduction

A number of converters for FC (Frequency Converter) and VSD (Variable Speed Drive) with large capacity are installed in industrial power systems. Issues on harmonics caused by such power electronics based equipment should be measured to maintain the normal system operation [1], [2]. Especially, interharmonics originated from self-commutated converters cause the torsional vibration at the rotor shaft of rotating machines [3]. In industrial power systems, turbine generators might be interconnected near the converter due to some constraints, for example, the installation location, costs, and so on. In this case, the influence of interharmonics to turbine generators should be investigated quantitatively. This paper presents a simple diagnostic tool for the torsional torque of rotor shaft of turbine generator which is interconnected with a power system equipped with self-commutated converters. The diagnostics is based on the analysis of measurement data in the field and the instantaneous value based power system simulation, in which EMTP-RV is adopted in this study.

The resonance between interharmonics from converters and the natural frequency of the rotor shaft causes the large torsional torque, which leads to the shaft damage. SSR (Sub-Synchronous Resonance) caused by the series capacitor compensation in a long-distance transmission line is a well-known phenomenon as a shaft torsional vibration [4]. On the other hand, the interaction between rotating machines and FC or VSD system is known as SSTI (Sub-Synchronous Torsional Interaction) [1], [2], [5]-[7]. When a turbine generator is interconnected to the vicinity of self-commutated converters, there should be issues on shaft torsional torque as well as variable speed motors. For example, the natural frequency of the rotor shaft of steam turbine generator is typically between a few and several tens of hertz. If there were air gap torque fluctuations with frequency near the natural frequency caused by interharmonics, which have frequency less than 100 Hz of the sideband wave caused by asynchronous PWM (Pulse Width Modulation) and the system control performance, the rotor shaft might be damaged by the torsional vibration.

In this paper, the resonance condition of the torsional vibration and the impact to the generator are investigated. In the developing diagnostic tool, first, interharmonics are detected by the frequency analysis of instantaneous voltage waveform measured near the target generator. Then, a three-phase sinusoidal voltage source based on the detected interharmonics is modeled in the power system simulation. A simple power system model, in which the generator is connected to the source through the appropriate impedance, is used to calculate the air gap torque of generator in the simulation. The frequency and amplitude of vibration torque obtained by the simulation is calculated by the frequency analysis. Thus, the resonance condition of the rotor shaft between turbine and generator can be evaluated by comparing the natural frequency and the analytic value obtained by the simulation study.

Some results on interharmonics analysis are presented by using measured voltage data in an industrial power system. The torsional vibration at rotor shaft is investigated for some conditions by the simulation, in which turbine and generator are represented by the mass model. The diagnostic result shows the risk of the torsional vibration and the shaft damage, which might be effectively applied to the design of the rotor shaft and the appropriate system operation.

II. Diagnostics of Torsional Vibration

A. Torsional Vibration of Generator Rotor Shaft

The torsional vibration between a turbine generator and a self-commutated converter might arise from two causes; one is the system control characteristics of the self-commutated converter, and the other is the sideband wave caused by the

M. Watanabe and Y. Mitani are with Kyushu Institute of Technology, Kitakyushu, 804-8550, Japan (e-mail: watanabe@ele.kyutech.ac.jp).

H. Iki is with Fuji Electric, Tokyo, Japan.

Y. Uriu is with Seikei University, Tokyo, Japan.

Y. Kado is with Asahi Kasei Corporation, Okayama, Japan.

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asynchronous PWM. In this study, the sideband wave is considered as the main factor of the torsional vibration. The interharmonics under 100 Hz caused by the sideband wave generate the fluctuation of the generator air gap torque. If the frequency of fluctuating torque would correspond to the natural frequency of the rotor shaft between the turbine and generator, that is, in the resonant condition, the torsional vibration might increase significantly.

B. *Diagnostic System for Torsional Vibration*

A diagnostic tool for the torsional vibration is proposed to avoid the damage of generator rotor shaft from the torsional torque caused by SSTI. The diagnostic consists of the following three steps.

1) Fig. 1 shows the configuration of diagnostic system for the torsional torque. All of interharmonics are detected by the frequency analysis with DFT (Discrete Fourier Transform) of measured line-to-line voltage and phase current at the bus near the generator.

2) An arbitrary three-phase voltage source with low-frequency components of interharmonics calculated by the step 1 is modeled on the power system simulation. Fig. 2 shows the simple circuit model, in which a turbine generator is interconnected with the above voltage source through a line with appropriate impedance. Here, an analysis tool for the electro-magnetic transient phenomena, EMTP-RV, is used.

The air gap torque of the generator T_e is calculated by:

$$T_e = \frac{p}{2}(\varphi_d i_q - \varphi_q i_d) \qquad (1)$$

where, p is the pole number of generator, φ_d and φ_q are the direct-axis and quadrature-axis flux, respectively, which can be calculated from the instantaneous three-phase voltage and current of the generator, i_d and i_q are the direct-axis and quadrature-axis current, respectively.

3) The frequency and amplitude of the torque vibration are evaluated by the frequency analysis with DFT of the torque calculated by (1). The obtained values are compared with the frequency characteristics of the rotor shaft between the turbine and generator. Thus, the torsional torque can be evaluated.

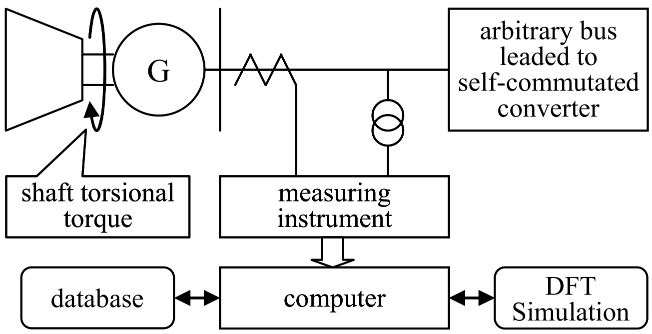


Fig. 1. Configuration of diagnostic system for shaft torsional torque.

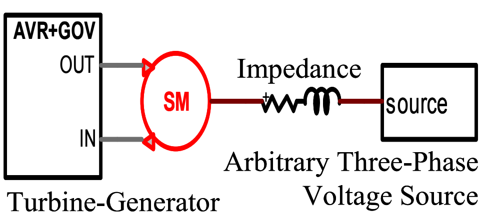


Fig. 2. Simple circuit model for the simulation study.

Here, the frequency of the torque vibration f_p can be calculated by (2) or (3).

1) In case of the balanced interharmonics:

$$f_p = |f_b - F(n)| \ \text{[Hz]} \qquad (2)$$

2) In case of the unbalanced interharmonics:

$$f_p = |f_b \pm F(n)| \ \text{[Hz]} \qquad (3)$$

where, f_b is the fundamental frequency, and $F(n)$ is the frequency of injected interharmonics. The rotational direction of the positive phase sequence current of interharmonics is the same as the direction of the flux of the fundamental component; therefore, the torque vibration has the frequency with the difference between the fundamental and interharmonics frequency. On the other hand, the rotational direction of the negative phase sequence current of interharmonics is the opposite direction of the flux of the fundamental component; therefore, the torque vibration has the frequency with the sum of the fundamental and interharmonics frequency.

III. Application of the Diagnostic System

A. *Analysis of Measured Data*

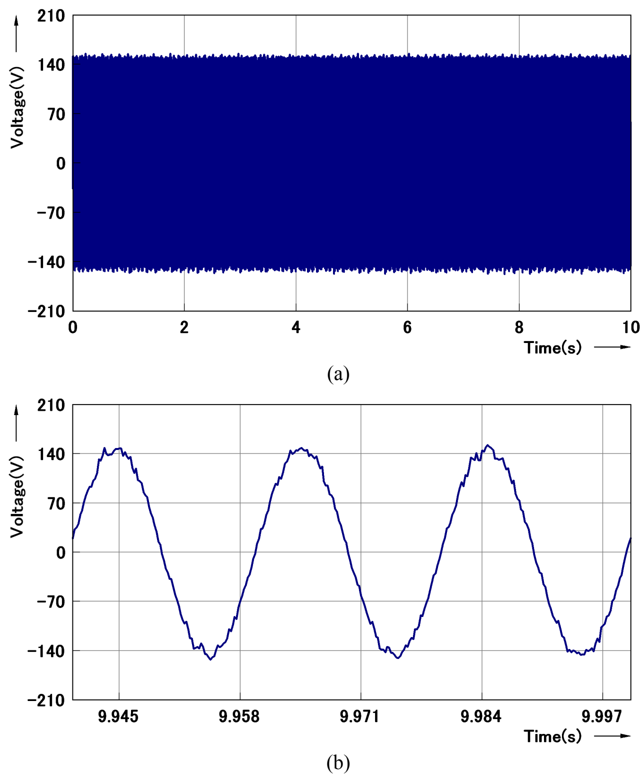


Fig. 3. Voltage waveform measured in an industrial power system: (a) line-to line voltage (b) close-up.

Fig. 3 shows the measured line-to-line voltage (the secondary side of the potential transformer) at the bus interconnected with a self-commutated converter. As shown in Fig. 3, the voltage includes harmonic component.

Here, interharmonics less than 100 Hz is considered, since the low-frequency resonant frequency of the torsional torque between the turbine and generator is mainly less than 50 Hz [1]. Fig. 4 shows the Fourier spectrum of the voltage shown in Fig. 3, here, the Chebyshev function has been applied as the window function of DFT to evaluate low-frequency components specifically. Interharmonics with 6.5, 10.8, and 63.1 Hz exist as shown in Fig. 4, while the fundamental frequency is 50 Hz. The maximum amplitude of interharmonics is 0.09 % of the fundamental component; however, such small interharmonics might generate a large torsional torque as shown in Section IV. Therefore, a quantitative diagnosis of especially low-frequency interharmonics should be critical.

B. Simulation Condition

A source with 13.8 kV and 50 Hz, to which interharmonics with 6, 10, and 63 Hz are injected, is modeled as an arbitrary three-phase voltage source in the power system simulation. Note that the voltage magnitude corresponds to the result shown in Fig. 4. Fig. 5 shows the line-to-line voltage waveform at the generator bus. Fig. 6 shows the Fourier spectrum of the waveform shown in Fig. 5, which reflects the similar characteristics with the real system shown in Fig. 4. Here, the turbine output of the generator is 1.0 p.u.

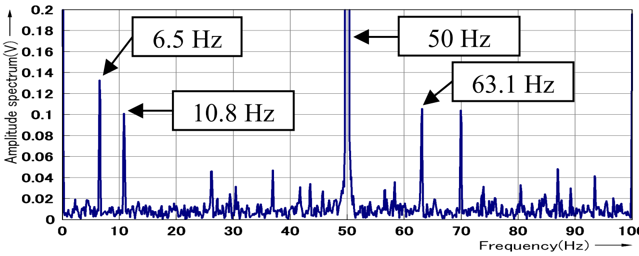


Fig. 4. Fourier spectrum of measured voltage.

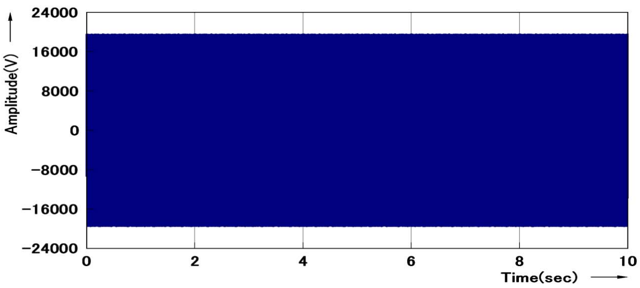


Fig. 5. Line-to-line voltage waveform at the generator bus in the simulation study.

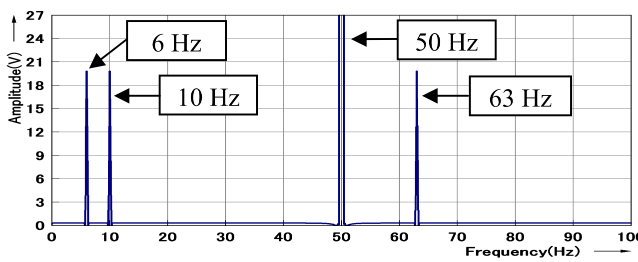


Fig. 6. Fourier spectrum of the waveform in Fig. 5.

In this study, both balanced and unbalanced conditions are considered. In case 1, the fundamental component with 50 Hz is 1.0 p.u., and balanced interharmonics with three frequencies are injected. Fig. 7 shows the voltage waveform. In case 2, unbalanced interharmonics are injected as shown in Fig. 8. Note that in Figs. 7 and 8, the voltage magnitude is in p.u..

C. Air Gap Torque Estimation

Figs. 9 and 10 show the generator air gap torque waveform and Fourier spectrum in each case, respectively. The torque vibration has frequencies with 13, 40, and 44 Hz as positive phase sequence component in case 1, on the other hand, it has 56 and 60 Hz as the negative phase sequence component in

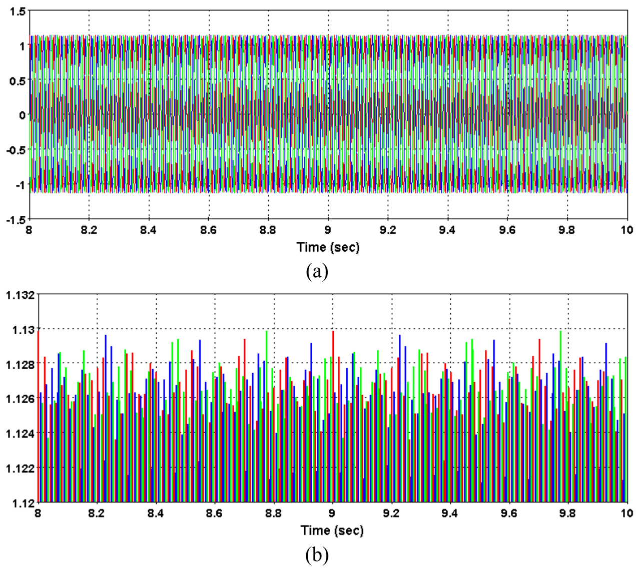


Fig. 7. Balanced voltage waveform: (a) voltage waveform. (b) close-up.

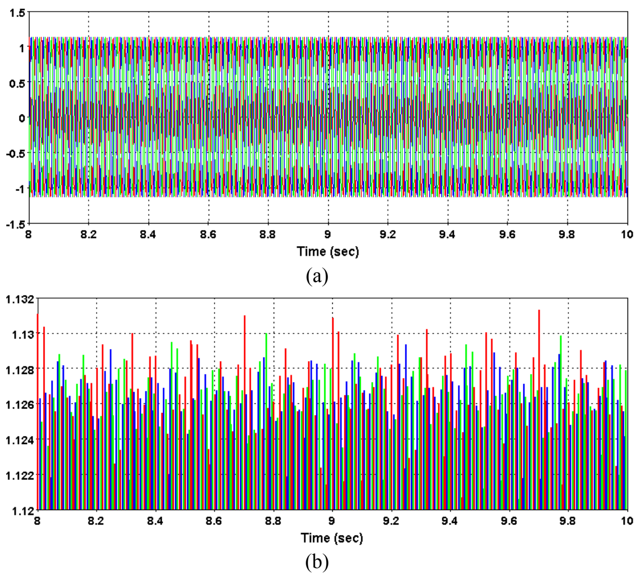
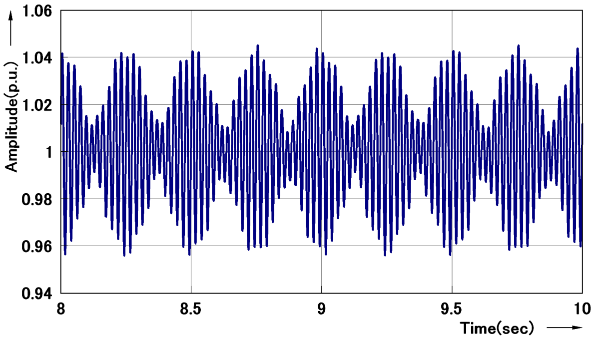
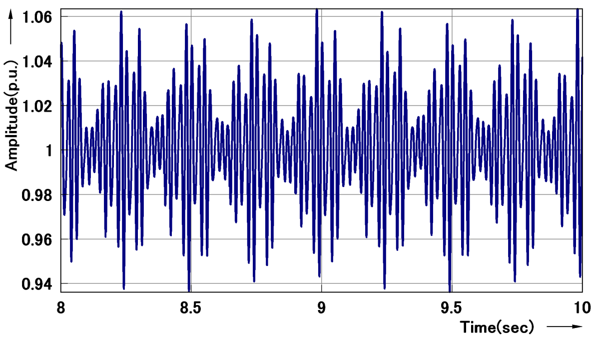


Fig. 8. Unbalanced voltage waveform: (a) voltage waveform. (b) close-up.

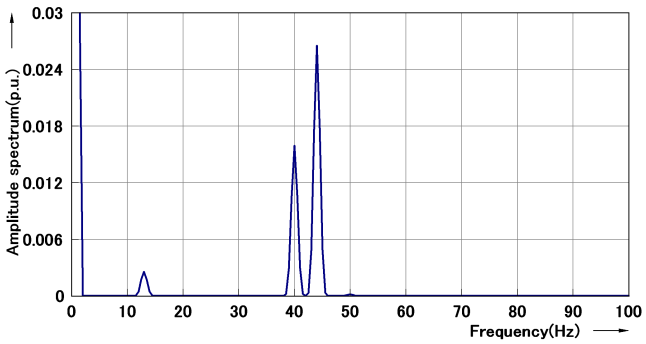


(a)

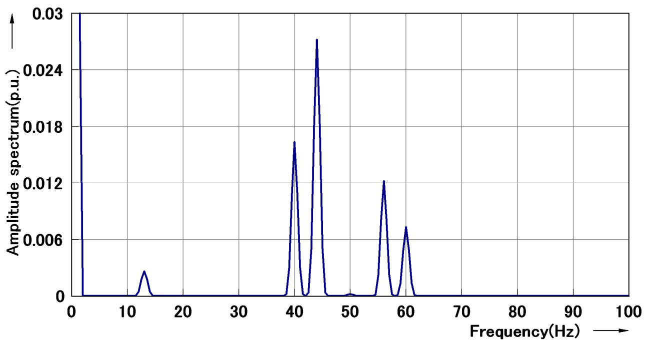


(b)

Fig. 9. Generator air-gap torque: (a) balanced. (b) unbalanced.



(a)



(b)

Fig. 10. Fourier spectrum of generator air-gap torque: (a) balanced. (b) unbalanced.

case 2 in addition to the positive phase sequence component with 13, 40, and 44 Hz. These results coincide with (2) and (3). Estimated results show that the maximum magnitude of the torque vibration is about 2.7 % of the fundamental component; if these components have the close frequency with the natural frequency of the rotor shaft, the torque vibration generates the torsional stress depending on the frequency characteristics. In case that the amplification ratio at that frequency is comparatively large, the excessive stress damages the rotor shaft.

Thus, the diagnostic tool for the torsional torque caused by SSTI can evaluate quantitatively the frequency and magnitude of low-frequency component of interharmonics by calculating the air gap torque fluctuation. As a result, the deviation from the natural frequency of the rotor shaft and the torsional stress can be evaluated.

IV. Torsional Torque Analysis

A. Rotor Shaft Model

The characteristics of the torsional torque on the rotor shaft between the turbine and generator is investigated by a power system simulation. Fig. 11 shows a simple circuit model with a turbine generator interconnected to the arbitrary three-phase voltage source, which has interharmonics component with 6, 10, and 63 Hz based on the result shown in Fig. 4, through the appropriate impedance. Here, the generator model is represented by three masses, which include a high pressure turbine, a low pressure turbine, and a generator as shown in Fig. 12, in order to study the behavior of the rotor shaft. The resonant frequency of the rotor shaft can be adjusted by tuning the physical constant, for example inertia constant or spring constant, depending on the analysis purpose.

B. Resonant Frequency Evaluation

The high pressure turbine, the low pressure turbine, and the generator are represented by a mass with the inertia M_1, M_2, and M_3, respectively. The position angle of each mass is θ_1, θ_2, and θ_3, respectively. The motion equation of each mass is represented by [4]:

$$\begin{aligned} M_1 \frac{d^2\theta_1}{dt^2} + k_{12}(\theta_1 - \theta_2) &= T_{m1} \\ M_2 \frac{d^2\theta_2}{dt^2} + k_{23}(\theta_2 - \theta_3) + k_{21}(\theta_2 - \theta_1) &= T_{m2} \\ M_3 \frac{d^2\theta_3}{dt^2} + k_{32}(\theta_3 - \theta_2) &= T_{e3} \end{aligned} \tag{4}$$

where, $k_{ij}(\theta_i - \theta_j)$ represents the torsional stress between the mass i and j (i, j = 1, 2, and 3), and $k_{ij} = k_{ji}$. T_{m1} and T_{m2} are the mechanical torque applied to the high pressure and the low pressure turbine, respectively, T_{e3} is the electrical torque applied to the generator rotor. Here, the damping coefficient is assumed to be zero to clarify the shaft vibration, though in fact a turbine generator has some damping effect by the viscosity inside of the shaft material.

Here, the state variables in motion equations (4) for each shaft are defined by:

$$\boldsymbol{x} = \begin{bmatrix} \theta_1 & \theta_2 & \theta_3 & \dot{\theta}_1 & \dot{\theta}_2 & \dot{\theta}_3 \end{bmatrix}^{\mathrm{T}}. \tag{5}$$

The state matrix $\boldsymbol{A}$ for the state vector $\boldsymbol{x}$ is represented by:

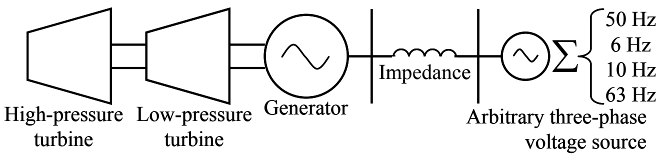


Fig. 11. Simple circuit model for diagnostic of torsional torque.

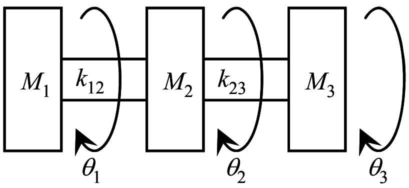


Fig. 12. Turbine and generator with three mass model.

$$\boldsymbol{A} = \left[\begin{array}{ccc|c} & \boldsymbol{O} & & \boldsymbol{I} \\ \hline -\dfrac{k_{12}}{M_1} & \dfrac{k_{12}}{M_1} & 0 & \\ \dfrac{k_{12}}{M_2} & -\dfrac{k_{12}+k_{23}}{M_2} & \dfrac{k_{23}}{M_2} & \boldsymbol{O} \\ 0 & \dfrac{k_{23}}{M_3} & -\dfrac{k_{23}}{M_3} & \end{array} \right] \tag{6}$$

where, $\boldsymbol{O}$ and $\boldsymbol{I}$ represent the zero and unit matrix, respectively. The resonant frequency can be evaluated by calculating eigenvalues λ from the characteristic equation:

$$\det(\lambda \boldsymbol{I} - \boldsymbol{A}) = 0 . \tag{7}$$

Eigenvalues λ have generally complex conjugate:

$$\lambda = \sigma \pm j\omega . \tag{8}$$

Since the damping coefficient is assumed to be zero, the real part of eigenvalues σ can be ignored. On the other hand, the resonant frequency f [Hz] of the rotor shaft is calculated by:

$$f = \frac{\omega}{2\pi} . \tag{9}$$

C. Shaft Torque Calculation

Here, the resonant frequency of the rotor shaft is assumed to be 44 Hz, which can be derived by (2), in order to resonate with low-frequency interharmonics with 6 Hz. The physical constants of each shaft have been adjusted based on (5) to (9).

The simulation duration is 450 seconds. In case 1, balanced low-frequency interharmonics with 6, 10, and 63 Hz are injected at 400 seconds after the simulation start. The system is in the steady state with balanced fundamental frequency for 400 seconds. On the other hand, in case 2, balanced low-frequency interharmonics with 6, 10, and 63 Hz are injected for 400 seconds after the simulation start. At 400 seconds, the interharmonics are eliminated, that is, the system is in the steady state with balanced fundamental frequency after 400 seconds.

In case 1, the resonance between interharmonics and the rotor shaft can be observed as shown in Fig. 13. The fluctuation range of the air gap torque is ± 0.08 p.u. in Fig. 13 (d); however, the maximum fluctuation range of the torque of the shaft between the low pressure turbine and the generator is ± 1.0 p.u. as shown in Fig. 13 (b). The result shows the large torsional stress to damage the rotor shaft might be applied.

Fig. 14 shows the result for case 2. The fluctuation range of the air gap torque is ± 0.04 p.u. in Fig. 14 (d); however, the maximum fluctuation range of the torque of the shaft between the low pressure turbine and the generator is ± 0.5 p.u. as shown in Fig. 14 (b). On the other hand, after the interharmonics are eliminated at 400 seconds, torsional vibrations of each mass generally attenuate.

V. Conclusions

This paper presents a simple approach for the diagnostics of the torsional vibration of a turbine generator interconnected with a self-commutated converter. The torsional vibration has been investigated by a power system simulation, in which a model based on the analysis of measured field data has been used. The sideband wave of a self-commutated converter might cause SSTI; obtained results from the developed tool could be utilized to mitigate the torsional vibration. For example, the tuning of internal control loop of the converter to shift the oscillation frequency could be effective as a corrective action [6]. The appropriate design of rotor shaft to avoid the resonance condition and the moderate system operation to avoid the self-excited vibration in the control loop should be considered.

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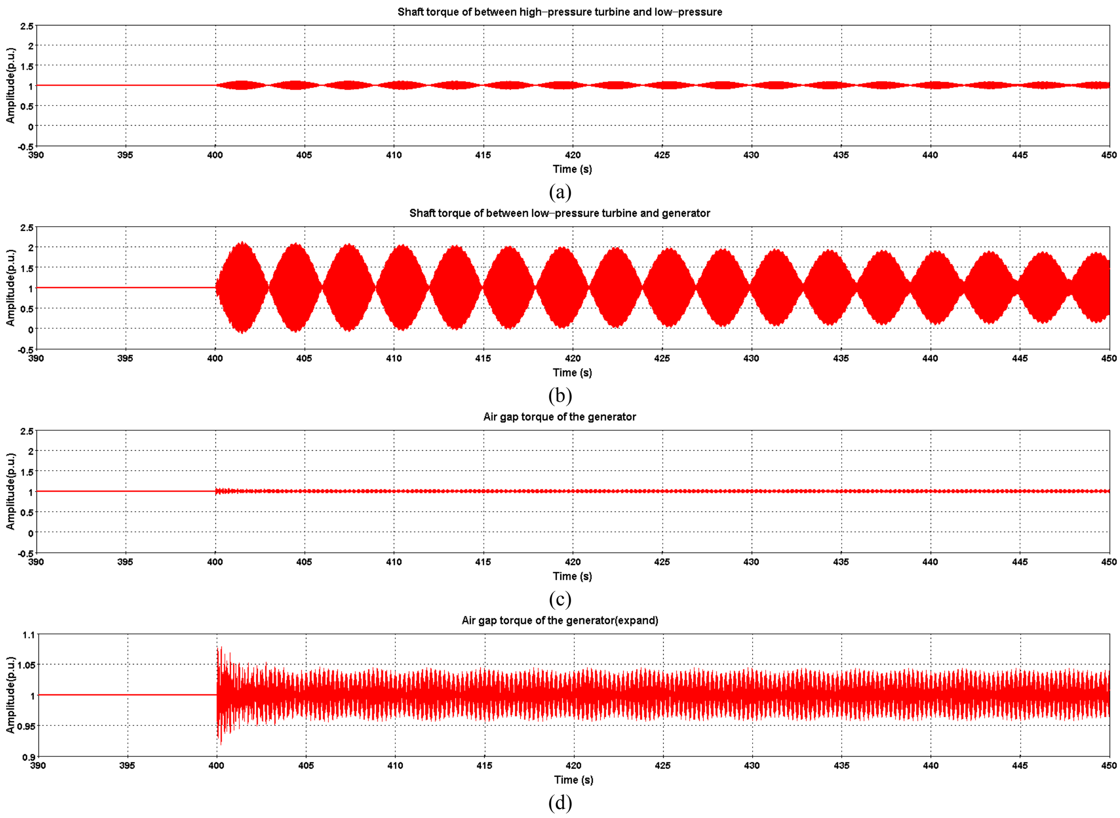

Fig. 13. Torque fluctuations in case 1: (a) shaft torque between high pressure and low pressure turbines. (b) shaft torque between low pressure turbine and generator (c) air gap torque (d) close-up.

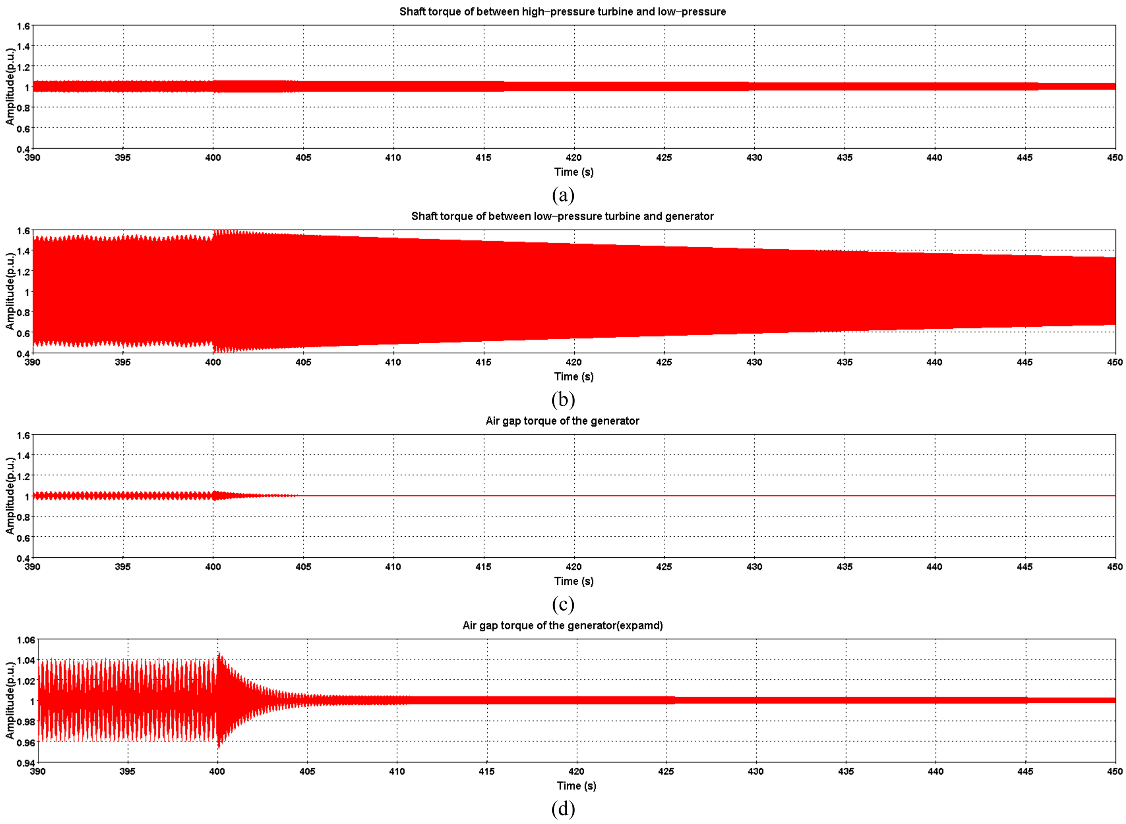

Fig. 14. Torque fluctuations in case 2: (a) shaft torque between high pressure and low pressure turbines. (b) shaft torque between low pressure turbine and generator (c) air gap torque (d) close-up.