A Novel Topology For Improving the Dynamic Performance of Saturated-Core Fault Current Limiter

Haocong Shen*, Jianyong Zheng*
Department of Electrical Engineering, Southeast University, Nanjing, 210096, China
*Corresponding author e-mail: 342965016@qq.com, jy_zheng@seu.edu.cn

Abstract. Saturated-core Fault Current Limiter (SFCL) is a new type of iron-core reactor which can regulate the output reactance of iron-core reactor by using DC bias. The traditional method of energy-release utilizes the energy-release resistance to consume the energy in DC coil. This method requires high voltage withstand of IGBT. This paper proposes a new topology to speed up the process of energy release by adding a reverse voltage on DC coil and reduce the voltage on IGBT. In this paper, a simulation model is established in Jmag whose data is imported into Matlab to be prepared for further analysis. Finally, two kinds of models are built in MATLAB to verify the superiority of the new topology.

1. Introduction
With the interconnection of power grids becomes closer, the current level of short-circuit faults in power systems is also increasing. In 2013, about 12% of the short-circuit currents exceeded 63kA [1] [2], and excessive short-circuit current will cause damage to equipment in the power system. SFCL has been widely used in 35kV, 200kV and 500kV power grid [3-5]. In normal operation, the core is saturated due to the magneto motive force generated by DC supply so that SFCL presents a small reactance which has little effect on the grid. When the short-circuit fault occurs, the energy of the DC coil is immediately released by the energy-released circle. By consuming the energy, the saturation of the reactor can be reduced, therefore the output reactance of the reactor can be increased to limit the fault current which prevent causing damage on the equipment in the power grid. However the traditional way of energy-release is to switch the IGBT which connected with the DC coil off and consume the energy in the DC coil through the resistance. Since the current in the inductor cannot be abruptly changed, at the moment of switching off the IGBT, the extreme change of the current in the IGBT will inevitably produce a high voltage on the IGBT which will do harm to IGBT. Even if zinc oxide could be introduced to protect the IGBT, the voltage on DC coil will be limited which definitely sacrifice the speed of energy-release. Therefore, SFCL with large capacity will not be able to has a good dynamic performance due to the voltage limitation of IGBT which greatly influence the application and development of SFCL.

Many scholars have proposed many similar current-limiters for the working principle of SFCL to seek different ways to solve the problem of DC current control. The permanent magnet biased SFCL [6-7] is proposed by using permanent magnets instead of DC supply to provide magneto motive force. This method not only emphasizes the adaptability of SFCL, but also eliminates many limitations of DC control. However the unidirectional magnetization characteristics of the permanent magnet (PM)
makes the normal working state of this type of SFCL’s saturation can’t be as high as it of the DC biased SFCL. The two cores will always remain in the unsaturated state during the interleaving period which has a great influence on the normal operation of power grid. Meanwhile the PM biased SFCL cannot completely eliminate the influence of the bias magnetic field as well as the DC bias SFCL which result in its current limiting capability is much worse than DC bias type SFCL. Some scholars suggest that the capability of current limiting can be increased by introducing additional reactance [8-9]. But this approach sacrifices the advantage of SFCL’s low reactance in normal state. Some scholars put forward bridge SFCL according to the working principle of bridge reactor [10-11], This method not only has good dynamic performance, but also retains good capability of current limiting. However, this method greatly increases the use of core which increases the cost of manufacturing. In addition, some scholars have put forward a method to change the reactance of the reactor by changing the air gap structure [12]. Some scholars have also studied the charging process of the DC coil for reducing the steady-state loss of the DC coil by replacing the charging power supply after the DC coil is charged [13]. However, there is no new method for DC energy release under current limitation, and there are still obvious defects in DC energy release.

Based on the analysis of the traditional energy release methods, a new topology is proposed in this paper. By adding a reverse voltage source on the DC coil and clamping the voltage through ZnO, the process of DC coil’s energy release can be accelerated while the IGBT is protected from damage of high voltage. In this paper, a simulation model is established in JMag. According to the model, different resistors are used to release energy from DC coil under traditional way to release energy. The current variation of the DC coil and the voltage across the IGBT are compared with different resistors which verifies the limitations of the traditional method. In order to verify the superiority of the novel energy-released method proposed in this paper compared with the traditional method, this paper introduces the data of flux linkage from the model in Jmag to establish a simulation model in Matlab and contrasts the two methods’ speed of energy-released which verify the superiority of the topology proposed in this paper reduces the voltage across the IGBT while rapidly energy releasing.

2. Working Principle

![Figure 1. Schematic diagram of traditional DC control loop](image)

Fig. 1 shows the schematic diagram of the traditional energy release circuit [13]. When the system works normally, the control system manipulate the output current of rectifier by hysteresis control algorithm to get continuous and stable DC current. When the system detects the fault, the control system switched the IGBT off, the rectifier circuit supplies power to the ZnO2, the energy in DC coil is released through ZnO1, and eventually consumed completely. In formula (1) $P$ is the instantaneous power of energy release, $u$ and $I$ represent the voltage and current at both ends of ZnO1, $t_0$ is the time of IGBT switches off, $t_1$ is the end time of the energy release. It is not difficult to see from Formula (1) the higher the voltage at both ends of DC coil, the faster the energy release, but it also poses a higher challenge to the voltage withstand of IGBT.
\[ p = ui \]

\[ W_Z = \int_{t_0}^{t_f} pdt = \int_{t_0}^{t_f} uidt \]  

(1)

\[ u = -N \frac{d\varphi}{dt} \]  

(2)

\[ \varphi = BS, B = \mu H \]

\[ u = -NS \frac{d(\mu H)}{dt} \]  

(3)

In formula (2) (3) \( N \) is the turns of DC coil; \( \varphi \) is the magnetic flux; \( B \) is the magnetic induction strength; \( S \) is the area of DC coil; \( H \) is the magnetic field strength; \( \mu \) is the core permeability. Since the BH curve does not exhibit a linear change, the slope \( \mu \) is the largest when it is close to the zero point. It is known by Ampere's law that there is a proportional relationship between the \( H \) and \( I \), therefore, the current changes sharply when the IGBT is switched off which leads to the non-linear change of \( H \). Considering the change of \( \mu \), large voltage are produced on the IGBT.

![Figure 2. (a) DC coil current variation curve](image1)

![Figure 2. (b) IGBT voltage curve at both ends](image2)

The demagnetization current curve of DC coil and the voltage curve at both ends of the IGBT under different energy-released resistance conditions are shown in Fig 2(a) and (b). It is not difficult to
see that with the increase of the resistance, the speed of energy release increases gradually, but the voltage of the two ends of the IGBT also increases rapidly, which also raises the stakes of IGBT being broken by overvoltage.

As shown in Fig. 3, a schematic diagram of the novel topology is presented. When the system works normally, it is similar to the traditional DC control circuit. When a short circuit fault occurs, after receiving the signal, IGBT1 and IGBT2 are switched off, and the DC coil discharges through D1, D2 and capacitor.

\[
ZnO \quad tL \quad R \quad dc \quad RR \quad UCei
\]

\[i_{dc} = Ce^\frac{-R}{L} - \frac{U}{R + R_{ZnO}} \quad (4)\]

Where \( R \) is coil resistance; \( L \) denotes coil inductance; \( C \) is constant depending on the steady-state DC current; \( R_{ZnO} \) is the resistance of ZnO; \( U \) is the voltage at both ends of the DC coil.

Compared with the traditional DC control circuit, the new DC control topology proposed in this paper increases the voltage on the DC coil because of adding the capacitor voltage. Due to IGBT is not directly connected to the DC coil, the energy release speed of the DC coil is accelerated by increasing the voltage at both ends of the DC coil through the capacitor in series with IGBT. The new DC topology proposed in this paper can not only accelerate the energy release, but also break through the limitation of IGBT’s voltage withstanding ability. At the same time, the ZnO paralleled to IGBT can effectively protect IGBT from over-voltage damage caused by transient energy release.

3. Simulation Results

In order to verify the superiority of the new DC control topology proposed in this paper, a model is established in MATLAB. By importing the data of AC and DC flux in JMag into the Lookup module of MATLAB, as shown in Formula (5), the voltage of AC coil can be obtained according to Formula (6). A simulation model can be built for the Saturated-core reactor based on the results obtained.

\[
\begin{align*}
\begin{bmatrix}
I_{dc}^{(1)} \\
I_{dc}^{(2)} \\
\vdots \\
I_{dc}^{(n)}
\end{bmatrix}
&= \begin{bmatrix}
\psi_{11} & \psi_{12} & \cdots & \psi_{1n} \\
\psi_{21} & \psi_{22} & \cdots & \psi_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\psi_{m1} & \psi_{m2} & \cdots & \psi_{mn}
\end{bmatrix}
\begin{bmatrix}
I_{ac}^{(1)} \\
I_{ac}^{(2)} \\
\vdots \\
I_{ac}^{(n)}
\end{bmatrix}
\Rightarrow A = \begin{bmatrix}
I_{ac}^{(1)} \\
I_{ac}^{(2)} \\
\vdots \\
I_{ac}^{(n)}
\end{bmatrix}
\begin{bmatrix}
I_{dc}^{(1)} \\
I_{dc}^{(2)} \\
\vdots \\
I_{dc}^{(n)}
\end{bmatrix}
\end{align*}
\]

\[
J_{dc}^* = \begin{bmatrix}
J_{dc}^{(1)} \\
J_{dc}^{(2)} \\
\vdots \\
J_{dc}^{(n)}
\end{bmatrix}
\quad (5)
\]
$$u = \frac{dy}{dt}$$

(6)

**Figure 4.** Comparison of DC current between the traditional DC control loop and the new DC control loop.

As shown in Fig. 4, the black curve is the current variation curve in the DC coil of the traditional DC control loop, and the red curve is the current variation diagram in the DC coil of the new DC control loop. In the time of 0~0.5s, the black curve is the normal charging process. There is almost no difference between the two DC control loops in the process of the current variation, ranging from 0.5s to 1.2s. In time, for the DC coil energy release process, it is not difficult to see from Fig. 5 that the new DC control loop energy release speed is significantly better than the traditional DC control loop, when the system fails, it can be faster to achieve the limitation of AC current.

4. Conclusion

In this paper, a new DC control structure is proposed. By adjusting the topology of the DC coil front-end rectifier circuit, the rectifier output voltage is connected with IGBT in reverse series, so that the speed of DC energy release can be accelerated. The rationality of the voltage at both ends of IGBT can be guaranteed, and the fast change of the current can be prevented. It can prevent the damage to IGBT from the high voltage generated by both ends of IGBT.

In this paper, a simulation model of magnetic saturated reactor is established in JMAG, and the operation mode of traditional DC control circuit is simulated. It is proved that the traditional DC control circuit will inevitably cause voltage increase on both ends of IGBT while increasing the energy release speed. In this paper, the models of traditional DC control circuit and new DC control circuit are established respectively in matlab. The time of charging and discharging is analyzed and compared. It is found that the new DC control circuit can speed up the DC coil energy release speed on the basis of protecting the voltage at both ends of IGBT from excessive.

The topology proposed in this paper can be used not only in magnetic saturated reactors, but also in other devices which need to be charged and discharged.

**References**

[1] Zhenya Liu, Qiping Zhang. Research on the Development Model of State Grid [J]. Journal of China Electrical Engineering, 2013, 33 (7): 1-10, 25.

[2] Lili Chen, Minxiang Huang, Hong Zhang, et al. [J], Power System Automation, 2009, 33 (11): 38-42

[3] Xin Y, Gong W Z, Niu X Y, et al. Manufacturing and Test of a 35 kV/90 MVA Saturated Iron-
Core Type Superconductive Fault Current Limiter for Live-Grid Operation [J]. IEEE Transactions on Applied Superconductivity, 2009, 19 (3): 1934-1937.

[4] Xin Y, Gong W Z, Hong H, et al. Development of a 220 kV/300 MVA superconductive fault current limiter [J]. Superconductor Science & Technology, 2012, 25 (10): -.

[5] Wei Z, Xin Y, Jin J, et al. Optimized Design of Coils and Iron Cores for a Saturated Iron Core Superconducting Fault Current Limiter [J]. IEEE Transactions on Applied Superconductivity, 2016, 26 (7): 1-4.

[6] Yuan, Jiaxin, et al. "A Novel Three-Phase Compact Saturated-Core Fault Current Limiter." IEEE Transactions on Magnetics 99 (2017): 1-1.

[7] Yuan J, Zhong Y, Lei Y, et al. A Novel Hybrid Saturated Core Fault Current Limiter Topology Considering Permanent Magnet Stability and Performance [J]. IEEE Transactions on Magnetics, 2017, PP (99): 1-1.

[8] Wanying Z, XuefengH, Hui Z, et al. Experimental Research on an Improved Saturated Core High Temperature Superconducting Fault Current Limiter [J]. TRANSACTIONS OF CHINA ELECTROTECHNICAL SOCIETY, 2014, 29 (11): 169-176.

[9] Wanying Z, XuefengH, Hui Z, et al.. Experimental Research on a Novel Saturated Core High Temperature Superconducting Fault Current Limiter [J]. TRANSACTIONS OF CHINA ELECTROTECHNICAL SOCIETY, 2015, 35 (2)

[10] J. Yuan, Y. Lei, L. Wei, et al., “A Novel Bridge-Type Hybrid Saturated-Core Fault Current Limiter Based on Permanent Magnets,” IEEE Trans. on Magnetics, vol. 51, no. 11, pp. 1-4, 2015.

[11] L. Wei, B. Chen, J. Yuan, et al., “Performance and Optimization Study of a Novel Compact Permanent-magnet-biased Fault Current Limiter,” IEEE Trans. on Magnetics, vol. PP, no. 99, pp. 1-1, 2017.

[12] Aliabad A D, Hajhoseini S. Optimal Design and Analysis of a Variable Reactor Fault Current Limiter [J]. IET Electric Power Applications, 2017.

[13] Cui J B, Sun Y W, Hong H, et al. Study on field suppression unit in DC excitation system for saturated iron-core superconducting fault current limiter [C]/ IEEE International Conference on Applied Superconductivity and Electromagnetic Devices. IEEE, 2014: 1-4