Field-circuit Coupled Modeling of a Novel Continuous Reactive Power Controllable Device for Power Flow Optimization

Weihao Liu¹, Kai Chen¹, Jian Tang¹, Zhangjie Cao¹, Li Hong¹ and Pan Song²*

¹Hangzhou Power Supply Company, STATE GRID Corporation of China, Hangzhou, Zhejiang, China
²Wuhan HaiO Electric Corporation, Wuhan, Hubei, China
*Corresponding author’s e-mail: copyright@whhve.cn

Abstract: The paper proposed a novel method that incorporates MATLAB and FEM simulation to study the dynamic characteristics of the magnetic devices. The semi-physical modeling method is easy to implement and effective in simulating the operation characteristic and speeding up the magnetic device research. The results can further apply to control the continuous reactive power controllable device and optimize the power flow in the power system.

1. Introduction
Reactive power control is the key technology for nowadays power grid⁴. The most used devices can perform dynamic reactive power control of which the rated operation voltage is limited to 35kV and below. The reason is that these devices consist of many power electronics components. The power electronics rated withstand voltage and current capacity are lower than traditional magnetic construct devices such as transformers, electric reactors. Considering that the magnetic-based devices are working much more stably, it is recommended that a magnetically controlled device is better for 110kV and above reactive power control.

Traditional modeling of the magnetically controlled device implements an equivalent circuit to simulate the transient electromagnetic phenomena. There are already various software that can archive this feature, such as PSCAD, EMTP or even Simulink. However, it is impossible to accurately model a device that has not been produced.

In this paper, a novel field-circuit coupled modeling method is proposed. The magnetic device is a digital model using the FEM method to represent its physical characteristics. The FEM model computes the current under a certain voltage. The results can be integrated into the electrical circuit simulation. This simulation method makes the model be semi-physical, and the benefit of this method is obvious. The researchers do not need to actually construct redundant prototypes of the magnetic device to validate the designs so that the research cost is reduced. Furthermore, the simulation results derived from this method can reflect both external circuit traits and internal electromagnetic field characteristics⁵.

2. Field-circuit coupled method
The method consists of 4 parts, including the magnetic FEM model of the magnetic construct device, a dynamic equivalent electric circuit model, the electromagnetic transient network, and the computation interface⁶. Take magnetically controlled reactor (MCR) as example, the schematic of the method is
shown in Fig. 1. MCR is a magnetic device of which the structure is similar to the transformer. MCR is usually used as controlled shunt variable reactance for reactive power compensation and Peterson coil (also called arc suppression coil) in the power system\cite{5}.

![Figure 1. Schematic of coupled field-circuit modeling method](image)

The FEM model can be regarded as a 2-port component with control voltage input and current output. The bus voltage $u_{kn}$ is derived from the nonlinear network. The control voltage $u_{dc1}$ and $u_{dc2}$ are given by the calculation from the electromagnetic network. The firing angle $\alpha$ in the rectifier circuit controls the $dc$ bias voltage in the MSMCR coil. The $dc$ bias voltage changes the saturation degree of the magnetic valve in the iron core.

The dynamic equivalent model is embedded in the nonlinear network. The simulation step of the electromagnetic network is 50 $\mu$s. When $\alpha$ changes, the output current $i_{harm}$, the loss $R_{coil}$, $R_{fe}$ and the reactance $L_{coil}$, $L_{fe}$ are calculated in the FEM model every 1000 $\mu$s. The results are transferred to the dynamic equivalent model via the parallel computation interface. The interface determines at what time the results are communicating between the FEM model and the dynamic equivalent model. Such a mechanism also appears between the FEM model and the electromagnetic network.

The FEM model and the electromagnetic transient network are called the detailed system and the external system. The parallel computation interface is to incorporate both the above-mentioned systems. Because the hybrid calculation speed mainly depends on the FEM model, the simulation time step of the detailed system is much larger than the external system. The two systems simulate independently and communicate with each other at specified time points. This method is suitable for an inductive magnetic device according to their hysteresis character of the current. The interface is realized using the Matlab/Simulink S-function.

3. Simulation of the semi-physical model

The FEM and built-in circuit of the MCR are shown in Fig. 5. In order to speed up the initial time of the FEM calculation, a resistive load is added. $V_1$, $V_2$, $V_3$ are the dc bias controlled voltage. $V_A$, $V_B$, $V_C$ are the power system voltage. The FEM model is first simulated to verify the MCR design. In later field-Circuit coupled modeling, the voltage sources will be replaced by the external circuit in power system simulation.
The internal electromagnetic field simulation results are shown in Fig.3(a) and the output current simulation results are shown in Fig.3(b). The output current of the MCR can be continuously controlled from 0 to its rated current.

4. Semi-physical integrated simulation in power system
The current-controlled sources are used to integrate the semi-physical model into the power system simulation. The method is much more straightforward than a dynamic equivalent circuit modeling and can be easily integrated into the power system simulation. The interface method is shown in Fig.4.
The method is validated in Simulink shown in Fig. 5. An S-function interface is built to get the real-time computation results from the FEM simulation. Using the controlled current source (CCS), the MCR can model an inductance branch.

The voltage and current of the CCS and the inductance branch for comparison are shown in Fig. 6.

The simulation results show that the good agreement of the output current and voltage indicates that the proposed method can precisely model the MCR as a normal inductor if the firing angle is fixed in the MCR control system. If control system is added to the Simulink block, the device can act as a reactive control device for later use in power flow optimization in Simulink.
Table 1. Current comparison between the CCS and the actual inductance component

| Component   | Max I (A) | Min I (A) | RMS(A) | Diff RMS (%) |
|-------------|-----------|-----------|--------|--------------|
| CCS         | 6.683461  | -4.90664  | 3.476876 | 0.01558      |
| Inductance  | 6.649384  | -4.90776  | 3.476335 | 0            |

5. Conclusion
This paper proposed a FEM-Simulink co-simulation method to perform a semi-physical model of a magnetic construct device. The simulation results show that the proposed method can precisely model the dynamic characteristics of the magnetic device in the power system. The method provides great simulation power to electric power research. It can be a useful tool for electrical device research.

Acknowledgments
This work is supported by the Science and Technology Project of Zhejiang Electric Power Company, STATE GRID Corporation of China(5211HZ1800W7).

References
[1] Xie Xin. Power system voltage and reactive power regulation control[J].Global Market, 2019,(31):152-153.
[2] Zhang Long. Research on optimization method of electromagnetic forming circuit based on finite element analysis[J].Electronic Design Engineering,2020,28(6):101-106.
[3] Wang Tiange, Hui Liangliang, Wang Yuyuan. Analysis of field-circuit coupling magnetic field of transformer-type controllable reactor[J].Electronic Design Engineering,2020,28(17):108-112.
[4] Chen, X. X., B. C. Chen, C. H. Tian, J. X. Yuan, and Y. Z. Liu, “Modeling and harmonic optimization of a two-stage saturable magnetically controlled reactor for an arc suppression coil,” IEEE. Trans. Industrial Electronics, Vol. 59, 2824–2831, Jul. 2012.
[5] Chen, X., J. Chen, and B. Chen, “Harmonic optimization for the multi-stage saturable magnetically controlled reactor using particle swarm optimization algorithm,” 2014 9th IEEE Conference on Industrial Electronics and Applications, 1804–1809, Hangzhou, China, 2014.