Reduction Effect of Semiconductor Type Fault Current Limiter on Interrupting Duty of a Circuit Breaker

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Abstract

Calculations were carried out to study the effect of a semiconductor type of fault current limiter (FCL) upon the interrupting duty imposed on a circuit breaker when a fault occurs at a distance of 1 to 8 km downstream from the load side terminals of the FCL. For comparison purpose, we also look at the interrupting condition when the fault happens very close to the terminals of the circuit breaker. The semiconductor type of FCL in current-limiting operation was assumed to have a limiting element composed of either an inductance or a resistance. For all fault locations, the insertion of the resistive FCL proved to decrease not only the fault current, but also the rate of rise of the recovery voltage (rrrv). For the inductive FCL, the rrrv depends mainly upon the stray capacitance C_p *of the limiting coil. Under short-line fault (SLF) condition, the introduction of the inductive FCL with* C_p= *100 nF is shown to reduce the severity of the SLF transient by reducing the fault current and the rrrv. However, for all fault locations, the insertion of the inductive FCL with* C_p= *10 nF was found to decrease the fault current, while increasing the rrrv.*

Key words: Fault current limiter, circuit breaker, transient recovery voltage, interrupting duty.

1 Introduction

High power semiconductors have been used in various devices such as power converters and energy storage systems. In addition to these devices, the semiconductors are also applied to fault current limiters (FCLs) that have a function of reducing fault current levels in transmission and distribution systems[1]-[5]. The FCL should have very low impedance under normal operating conditions and high impedance under fault conditions. Some papers have described the prototype of the FCLs and the performance of their limiting function[1]-[4].

After being limited by the FCL, the current is interrupted at its current zero by a circuit breaker. After the interruption of the fault current, a transient recovery voltage (TRV) appears across the contacts of the circuit breaker. To perform a succesful interruption, the circuit breaker must withstand against the TRV without re-establishment of the arc between the contacts.

The FCL can vary the TRV, thus leading to a change in the interrupting condition imposed on the circuit breaker. Nonetheless, introducing the FCL into the power systems does not necessarily offer favorite interrupting condition to the circuit breaker. Therefore, it is important to study the variation of the TRV due to the insertion of the FCL. So far, a previous paper has described the variation of the TRV due to the insertion of a cryoresisitive FCL[6]. Nonetheless, this previous research was performed under restricted condition so that the dependence of the TRV on various FCL parameters such as the limiting impedance was not studied.

As a consequence, the present work was done to study the influence of the FCL on the interrupting duty of a circuit breaker, i.e. the interrupting current and the TRV across the circuit breaker. In this study, the interrupting duty to which the circuit breaker is subjected was calculated for various FCL parameters under different fault locations. Until now, we have reported the variation of the interrupting condition under breaker terminal fault (BTF) regime due to the insertion of an FCL[7].

This paper focuses on a short-line fault (SLF), namely a fault occurring at a distance of several kilometers away from the load side terminals of the circuit breaker. It is well known that the SLF causes the rate of rise of the recovery voltage (rrrv) to be higher than that of the BTF. The FCL was assumed to have a limiting element consisting of either an inductance or a resistance. In this research, the results of the interrupting duty imposed on a circuit breaker under BTF condition were also presented.

2 Insertion of FCL into the power system

The system voltage and the power frequency of the transmission power system are set to be 275 kV and 60 Hz, respectively. A symmetrical three-phase-to-ground short-circuit fault is assumed to occur at a distance l of 0, 1, 4 and 8 km away from the load side terminals of the FCL. The fault at a distance of 0 km corresponds to what is called a breaker terminal fault (BTF). The fault at 1, 4 and 8 km corresponds to a short-line fault (SLF). Figure 1 shows the single-phase equivalent circuit used in the present research. A simple circuit is used to find out the fundamental aspect of the variation of the TRV due to the insertion of an FCL. In the power-source-side circuit, an inductance L and a capacitance C were determined to be 6.69 mH and 750 nF respectively. This is because under BTF condition, the circuit breaker in the absence of the FCL was assumed to interrupt a BTF current of 63 kA_{rms} under a rrrv of 2.3 kV/μs[8]. In the absence of the FCL, the SLF current at a distance l of 1, 4 and 8 km is equal to 90, 68 and 51 % of the BTF current respectively. The capacitor C_{FCL} simulates a stray capacitance of the FCL to the ground and is set to be 1 nF. The inductance and the capacitance per unit length of the transmission line are 0.8 mH/km and 15 nF/km respectively.

Figure 2 shows a typical example of the circuit diagram of a semiconductor-type of FCL. Immediately after the

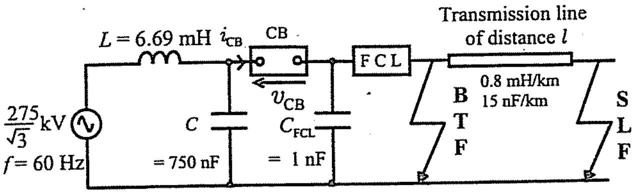
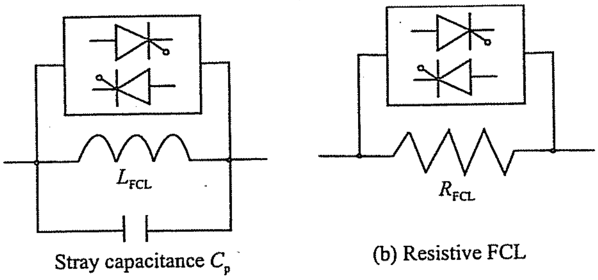


Figure 1. Single-phase equivalent circuit of a symmetrical three-phase-to-ground short circuit.



(a) Inductive FCL

(b) Resistive FCL

Figure 2. Equivalent circuit for each semiconductor type of FCL in current-limiting operation

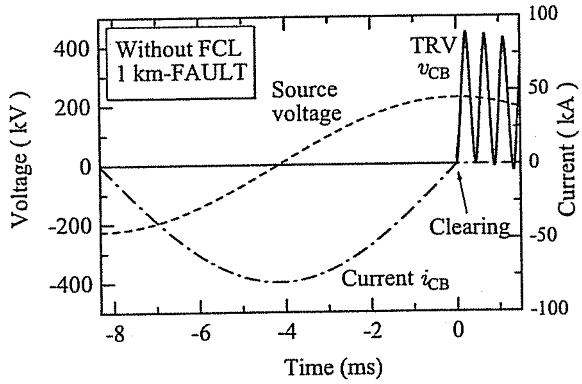


Figure 3. TRV following interruption of the fault current in the absence of the FCL.

FCL detects the fault current, the semiconductor devices operate to commute the fault current to a limiting impedance. In other words, the fault current flows through the limiting impedance when the FCL is in its limiting operation. Either an inductance L_{FCL} or a resistance R_{FCL} is used as limiting impedance. Thus, the semiconductor type of FCL in current-limiting operation produced an impedance Z_{FCL} consisting of either an inductance (L-Type FCL) or a resistance (R-Type FCL). In both models of FCL, the impedance Z_{FCL} of the FCL was set to be in the range of 1 to 5 Ω. For the L-Type FCL, a capacitance C_p is connected in parallel with the limiting coil to simulate a stray capacitance appearing in the winding of the coil. The capacitance C_p is set to be in the range of 10 to 100 nF. The stray capacitance C_p has so much higher impedance than the inductance L_{FCL} that the impedance Z_{FCL} is equal to the impedance of the inductance L_{FCL}.

The calculation with the aid of the Electro-Magnetic Transients Program (ATP-EMTP) was performed to determine the instantaneous values of the transient recovery voltage v_{CB} appearing after current zero and the current i_{CB} flowing through the contacts of the circuit breaker before current zero. The current interruption process in the circuit breaker was supposed to be similar as that of an ideal switch. The current i_{CB} is assumed to have no dc component. In other words, the current i_{CB} flowing in the circuit in the absence of the FCL is a totally reactive symmetrical current; which means that at the instant when current reaches its zero, the system voltage will be at its peak.

3 Examples of waveforms of TRV

3.1 Resistive FCL

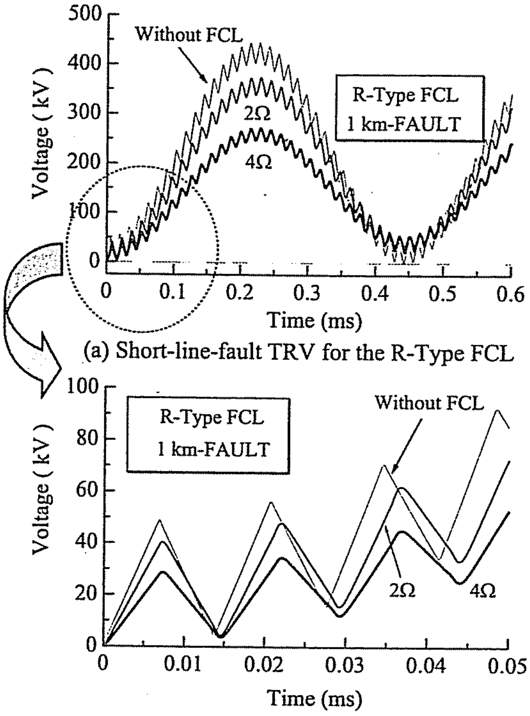
Figure 3 indicates the waveforms of the current i_{CB}, the source voltage and the TRV v_{CB} across the contacts of the circuit breaker in the absence of the FCL. These waveforms were calculated when the fault occurs at a distance l of 1 km away from the load-side terminals of the FCL. After the interruption of the fault current at a time of 0 msec, the TRV is applied between the contacts of the circuit breaker. The TRV across the breaker contacts is made up of the source-side and line-side oscillations.

Figure 4(a) gives the waveforms of the TRV v_{CB} in case of the resistive FCL for Z_{FCL}= 2 and 4 Ω during a time of 0 to 0.6 msec. These waveforms were evaluated for l = 1 km. For comparison purpose, figure 4(a) also represents the waveform of TRV in the absence of the FCL. All three waveforms shown in figure 4(a) are superimposed by sawtooth waves which arise from the voltage applied between the short-line and the ground. As illustrated in figure 4(a), the TRV in the absence of the FCL reaches a peak value of 446 kV at a time of 0.228 msec. In addition, the peak value of the TRV for the resistive FCL decreases from 446 to 273 kV with increasing Z_{FCL} from 0 to 4 Ω.

Figure 4(b) indicates the waveforms of the initial transient recovery voltage (ITRV) during a time of 0 to 0.1 msec. Immediately after the fault interruption, the ITRV in the absence of the FCL reaches a first peak value of 49 kV at a time of 0.007 msec. From these values, the rrrv was determined to be 7.1 kV/μs. In a similar way, the rrrv was determined from the waveforms of the ITRV to be 5.7 and 4 kV/μs for Z_{FCL}= 2 and 4 Ω respectively.

3.2 Inductive FCL

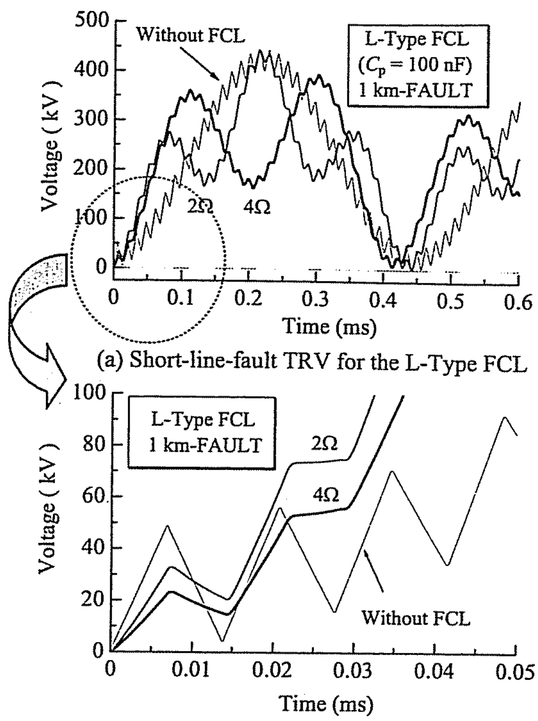
Figure 5(a) illustrates the waveforms of the TRV in case of the inductive FCL for Z_{FCL} = 2 and 4 Ω, as well as the waveform of the TRV in the absence of the FCL. The waveforms of TRV for the inductive FCL were determined for C_p= 100 nF and l = 1 km during a time of 0 to 0.6 msec. The initial TRV for the inductive FCL in case of C_p= 100 nF is given in figure 5(b) during a time of 0 to 0.1 msec. As outlined earlier, the rrrv in the absence of the FCL is 7.1 kV/μs. The rrrv arising from the waveforms of the ITRV for the inductive FCL was determined in a similar way as that for the resistive FCL mentioned before. After current zero, the rrrv for l = 1 km in case of the inductive FCL



(a) Short-line-fault TRV for the R-Type FCL

(b) Initial short-line-fault TRV for the R-Type FCL

Figure 4. Waveforms of short-line fault TRV for the resistive FCL.



(a) Short-line-fault TRV for the L-Type FCL

(b) Initial short-line-fault TRV for the L-Type FCL

Figure 5. Waveforms of short-line fault TRV in case of the inductive FCL for C_p= 100 nF.

with C_p= 100 nF was found to be equal to 4.6 and 3.2 kV/μs for Z_{FCL}= 2 and 4 Ω respectively.

4 Effect of FCL on interrupting duty

4.1 Rate of rise of recovery voltage

Figure 6 shows the rate of rise of the TRV for the resistive FCL plotted against the limiting impedance Z_{FCL}. For comparison purpose, this plot also indicates the variation of the rrrv due to the insertion of the resistive FCL under BTF condition. In the absence of the FCL, i.e. for Z_{FCL} = 0 Ω, the rates of rise of recovery voltage for an SLF occurring at a distance l of 1, 4 and 8 km are higher than that for the BTF. Especially, the rate of rise of TRV for l = 1 km is about 3 times as high as that for the BTF. In the presence of the resistive FCL, the rrrv for l = 1 km decreases by 50%, i.e. from 7.1 to 3.5 kV/μs with Z_{FCL} from 0 to 5 Ω. Similar dependences of the rrrv on the limiting impedance Z_{FCL} are seen for the SLF at a distance l of 4 and 8 km, as well as for the BTF. For instance, under BTF condition, the insertion of the resistive FCL reduced the rrrv by 52%, from 2.3 to 1.1 kV/μs for Z_{FCL} from 0 to 5 Ω. These reductions in the rate of rise of the TRV imposes a less severe condition upon the circuit breaker compared to the case where the FCL is not introduced into the power system.

Figure 7 presents the rate of rise of the TRV for the inductive FCL as a function of the limiting impedance Z_{FCL}. The rate of rise of the TRV plotted in figures 7(a) and (b) were obtained for C_p= 100 and C_p= 10 nF respectively. As can be seen in figure 7(a), the rrrv at a distance l of 1 km decreased by 61%, from 7.1 to 2.8 kV/μs with an increase in Z_{FCL} from 0 to 5 Ω. However, for the SLF at l = 4 km, a rise in Z_{FCL} from 0 to 1 Ω raises the rrrv from 5.7 to 6.3 kV/μs and a further increase in Z_{FCL} from 1 to 5 Ω lessens the rrrv from 6.3 to 3.6 kV/μs. Similar dependence of the rrrv on Z_{FCL} is seen for the SLF at a distance of 8 km. On the other hand, under BTF condition, the rrrv for C_p= 100 nF increases from 2.3 to 3.5 kV/μs as Z_{FCL} grows from 0 to 5 Ω. Figure 7(a) reveals that under SLF condition, the rate of rise of the TRV is lower for an inductive FCL of 5 Ω than that in the absence of the FCL.

Figure 7(b) shows the rrrv for C_p= 10 nF. For all fault locations, the insertion of an inductive FCL with C_p= 10 nF causes the rrrv to be higher than that in the absence of the FCL. For instance, in case of an SLF occurring at a distance of 1 km, the rrrv for Z_{FCL}= 1 Ω is 10.7 kV/μs. This rrrv is 1.5 times as large as that in the absence of the FCL. By making a comparison between figures 7(a) and 7(b), the rrrv for the inductive FCL is found to depend considerably on the stray capacitance C_p. This dependence will be discussed in section 4.1.

4.2 Interrupting duty of the circuit breaker

In figure 8(a), the rrrv for the resistive FCL described in the previous section is plotted against the limited current. The fault location is written in the vicinity of the plotted marks. Filled circles represent the case where the FCL is not inserted into the power system. In other words, the circuit breaker in the absence of the FCL is subjected to break the current under the interrupting

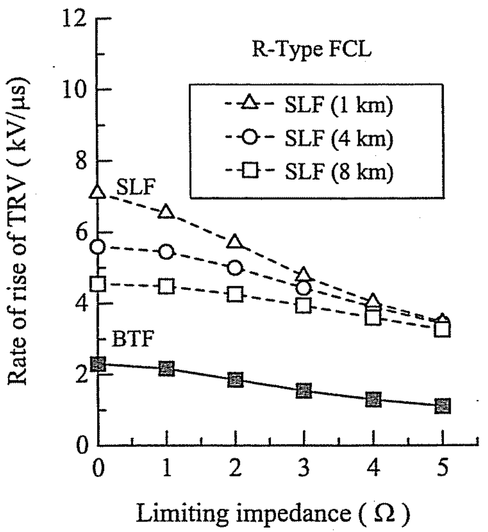
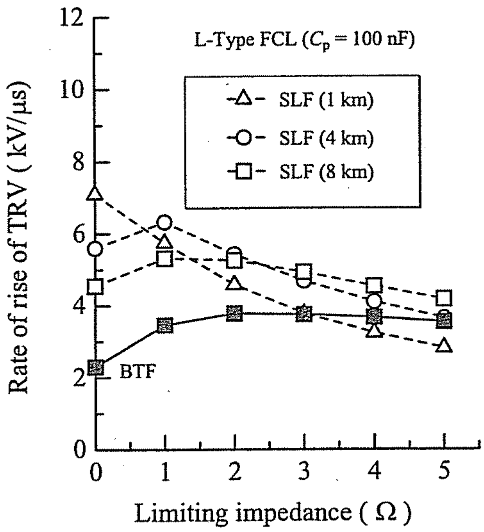
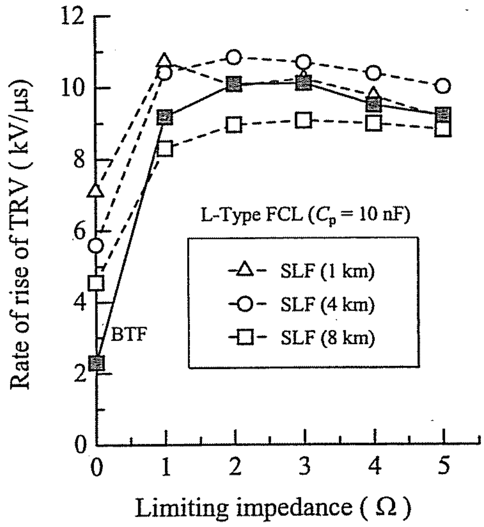


Figure 6. Rate of rise of the TRV as a function of the limiting impedance for the resistive FCL.



(a) Inductive FCL with $C_p = 100$ nF



(b) Inductive FCL with $C_p = 10$ nF

Figure 7. Rate of rise of the TRV as a function of the limiting impedance for the inductive FCL.

condition shown by the filled circles. Figure 8(a) also shows the interrupting-condition curve of the circuit breaker connected with a resistive FCL of 2 and 5 Ω. Under BTF and SLF conditions, the introduction of the resistive FCL results in a reduction in both the current and the rate of rise of the TRV. For example, under BTF condition, an increase in Z_{FCL} from 0 to 5 Ω decreases the rrrv from 2.3 to 1.1 kV/μs and the current from 63 to 28 kA$_{rms}$. On the other hand, for l = 1 km, a rise in the limiting resistance from 0 to 5 Ω reduces the rrrv from 7.1 to 3.5 kV/μs and the current from 56 to 28 kA$_{rms}$.

Figure 8(b) summarizes the interrupting condition to which the circuit breaker is subjected in the presence of the inductive FCL with C_p= 10 and 100 nF. Under BTF condition, the presence of the inductive FCL in the power system lessens the current, while increasing the rrrv. For example, as can be seen in figure 8(b), an inductive FCL of 5 Ω with C_p= 100 nF decreases the current to 21 kA$_{rms}$, while enhancing the rrrv to 3.5 kV/μs. In contrast to the BTF condition, for l = 1 km, the inductive FCL with C_p= 100 nF decreases both the current and the rrrv. The same reduction effect is also found when the fault happens at a distance of 4 km and the limiting impedance Z_{FCL} is above or equal to 2 Ω. Whereas being shown in figure 8(b), the interruption condition for C_p= 10 nF will be discussed in section 4.2.

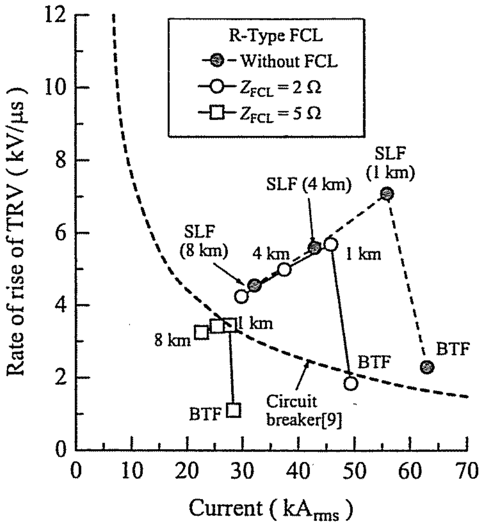
5 Discussion

5.1 Dependence of rrrv on the coil stray capacitance for an inductive FCL

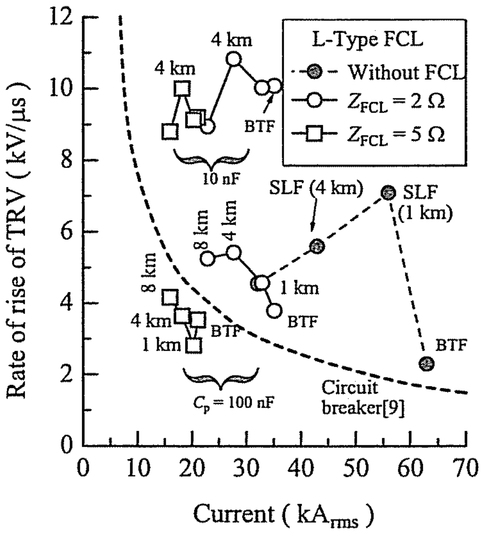
In the preceding section, the rrrv in case of the inductive FCL was calculated for C_p equal to 10 and 100 nF. To discuss the dependence of the rrrv on C_p, the rrrv was also determined for C_p = 20, 40 and 70 nF. Figure 9 indicates the rrrv for an inductive FCL with Z_{FCL} = 1 and 5 Ω as a function of C_p. As shown in this figure, the rrrv under BTF condition is almost independent of Z_{FCL}, while depending upon C_p in the range from 10 to 100 nF. For instance, in both cases, i.e. for Z_{FCL} equal to 1 and 5 Ω, as C_p increases from 10 to 100 nF, the rrrv decreases nearly from 9.2 to 3.5 kV/μs.

This dependence can be interpreted as follows. The rrrv is determined by the voltage across C_{FCL} or C at current zero and the frequency of the voltage oscillation after current zero. The increase in Z_{FCL}, i.e. L_{FCL}, enlarges the magnitude of the voltage across C_{FCL}, but reduces the frequency of the voltage so that the rrrv is almost independent of Z_{FCL}. On the other hand, C_p only influences the frequency of the line-side voltage of the circuit breaker. Thus, the rrrv for the inductive FCL depends on C_p.

A similar dependence of C_p on the rrrv was also seen for an SLF occurring at a distance of 8 km. However, contrary to the BTF condition, figure 9 reveals that the rrrv for an inductive FCL having a stray capacitance



(a) Resistive FCL



(b) Inductive FCL

Figure 8. Interrupting condition of the circuit breaker connected with FCL.

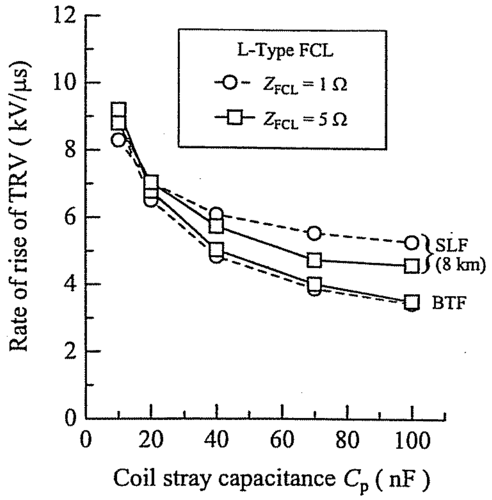


Figure 9. Dependence of the rrrv on the stray capacitance of the limiting coil.

C_p above 40 nF depends not only on C_p, but also on the limiting inductance L_{FCL}. Moreover, for C_p above 70 nF, the rrrv is independent of C_p, while depending on L_{FCL}. This fact can be explained as follows. The rate of rise of the recovery voltage across the circuit breaker arises principally from the line-side voltage of the circuit breaker since the frequency of the line-side transient is very much higher than that of the source-side transient. For C_p above 70 nF, the stray capacitance C_p has a little effect on the high-frequency oscillation of the line-side voltage of the circuit breaker, while the magnitude of the voltage is determined by Z_{FCL}, i.e. L_{FCL}. Thus, the rrrv tends to depend on L_{FCL}.

5.2 Interrupting condition

The interrupting capability of a circuit breaker is also shown in figure 8(a) as an example[9]. As can be seen in this figure, the rrrv of the interrupting condition in the absence of the FCL is higher than the critical rrrv of the circuit breaker for the same current. For all fault locations, figure 8(a) shows that the circuit breaker is not capable of breaking the current in the absence of the FCL. However, the insertion of a resistive FCL with Z_{FCL} = 5 Ω causes the rrrv to be less than the critical rrrv of the circuit breaker for all fault locations. This result indicates that the resistive FCL allows the interrupting condition to be less severe, thus making it possible for the circuit breaker to achieve a successful interruption. This fact also suggests that at least a limiting impedance of 5 Ω is required to allow the circuit breaker to interrupt the current successfully under BTF and SLF conditions.

Figure 8(b) also presents the interrupting performance of the same circuit breaker. As illustrated in this figure, in case of C_p = 100 nF, the inductive FCL with Z_{FCL} = 5 Ω is found to enable the circuit breaker to break the current for all fault locations. However, the inductive FCL with C_p = 10 nF causes the rrrv of the interruption condition to exceed the critical rrrv for all fault locations. Thus, this may give rise to a failure interruption. To summarize, as far as the present calculation conditions are concerned, these results show that when the inductive FCL is inserted into the power system, to allow the circuit breaker to achieve a satisfactory interruption, at least a limiting impedance of 5 Ω and as well as a stray capacitance C_p of 100 nF should be used.

6 Conclusion

We investigated the interrupting duty imposed on a circuit breaker connected with semiconductor type of FCL when a fault occurs at a distance of 0 to 8 km away from the load side terminals of the FCL. The insertion of the resistive FCL into the power system is found to decrease the first peak value of the TRV and the consequent reduction in the rate of rise of the recovery voltage. Moreover, for an SLF at a distance of 1 km, the presence of a resistive FCL of 5 Ω reduces both the rrrv and the current by 50% so that the circuit breaker can clear the fault in a less severe condition compared to the case where the FCL is not inserted into the system. On the other hand, while the presence of an inductive FCL in the circuit lessens the current, the behavior of the rrrv depends principally upon the magnitude of the stray capacitance C_P. For C_P =10 nF, the rrrv of the inductive FCL is at least 1.5 times as high as that in the absence of the FCL. However, for an inductive FCL of 5 Ω with C_P=100 nF, the rrrv is reduced by 61% in case of an SLF occurring at a distance of 1 km. Further, for all fault locations, the rrrv for the inductive FCL diminishes as C_P increases.

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