Setting method of parameters for SN transition fault current limiter into 6.6kV distribution system

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Abstract. A fault current limiter (FCL) is an outstanding apparatus which the impedance does not appear when no fault occurs, but the impedance appears only when a fault occurs in a power system. The operation of the FCL causes the effective reduction of the fault current. Although there are various kinds of FCLs in principles which have ever proposed, we think that a SN transition FCL with small normal loss will be promising since it is connected in series. However, we need to solve many problems toward practical use. In this paper, we propose the setting method of the parameters in the case of applying a SN transition FCLs to the feeders, or the busbar, or the lower voltage side of the transformers in the 6.6kV model distribution system. And we evaluate how to introduce the FCLs into it from the point of the requirements and the design. Finally, we suggest the hopeful installation of the FCLs into the distribution system.

1. Introduction
The opportunities of connecting distributed generators to 6.6kV distribution systems are increasing due to deregulation of power industry. On the other hand, a 6.6kV distribution system in Japan has the following features unlike the transmission systems.
- Insulated neutral point to earth method
- The breaking capacity is 12.5kA.
- Few power sources are connected.
- The bus configuration is single busbar with the section in which the disconnector is usually open.
- The system configuration is radial and most of feeders have many tapped lines.
- Voltage control is applied for each section.
- A conductor with smaller diameter is used at near the end of a feeder

There are fears of unnecessary tripping of a healthy feeder due to the fault current supply from distributed generators, or equipment damage, or melt of a feeder, when a short circuit fault occurs in a distribution system to which distributed generators with large capacity are connected. If the fault current limiter (FCL) which can reduce the fault current effectively at a short circuit fault can be introduced into a distribution system, it can contribute to a countermeasure against short circuit current and a means of prolonging of life cycle of creaky facilities.

Generally the impedance of a FCL is very small under the normal conditions but appears only in a fault, so the fault current can be reduced appropriately. Although research and development about a superconducting FCL has been done worldwide, no superconducting FCL has been practically introduced into a power system. On the other hand, we have developed the setting method of the parameters of a SN transition FCL or a rectifier type superconducting FCL which installed at an
transmission overhead line or a busbar[1][2], and the performance verification tests for SN transition FCL were carried out in the power system simulator of CRIEPI[3].

From the background as mentioned above, the setting method of the parameters for SN transition FCL installed at the feeders or the lower voltage (LV) side of the transformers or the busbar considering the requirements from the power system, and the effective introduction of the FCLs by evaluating from design, manufacture, and cost (the number of required modules) are described in this paper.

2. Analysis conditions

Fig.1 shows the 66kV/6.6kV model distribution system. The bus configuration for a distribution system is the single bus-bar which is usually separated by a disconnector due to short circuit capacity. This configuration is henceforth called “System 1”. When it is necessary to interchange the electric power to the outage area through this section at a fault, it will be closed. This system to be operated with the closed disconnector is henceforth called “System 2”. In the model power system, the fault current against a short circuit fault near the busbar is set for the value which exceeds the breaking capacity of the breaker (for example, CB9) due to the connection of distributed generators with large capacity. Tab.1 shows the constants of the model power system. In System 1, various kinds of faults can occur at F1-F10 on the feeder 9, F21-F30 on the feeder 10 and F0, and in System 2, various kinds of faults can also occur at F11-F20 on the feeder 1. Of course, a fault with fault resistance can be considered.

In a distribution system, generally, the overcurrent relays (OCR) for a short circuit fault (OCHi) at the high voltage (HV) side of transformers, the OCRs for a short circuit fault (OCFi) and ground directional relays for an earth fault in all feeders, and a ground overvoltage relay at a bus-bar are installed. However, the earthing of the power system as shown in Fig. 1 is insulated neutral point to earth method, so the fault current against 1LG is very small. Therefore, a FCL can operate against only a short circuit fault. Each OCR is set as can detect 2LG at the end of the feeder (See Tab.2). Moreover, the time characteristics of the OCRs are the inverse time characteristics and they will operate at 200msec against a short circuit fault near the busbar and at 450msec against a short circuit fault at the end of the feeder. The time characteristics of the OCHs are the constant time characteristics with the time delay of 500msec.

![Fig.1 Model distribution system](image)

The SN transition FCLs are installed in the feeders, the LV side of the transformers, or the bus-bar. Since these FCLs have very small loss, and are passive types, that is, they have no operation part or no fault detection element, introducing them into distribution systems is hopeful. We studied the setting method of the parameters using the simple FCL model already developed as shown in Fig. 2[1], in this
paper. The FCL is composed of series- and parallel-connected elements with 100 Ampere of Ic and 2 Ω of RLF (See Fig. 3). Fig. 3 shows the operating characteristic of the EMTP model of the FCL shown in Fig. 2. That is, if fault current exceeds the trigger current ILS, resistance will become RLF after the operating time TOP. This model has no temperature dependency in resistance.

| Tab. 1 Constants of the model distribution system |
|-----------------------------------------------|
| Voltage                                      | 66kV/6.6kV                                    |
| Frequency                                    | 50Hz                                         |
| Line Constant of a feeder                    | 0.0523+j0.1907pu                              |
| Back impedance                               | j0.01729pu(System 1)                          |
| Main Transformer                             | j0.04229pu(System 2)                          |
| Load current                                 | 280A                                         |
| Impedance of the feeder connected with DGs   | 0.0523-j0.1907pu                             |

Fig. 2 EMTP model for a SN transition type

3. Setting Method of the Parameters for SN Transition FCL[4]

3.1. Parameters for SN Transition FCL
Tab. 2 shows the parameters of a SN transition FCL[1]. Among these, RLF and ILS are the parameters which a user should specify. Depending on an introduction point, TOP and TRE (although the resetting time should be also taken into consideration because an automatic reclosing is available for an overhead line, a mechanism to reset to the normal condition is not clear. We didn't consider it.) may be required as specification. ILm is important for the design of the FCL. ILf should be specified as become below the rated breaking capacity.

| Tab. 2 Parameters for a SN transition superconducting fault current limiter |
|------------------------------------------|
| Parameters                      | Definition                                      |
| Operating start current (ILS) | Current which initiates operation of limiting |
| Operating time (TOP)            | Time to reach the initial value of the limiting resistance after quench |
| Limiting resistance (RLf)      | Resistance which appears after the initiation of current limiting |
| Reset time (TRE)               | Time to enable normal operation after finishing current limiting |
| Maximum current through FCL (ILm) | Maximum current through fault current limiter during limiting operation |
| Reduced current at tripping (ILf) | Reduced fault current at fault clearance |

3.2. Setting method of the Operating Start Current
It is necessary for decision of ILS to take into consideration the operating duty and the non-operation duty. In Fig. 1, the maximum current which the FCL should stay in non-operation is assumed to be the inrush current at being parallel in the transformer with no-load. The peak value of the inrush current can be estimated from the capacity of the transformer. When the 2MVA transformer with no-load
installed at the end of the feeder is connected, the peak of the inrush current is taken as 2500A_0-p (peak value of inrush current = rated load current in rms x the multiple according to the capacity = 175A x 14 ≒ 2500A_0-p). In addition, for installation of FCLs at the LV side of the transformer or the busbar, when one of the transformers is out of operation, the whole of inrush current will pass the FCL. Therefore, ILS should be set for the above-mentioned value. As mentioned above, ILS should set for more than the non-operation duty (Inoop). On the other hand, the upper limit of ILS should be below the breaking capacity (ICB).

Therefore, the setting range of ILS can be expressed as equation (1).

\[ I_{\text{Inoop}} \leq I_{\text{LS}} \leq I_{\text{CB}} \cdots (1) \]

3.3. Setting Method of RLf

3.3.1. Solution of Current through FCL at operation of FCL

Fig. 3 shows the equivalent circuit against 3LG in the feeder to which no distributed generator is connected. FCLs are expressed as FCLL, or FCLT, or FCLB in this figure.

When the FCL operates, the desired resistance (RLf) appears and when it does not operate, RLf is 0. Plural distributed generators are expressed as one generator and an equivalent impedance in this figure. E1 and EG are voltage of the upper voltage class power system and the terminal voltage of the equivalent distributed generator, respectively.

XB is the back impedance to adjust the fault current, XT is the impedance of the transformer, and XG is the equivalent impedance including the line impedance and the transformer impedance. XL is the feeder impedance for the total length and RLf is the fault resistance. "a" is the constant which is in proportion to the distance to the fault point, which can be 0 ≤ a ≤ 1. FCLL, FCLT, and FCLB mean the FCLs installed at the feeders, or the LV side of the transformers or the busbar, respectively.

The current through the CB (I) as shown in Fig.3 is easily solved by using Kirchhoff's law.

3.3.2. Setting Method of RLf

As an example, the setting method of RLf when the FCLs are installed at the feeders is described here. The fault current containing 100% of transient DC component should be reduced below the breaking capacity ICB of a breaker against 3LG near the busbar, considering the worst case. The OCR installed in the feeder and the OCR installed at the HV side of the transformer should be set as can operate even if the FCL would operate against 3LG at the farthest end of the feeder. This setting method can achieve the prevention of the fault extension even if the relay could not operate or the CB could not open. That is, let 2I be the fault current through the CB against 3LG near the busbar, I' and I1' be the fault current through the CB and the relay input at the HV side of the transformer against 3LG at the farthest point at which the FCL may operate, respectively. These currents are required to satisfy equation (2).

\[ 2I \leq I_{\text{CB}} , \ I' \geq I_{\text{OC}} , \ I_{1}' \geq I_{\text{OCH}} \cdots (2) \]

Fig. 5 shows the relation between the currents and RLf, which is calculated from the equivalent circuit against 3LG described in the previous section. According to this, the setting range of RLf for System 1 is shown in equation (3).

\[ 0.58 \leq R_{\text{Lf}} \leq 2.08 \cdots (3) \]
Fig. 6 shows the current through CB together with the current without FCL, where RLf is set for the minimum value calculated by equation (3). It can be seen that the proposed setting method enables the fault current to reduce below ICB.

Fig. 5 Desirable setting range of limiting resistance where FCLs are installed at feeders

3.3.3. Response of Protection Relays

Even if a FCL would operate, the response of existing protection relays must not be influenced. FCLs are installed at the feeders in Fig. 1. In this case, the FCL operates against a short circuit fault at F10 or F30. The OCR at the feeder and at the HV side of the transformer should operate under the above condition.

As an example, Fig. 7 shows the response of the OCRs against 3LG at F10 which is located at the end of the feeder 9. According to this, the OCR installed in the faulted feeder and the OCR at the HV side of the transformer operate correctly.

On the other hand, the response of the OCR in the healthy feeder is incorrect inoperation. Since the OCR at HV side of the transformer can also detect this fault simultaneously, it can be seen that fault extension can be prevented when the relay would not operate or the breaker would not open. The setting method of RLf proposed here is appropriate, as mentioned above.

3.4. Current through FCL

Fig. 8 shows the relation between the maximum current through the FCL and RLf, for every installation of the FCLs. The maximum current through FCL becomes small, as RLf becomes large, according to this. Moreover, if RLf would be set for the value in setting range, the maximum current through FCL is below the breaking capacity. Therefore, no countermeasure is required.

3.5. Voltage across FCL at operation of FCL

Fig. 9 shows the relation between the voltage across the FCL at operation of the FCL operation and RLf. The voltage across the FCL becomes large, as RLf becomes large, according to this. Moreover, in the setting range of RLf, the voltage across the FCL is below the healthy phase voltage increased at the time of 1LG. Therefore, it can be seen that the measure on insulation is unnecessary.
3.6. Estimated Temperature of FCL Module

3.6.1. Consumed Energy The energy is processed in the form of heat, as RLF in a SN transition superconducting FCL appears due to SN transition when a fault occurs. Therefore, very large consumed energy may have misgivings about breakage of a superconductor due to a temperature rise. Here, Joule's heat is calculated by equation (4).

$$\varepsilon = \int_0^T I_{FCL}^2(t) R_{FCL}(t)dt \cdots (4)$$

Where $I_{FCL}$: Current through FCL, $R_{FCL}$: Resistance of FCL after a fault, $T$: Time to fault clearance

3.6.2. Estimation of Module Temperature According to the experimental result in the power system simulator of CRIEPI for the FCL modules which are composed of the superconducting thin films, the generated heat is consumed in AlN (nitriding aluminum)[3]. Under the heat insulation condition, the temperature of a superconductivity thin film is estimated by the following equation.

$$T(K) = 0.0068 \times Q / (p \times s) + 90 \cdots (5)$$

Where $Q$ is the consumed energy which calculated in the previous section, and $s$ and $p$ are the series-parallel number of superconducting FCL modules, respectively.

As an example, Fig.10 shows the FCL module temperature estimated from the equation (5) where the FCL is installed in the feeders. According to this, it is estimated that a rise in heat will become below the safety operation temperature regardless of fault conditions.
Although any quantitative analysis about the safety operation temperature has not been made yet, the possibility of breakage is experientially high when the rise in heat reaches 450K. However, if no voltage is applied across the FCL after a fault, even if the temperature rise becomes about 400K temperature, we verified that cooling for more than 1 minute enabled the FCL to recover to the superconducting condition. The safety operation temperature is set to 400K in this paper.

When installing a SN transition FCL in a feeder, it can be seen that breakage of a superconductor can be avoided by the setting method of RLF which expects the superposition for 100% of transient DC component. Furthermore, as shown in Fig. 11, according to the proposed setting method of RLF, the temperature of the superconductivity can be kept below the safety operation temperature.

3.7. Setting Method of Desirable Parameters

We have developed the setting method of the parameters considering the coordination between the responses of the existing protection relays and that of the FCLs, assuming that a superconducting FCL is introduced into a trunk transmission system. And various kinds of the performance tests using the small FCL modules were performed in the power system simulator of CRIEPI, reflecting the setting method of the parameter. According to the setting method, the parameters are set as avoid the influence upon the responses of the existing protection relays considering both the operating duty and the non-operation duty reflecting the requirements from the power system. In response, the setting method proposed in this paper achieves the followings; since the highest temperature will reach below the safety operation temperature based upon the estimation of the rise in heat of a superconductor, breakage of a superconductivity can be avoided and RLF is set for the minimum value within the setting range so the initial cost will become into the minimum. Fig.12 shows the flowchart which tells the setting method of the parameters for the SN transition FCL.

4. Evaluation of Introduction of SN Transition FCL into a Distribution System[4]

We evaluate the effective introduction of the SN transition FCLs into the distribution system by considering the requirements from a system, the requirements for a design / manufacture and the number of modules where the FCLs are installed in the feeders or the HV side of the transformers or the bus-bar (See Tab.3). All of the requirements from the distribution system and from design / manufacture are satisfied in case of installation of FCLs in the feeders. If FCLs are installed in all the feeders, cost goes up. Depending on the system conditions, the measure to the existing protection relays is required in case of installation of FCLs in the LV side of the transformers. Before considering the introduction of the FCL, the reconstruction of the voltage control is required in case of installation of FCLs at the busbar. And since there is a severe problem that the fault current cannot be reduced to below the breaking capacity depending on the system conditions, this installation cannot be recommended.

As mentioned above, if the initial cost problem is excluded, the installation of FCLs in the feeders is the most excellent way. If the introduction of a FCL in only a feeder to which a lot of distributed
generators are connected can effectively reduce the fault current at a short circuit fault, we recommend the introduction of FCLs in the feeder.

| Tab.3 Introduction Estimation of SN Transition Type Superconducting FCL |
|-----------------|-----------------|-----------------|
|                 | Feeder          | LV side of transformer | Busbar                     |
| Number of FCLs  | △ (Basically number of feeders) | ○ (Feeder to be required to install FCLs) | ○ (2 number of transformers)  | ○ (Only 1)  |
| Requirements from the power system | ○ (Requirements can be satisfied independent of system conditions) | △ (Healthy circuit may be mistripped according to infeed of fault current depending on the total capacity of DGs.) |  △ (Fault current may not be reduced below to breaking capacity depending on system conditions.) |
| - Protection relay coordination |
| - Reduction of fault current |
| - Prevention of unwanted operation of FCL |
| Requirements from design & manufacture | ○ (Smaller RLF is required compared with that of LV side of transformer.) | △ (The largest RLF is required among these installations.) | ○ (The smallest RLF is required for busbar installation if applicable.) |
| - Limiting resistance |
| - Voltage across FCL |
| - Maximum current through FCL |
| - Superconductor temperature |
| Others |  |  |  |
| Evaluation for Introduction of FCL | ○ (Most excellent introduction) | ○ (Depending on system conditions) | × (Not recommendable) |

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