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# Fast Response Research of Magnetically Controlled Reactor

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### Abstract

*As a kind of reactive power compensation equipment with control flexibility and high reliability, magnetically controlled reactor (MCR) is widely used in reactive power compensation, over-voltage limitation and other aspects. However, low responding speed has severely limited the application of MCR. Especially when applied to suppress voltage flicker and arc suppression coil, the slow response of MCR will decrease the stability of control system, even causing the system shock. To improve the response performance of MCR, in this paper, the working principle of MCR has been analyzed, and a fast response structure of MCR has been designed with the novel fast response structure, fast excitation and rapid demagnetization can be achieved. According to the simulation and experiment results, the effectiveness of the proposed structure is verified by limiting the response time in 30ms.*

***Keywords:*** *magnetically controlled reactor, fast excitation, rapid demagnetization, IGBT*

## 1. Introduction

With the advancing of the voltage and increasingly complex of the network, the existing traditional reactor compensation devices can't deal with the overvoltage and voltage fluctuations well. The magnetically controlled reactor (MCR) has been taken more and more attention and promotion for its flexible adjustment and high reliability. The magnetically controlled reactor is one type of the saturable reactor that is based on the working principle of a magnetic magnifier. The reactance of an MCR is changed by controlling the DC current through the control winding, which saturates the iron core (Xuxuan Chen, *et al.*, 2012).

The advantage of the MCR is that the MCR can be implemented in ultrahigh-voltage (UHV) power systems and quiet economical and operational. With its excellent performance, the MCR is widely used in reactive power compensation, over-voltage limitation and other aspects. However, low response speed is still a major problem for the application of MCR. Especially when applied to suppress voltage flicker and arc suppression coil, the slow response of MCR will decrease the stability of control system, even causing the system shock. So some measures must be adopt to improve the response speed

To solve this problem, reference (Haitao Liu. *et al.*, 2011) proposed to enhance the response speed by increasing the tap of MCR, but this method will increase the power loss and reduce system reliability in the same time. Reference (Kong Ning. et al, 2011) proposed a DC chopper fast excitation method which improving the response speed of MCR by increasing the pulse width of the IGBT with the pulse width modulation (PWM), but failed to improve the demagnetization speed. Reference (Heming Li. et al, 2014)

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proposed a rapid demagnetization method with series demagnetization resistance which increasing the losses and decreasing system reliability.

For the above limitations of the solutions, this paper presents new rapid response structure based on the IGBT. The IGBT rectifier circuit is used to controlling the magnitude and direction of the excitation current, which overcome the drawbacks of the prior structures. In this paper, the working principle and response characteristics of MCR were analyzed first, then appropriate fast response structure and working conditions control method were proposed. The simulation results showed that, the proposed fast response structure can shorten the response time to less than 30ms, effectively improve the performance of MCR, even providing help for its application and promotion.

## 2. Working Principle Analysis of MCR

Figure1 shows the structural principle of the magnetically controlled reactor: The structure and shape are almost identical with ordinary power transformers, the differences focus on some smaller cross-sectional areas structure which named "magnetic valve" in the core column of MCR, and there are unique DC excitation current loop in the winding structure.

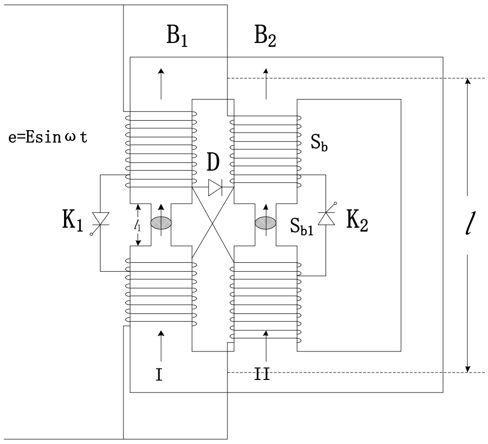



**Figure 1. The Structure of MCR**

When the MCR is connected to AC system, the reactor core permeability can change with reactor winding loop DC excitation current by controlling the external control system, so as to change the inductance effective.

Figure2 shows the analysis of magnetic saturation in MCR. The DC excitation current is actually control the DC component of magnetic flux density $B_d$ in the core.

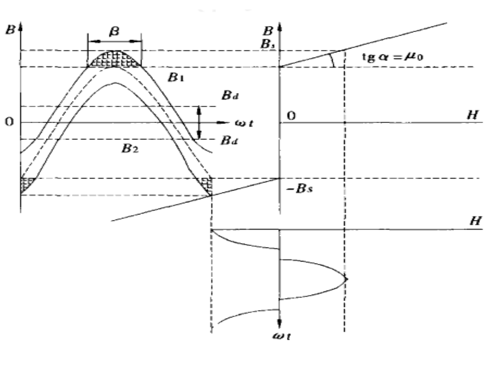



**Figure 2. The Analysis of Magnetic Saturation**

The response time which adjusting the capacity of MCR is extremely important in the application such as the dynamic reactive power compensation. From the derivation, the response cycles of MCR capacity from no load to rated is estimated to be:

$$n = \frac{1-\delta}{2\delta} \tag{1}$$

The response time is inversely proportional to the tap $\delta$ of MCR. For large-capacity magnetic reactor, the general value of tap $\delta$ is quite small, so the response time from the load to the rated capacity is about 0.19 ~ 0.66s. It is absolutely not allowed in application like suppress voltage fluctuations flicker, so some effective measures must be taken to improve the response speed.

According to the principle of DC excitation current, the method that changing reactor capacity rapidly means changing the DC component of the core magnetic flux density rapidly, which can achieved by increasing the DC control voltage and some other methods.

Figure 3 shows the working principle of MCR.

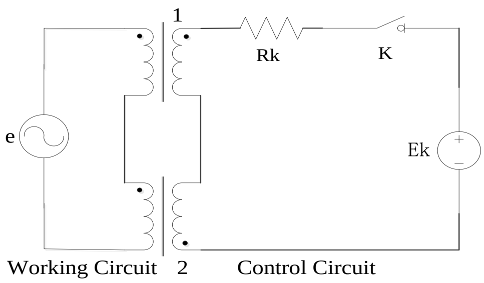



**Figure 3. Working Principle of MCR**

The control loop in right side is a DC voltage source connected with impedance to provide the required DC excitation current, and the relationship between the DC control voltage magnitude and excitation speed can be derived.

The DC control loop equation is as follows:

$$E_k = R_k i_k + N_k A_b \left( \frac{dB_1}{dt} - \frac{dB_2}{dt} \right) \tag{2}$$

In which Ab is the Core cross-sectional area; $B_1$ and $B_2$ means the Magnetic flux density in core 1 and core 2.

The DC component of magnetic flux density is $B_d = B_1 - B_2$

Then we can get that:

$$\frac{dB_d}{dt} = \frac{E_k - R_k i_k}{N_k A_b} \approx \frac{E_k}{N_k A_b} \tag{3}$$

The change speed of DC component of Magnetic flux density in core is related to the value of DC control voltage, so the excitation speed can be improved with the use of high DC control voltage which will increase the DC excitation current rapidly.

Similarly with the excitation process, how to reduce the value of the DC excitation current quickly is directly effect on the demagnetization process, adding a reverse excitation power can be taken into consideration. In demagnetization process, the loop equation can be expressed as:

$$\frac{dB_d}{dt} = \frac{-E_k - R_k i_k}{N_k A_b} \approx \frac{-E_k}{N_k A_b} \tag{4}$$

So we can see that in demagnetization process, the demagnetization speed can be improved by adding high negative DC control voltage.

## 3. Fast Response Structure

Due to the high cost and inconvenient of large-capacity DC source, AC voltage source was used to providing the DC excitation current in this paper, based on the structure of traditional MCR, a new rapid response structure was proposed in this paper. The required DC excitation current was provided by the all-controlled rectifier bridge which composed by several IGBTs. By adjusting the magnitude and direction of the DC excitation current in control winding, the fast adjustment of MCR output capacity can be achieved. Figure4 shows the structure of the fast response.

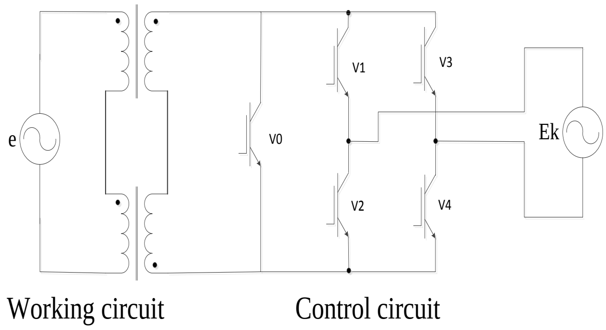



**Figure 4. Fast Response Structure of MCR**

By controlling the duty cycle of the IGBTs, high duty cycle will be set when need to fast excitation, and a large DC control current is provided by the rectifier circuit, the DC component will increased quickly which then improve the speed of excitation. In normal operation of MCR, the IGBT working at a lower duty cycle, providing the necessary working current by control the conduction angle. When we need to reduce capacity with fast demagnetization, a negative DC current which can offset the original excitation current will access to the demagnetization circuit by changing the IGBT switch status.

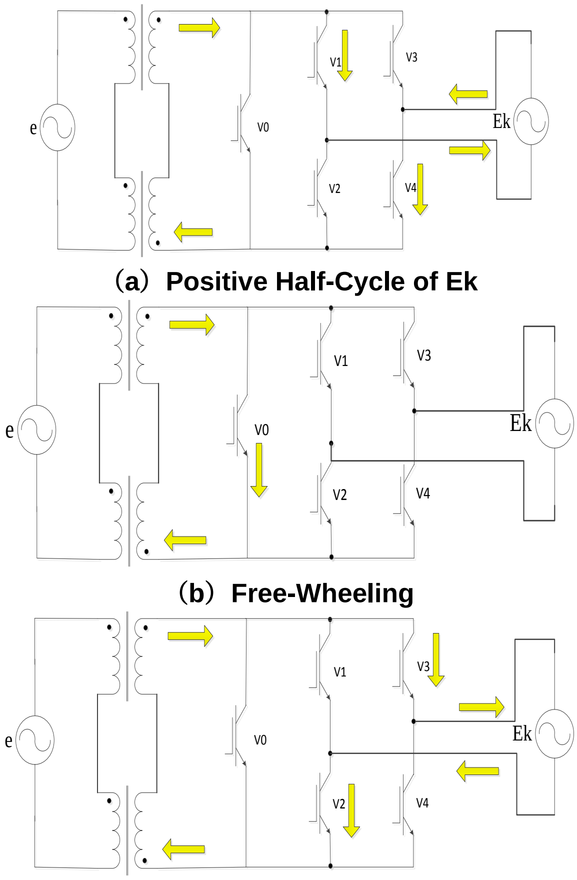
### 3.1. Fast Excitation Process

When the system needs to adjust the capacity of MCR quickly, larger DC excitation current will be needed. As the larger DC excitation current injected, the core will reach saturation faster, which means the faster response of MCR.

When the system detects a signal of increasing the capacity of MCR, the IGBTs will be converted to a high duty cycle state with PWM, and working at larger conduction angle. With a large positive DC control current, the DC component of magnetic flux density will increases rapidly, which means the fast excitation.

Figure5 shows the current flow diagram of fast excitation process. As Figure5 (a) shows, control V1 and V4 conduction with high duty cycle when reaching the firing angle $\alpha$ in positive half cycle of $E_k$. When working in the negative half-cycle, control V2 and V3 conduction and shows the current flow diagrams in Figure5 (b). When working at 0 ~ $\alpha$ , 180 ~ (180+ $\alpha$ ), the DC control current is freewheeling through V0.




(a) Positive Half-Cycle of Ek

(b) Free-Wheeling

(c) Negative Half-Cycle of Ek

**Figure 5. Circuit of the Excitation Process**

### 3.2. Steady Process

When the MCR reaching the required capacity, control four IGBTs disconnect immediately and make the V0 conducting and freewheeling. In addition, the IGBTs will be adjusted to a low duty cycle with the PWM and then turn off V0 to achieve steady-state freewheeling. According to the required capacity corresponding to the excitation current, the conduction angle was controlled to providing the required DC excitation current with the rectifier circuit. In consideration of maintaining the circuit loss, the output capacity of the MCR will maintain on a required stable value.

### 3.3. Rapid Demagnetization Process

When the system detects a signal of decreasing the capacity of MCR, the conduction mode of IGBTs will be changed quickly and providing a large negative DC control current. With a large negative DC control current, the original positive DC excitation current will be offset rapidly, which means the rapid demagnetization.

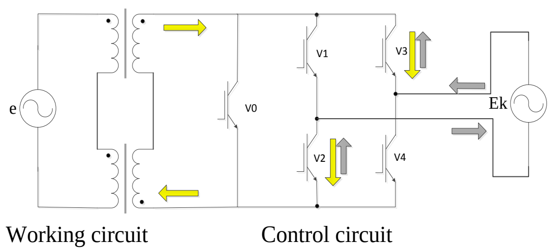



**Figure 6. Circuit of the Demagnetization Process**

Figure 6 shows the current flow diagram of rapid demagnetization process. The IGBTs working in the high duty cycle which will output a larger negative DC demagnetization current. In the demagnetization process, the negative demagnetization current will offset the original DC excitation current, so that the original DC flux density component decline rapid. This process can be seen as reverse energy transportation from MCR to the supply-side system. Compared to the rapid demagnetization method by series resistance, the proposed method in this paper showed faster speed and less loss of energy.

## 4. Simulation and Experimental Analysis

In order to analysis the response characteristics of MCR, simulation model based on the equivalent circuit model of MCR was established in this paper.

Figure 7 shows the simulation model of fast response properties: This model consists of two parts, the left part of the structure using two identical saturated transformers to simulate its core saturation characteristics, the right part is the full-controlled rectifier bridge consisted by IGBTs to provide required DC control current in variety operating state.

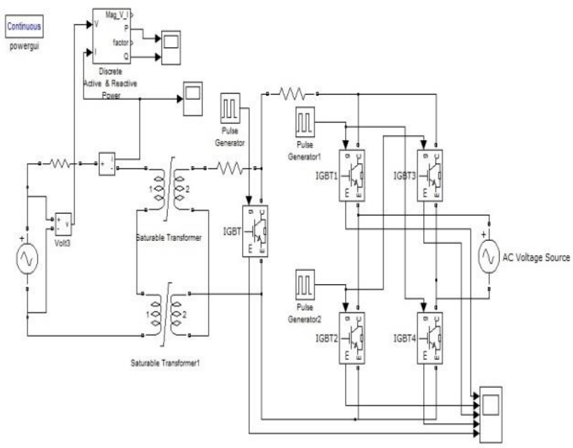
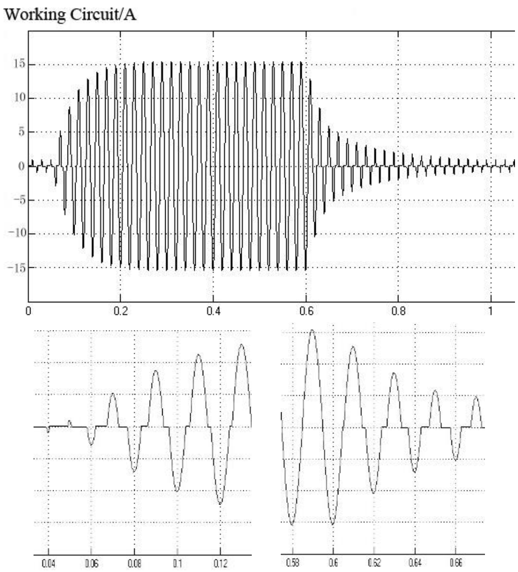



**Figure 7. Simulation Model of MCR**

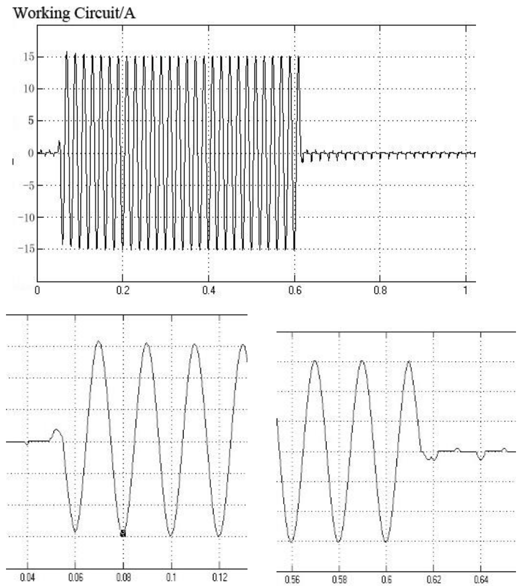
The rated voltage and capacity in this model is 380V/4kW. In the simulation, MCR capacity was changed from no load to rated first, and keeping stable for a certain time, then change the capacity from rated load to no load.

Figure8 (a) shows the working current response waveform and its partially enlarged waveforms of the ordinary external excitation MCR which without fast response structure. Figure8 (b) shows the working current response waveform of the MCR which added the proposed fast response structure.




**(a) Without Fast Response Structure**




**(b) With the Proposed Fast Response Structure**

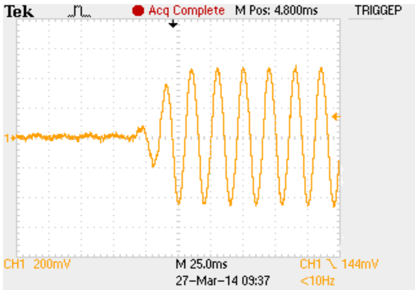
**Figure 8. The Working Current Waveform**

From the illustrated response waveform we can see that the capacity of MCR change from no load to rate at 0.1s and then drop from full capacity to no load at 0.6s. The figure shows that the MCR with rapid response structure can increased from zero to rated capacity in only 20ms and reduce from the rated to zero capacity within 30ms.

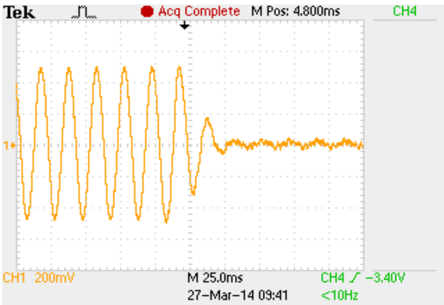
In order to verify the proposed methods, the corresponding small-capacity experimental model has been established. Figure 9 shows the physical map of experimental MCR.

**Figure 9. The Physical Map of Experimental MCR**

Oscilloscope has been used for the measurement records in capacity adjustment process, and show the working current response waveform in Figure 10:




**(a) From No Load To Rated**




**(b) From Rated To No Load**

**Figure 10. Working Current Waveform of the Fast Response Experiment**

From the experiment waveforms, the response time of excitation and demagnetization process with rapid response structure can be reduced to less than 30ms, which consistent with the simulation results and demonstrate the effectiveness of the proposed structure.

## 5. Conclusion

For the problem that the response speed of MCR limiting its application in the case of dynamic reactive power compensation, this paper presents a complex fast response structures based on the analysis of mechanism. The simulation model of MCR was established in Simulink, and a physics experiment was built to verify the model.

According to the simulation and experiment, the proposed fast response structure based on IGBT could improve the response speed of MCR obviously. The response time can be limited to less than 30ms, which will compensate the defect of MCR effectively.

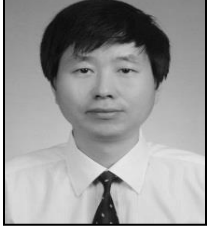
 

For higher voltage levels, series of multiple IGBT sets will be used as partial voltage method to improving the voltage capability of DC excitation circuit, so as to adapting the promotion of MCR in UHV field.

## References

[1] X. Chen, B. Chen, C. Tian, J. Yuan and Y. Liu, "Modeling and Harmonic Optimization of a Two-Stage Saturable Magnetically Controlled Reactor for an Arc Suppression Coil", In: IEEE Transactions on Industrial Electronics, vol. 59, no. 7, **(2012)**, pp. 2824 – 2831.
[2] T. Wass, S. Hornfeldt and S. Valdemarsson, "Magnetic circuit for a controllable reactor", In IEEE Transactions on Magnetics, no. 9, **(2006)**, pp. 2196-2200.
[3] S. Zhao, Z. Yin and H. Liu, "Physical Design and Control Method of Fast Response Magnetically Controlled Reactors", In Proceedings of the CSEE, vol. 33, no. 15, **(2013)**, pp. 149-155.
[4] B. Chen, "Theory and application of saturated controllable reactor", Press of Wuhan University of Hydraulic and Electic Engineering, Wuhan **(1999)**, pp.103-189.
[5] H. Liu, Y. Liu, "Improving the response speed of the magnetic valve controllable reactor through increasing the ratio of the tap", In Electrotechnics, vol. 11, no. 3, **(2011),** pp. 68-69.
[6] K. Ning, "Reactive power and voltage control of UHV AC transmission system based on MCR", North China Electric Power University, Beijing **(2011)**, pp.23-24.
[7] H. Li, H. Liu and Z. Yin, "Design of Control System Based on Magnetically Controlled Reactor", In High Voltage Engineering, vol. 40, no. 1, **(2014),** pp. 275-281.
[8] M. Tian, Q. Li and Q. Li, "A controllable reactor of transformer type", In IEEE Transactions on Power Delivery, vol. 19, no. 4, **(2004)**, pp. 1718-1726.
[9] A. Luo, Z. Shuai, W. Zhu and Z. J. Shen, "Combined System for Harmonic Suppression and Reactive Power Compensation", In IEEE Transactions on Industrial Electronics, vol. 56, no. 2, **(2009),** pp. 418-428.
[10] S. Rahmani, A. Hamadi, K. Al-Haddad and L .A. Dessaint, "A Combination of Shunt Hybrid Power Filter and Thyristor-Controlled Reactor for Power Quality", In IEEE Transactions on Industrial Electronics, no. 5, **(2014)**, pp. 2152-2164.
[11] A. N. Belyaev and S. V. Smolovik, "Steady-state and transient stability of 500 kV long-distance AC transmission lines with magnetically controlled shunt reactors", In IEEE Power Tech Conference, **(2014)** June 27-30, pp.534-538.
[12] T. Zheng and Y. Zhao, "Analysis on the effects of energization mode for magnetically controlled shunt reactor", In: PES General Meeting | Conference & Exposition, **(2014)** July 27-3, pp. 1-5, United States.
[13] J. Tian, Q. Chen, L. Cheng and Y. Zhang, "Arc-suppression coil based on transformer with controlled load", In IET Electric Power Applications, vol. 5, no. 8, **(2011)**, pp. 644-653.
[14] L. Haipeng, Y. Zhongdong and Z. Shishuo, "Research on the Quickness of Magnetically Controlled Reactor", In: Power Electronics, vol. 47, no. 1, **(2013)**, pp. 15-17.

## Author



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