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The impact on large generators through harmonic currents caused by rapid control

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SUMMARY

With the development of the power system, a large number of electrical equipments based on rapid control are widely used in electric power production and transmission process, building a strong and smart power grid which plays an important role in economic and energy-saving power plants. However, the application of new technology has also brought some harmonics which will impact on the safe operation of primary equipment. It is urgent to focus on and solve this problem to avoid serious accident.

The interaction between the generator and the grid is a complex process. This article focuses on the large number of typical fast control system, especially analyzing harmonic problem caused by HVDC transmission, AC series compensation transmission and inverter. It is significant to research harmonics of these key electricity production equipment and transmission equipment.

Harmonic current analysis of rapid control in this paper is based on problems of the generator and power system resonance and generator set torsional vibration occurred in recent years, which are urgent to be resolved. The aim of the research is to obtain the measures of harmonic current protection and mitigation, through revealing the nature of the problem of harmonic currents generated. The research in this paper is carried out from the grid side and the generation side, analyzing main harmonic sources and the system harmonic instability, rapid control power element output characteristics in the normal and abnormal working state and the closed loop control robustness, sensitivity factors, and fast power control components, focusing on the effect of the harmonic current of sub-synchronization frequency. This research provides the technical scheme of practical application from such two aspects as protection measures and control measures.

Firstly, this paper introduces the actual operating condition of the DC system, series compensation system as well as the convener, refers to specific cases to illustrate the problems existing in actual operation of these devices and solutions after these problems happened, and then in depth analyzes harmonic factors, characteristics, energy and response from working mechanism, control principle and parameter design of these devices; secondly, it analyzes the impact of the harmonics on the turbine generator and auxiliary equipment, especially researches the torsional vibration caused by subsynchronous harmonic through the real-time simulation, and analyzes the torsional vibration of generator under the condition of typical underdamped DC system as well as the torsional vibration problems caused by inverter of auxiliary equipment; finally, considering the condition of harmonics generation and unit safe, it proposes economic measures to solve harmonic problems, provides the reference for operating department and realizes the equipment economic and reliable operation eventually.

KEYWORDS

HVDC transmission, AC series compensation transmission, Harmonic current, Torsional vibration, Auxiliary equipment

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1 INTRODUCTION

The core content of the construction in electric power industry is the production and transmission of electricity. The safe, stable and economic operation of plants and power grid has an essential role to play in the electric power industry. In the past twenty years, electric power system has entered the age of modern power system which is marked by information, flexibility and marketization. Unlike the electric power construction planning of European or American countries, China's power industry development planning is to build a safe, reliable and interconnected power grid which can satisfy the requirement of electric transmission quality and marketization operation around 2020. On one hand, AC/DC united transmission and long-distance series compensated transmission will become common in the grid. This will be good for the safety and economy of grid and has a great significance for energy outbound transportation. On the other hand, the focus of power plant is environmental protection and economic sustainable development of the power generation. With the technology improvement of the high voltage convertor (HVC), more and more HVC are applied in power generating equipment as the high voltage frequency converter can greatly save the energy consumption and has very considerable economic and social benefits for power plants [1].

Technological advances bring some new problems while they yield considerable economic and social benefits. HVDC technology, Thyristor Controlled Series Compensation (TCSC) technology and high voltage converter technology are all based on fast control of power electronic device which has a very wide band frequency characteristic and is enough to make the signal of subsynchronous resonance frequency. Once the subsynchronous frequency signals pass the generator and there is not enough control strategy of subsynchronous oscillation, it will lead to fluctuations in voltage, current and electric equipment. Even more serious, it will cause torsional vibration of generator and auxiliary motor in power plant, and even lead to the instability of the system. The following content explains the real-time monitoring and effective response to the harmonic current caused by rapid control in power electric devices in details from several aspects such as the mechanism of subsynchronous oscillation caused by rapid control, and the impact on the safety of the generator.

2 USAGE OF MAJOR FAST CONTROL EQUIPMENT

Fast control technologies based on the Thyristor and full-controlled semiconductor device such as IGBT matures, thyristor controlled series compensation (TCSC), the traditional DC transmission, flexible DC transmission and high voltage converter have been gradually applied in the power grid and power plants for the stability control of system.

TCSC has been successfully applied in a long-distance transmission system in China's northeast region. In this project, the transmission line is about 378 km long, combined with 15% degrees of TCSC and 30% degrees of the fixed series compensation (FSC) in order to improve the limit capacity of transmission. The torsional vibration of shaft system occurred in the same two type units of one power plant in 2008. The cause was known as the operation of TCSC and there was still a small continuous torsional vibration phenomenon after optimized parameters of TCSC. After the event researchers found that there was a continuous energy interaction between the units and the power grid from the spectrum analysis result of current signals in the grid side.

DC system has multiple applications in domestic case such as the regional power grid interconnection, and the direct long-range transmission from energy points to load centers. The risk of subsynchronous between the DC controller and generator was greatly increased especially in the island operation mode of DC system. In 2012, TSR was tripped in a power plant because of the continued substantial torsional vibration caused by the abnormal pulse generation of rectifier.

High voltage convertor has been widely applied to various control of large load motor because of its energy-saving feature; it also brings the motor shaft torsional vibration problem and affects the safe and stable operation of the unit. A typical torsional vibration accident took place in early 2012 in southern China. The shaft was 45 degrees damaged because the motor was not reformed according to the requirements. This incident reflects the increased risk of torsional subsynchronous vibration when installing the high voltage frequency convertor for energy saving. This is a phenomenon worthy of further study and attention.

Judging by the above analysis of usage of these fast control devices, large generators especially turbine has to face to the risk of instability caused by subsynchronous resonance in addition to the risk of overvoltage, overheating and other risks. So, the in-depth analysis and research on the mechanisms of SSO is urgently needed.

3 MECHANISM OF SSO CAUSED BY RAPID CONTROL

3.1 Control principle and measures of TCSC

The schematic diagram of TCSC is shown in Fig.1[2]:

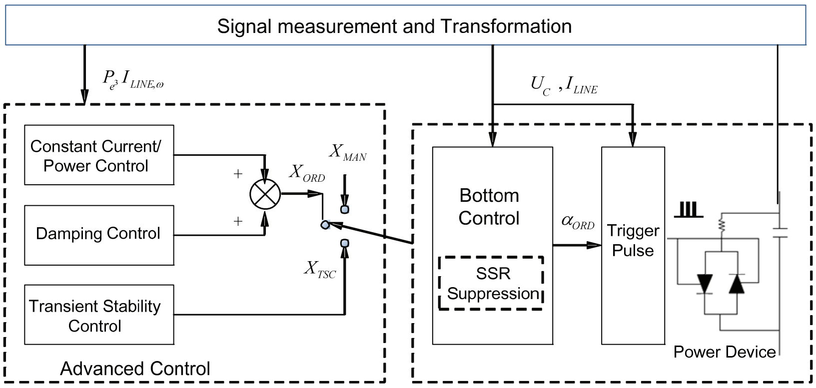

Fig.1: Schematic diagram of TCSC

Related studies show that the impedance characteristics of TCSC has changed compared with FSC, but this change can not suppress SSO in all cases.

According to control principle and impedance characteristics of TCSC, the following two reasons may lead to SSO:

1) TCSC adjusts transmission power by the calculated impedance of fundamental frequency, whose control parameters have narrowband characteristics in the vicinity of the fundamental frequency. If the impedance in the subsynchronous frequency range is capacitive, and the system damping is underdamped, SSO may occur.
2) The control frequency of TCSC is generally more than 2 kHz, and it is possible to turn into an excitation source at this point, and even a positive damping system may also have slight sustained oscillations. TCSC is a current and power closed-loop control system, and compared with fundamental component, subsynchronous component is difficult to identify. Analytical data shows subsynchronous current does not exceed 0.6% of fundamental current, which means TCSC can not eliminate the disturbance caused by itsself.

3.2 Control principle of DC system

The schematic diagram of DC system is shown in Fig.2[4]:

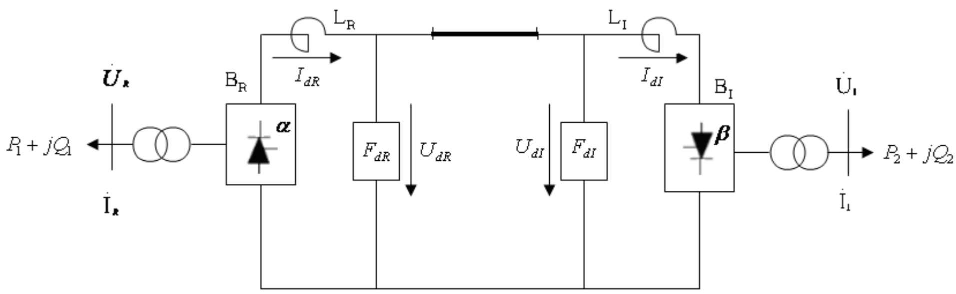

Fig.2: Schematic diagram of HVDC system

SSO caused by DC system control has been studied for a long time, under normal condition, while DC system and turbine generator interacts because of the following two reasons:

1) Turbine shaft is so flexible that small perturbations can affect amplitude and phase of the generator voltage which will change DC current, and then, DC current change will affect the system electromagnetic torque which will act on the shaft. All of these form a closed-loop system, SSO will occur once positive feedback is constituted in this loop.
2) Inappropriate control parameters of DC system may play a negative damping effect.

The abnormal condition and inregular output of control devices should be concerned.

Abnormity of DC system, such as abnormal trigger pulse, may lead to serious consequences. During normal condition, pulse delay from AC to DC among three-phase current is consistent, which will not cause harmonic current after commutation. However, if the control pulse changes abnormally, disturbances may occur, especially when the frequency of disturbance matches with mode frequency of generator, the system will fall into SSO.

3.3 Control principle of high-voltage inverter

The schematic diagram of high-voltage inverter is shown in Fig.3[5]:

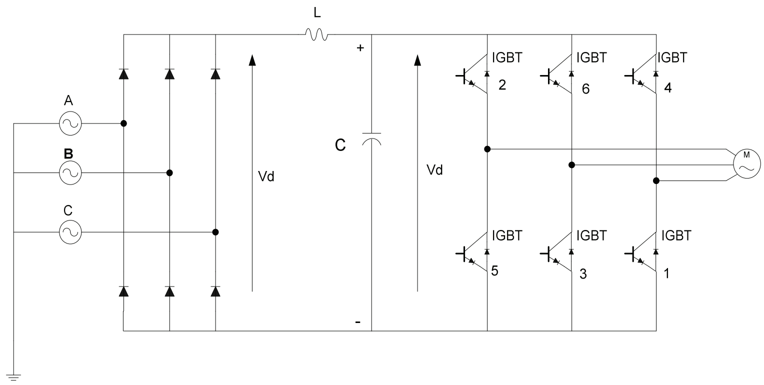

Fig.3: The schematic diagram of high-voltage inverter

As a common technology, traditional AC-DC-AC is widely used in high voltage converter whose main circuit uses H-bridge cascade and control technology adopts the Sinusoidal Pulse Width Modulation (SPWM). During actual operation, high voltage converter may output harmonic, the reasons are as follows:

1) The output characteristics of converter are affected by sample frequency, execution time of system and switching frequency of main circuit, and the main harmonic frequency is fc ±Nfm (Where, fc—sample frequency, fm—output frequency of the converter, N—integers, 1,2,3, ..., etc.)
2) Fluctuations of DC bus voltage make converter output non-integer multiples of harmonics;
3) The output voltage of converter will contain DC component if modulated wave or carrier wave has DC bias. As the stator resistance is very small, a low DC voltage would produce large DC current and torque ripple with fm[6].
4) The converter needs to set on/off time of each IGBT, and when the setting is not appropriate, a complex torque with multi harmonic frequencies will occur.

All the above reasons may excite the motor torsional vibration not only at intrinsic frequency but also over a large frequency range.

4 THE IMPACT ON GENERATORS AND COUNTERMEASURES

4.1 Impact on generators

The above section analyzes the reason of SSO caused by rapid control equipment. Since the subsynchronous current shares a small proportion in the line current, and the torsional amplitude on shaft is not large, SSO is often ignored. However, such small and sustained vibration exerts huge impacts on the shaft, which needs to be paid attention to prevent serious consequences. In fact, SSO mainly impacts fatigue life of shaft, and this fatigue loss is unrecoverable[7].

Fatigue-Life curve of shaft is shown in Fig.4:

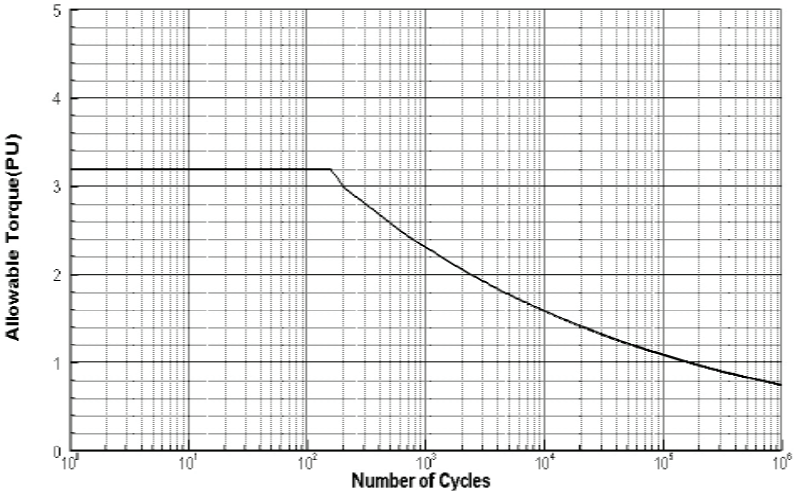

Fig.4: Fatigue-Life curve

Fatigue-life curve shows: the shaft life at a specific frequency is related with torsional amplitude, and reducing torsional amplitude is the key to reduce the impact on shaft. According to research results, reducing torsional amplitude means reducing energy of subsynchronous interaction, and there are two ways, one is to improve electrical damping level of system by adding supplementary modules or equipment, while the other is to increase filters with subsynchronous frequencies on transmission line, which costs more. This paper mainly elaborates supplementary control methods for improving damping and focuses on two things:

1) The identification of subsynchronous signals;
2) The effectiveness of control methods.

4.2 Countermeasures

4.2.1 An supplementary damping control functional block is designed in TCSC, and the schematic diagram is shown in Fig.5;

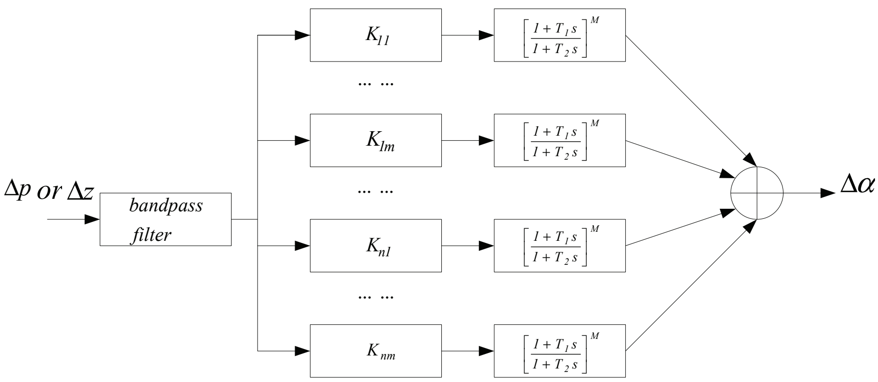

Fig.5: Schematic diagram of additional functional block of TCSC

Where, K_{11} denotes the mode 1 gain of the first generator; $K_{1\mathrm{m}}$ denotes the mode m gain of the first generator; $K_{\mathrm{n}1}$ denotes the mode 1 gain of the n-th generator; K_{nm} denotes the mode m gain of the n-th generator;

The control strategy of functional block can be interpreted as: If the generator speed is higher than synchronous speed, TCSC will raise the equivalent capacitance, try to absorb more power from generator, and reduce its rotational speed; In contrast, TCSC will lower the equivalent capacitance to reduce transmission power.

Schematic diagram shows: this additional control has the following features:

1) Each subsynchronous oscillation mode forms a closed-loop damping control, and if condition permits, all generators accessing the system can be set with different control loops, which is economical, flexible and can be expanded easily without additional equipment;

2) The rotational speed of generator is most sensitive to SSO, but TCSC doesn't choose the rotational speed as input signal to control the subsynchronous impedance, as TCSC installed in series compensation station can not get rotational speed in real time. According to the data mentioned above, subsynchronous current of generator does not exceed 0.6% of fundamental current, AND the ratio will be less if extracting subsynchronous current from 500kV transmission line, because TCSC can not suppress SSO caused by small disturbance.

4.2.2 An additional functional block is also designed for DC system, and the control block diagram is shown in Fig.6.

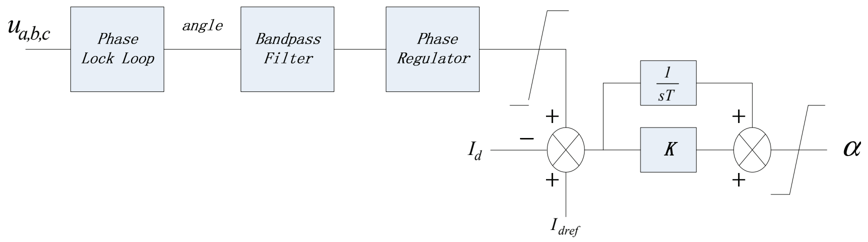

Fig.6: Diagram of additional functional block for DC system

The features of additional damping control for DC system are similar to TCSC, and the only difference is DC system adopts bus voltage of converter station as input signal, and the output is added to given DC current. To ensure subsynchronous control does not affect DC control, subsynchronous current should work in the range of 1%~5% of the DC rated current.

4.2.3 From the reason of SSO caused by converter, the additional damping control can be integrated into converter by adding subsynchronous control signal into modulated SPMW signal, thus subsynchronous electromagnetic torque will generate, so as to achieve the purpose of suppressing SSO.

Build simulation models using matlab software, with parameters referred from an electric motor.

Rated power: 5000Kw; rated voltage: 6000V, rated current: 572A, rated speed: 764rpm, efficiency: 97%, power factor: 0.867, rotor inertia: 900kg.mm, rated torque: 65000Nm.

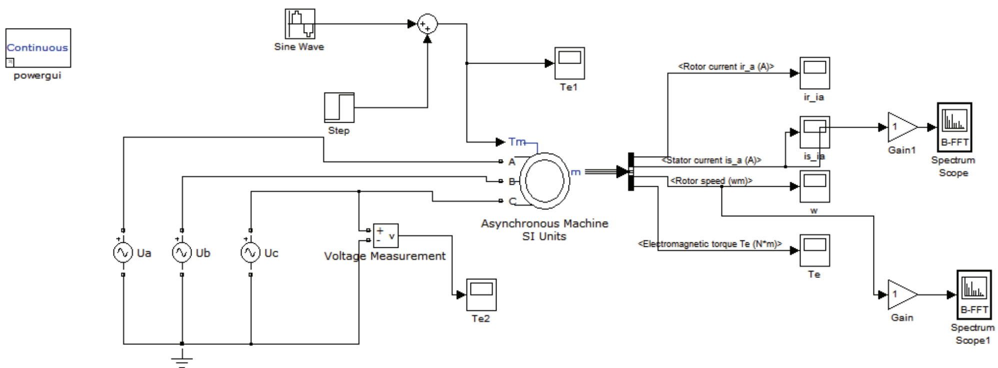

Fig.7: Perturbation model of motor

The second intrinsic frequency of the motor is 30Hz, injecting different amplitude torque with the frequency of 30Hz, and the subsynchronous current and speed deviation are shown in the following table:

Tab.1: Subsynchronous current and speed deviation

Subsynchronous torque(Nm)	Subsynchronous current level(%)	Speed deviation(rad/s)
4000	0.10	0.03
10000	0.21	0.07
20000	0.60	0.16

60000	1.96	0.40

From the table, resolution of speed deviation can be controlled within less than 0.01rad/s easily, while extracting subsynchronous signal from current is difficult to realize the accuracy. So selecting the speed deviation as input signal is a better way to make up a closed-loop control system.b

Based on the above analysis, these measures can effectively suppress serious subsynchronous oscillation, but the following aspects need to be considered and improved:

1) For small amplitude and sustained oscillation, neither TCSC nor DC system can effectively suppress, so, other additional measures need to be considered;
2) Protective measures need to be considered when TCSC or DC system falls into malfunction;

Therefore, suppression measures injecting subsynchronous current are necessary, as they have higher sensitivity. Adding additional subsynchronous damping control into excitation system or generator terminal can achieve good suppression result. The schematic diagrams of two measures are as shown below:

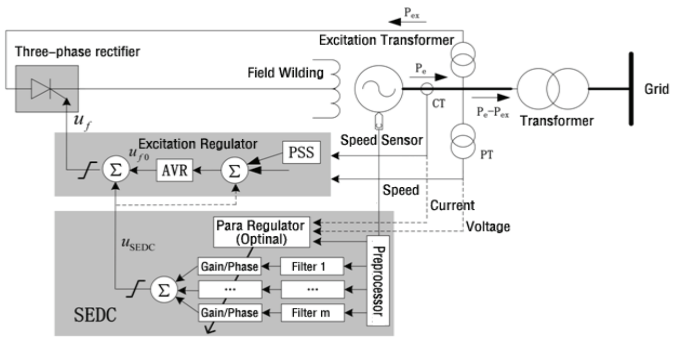

Fig.8: Schematic diagram of Supplementary Excitation Damping Control(SEDC)

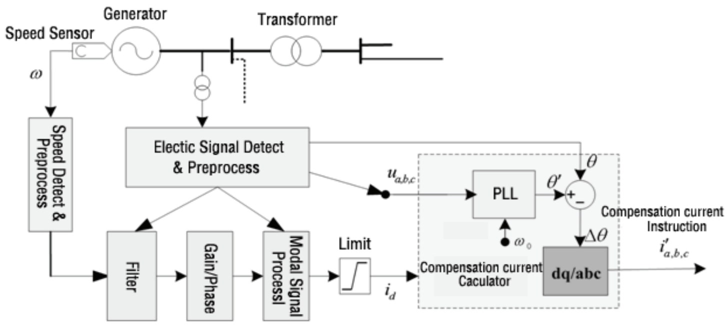

Fig.9: Schematic diagram of Generator Terminal Subsynchronous Damping control (GTSDC)

The fact proves that installation of SEDC or GTSDC is quite effective for suppressing SSO, especially for small disturbances which can not be recognized from line current, and the two suppression measures can avoid fatigue damage of shaft. The Fig.10 shows the speed deviation falls from 0.12rad/s to 0.02rad/s after SEDC is put into operation in 28s.

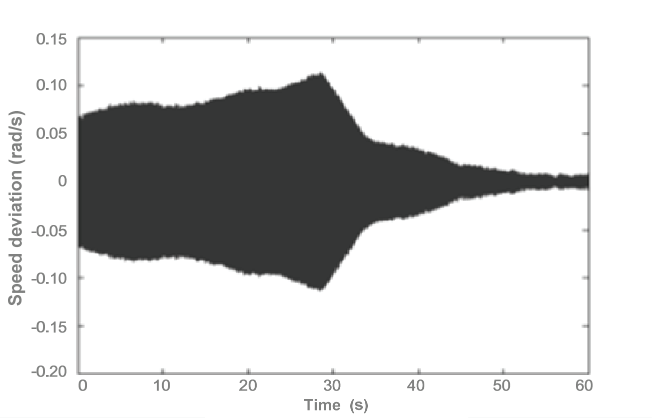

Fig.10: Changes of speed deviation when SEDC works from off to on

5 CONCLUSIONS

Currently, torsional vibration problems brought by SSO have seriously threatened the safe operation of the unit, the HVDC system, series compensation systems, and converter fast control broadband while features and dead zone of closed-loop control of the controller are the main factors. By analyzing the SSO suppression measures, it can be seen that the SSO problem is not completely resolved leaving the supply side. The actual situation shows that implementing supply-side suppression measures based on SSO signal high-precision identification can effectively release the SSO damage to unit. In practical engineering solutions, supply-side suppression measures must be considered.

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