Depressing Turbine-Generator Supersynchronous Torsional Torques by Using Virtual Inertia

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***Abstract*—**Single-pole switching scheme is widely used in the Extra High Voltage system. However, the substantial negative-sequence current injected to the turbine-generators imposes the electromagnetic (E/M) torque of double system- frequency components during the dead time (between single-pole clearing and line reclosing). This would induce supersynchronous resonance (SPSR) torque amplifications on low pressure turbine generator blades and even lead to fatigue damage. This paper proposes the design of a mechanical filter (MF) with natural frequency close to double-system frequency. From the simulation results, it is found that such a filter not only successfully damps the resonant effect, but also has the characteristics of feasibility and compact.

***Keywords*—**Single-pole, Supersynchronous, Blade, Unbalance, filter.

I. INTRODUCTION

IT is well-known that the advantages of single-pole switching technique on respective line [1-4], resulting from the frequent single-line to ground fault. A great benefit on enhancing transient stability is gained. However, the persistently negative-sequence currents inject to nearby turbine generators during the dead time. An increasing concern is the induced electromagnetic disturbing torque with double system frequency component, which could excite SPSR effect and damaging torques on LP final row (L0) or next-to-final (L1) row turbine-generator blades [2, 4].

To limit such an SPSR effect on blades is the motivation behind the development of our proposed method. A double system-frequency filter is designed and renders a low inertia constant during normal system operations. Only during the dead time, does the filter resonant and produce a considerable inertia that combined with generator-rotor one to make the turbine system, especially the blades, less sensitive to the E/M torque disturbance of double system-frequency frequency. Thereby, the SPSR torque magnification in turbine blades is damped effectively.

II. SYSTEM STUDIED

Fig. 1 schematically shows the one line diagram for the investigations of this paper. The practical steam turbine unit, including a high-pressure stage (HP) and two low-pressure (LP) stage steam turbines, analysed in this study is a close-coupled and cross-compound reheat unit. The rated capacitor of the generator, installed in 1984, is 951MW. There are eleven rows of blades in the LP steam turbine. The first nine rows of blades are shrouded and the last two rows of blades are freestanding structures in which the tip diameter of the longest blade is 4531mm and its length is 1166mm. The simulation electrical and mechanical data can be obtained from [2]. Matlab-Sim Power System program is adopted for studied system simulation [5].

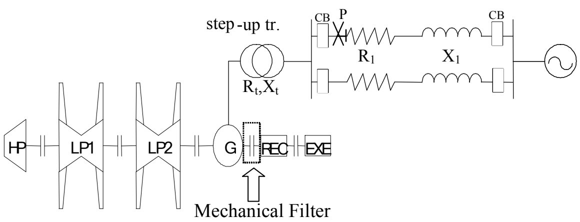


Fig. 1. Studied system

III. FREQUENCY SCANNING [2]

In this paper, the vibration modes of the turbine system have been analyzed by using the frequency-scanning method. Suppose that the terminal of generator rotor is a shaker with electromagnetic torque of one per unit, the frequency-scanning inspects the natural frequencies of steam turbines from 0.01 Hz to 140 Hz with a interval of 0.01 Hz. Ten vibration modes are then present in the turbine system, which are listed in Table 1. The scanning results are shown in Fig. 2, which illustrates the torque responses of blades of LP1R and LP2R and shaft section of LP2R-GEN. It can be observed that the vibration modes 7 and 8 are next to the double-frequency (120Hz) [6]. Consequently, the SPSR effect in blades is expectable. However, such an effect in shafts is insignificant owing to the low response of the 120Hz. The SPSR phenomenon could not take place in turbine shafts.

TABLE I VIBRATION MODES (HZ)

1	2	3	4	5	6	7	8	9	10
19.40	37.39	40.25	47.01	100.22	102.19	119.78	119.95	127.75	129.09

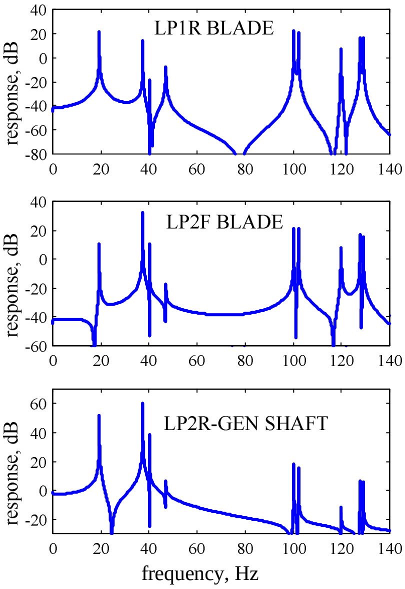


Fig. 2. Results of frequency scanning

IV. Mechanical Filter Design

It is known that augmenting the inertia of the generator rotor is a solution for depressing turbine shaft and blade vibrations under the excitation of all frequencies [8]. However, this makes the generator rotor clumsier. This approach conflicts with the tendency for generator design and affects the generating efficiency. In contrast, the authors proposed a concept of virtual extra inertia adding to the generator rotor only under double system frequency excitation. Its principle is to design a double system-frequency mechanical filter, consisting of proper flywheel inertia and shaft stiffness.

The filter is installed between the generator and the rectifier rotor shown in Fig. 3(a). According to the rules of electromechanical similarity [7], the mass-spring-damping model of turbine can be transferred to inductance-capacitance reciprocal-resistance model as drawn in Fig. 3(b). According to the negligible quantity of inertia and stiffness on the rectifier and exciter sections ((nearly short-circuited), the filter can be designed independently and become a parallel resonant circuit. Aimed at the depression of the double system-frequency excitation, this mechanical filter with 120Hz Parallel resonant frequency provides very large impedance, combining the self impedance of generator rotor. This effect is similar to add generator inertia and called virtual inertia in this paper. Thus the voltage drop under the 120Hz excitation on blade (analogous to blade torque vibration) is significantly reduced. For a turbine-generator with 4 poles and 60Hz, the resonant frequency of the filter can be deduced by

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K_{GEN-MF}}{H_{MF}} \times \frac{377}{4}} \qquad (1)$$

where the K_{GEN-MF} and H_{MF} are the stiffness coefficient of GEN-Mechanical Filter shaft and the inertia constant of the Flywheel of mechanical filter rotor, respectively. Assume that K_{GEN-MF} is 325.2832 MW/MVA-rad, and then the corresponding filter inertia and resonant frequency will be 0.0505 sec and 124Hz, respectively. After equipping with this proposed filter, the double system-frequency peak torque responses for all the blades have seen significantly damped as compared from Figs. 2 and 4. Further comparing other frequency bands except more than resonant frequency one, their responses almost remain unchanged. This implies that the filter will not affect the normal operation due to the distinct frequency excitation.

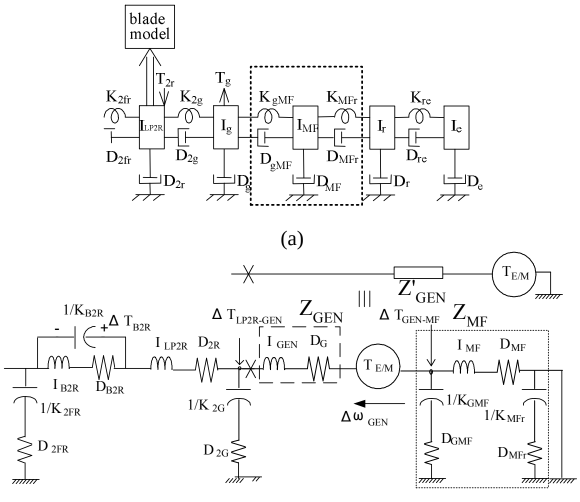


Fig. 3. The proposed mechanical filter (a)mechnical model (b) analogous electrical model

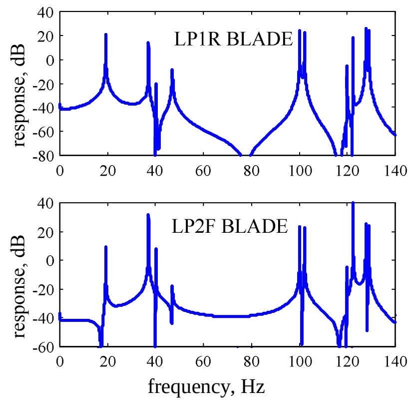


Fig. 4. As for Fig. 2, but with proposed mechanical filter.

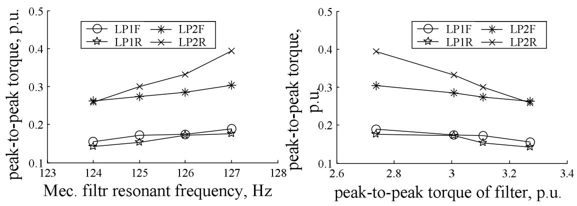
V. Time Domain Simulation Results

In order to demonstrate the effect of the designed filter, a successful reclosing of a 3-60 cycle's single-phase to ground fault occurred at the front end of the transmission line near the CB after 0.1 s in Fig. 1 is applied. The E/M disturbing toque and blade vibrations with and without the filter in service are depicted in Fig. 5, in which one can see that, during the dead time (between single-pole tripping and line reclosure, 0.15~1.15s), the main component E/M torque is of 120Hz which imposes SPSR torque amplification on each blade in Fig. 5(a). Then the successful damping results by the proposed filter is illustrated in Fig. 5(b), which agrees with the deduction of section 4. It should be noted that the blade vibrations imposed by the fault inception to single-line tripping (0.1~0.15) cannot be effectively suppressed following the main system-frequency excitation of E/M torque.

5.1. Effect of the filter resonant frequency

The relationship between the resonant frequency of the filter and peak-to-peak torque vibrations is illustrated in Fig. 6. By maintaining constant stiffness coefficient on the GEN-MF shaft, the effectiveness on damping torque is enhanced as resonant frequency of the filter decreases by increasing the flywheel inertia constant. However, if the resonant frequency of the filter is too close to the double system-frequency. A large torque level will be imposed in the filter shaft, may damaging the mechanical filter. Therefore, a compromised between effectiveness and filter stresses should be made. Fig. 6(b) examines the relationship between the torques induced in the filter shaft and in the blades. It is recommended that the filter shaft stresses be not beyond other turbine shafts.

Therefore, it is worth noting that a mechanical filter is not designed to eliminate the blade vibrations but to share them. Therefore, the capacity of the mechanical filter must be carefully designed to endure this sharing stresses on the shaft against fatigue damage. Fortunately, shaft section is obviously easy to strengthen than blade sections. Therefore, the proposed filter equipped in rotor-and-shaft section is a feasible method.



(a) (b)

Fig. 6. (a)Relationship between the resonant frequency of the filter and the peak-to-peak torques induced in each blade section (b) Relationship between the peak-to-peak torques induced in the filter shaft and each blade section

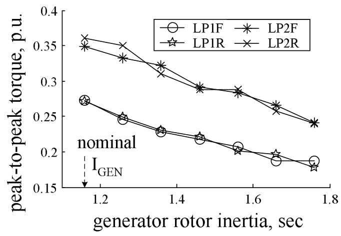


Fig. 7. The effect of generator rotor inertia.

5.2. Comparison between the practical and virtual inertia

Fig. 7 shows the blade vibration torques reduction as practice inertia of generator rotor increases. Comparing to Fig. 6(a), the proposed filter requires only one-tenth the practical inertia to be added to obtain the same suppression quantity on the blade vibrations. (0.26 pu for LP2R blade) The proposed mechanical filter has the advantages of compact and less weight.

VI. CONCLUSIONS

From the simulation study results, the following conclusions can be drawn.

Since the single-phase to ground fault represents more than 90% of transmission line faults, the LP turbine long blades of nearby generators connected to single-pole switching transmission systems suffer possibility of supersynchronous resonance. The virtual inertia produced by a double system-frequency mechanical filter does damp the SPSR phenomenon of blades. Based on equal depression goal, the proposed filter only needs one-tenth inertia as compared to the additional one of a practical generator rotor.

The function of the proposed compact mechanical filter is not to depress the blade vibrations but to share them to its filter shaft. The resonant frequency should be adequately apart from the double system-frequency against the high stresses exciting in self-shaft.

In fact, high cost needs to be paid to change blade natural frequency to escape the SPSR zone by tuning the blade inertia or stiffness. The proposed filter provides a feasible method.

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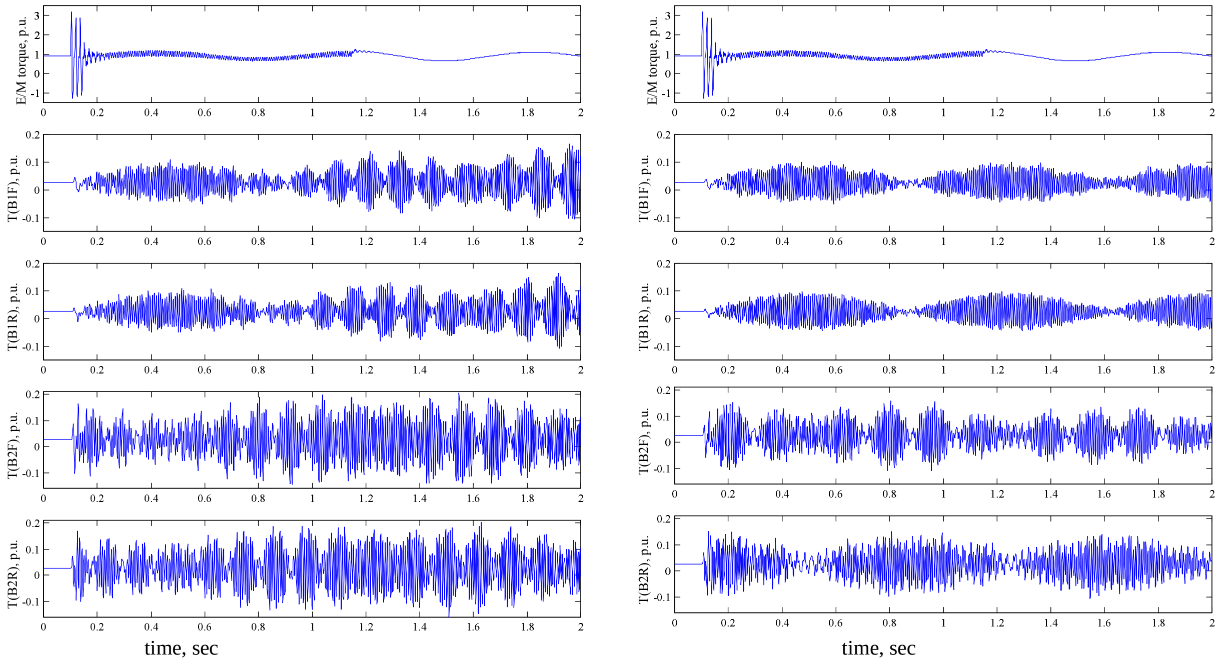
REFERENCES

[1] E. W. Kimbark, “Suppression of grounding fault arc on single-pole switched EHV lines by shunt reactor,” IEEE Trans. PAS., vol. 83, pp. 285-290, March 1964.
[2] J. I. Tsai, "A New Single-Pole Switching Technique for Suppressing Turbine-Generator Torsional Vibrations and Enhancing Power Stability and Continuity," IET Proceedings - Generation, Transmission and Distribution, vol. 1, no. 5, pp. 804-810, Sept. 2007.
[3] S. O. Faried, "An adaptive short time compensation scheme for improving power system stability and reducing turbine-generator shaft torsional," IEEE Trans. Power Systems, Vol. 15, No. 2, pp. 785-790, 2000.
[4] J. Gonzalez, G. C. Kung, C. Raczkowski, C. W. Taylor and D. Thonn, "Effects of single- and three-pole switching and high-speed reclosing on turbogenerator shafts and blades," IEEE Trans. Power Apparatus and Systems, vol.103, no. 11, pp. 3218-3228, 1984.
[5] Power System Blockset for Use With Simulink User’s Guide, June 2001.
[6] Slow Transient Task Force of IEEE Working Group, "Modelling and analysis guidelines for slow transients. Part I. Torsional oscillations; transient torques; turbine blade vibrations; fast bus transfer," IEEE Trans. Power Delivery, vol. 10, no. 4, 1995.
[7] R Gerber, Theory of Electroacoustics, Salford, New York, pp.1-56, 1979.
[8] J. J. Grainger and W. D. Stevenson, "Power system analysis," McGraw-Hill, Inc. 1994.



(a) (b)

Fig. 5. Electromagnetic toque and blade vibrations during successful single-pole reclosing of a 3-60 cycle's single-phase to ground fault (a) without and (b) with the proposed mechanical filter in service.