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Saturable-Core FCL Based on the Normal Conductor Direct Current Coil

by

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SUMMARY

Due to the increase of power demand, the generation and parallel transmission capacity and voltage level of power system are increasing with more and more interconnections within the grid, and that the increase of fault current tends to be more and more heavy which brings great damage to existed power-system equipment and reduces the power consumption. Although the traditional isolation fault method—relays + circuit breaker—is effective, the increasing levels of fault current exceed the breaking capabilities of circuit breakers. In the past decades, a variety of fault current limiter is applied to limit the fault current to the accepted level. Generally, two categories are included: 'permanent impedance increase' and 'impedance increase based on operation of power system'. The former, such as high impedance transformers and current-limiting reactors, adds extra impedance during both normal and fault conditions of power system. What is worse, the fixed impedance reduces power system efficiency and in some cases it can destroy system stability. The latter category includes novel fault current limiters using superconductors (SFCL) and/or semiconductors. SFCLs introduce negligible impedance during normal operation and are almost invisible to the power system. Once a fault occurs, however, the impedance of the FCLs increases and reduces the fault current to an acceptable level. saturable core SFCL utilizes the dynamic behaviour of the magnetic properties of iron core to change the inductive reactance on the AC line with superconductive winding as DC coil which provides a magnetic bias. Because of the instability of Superconducting performance and its expensive cost, the SFCL is only at the experimental Stage and is not for the commercial use.

The paper presents another FCL with normal conductor DC coil, whose structure and physical principle are based on the saturable core SFCL. Via the study and simulation in the PSCAD, the results indicate that saturable core FCL Based on the Normal Conductor Direct Current Coil (NFCL) is effective to power grid---at stable condition of power grid, the impedance is so low that it can be negligible and the ratio of the voltage drop is less than 2%, in the event of fault, the impedance is so high that the fault current can be limited to an acceptable level where the circuit breaker can operate safely and the ratio of the voltage drop is more than 50%. Besides, it can meet the requirements of auto-reclosing of circuit breaker with the aid of rapid demagnetization and rapid excitation auxiliary circuit. In addition, NFCL economy is better than SFCL with the same performance because the price of normal conductor is lower than that of superconductor and stability is more stable because of the better electrical characters of normal conductor compared to the superconductor.

KEYWORDS

Superconducting Fault Current Limiter (SFCL); Saturable-core FCL Based on the Normal Conductor Direct Current Coil (NFCL); Rapid Demagnetization Auxiliary Circuit; Rapid Excitation Auxiliary Circuit; Auto reclose

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1. Introduction

EHV/UHV grid formation and regional power grid interconnection is to meet with a considerable increase of electrical power demand, and that the growth of power circuit capacities has caused fault currents to increase beyond capabilities of existed equipment; at the same time, With the process of smart grid construction, more and more distributed power is being connected with the power grid (this kind of power factory will bring about the increase of fault current). The power system faces a new challenge that the short-circuit current of each voltage level is increasing. Raising the level of short-circuit current, which requires pressure capacity of power transmission equipment must be further improved. Compared to power grid re-planning, upgrading substations and lines' equipment and other measures, grid deployment of fault current limiter(FCL) is a smaller investment which is also the most effective way to limit the fault current to an acceptable level [1,2,3].

To overcome the high fault current in event of a short-circuit fault on power lines, many kinds of Fault current limiters (FCL) are installed in power lines and power plant exports in the last decades. Different technologies have been employed to design FCL, generally speaking, FCLs is divided into three categories at the view of power material:

1) Classical FCL such as the series reactors and current-limiting fuses;
2) FCL based on Power Electronics;
3) FCL based on Superconductor, which is also called SFCL---Superconductor Fault current limiter.

Reference [1] describes three kinds of fault current limiter based on power electronic devices, which have been used in the former Soviet Union, Germany, Japan and etc. Reference[2] describes that superconducting fault current limiter is divided into resistive and inductive types according to the physical properties of the SFCL; on the basis that whether SFCL loses the superconductivity during the process of SFCL operation at the event of fault, SFCL is divided into superconductivity-quench and superconductivity non-quench types; for saturable Core superconducting fault current limiter, on the basis whether superconducting control coil is disconnected, saturable core SFCL is divided into active and passive types.

Reference [3,19] provides an initial perspective on utility needs and prescribed ideal characteristics for FCLs. The general characteristics---low impedance in the steady state; high impedance in the transient state and rapid recovery time and other characteristics --- of FCL is to meet with the power grid; the superconductor temperature, the size and the degree of magnetic saturation field is the most important three elements for magnetic controlled SFCL; At the same time, several demonstration projects included the USA, Europe, Russian, China , Japan, Korean are described, In particular, the advantages of saturable core SFCL is given out.

Reference [4] indicates that fault current limiter improves transient stability and power quality.

Reference [5] introduces the operation condition of the active saturable core SFCL at china.

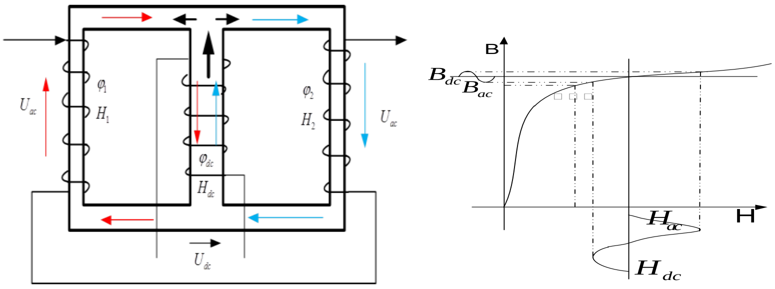
Reference [14] gives out the simulation result of saturable core SFCL; Reference [17] summarizes the detailed application design--- "circuit breaker + Relay + superconducting fault current limiter".

In this paper, the operation of FCLs and the amount of impedance which are required to meet with the requirements of transmission line and power plant exports are concerned. At the steady state of power grid, the FCL appears low impendence whose impacts to the power grid can be

neglected; Whenever a fault occurs, the FCL appears a series impedance is inserted to limit the fault current to an acceptable value that downstream circuit breakers is available to trip.
Saturable core FCL Based on the Normal Conductor Direct Current Coil is presented in this paper, according to the principle and the present application situation of the saturable core FCL type super conductor fault current limiter. The simulation model of NFCL is established in the 500kV power grid on the PSCAD simulation software, and by the study, properties of NFCL meet with the requirements of power utility for FCL.
Since FCL's are installed in each phase of the line, the fault is viewed in perspective of per phase. For the purposes of this study, we consider phase to ground fault and phase to phase fault scenarios.

2. Model of NFCL

2.1 Principle of saturable core SFCL
Saturable core SFCL utilizes the dynamic behavior of the magnetic properties of iron to change the inductive reactance on the AC line [2]. The concept utilizes three iron cores, two AC windings for each phase and one DC windings which is depicted in the Fig1.a [3]. The AC windings are made of conventional conductors that are wrapped around the core to form an inductance in series with the AC line. The iron core also has a constant-current superconductive winding that provides a magnetic bias.



(a) structure of SFCL (b) principle of B-H curve

Fig 1. the concept of saturable core SFCL

When the AC current is less than the maximum rating for the local power system, the HTS (High Temperature Superconductor coil, direct current coil) fully saturates the iron so that it has a relative permeability of one. To the AC coils, the iron acts like air, so the AC impedance (inductive reactance) is similar to that of an air-core reactor. In the event of fault occurrence, the fault current forces the core out of saturation, resulting in increased line impedance during part of each half cycle. The result is a considerable reduction in peak fault current. During a limiting action, the dynamic action of the core moving instantaneously in and out of saturation produces harmonics in the current waveform. However, under normal conditions, the voltage and current waveforms are neglected by the saturable core SFCL. Essentially, the saturable core SFCL is a variable-inductance iron-core reactor that has the impedance of an air-core reactor under normal grid conditions and very high impedance during fault events. Unlike resistive SFCLs which may require time between limiting actions to cool the superconducting components and other FCLs, the saturable core approach can manage auto reclose in succession because the superconductor does not quench.
However, for the saturable core SFCL, there are three disadvantages:
1) HTS is very expensive and easy to break, and the superconductivity coil is hard to produce;

2) For HTS, there must be harsh superconductivity environment which need extra equipment and power losses;
3) The way to combine superconductor coil and normal conductor coil in the SFCL has not been solved.

2.2 NFCL

Inductance value of the ac winding:

$$X = \omega L = \omega \mu N^2 \frac{S}{l} \ldots\ldots(1)$$

Where: $\omega = 2\pi f$, S is the core cross-sectional area , l is the average length of the magnetic path , μ is permeability , N is the number of winding turns。When the length and geometry of the core has been determined by the design and construction, the inductance value is only relevant to μ and proportional to μ .

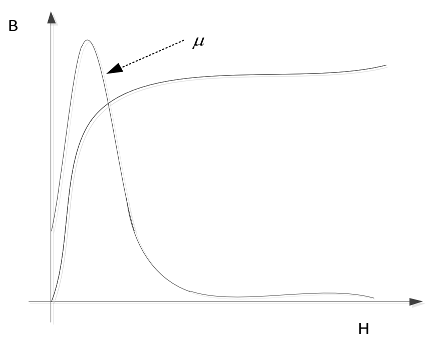


Fig 2. Magnetization curves and permeability curve of core

According to the magnetic state changeable schematic of core electrified by the AC and DC current, the magnetic field intensity and magnetic induction intensity equation is described below:

$$H = H_{dc} + H_{ac}\sin(\omega t + \theta) \ldots\ldots(2)$$

$$B = \mu(H_{dc} + H_{ac}\sin(\omega t + \theta)) = B_{dc} \pm B_{ac} \geq B_{dc} - B_{ac} \ldots\ldots(3)$$

The iron core also has a constant-current superconductive winding that provides a magnetic bias. If $B_{dc} - B_{ac} \geq B_s$, Where B_s is the saturation flux density, the impedance of saturable core SFCL is similar to that of an air-core reactor, which can be neglected by the power grid which is not enough to affect the natural attribute of the line. If $B_{dc} - B_{ac} \approx 0$, the impedance brings out the considerable impacts to the power system. The saturable-core SFCL need not use a superconducting coil.

Therefore, the paper presents the saturable-core FCL based on the normal conductor direct current coil. About the size , weight and prototypes, compared to the SFCL which used the special core to in order to combine the superconductor and normal conductor, the core of NFCL is similar to the classical transformer which is easy to produce, without the extra the Dewar equipment; for the power losses and cost, the advantage of NFCL is obvious.

2.3 Simulation Model of NFCL In the pscad

The paper presents another FCL with conventional DC coil, whose structure and physical principle are based on the saturable core SFCL. Via the study and simulation in the PSCAD, the results indicate that saturable core FCL Based on the Normal Conductor Direct Current Coil (NFCL) is effective to power grid

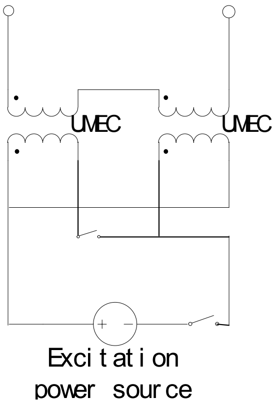


Fig 3. Simulation model of NFCL in PSCAD

3. Design of Rapid Demagnetization and Rapid Excitation Auxiliary Circuit

Reference [2, 5] presents the improved saturable core SFCL, which quenches the DC power source during the event of fault in order to protect the DC coil and also provides the higher DC power source to coordinate the auto reclose of power grid. In the reference, the experiments of SFCL in the 35kV china southern power grid show the availability of this kind of SFCL.
In this paper, passive rapid demagnetization auxiliary circuit and passive rapid excitation auxiliary circuit are designed to protect the DC coil during the fault event and coordinate the auto reclose process.

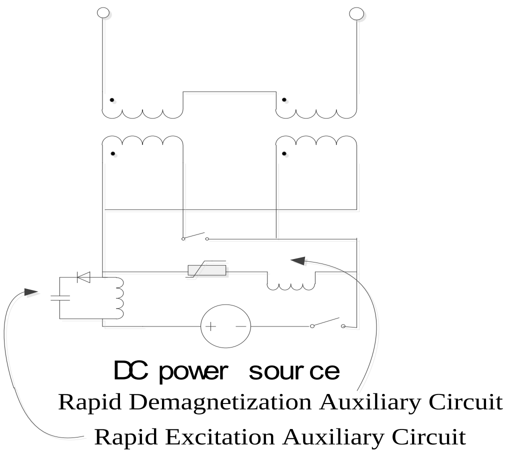


Fig 4. Model of NFCL with Rapid demagnetization and Rapid Excitation auxiliary circuit

4. Simulation

In this paper , NFCL simulation model is used in the PSCAD, which is made by the two UMEC type transformer in the series.

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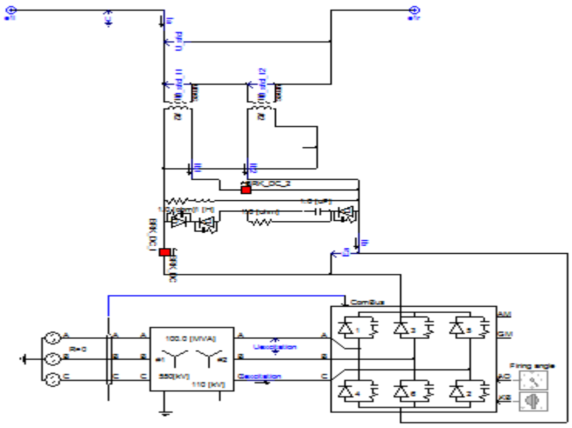

Fig 5. Simulation details of NFCL in the pscad

In order to study the dynamic characters of NFCL, the simulation description and process are set below and in the Fig 5:

(1) Power system voltage is 500kV settable via source equivalents.
(2) Simulates two substations connected via one transmission line.
(3) Fault position at the middle of two substations.
(4) Fault type: Phase A to Ground (temporary)
(5) Fault occur: 1 seconds
(6) Fault clearance time: 1.2 seconds
(7) Auto reclose time: 1.8 seconds

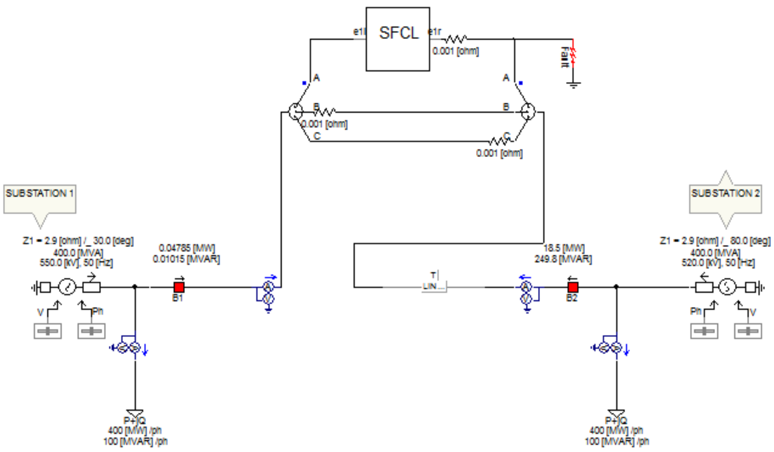

Fig 6. Simulation of the 500kV power system with FCL

Simulation results:

Short circuit voltage increase to 73.8% (234kV/319kV) of rated voltage, which greatly improve transient voltage stability.

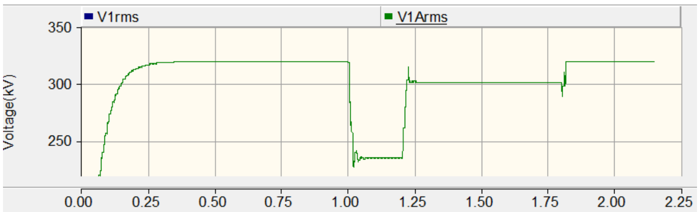

Fig 7.Voltage changes with the simulation process

The simulation proves the correctness of NFCL model and parameter should redesign according different project requirements.

5. Conclusion

Normal conducting fault current limiter (NFCL) utilizes superconducting materials to limit the current directly or to supply a DC bias current that affects the level of magnetization of a saturable iron core. The simulation presents that NFCL' characters meet with the requirements of power utility for FCL, besides, which processes some advantages at the cost, size and usage.

6. References

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