Design of Blocking Filter and Control System to Prevent the Subsynchronous Resonance in Power Systems

Chau Le Thi Minh[1,*] and Tung Le-Duc[1]

ARTICLE INFO

Article history:
Received: 31 January 2024
Revised: 5 April 2024
Accepted: 10 May 2024
Online: 31 March 2025

Keywords:
Power system stability
Sub-synchronous resonance
Passive filter
Controller

ABSTRACT

Sub-Synchronous Resonance (SSR) can have significant consequences for the stability and reliability of power systems. This paper presents a control method, using the blocking filters, to prevent sub-synchronous resonance problems in the electrical power system. This study proposed an algorithm to prevent low-frequency wave sources from the grid to the generator to avoid resonance and mitigate the risk of SSR phenomenon. The algorithm, is developed to define filter parameters to eliminate frequencies that would cause resonant oscillations on turbine generator shaft sections. In this approach, a controller is also added to enhance flexibility in operating the filter equipment. The calculation results, based on the IEEE First Benchmark standard model, confirm the efficiency of the proposed method. The computational analysis, through the eigenvalue methods, shows a good match with the time domain simulation results.

1. INTRODUCTION

Sub-Synchronous Resonance (SSR) in the power system has been reported to cause severe damages to turbine generator shafts that disrupts power supply and subsequently affect energy security and socio-political stability of a country [1].

To meet the needs of socio-economic development, Vietnam's power system has been continuously expanding both in scale and operational complexity coupling with increasing demand on system stability. Before 2015, Vietnam's power system did not have a specific record of the occurrence of SSR phenomenon. However, in 2015, an accident, happened at unit number one of Vung Ang thermal power plant, due to the turbine shaft cracking caused the unit's operation to stop. Preliminary analysis suggested that the incident is due to the phenomenon of sub-synchronic resonance.

For years, the phenomenon of SSR has been studied extensively in the world [1]-[16]. In Vietnam, many studies have been conducted in recent years. In [2, 3], a standard model in the calculation tools for SSR simulation calculation was proposed. Different research methods on SSR were also reviewed and analyzed in [2, 4]. Certain studies suggested to replace the vertical capacitor with a flexible reactive power compensator to eliminate SSR [5].

In this paper, passive filter is proposed to eliminate this SSR issue in power system. This method still uses vertical capacitors on the line to improve transmission capacity and system stability. In Section 2, the principle and method to select filter parameters will be introduced. The design of the controller for passive filter, is detailed in Section 3. Section 4 discusses the results applied to the standard grid proposed by IEEE. Conclusions and directions for further research are presented in Section 5.

2. PASSIVE FILTER FOR REDUC-TION OF SSR

2.1. Structure and principle of passive filter

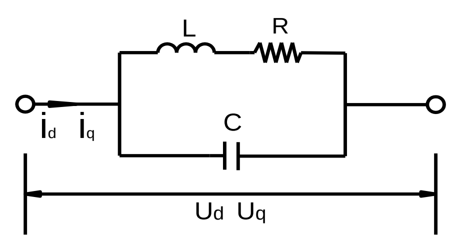

Fig. 1. Passive filter elements.

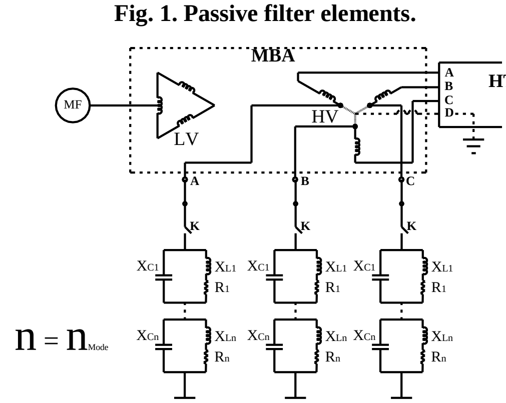

Fig. 2. Filter installation location.

[1]*School of Electrical Engineering, Hanoi University of Science and Technology, no. 1 Dai Co Viet St., Ha Noi, Vietnam.*
**Corresponding author:* Chau Le-Thi-Minh; E-mail: chau.lethiminh@hust.edu.vn.

A filter consists of an inductor L, a resistor R and a capacitor C as shown in figure 1. The filter is designed to generate a high impedance to deal with the current of the frequency to be blocked and a low impedance for a current of a different frequency. Thus, the number of filters must be equal to the number of "Modes" of the turbine shaft.

To prevent low-frequency waves from entering the generator, a filter is placed in series between the generator and the electrical system, namely the neutral end of the transformer's high-voltage winding (figure 2) [6].

2.2. Design of passive filter

The sub-synchronous resonance phenomenon is triggered by the current, oscillating at electric frequency fe, which is originally caused by a vertical compensating capacitor. This method aims to block this current to eliminate SSR phenomenon by connecting a passive filter in series right before the generator. Each turbine shaft segment of a thermoelectric generator has a natural oscillation frequency. Therefore, to prevent resonance, each of these shaft segments needs to be protected by a separate filter. Let's consider the method of determining the filter parameter including the values of R, L and C [6, 7, 8].

The total impedance seen from the two ends of the filter is determined as follows:

$$Z(\omega) = (LntR)//C = \frac{R + j\omega L}{1 + j\omega RC - \omega^2 LC} \quad (1)$$

When R is small, $Z(\omega)$ reachesmaximum value at resonant frequency:

$$\omega_p = \frac{1}{\sqrt{LC}} \quad (2)$$

Then, at the resonant frequency ω_p, the total impedance is:

$$Z_p = \frac{R + j\omega_p L}{j\omega_p RC} \quad (3)$$

When $\omega_0 L >> R$, we have (Q is grand):

$$Z_p = \frac{L}{RC} \quad (4)$$

with Q is the quality factor of the reactor:

$$Q = \frac{2\pi f_o L}{R} \quad (5)$$

Total impedance at fundamental frequency:

$$Z_{fo} = -\frac{\omega_0 L}{\frac{\omega_0}{\omega_p} - 1} \quad (6)$$

It is obvious that high value of inductor L leads to a large impedance value at resonant frequency Z_p (the filter operates effectively), but, at the same time, also increases the impedance Z_{fo} at fundamental frequency. As a result, the compensation level of the vertical capacitor must be increased accordingly [6].

In theory, the smaller the value of the resistor R, the larger the Q [9], but, in [7], Q is reported to have a value ranging from between 50 and 200.

The algorithm diagram for determining parameters for the filter with the input being the natural frequencies of the turbine shaft segments is presented in [10].

3. DESIGN OF CONTROLLER FOR PASSIVE FILTER

At high compensation level, a passive filter, connecting in series to the line, is crucial to minimize the effect of sub-synchronous resonance. However, at low compensation level, this same filter fails to mitigate the undesired effect but increases line impedance and voltage loss, consequently. It is obvious that effective control of the passive filter is critical to deal with sub-synchronous resonance. The proposed approach uses the oscillations of the torque of the mechanical shafts in the generator turbine as a control signal to switch the impedance of the filter. The passive locator model combined with the switching controller is built on EMTP software as shown in Figure 3.

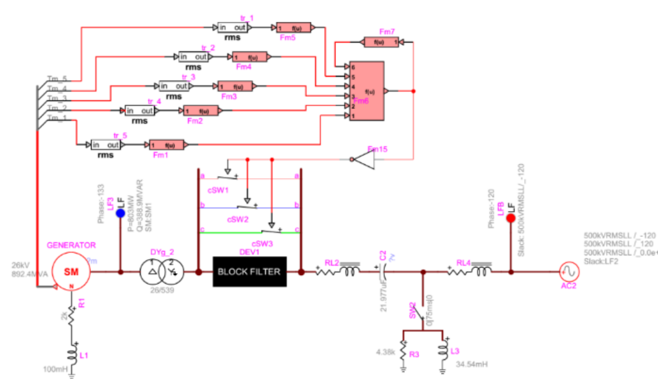

Fig. 3. Simulation diagram with filter switching control.

The torque fluctuation signals are measured then passed through the comparators F_{m1}, F_{m2}, F_{m3}, F_{m4}, F_{m5} to compare with the reference value. The output signal of these comparators is then fed into the signal synthesizer and subsequently through the F_{m6} block. If a certain axis reaches the given torsion threshold, a signal will be sent to close the filter into the circuit. It is necessary to consider the power system operation in the steady state and the fault condition cases to determine the adjustment value for the controller. Based on the consideration of the torque value when simulating in both cases (steady state and SSR resonance) with different compensation capacities, the allowable torque threshold value is 1.1 pu in steady state to ensure long-term and stable operation of the turbine shaft. To ensure that there is no mistaken control, the adjustment value is usually set to be greater than 1.1 pu:

$$T_a = K_s * T_n \quad (7)$$

where:

- T_a : Torque adjustment
- T_n : Rated torque
- Ks: Safety factor (Ks=1.2 – 1.4)

The efficiency of the non-permanent filter was tested to prove that the filter is only closed when axial torque occurs during the SSR phenomenon.

4. APPLICATION TO IEEE STANDARD MODEL

The First Benchmark standard model (FBM) was built by IEEE for the purpose of studying the sub-synchronous resonance phenomenon (Figure 6). Research on the standard model is highly convenient and accurate because the given parameters are consistent with the actual ones. Furthermore, IEEE has also released preliminary research results, thereby helping researchers have a basis for comparing and verifying the results as a premise for further research. The parameters of the model are introduced in Table 1 and Table 2 [11].

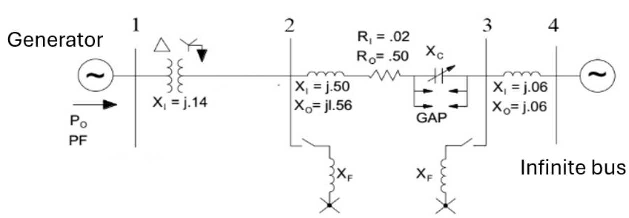

Fig.4. First Benchmark model diagram.

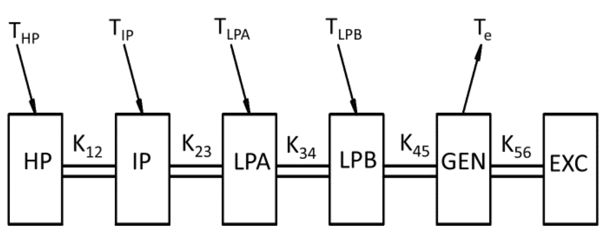

Fig.5. First Benchmark model turbine shaft diagram.

Table 1. First Benchmark model grid parameters [9]

Parameter	Positive order components	Zero-order components
Line resistance	0.02	0.5
Transformer reactance	0.14	0.14
Line reactance	0.5	1.56
System reactance	0.06	0.06
Capacitor (To the case of 74.2% compensation)	0371	0.371

Table 2. First Benchmark model turbine parameters [9]

Inertia	Inertia constant (H)	Shaft	Stiffness K (pu)
HP Block	0.092897	HP-IP	19.303
IP Block	0.155589	IP-LPA	34.929
LPA Block	0.858670	LPA-LPB	52.038
LPB Block	0.884215	LPB-GEN	70.858
GEN Block	0.868495	GEN-EXC	2.82
EXC Block	0.0342165		

This model includes a generator, a turbine consisting of 6 blocks HP, IP, LPA, LPB, GEN and EXC, connected in series with a step-up transformer, a line with vertical capacitors and finally an extremely large node. Thus, for the FBM model, the turbine - generator shaft has 5 Modes requiring 5 filters to remove specific oscillation frequencies as shown in table 3 [4].

Table 3. Natural oscillation frequency of the generator turbine shaft

Mode	Imaginary part of eigenvalue	Oscillation frequency (Hz)
Mode 1	98.71	15.71
Mode 2	126.98	20.21
Mode 3	160.53	25.55
Mode 4	202.88	32.29
Mode 5	298.19	47.46

Table 4. Results of calculating filter parameters

	L (H)	C (F)	R (Omh)
Filter Mode 1	0.026362994	0.000489862	0.033128715
Filter Mode 2	0.018873138	0.000847755	0.023716684
Filter Mode 3	0.055101344	0.000387279	0.069242391
Filter Mode 4	0.043281793	0.000761913	0.054389505
Filter Mode 5	0.1405641	0.001145233	0.176638058

By applying the algorithm in section 2, the parameters of the 5 filters can be determined as shown in Table 4. In [8], the eigenvalues and eigenvectors show that all real parts of the eigenvalues are negative meaning that all eigenvalues are on the left of the imaginary axis. According to the stability criteria, it can be conluded that the system is stable or ,in other words, the SSR phenomenon does not occur once the filter is installed.

The EMTP simulation tool is employed to model the IEEE FBM diagram and builds a 5-filter model with parameters shown in Table 4. Simulation scenario and short circuit excitation at node 3 (Figure 6) at time 0.1s over a period of 0.075s with different compensation cases, before and after filter installation.

Two cases areconsidered in the simulation:20% compensation and 74.2% compensation.

4.1. Simulation without filter

The simulation results, shown in Figure 8, are consistent with the results given by IEEE. It can be observed that for 20% compensation, subsynchronous frequency resonance does not occur. While, in the case of 74.2% compensation, the amplitude of torque fluctuations between axes tends to increase many times (resonant form) after the incident and thus SSR happened.

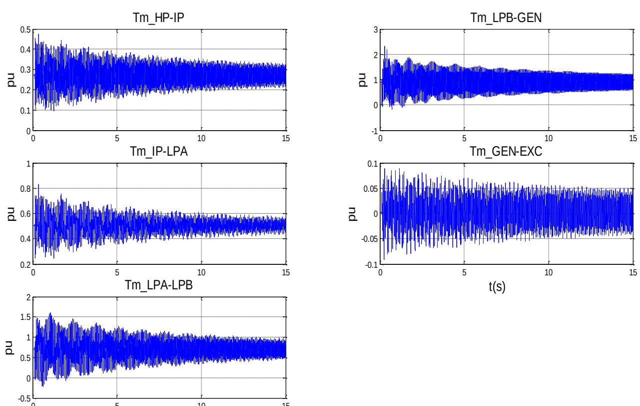

Fig. 6. Torque (pu) on axes in the case of 20% compensation.

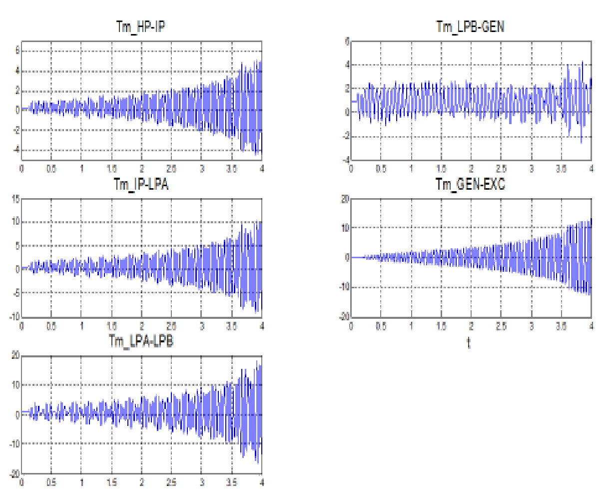

Fig. 7. Torque (pu) on axes in the case of 74.2% compensation

4.2. Simulation with filter

Once being used, filter will be automatically controlled to close the connection to the system when an SSR problem occurs (torque spike due to resonance).

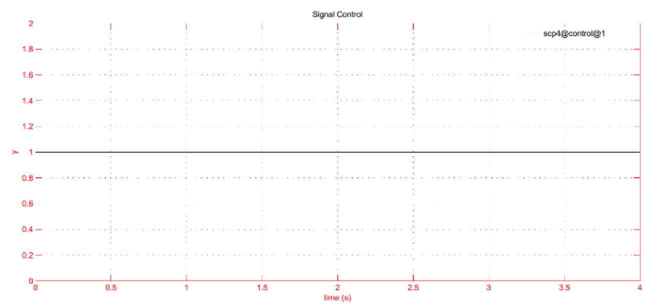

Fig. 8. Filter switching control signal in the case of 20% compensation.

From the above simulation results, it can be observed that, for low vertical compensation levels (20%), subsynchronous frequency resonance does not occur hence, no control signal presents as the passive filter is not connected to the system (figure 8).

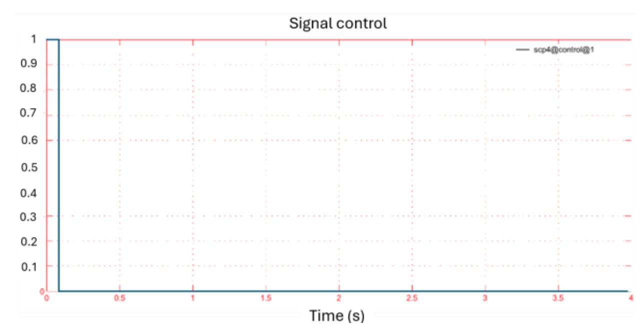

Fig. 9. Filter switching control signal in the case of 74.2% compensation.

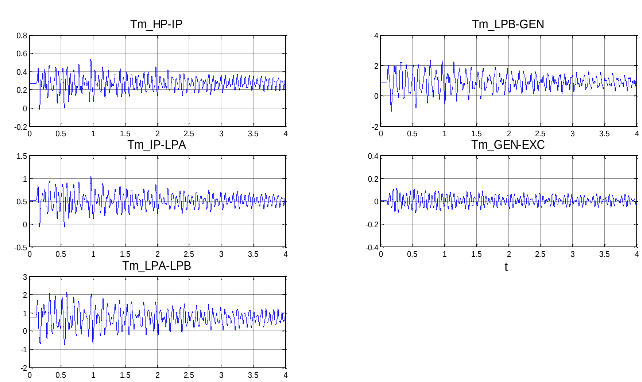

Fig.10. Torque (pu) on axes in the case of 74.2% compensation.

At a high compensation level (74.2%), once the SSR phenomenon causes an increasing torque, the controller detects the problem and sends a control signal to close the passive filter into the system (figure 9). The torque responses of the turbine shafts show that the SSR phenomenon was effectively prevented (figure 10).

5. CONCLUSIONS

In this article, the author has presented a method using passive filters to prevent subsynchronous resonance problems in power systems. The operating principle controller design methods was introduced as well.

The simulation results with the IEEE standard model proved the correctness and feasibility of the proposed method. Similar results of both the eigenvalue method and the time domain simulation method confirms that the filter is capable of preventing SSR problems. Research on applying filters to eliminate SSR in Vietnam's power system will be invested and developed in the near future.

ACKNOWLEDGMENT

This research is funded by the Ministry of Education and Training, Vietnam under the grant number CT2022.07.BKA.04.

REFERENCES

[1] D. N. Walker, C. E. Bowler, R.L Jackson and D.A Hodges. 1975. Results of subsynchronous resonance test at Mohave. IEEE Transactions on PAS. 94(5):1878- 1889.

[2] Tung Le Duc. 2016. Mô phỏng các mô hình chuẩn IEEE trong ATP/EMTP phục vụ cho nghiên cứu hiện tượng cộng hưởng dưới đồng bộ. Journal of Science and Technology – Technical Universities. 110(1):1-6.

[3] T.N. Minh, L.Đ. Tung, N.H. Viet, N.T. Đuc và L.G. Thi. 2017. Xây dựng mô hình máy phát - turbine nhiệt điện trong Matlab phục vụ nghiên cứu cộng hưởng tần số dưới đồng bộ". The University of Danang - Journal of Science and Technology. 5(114): 61-65.

[4] Tung Le Duc. 2020. Phương pháp trị riêng trong phân tích hiện tượng cộng hưởng dưới đồng bộ. Áp dụng cho mô hình IEEE FIRST BENCHMARK. TNU Journal of Science and Technology. 6(1): 229-236,.

[5] T. V. Dinh, H. A. Nguyen, and C. Q. Le. 2015. Selection of Facts device to prevent Subsynchronous resonance at Vung Ang I, II Thermal Power Plants," (in Vietnamese). DU Journal of Science and Technology, 7(1): 71-75.

[6] Xiaorong Xie. 2013. Applying Improved Blocking Filters to the SSR Problem of the Tuoketuo Power System. IEEE Transactions on Power Systems. 28 (1): 227-235.

[7] D.J.N. Limebeer, R.G. Harley, M.A. Lahoud. 1981. Suppressing subsynchronous resonance with static filters. IEE. PROC, 128(1): 33-44.

[8] S. Wangsathitwong, S. Sirisumrannukul, S. Chatratana, and W. Deleroi. 2009. Control of Line Side Converter for Doubly Fed Induction Generator with Active Power Filter and Load Balancing. GMSARN International Journal, 3(2): 65-72.

[9] Vo Ngoc Dieu, Le Anh Dung, and Nguyen Phuc Khai. 2013. Transient Stability Constrained Optimal Power Flow Using Improved Particle Swarm Optimization. GMSARN International Journal. 7(1): 87-94.

[10] Tung Le Duc. 2020. Using the blocking filter to prevent subsynchronous resonance, application to IEEE First Benchmark system. The University of Danang - Journal of Science and Technology. 18 (07): 47-50.

[11] IEEE SSR Task Foree. 1977. First Benchmark Model For Computer Simulation of Subsynchronous Resonance. IEEE Trans on Power Apparatus and Systems. 96(4): 1565-1572.

[12] ZHANG Zhi-qiang and XIAO Xiang-ning. 2009. Analysis and Mitigation of SSR Based on SVC in Series Compensated System. International Conference on Energy and Environment Technology. Guilin, China 16-18 October. IEEE Publishers.

[13] IEEE SSR Task Foree. 1985. Second Benchmark Model For Computer Simulation of Subsynchronous Resonance. IEEE Trans on Power Apparatus and Systems, 104 (5): 1057-1066.

[14] P.M. Andreson, B.L. Agrawal, J.E. Van Ness. 1990. Subsynchronous Resonance In Power Systems. IEEE PRESS.

[15] L. Dong, J. Kong, J. Feng and Y. Zhang. 2019. Subsynchronous Resonance Mitigation for Series Compensation Transmission System of DFIG Based on PR Control. 2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG). Xi'an, China. 03-06 June. IEEE Publishers.

[16] X. Yanhui and S. Ge. 2012. Effect of shaft parameter uncertainty on subsynchronous resonance simulation. 2012 Power Engineering and Automation Conference. Wuhan, China. 18-20 September. IEEE Publishers.