On the Adaptive Damper System of the Electric Reactor Based on Magnetorheological Fluid

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Abstract. The electric reactor will generate irregular electromagnetic vibration during the onsite operation of substation. If so for a long time, it will cause problems such as broken indoor floor and loose connecting parts, endanger the building structure or damage to the building, thus leading to waste of land resources in indoor substation. In order to effectively suppress the irregular electromagnetic vibration of the electric reactor, this paper proposed an adaptive damper system of the electric reactor based on magnetorheological fluid to realize the all-around vibration suppression of reactor field vibration. This system placed the homemade damper in the center of each surface of the reactor, and used external filter circuit and signal amplification circuit to process the vibration signal and transform it into electrical signal, which controlled the single-chip microcomputer to regulate the damper to output the damping force, forming an adaptive damper system based on the magnetorheological fluid. Then, the good performance of vibration reduction of the system was verified by the onsite vibration reduction test of the reactor. And the adaptive regulate ability of the system is superior and is of good engineering application value.

1. Introduction
The electric reactor will generate irregular electromagnetic vibration during the onsite operation of substation. Electromagnetic force is one of the key factors that lead to electromagnetic vibration of reactor, which is also called Maxwell force. It is a certain force generated when the main magnetic flux passes through the air gap between a high-permeability iron core and a low-permeability gap that reduces the magnetic field energy, forcing the reactor core to be deformed periodically[1]. Magnetostrictive effect is another main factor causing the electromagnetic vibration of the reactor. Under the effect of applied magnetic field, the iron core changes its own magnetization state, which changes the size and volume of itself, and then generates the irregular electromagnetic vibration[2]. If so for a long time, it will cause problems such as broken indoor floor and loose connecting parts, endanger the building structure or damage to the building, leading to waste of land resources in indoor substation[3]. So, it is of very necessity to effectively suppress the irregular electromagnetic vibration of electric reactor.

Now, the researches on vibration damping of electric reactor are roughly divided into two levels: internal and external. The first is internal factor. That is to reduce the vibration at source on the internal structure of the transformer based on the principles of electromagnetic force and magnetostrictive effect generated during the operation of reactor. The methods commonly used are changing the iron core...
structure of the reactor, adding cushion block of special materials to iron yoke, adding negative giant magnetostrictive material to air gap, filling the iron core gap with flexible and high permeability composite damping material, changing the connecting structure between the core and the oil tank body, etc. [4-6] As for the external factor, cushion damping method, hydraulic damping method, failing temperature methods with induced draft fan, shock absorption method with base spring and so on are in common use at present [7-8]. However, there is a big problem with the approaches based on internal factors. That is, the internal structure of the electrical reactor is changed during the production of electrical reactor by the manufacturer. In other words, the structure and material of the iron core shall be changed before delivery [9]. While there is a hidden danger of ideal operation effect in the filed operation of electrical reactor by the grid working staff due to the inconvenience and difficulty. At the same time, the damping effect of multiple damping cases proposed based on external factor fails to achieve satisfactory vibration damping effect, fails to intelligently regulate the magnitude of vibration damping force. And more importantly, it fails to realize the adaptive adjustment of vibration signals [10].

In order to solve the aforementioned problems, this paper proposed an adaptive damper system of the electric reactor based on magnetorheological fluid to realize the all-around vibration suppression of reactor field vibration. This method was to first place a magnetorheological damper at the front, back, left and right of the bottom of base along the center respectively. There were four magnetorheological dampers in total. The said magnetorheological damper is a simple and effective homemade damper based on the principle of magnetorheological fluid principle. Then, a vibration sensor was placed at the center of the four surfaces of the reactor, input the signal of the vibration sensor into the Singlechip microcomputer after amplification and filtering, connected power amplifier circuit with the Singlechip microcomputer and controlled by it, and then connected the output end of the power amplifier to the input end of the magnetorheological damper coils, and regulated the damping force of the homemade magnetorheological damper through the coil current, so as to conduct the adaptive control of the vibration of the electric reactor. When the electromagnetic vibration was about to occur on any surface of the reactor, the vibration sensor would monitor the corresponding vibration acceleration, and carried out the proportional control of the excitation power supply by the acceleration, in order to conduct the adaptive regulation of electromagnetic vibration of the electric reactor, and further effectively suppressed the vibration at all directions of the electric reactor.

2. Homemade Magnetorheological Damper

2.1. Magnetorheological Fluid
Magnetorheological damper is an engineering application practice based on the principle of magnetorheological fluid, which consists of the special suspension liquid, the base liquid and the high permeability magnetic conductivity and the anti-precipitation additive that can respond to the surrounding magnetic field instantaneously [11], the micro-schematic is shown in figure 1:

![Fig1. Micro-schematic Diagram of the Magnetorheological Fluid](image-url)
Soft magnetic particles are the most important part of magnetorheological fluids, disperses in the base fluid and plays a decisive role in determining the shear yield stress of magnetorheological fluids. On the macro level, the reason why magnetorheological fluid can change from liquid state to semi-solid state is that under the action of external field, magnetorheological fluid will generate magnetic dipole, which causes soft magnetic particles to form a tight chain structure along the direction of magnetic field through attraction. The function of the base fluid is to serve as the carrier of the soft magnetic particles and uniformly disperse the soft magnetic particles to provide enough space for the particles. The base fluid affects the property of MRF to a great extent[12-13].

The most essential characteristic of the magnetorheological fluid is the magnetorheological fluid effect. That is, in the absence of magnetic field, the state of magnetorheological fluid is characterized as Newtonian fluid. If a magnetic field is applied outside the magnetorheological fluid, the magnetorheological fluid will be transformed from a conventional free-flowing state to a semi-solid or solid-like state instantaneously. With the increment of the magnetic field intensity, the viscosity and shear yield stress of magnetorheological fluid will also increase. If the externally applied magnetic field reaches a certain critical value, the magnetorheological fluid will stop flowing and completely solidify. It is reversible. The magnetorheological fluid will return to its original free-flowing Newtonian state after the removal of the externally applied magnetic field, which is known as the magnetorheological fluid effect.

When there is no external magnetic field, the magnetic particle distribution of magnetorheological fluid is irregular; and when there is an external magnetic field, the magnetic particles will form a chain magnetic particle chain or a filamentary structure in the direction of the magnetic field, which will hinder the continuous flow of the magnetorheological fluid, as shown in Figure 2.

2.2. Working Principle of Homemade Magnetorheological Damper
The homemade magnetorheological damper operates based on the principle magnetorheological effect. It can regulate the damping force by changing the magnitude of the external applied magnetic field and adjusting the output damping force of the magnetorheological damper. During the operation of the damper, it can be divided into squeeze mode, shearing mode and flow mode according to different flow modes of magnetorheological fluid. The dampers used in this paper work in the mixed mode of shearing mode and flow mode are as shown in Figure 3 and Figure 4 below.
The mixed mode of shearing mode and flow mode of the magnetorheological fluid is one of the most widely used operating modes of magnetorheological damper. In mixed mode, there is no motion between the pole plates of the magnetorheological damper. Apply a magnetic field outside in a direction perpendicular to the plane of pole plates. The magnetorheological fluid flows through the damping channel clearance in a direction perpendicular to the externally applied magnetic field with the action of external pressure. In this case, the chain structure in the damping channels that causes the formation of magnetized particles will hinder the flow of the magnetorheological fluid, thus generating damping forces.

The structure of the magnetorheological fluid are shown in figure 5. When the movable piston moves up and down, the magnetorheological fluid inside the cavity will be driven to flow accordingly. By this time, the magnetorheological fluid can flow back and forth between the two cavities only through the conduction hole. The flow mode modal above-mentioned can be applied to this process at this time. In the meanwhile, when the piston moves in a cavity with magnetorheological fluid, one end of the piston is in motion and one end of the damper shell is stationary, which corresponds to the relative motion of the pole plates. And then the shearing mode can be applied in this process. At the same time, install coil winding between the magnetorheological fluid and the shell and lead coil leads, and changes the damping force of the homemade damper by changing the current through the coils. It can be drawn from the principle of magnetorheological fluid that the larger the magnetic field the magnetorheological fluid is located in, the larger the damping force will be. At this point, the output of the external power supply can be controlled to control the magnetic field of the coils, and so as to control the damping force generated by the magnetorheological damper. See figure 5 for the shape of the homemade magnetorheological damper.

Bingham model can be introduced in the relation between damping force and current, the relation between the corresponding parameters is shown in formula (1) and formula (2) below:

\[ F = F_\eta + F_x = \left( \frac{12\eta l A_v^2}{bh^3} + \frac{\eta b l}{h} \right) v + \left( \frac{3l A_p}{h} + bl \right) \tau_y \]  

\[ \tau_y = A_1 e^{-1} + A_2 \ln(I + e) + A_3 I \]  

Whereas, \( F \) is the damping force exerted on the piston, \( l \) is the effective length of the piston in mm; \( v \) is the motion velocity of the magnetorheological fluid in the direction of \( y \) in m/s; \( h \) is the diameter of the drill way in m; \( b \) is the diameter of the cylinder in m; \( \eta \) is the dynamic viscosity coefficient in Pa·s; and \( A_p \) is the effective area of the piston in m².
3. Adaptive Damper System of the Electric Reactor Based on Magnetorheological Fluid

The intelligent damper system of the electric reactor consists of one shunt reactor, four homemade MR dampers, four vibration sensors, signal processing module, single chip microcomputer control module and power amplifier. The overall damper system are shown in figure 6.

Fig6. Overall System Diagram of Vibration Attenuation

3.1 The Function Realization of the Damper System

Install four homemade MR dampers at the bottom of the reactor base, connect the free end of the damper piston to the base bottom of the electric reactor, and fix the other ends of the shell to the ground. Then, install a homemade damper at the centers of four peripheral edges at the bottom, front, back, left and right of the reactor base, respectively. The four dampers are distributed in a pairwise and symmetrical manner. See details in figure 7. This installation not only can accurately detect the vibration situation at the four surfaces of the electric reactor, but guarantee the stability of the base of the reactor.

Fig7. Damper Distribution at the Base

Then, install a vibration sensor at the center of the front, back, left and right surface of the electric reactor respectively. This sensor is able to accurately detect the real time vibration data of the electric reactor and transmit the signals related to vibration to the next module of the damper system (i.e. signal processing module). The signal sent includes vibration acceleration, time and other parameters, and the signal processing module includes filter circuit and signal amplification circuit.

The filter circuit is to filter the DC signal and low-frequency signal existing in the signal. Due to that the output signal of vibration sensor is the superposition of DC signal and vibration signal, the signal includes vibration signal and a large amount of DC or low-frequency signals, which will not only affect the subsequent amplification circuit, but also directly affect the STFT variation results. So the four-order Butterworth high-pass filter is designed to filter the DC and low-frequency signals. The filter circuit design is shown in figure 8 below.
If the filtered vibration signal is too small, it will have a great impact on the acquisition accuracy of back-end AD. And so it is necessary to design a high-accuracy signal amplifier to satisfy the requirements of back-end acquisition. The signal amplification circuit will amplify the relevant information of the vibration. Different amplification multiples can be set for signals with different amplitudes to achieve signal tracking amplification. The feedback amplification circuit adopted in this paper has the initial magnification is 1 time. Based on the collected data, it determines the amplification factor required by the signal, and collects again after amplification, and then amplifies the data again.

Input the filtered signal into the signal amplification circuit for amplification, and then input the output signal of the amplifier into the STM32 single-chip model. The single-chip modal is used for processing the signal outputted by the amplifier, including ADC acquisition module, digital filter modal and power amplifier control model and so on. Among them, the ADC acquisition module is used to collect and amplify the output signals of the circuit and conduct analog-digital conversion; the digital filter model is used to filter the irrelevant signals such as interference signal; and the power amplifier control module is to perform the real-time control of the subsequent power amplifier working state through the program, so as to control the current and voltage outputted by the power amplifier.

Select the power amplifier of class A and class B for the power amplifier module that consider the output efficiency and output signal distortion. It controls the magnification times through the single-chip power amplifier control module. When the vibration signal is large, control the power amplifier to output a large current signal. When it is small, control the power amplifier to output a small current signal.

In the end, output the output signal of the power amplifier into the coiling lead of the homemade magnetorheological damper. The larger the input current is, the larger the internal flux of the damper is. According to the principle of magnetorheological fluid, the output damping force of the homemade damper is also larger, so that the larger the vibration is, the larger the corresponding vibration suppression will be. After completing the regulation and control of the whole system, the sensor will monitor the vibration data of the electric reactor again and circulate the next process, enabling the system to have the adaptive ability of self-regulation and control.

3.2 Overall Control Strategy Flow
Generally speaking, the damper system uses vibration signal to indirectly control the damping force of the homemade damper through the adaptive control. The control process consists of a closed-cycle control, determining whether the reactor shall be vibrated again by monitoring the vibration information after vibration attenuation. The overall control flow of the adaptive damper system of the electrical reactor is shown in figure 9.
4. Onsite Test Verification

This experiment was carried out in Chongqing Electric Power Design Institute, and the vibration test and vibration attenuation test were carried out for 500KV parallel reactor in substation, which is shown as follows. Loaded the damper system into the parallel electrical reactor, installed the vibration acceleration sensor at the center of the front and left surfaces of the electrical reactor respectively, and installed the four magnetorheological dampers symmetrically at the base of the reactor. Then, the feasibility and adaptivity of the damper system were verified through the comparison of the vibration parameter of the electrical reactor before and after vibration.

![Fig9. Overall Control Strategy Flow](image)

Four vibration sensors were place at the center of the front, back, left and right surface of the electric reactor and no damper system was added. Based on the electromagnetic vibration acceleration data of the reactor on the natural conditions of sensor monitoring, the accelerations of measuring points were collected randomly through the vibration sensor.

![Fig10. 500KV Field Parallel Electric Reactor](image)
Kept the sensor placed in the position same as Test. At the same time, four symmetrical magnetorheological dampers were placed at the bottom of the electrical reactor base, and then the vibration signal processing circuit, single chip microcomputer circuit and power amplifier were connected to this monitoring system. The acceleration data of the vibration sensors monitored at the same period of time were read.

The vibration data of the electrical reactor under natural conditions and after vibration attenuation were compared, and the waveform difference was shown in the drawings. The test data are shown in figure 11, figure 12, figure 13 and figure 14 below.

![Vibration Data before and after Vibration Attenuation on the Front](Fig11)

![Vibration Data before and after Vibration Attenuation on the Back](Fig12)
It can be drawn from the original waveform of the four surfaces that it was of inconsistency of the vibration of the four surfaces of the electrical reactor under natural conditions. There was a big difference between the vibration acceleration curves of each surfaces, and the vibration of front and back, left side and right surfaces was not distributed symmetrically. At one time, the vibration acceleration of the electrical reactor’s four surfaces was kept in a stable state as the time increased. The acceleration curves are shown in approximately periodic distribution, and the vibration period is about 0.02s. Moreover, the maximum original vibration acceleration of the reactor is less than 10m/s².

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What can we learn after comparing the waveform after vibration attenuation with the original vibration waveform is that the acceleration waveform of the reactor presented a convergent distribution with the increase of time, and the acceleration value gradually approached 0 after the introduction of the
damper system proposed in this paper. In addition, when the reactor was nearly stopped, the reactor would not bounce back from vibration and remained in a stable stopped state as the test time continued to increase. As the test result shown, the damper system could effectively suppress the electromagnetic vibration of the reactor after being applied in the field, and the damping effect was good. And from the analysis of the four data curves, when the original vibration acceleration of the reactor is at a larger value, the vibration acceleration value of the reactor at the same time is greater when the vibration reduction system is applied. In other words, the magnetorheological damper provided greater damping force. When it is at a smaller value, the magnetorheological damper provided smaller damping force. Moreover, the whole vibration reduction test process was carried out independently after adding the vibration reduction system, which proved that the good self-adaptability to vibration attenuation of the system.

Meanwhile, the harmonic injection method is the most frequently used method in the vibration attenuation of the electrical reactor. In the field test, the harmonic injection method was introduced into the front surface of the reactor for vibration attenuation. At the same time, the difference between it and the damper system in this paper was compared, and the acceleration change curves of the two are collected through the vibration sensor, which are shown in figure 15 below.

![Fig15. Comparison on Vibration Attenuation of Two Methods on the Front Surface of the Electric Reactor](image)

By comparing the harmonic injection method in fig. 15 and the magnetorheological damping method in this paper, it can be learned that the vibration attenuation effect of this method is distinctly better than the harmonic injection method. The harmonic injection method only suppresses the electromagnetic vibration at the peak of acceleration. While at a relatively small acceleration, the signal curve coincides with the original signal curve after vibration attenuation, no vibration suppression is performed and no self-adaptability of vibration reduction is shown. On the contrary, the damping system proposed in this paper can adjust the damping force of magnetorheological damper autonomously based on the value of vibration acceleration. In the whole vibration process, the damper system can suppress the vibration accordingly, and shows good vibration attenuation effect and superior self-adaptability.

5. Conclusion

Based on the principle of magnetorheological fluid, a set of damper system based on homemade magnetorheological fluid damper was proposed in this paper. Through the electromagnetic vibration test
of the reactor in the field, the vibration damping performance and its self-adaptability of the vibration damping system were emphatically studied, and the main conclusions are as follows:

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(1) This damper system can effectively suppress the magnetic vibration of electric reactor and carry out the vibration attenuation in all directions of four surfaces of electric reactors. Compared to the damper system currently in use, this system has simple structure and convenient operation.

(2) This method is more effective than the current harmonic injection method in vibration attenuation. Besides, it can suppress the magnetic vibration of electric reactor at different vibration intensities. No vibration springback is shown after vibration attenuation and the performance of vibration attenuation is stable.

(3) This system has good adaptivity and can autonomously adjust the damping force outputted with magnetorheological damper according to different field vibration acceleration, so as to carry out the vibration suppression corresponding to the different vibration intensity of the reactor.

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