Effect Analysis of Thyristor Controlled Ground Fault Current Limiting System for Ungrounded Power Distribution Systems

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Abstract — **A thyristor controlled ground fault current limiting system (TGCL) was proposed to prevent one-line ground fault current rises due to increased capacitance to ground. The TGCL can control its compensating reactor optimally for capacitance to ground. Control is ensured by an in-phase control method for zero-phase sequence voltage and current. The protecting characteristics of the TGCL and its control algorithm are estimated by simulation analysis considering various fault conditions. The TGCL can detect and reduce the one-line ground fault current to below 20A within 50ms after a fault occurrence. The results of effect analysis show the TGCL is a valuable protection system for high ground fault current distribution systems.**

Keywords: Fault Current Limiter, Ground Fault, Thyristor Control, Fault Protection, Power Distribution System, Digital Analysis, ATP, EMTP.

1. INTRODUCTION

In power distribution systems, it is very important that faults are detected precisely and are excluded quickly, because distribution systems are connected to customers directly. Many 6.6kV distribution systems in Japan have adopted the three phase and three wire ungrounded type. One-line ground faults make up the greater part of fault modes in these power distribution systems [1][2]. The sign of fault currents being experienced has been showing a steadily increasing trend due to increased capacitance to ground, because distribution systems in city centers are making greater use of underground cables and they have longer total lengths of feeders. Consequently, there is some concern that the one-line ground fault current may exceed the present maximum value which is required by the Japanese Technical Standards for Electrical Installations. Increment of the fault current can, in particular, cause a potential rise in low-voltage lines when in contact with high-voltage lines. This means that more ground work is needed for the class B grounding and furthermore the zero-phase voltage detection sensitivity of ground fault protection relays has to be readjusted.

Therefore, the authors proposed a thyristor controlled ground fault current limiting system (TGCL) which could control its compensating reactors optimally for capacitance to ground [3]. Control is ensured by an in-phase control method for zero-phase sequence voltage and current.

In this paper, the protecting characteristics of the TGCL and its control algorithm are estimated by simulation analysis considering various fault conditions, i.e. fault locations, fault voltage phases and fault levels. As an analytical model, a one-bank and six-feeder distribution system is assumed as one of two bank configurations. The electro-magnetic transients program EMTP is used to analyze how this system limits and controls ground fault currents. The TGCL can detect and reduce the one-line ground fault current to below 20A within 50ms after a fault occurrence. The results of effect analysis show the TGCL is a valuable protection system for high ground fault current distribution systems.

2. THYRISTOR CONTROLLED GROUND FAULT CURRENT LIMITING SYSTEM (TGCL)

2.1 *Overall Configuration*

Fig. 1 shows the overall configuration of the TGCL when applied to a typical distribution system, i.e. a one bank and six feeder distribution system. The TGCL uses semi-conductor technology, thus optimizing the compensating reactor level that compensates for the capacitance to ground. The TGCL consists of a main ground fault current limiter, which varies the compensating reactor level quickly, and the TGCL's controller.

Fig. 2 shows a typical equivalent circuit when a one-line ground fault occurs on the feeder F1 shown in Fig. 1. In the figure, V (=6.6kV) is the line-to-line voltage, Rn is the converted resistance in the primary winding of the current limiting resistor in the tertiary winding of a grounding potential transformer (GPT), Rg is the grounding resistance at the fault point, and C_{F1} through C_{F6} are the capacitances to ground of all three phases of each distribution line. The ground fault current Ig has a tendency to increase due to increased charging currents I_{C1} through I_{C6} of capacitance to ground, because distribution systems have long underground cables recently. The compensating reactor L is provided between the neutral point and ground. If reactor L is controlled to the optimum value, the ground fault current can be limited.

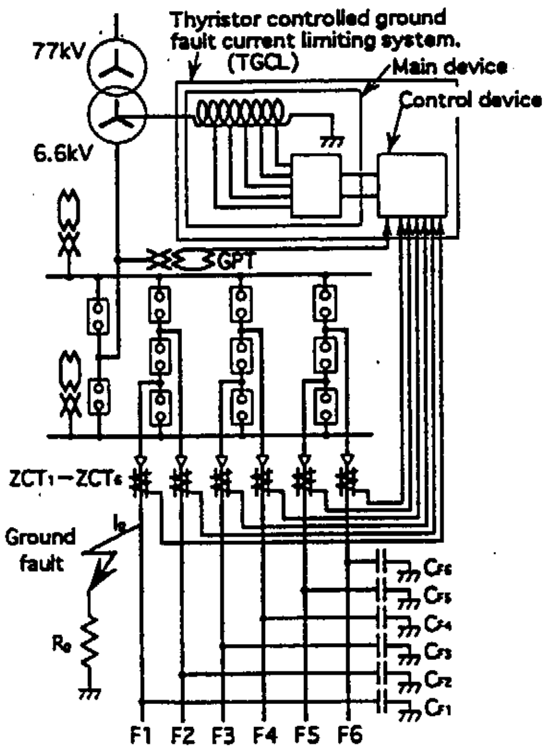


Fig. 1. Thyristor controlled ground fault current limiting system.

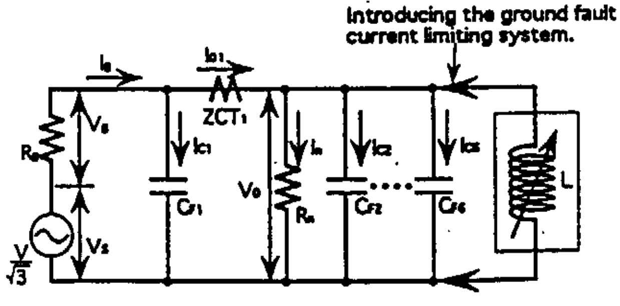


Fig. 2. An equivalent circuit of the ground fault current limiting system.

2.2 Control Method

As a means of controlling the TGCL, a zero-phase voltage/current in-phase control was proposed. This section describes its principle. If there is no compensating reactor L in Fig. 2, the ground fault current Ig can be expressed as follows:

$$I_g = \frac{V}{\sqrt{3}} \cdot \frac{\frac{1}{R_n} + j\omega C}{1 + R_g\left(\frac{1}{R_n} + j\omega C\right)} \tag{1}$$

where $C = C_{F1} + C_{F2} + \cdots + C_{F6}$.

On the other hand, if a compensating reactor L is connected as shown in Fig. 2, the ground fault current Ig can be expressed as follows:

$$I_g = \frac{V}{\sqrt{3}} \cdot \frac{\frac{1}{R_n} + j\omega C + \frac{1}{j\omega L}}{1 + R_g\left(\frac{1}{R_n} + j\omega C + \frac{1}{j\omega L}\right)}. \tag{2}$$

When a ground fault occurs at the feeder F1 as shown in Fig. 2, the monitoring current I_{01} in the zero-phase sequence current transformer ZCT_1 is the sum of the charging currents I_{C2} to I_{C6} of capacitance to ground of sound lines and the current I_n of the current limiting resistor in the tertiary winding of a GPT. Consequently, compensating with a reactor L equal to the capacitive component of the zero-phase current I_{01} cancels the ground fault current component coming in from the sound lines, thus limiting the ground fault current Ig. At this time, the compensating reactor L and the ground fault current Ig can be expressed as follows:

$$\frac{1}{\omega L} = \omega(C - C_{F1}), \tag{3}$$

$$I_g = \frac{V}{\sqrt{3}} \cdot \frac{\frac{1}{R_n} + j\omega C_{F1}}{1 + R_g\left(\frac{1}{R_n} + j\omega C_{F1}\right)}. \tag{4}$$

This control method is designed to put the zero-phase sequence current I_{01} in phase with the zero-phase sequence voltage V_0. In this method, the charging current of the capacitance to ground C_{F1} of the fault line remains uncompensated. However, limiting the ground fault current to 20A or below, which is the present current maximum level, ensures the present security level in grounding works. Another advantage is that there is little effect on the setting of present ground fault directional relays (DGs). DGs are located in the distribution station, and TGCL's controller can use the GPT/ZCTs in common with DGs. These advantages ensure this method is effective for controlling the TGCL.

2.3 Configuration of a Ground Fault Current Limiter

Fig. 3 shows an example of a main circuit of the TGCL. In it, a compensating reactor is inserted into the neutral point of the secondary winding of the main transformer in the distribution substation. It is a fast tap-changing system using solid-state switches composed of thyristors. The switches are turned on and off so as to achieve the required compensation level. A typical configuration of taps is shown at intervals of 3A and 30A in the maximum compensating reactor level. The main components are a compensating reactor, a resistor connected in parallel with the compensating reactor, and solid-state switches that switch between taps on the compensating reactor to adjust the compensation level. The resistor is used to secure a zero-phase sequence minimum current of DGs.

The TGCL is suitable for power distribution system having long and complex underground cables, because it can compensate for charging current of all the feeder's capacitances collectively.

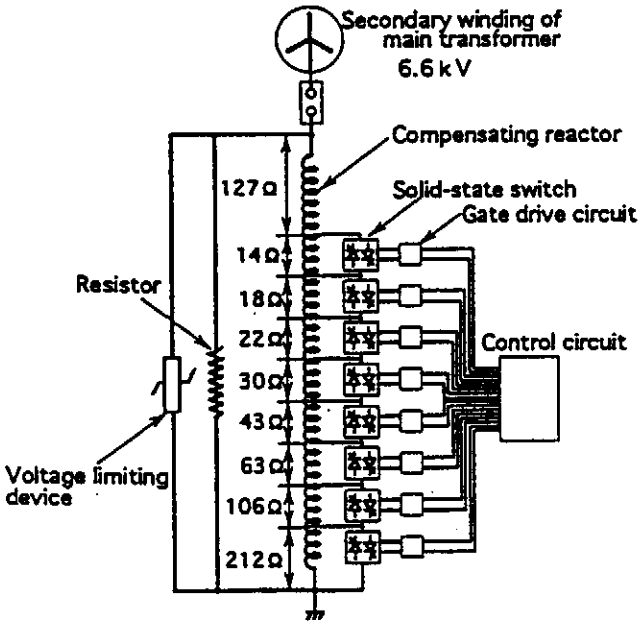
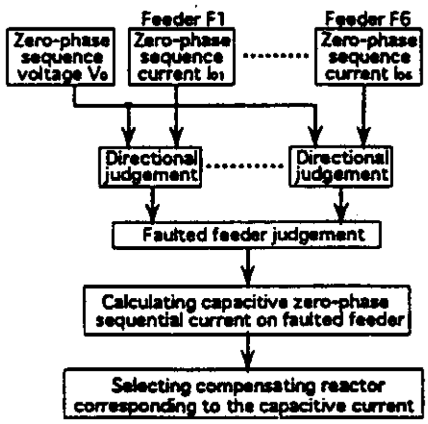


Fig. 3. Main circuit of the ground fault current limiter.

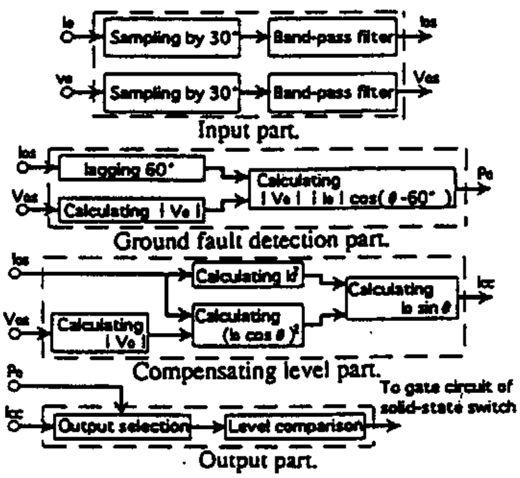
2.4 Control Circuit

Fig. 4 shows the control method used in the controller of the TGCL. Fig. 4(a) is the flowchart of ground fault current limiting control. On the basis of the zero-phase sequence voltage V_0 and the zero-phase currents I_{01} through I_{06}, the direction of a ground fault can be determined to find the faulted feeder. The capacitive component of the zero-phase sequence current coming into the faulted feeder is the ground fault current to be compensated for. Therefore, the corresponding tap of the compensating reactor is selected.

Fig. 4(b) shows the control algorithm of the zero-phase sequence voltage/current in-phase control. This digital relay control is designed to sample the 60Hz fundamental wave components of the zero-phase sequence voltage V_0 and the zero-phase sequence current I_0 and to perform arithmetic computations on the effective value. The V_0 and I_0 constitute a phase difference θ. The ground fault detection part detects fault occurrence and judges internal and external faults by monitoring around a phase lagging 60 degrees behind the zero-phase sequence current I_0. The compensation level part performs arithmetic computations on the sine component of the zero-phase sequence current I_0. The sine component is the capacitive component of the ground fault current. The calculated reactor level is used to limit the ground fault current. The computation result at the end of two cycles after the fault detection (when the computation result stabilizes at a constant value) is used as the compensation level. The constant value is due to a reduced compensation error resulting from transient computations. If the compensation level deviates from the compensating reactor level for reasons related to the system configuration or tap interval, the tap closest in lack of compensation is selected. This causes the zero-phase current always to remain in phase with, or ahead of, the zero-phase sequence voltage. This means that the control algorithm is realistic because it has little effect on present DGs.



(a) Flowchart of ground fault current limiting control.



(b) Control block diagram.

Fig. 4. Control method of ground fault current limiter.

3. ANALYSIS METHOD

3.1 Analytical Model

To make an analytical model, a substation with relatively long cable feeders was selected. A one-bank and six-feeder distribution system was assumed as one of two bank configurations. Fig. 5 shows the analysis model of the power distribution system. The model considered the types and lengths of the various cable feeders, which are the dominating factors that determine the capacitance to ground of the distribution system. The cables had a total length of 13.1km, with a charging current of capacitance to ground of 33A. The model omitted the overhead lines.

A compensating reactor was inserted into the neutral point of the secondary winding of the main transformer in the distribution substation. The electro-magnetic transients program EMTP was used to analyze how this system limits and controls ground fault currents [4]. The controller judges faults by zero-phase voltage/current in-phase control and simulates arithmetic computations on the compensation level. The proposed controller was modeled with the transient analysis of control systems TACS of EMTP. All taps on the TGCL were turned off. This corresponds to an initial compensation level of 6A, before a fault occurrence. The compensation level applied after the fault occurrence was optimized by turning on or off the solid-state switches.

3.2 Analytical Conditions

The protecting characteristics of the TGCL and its control algorithm are estimated by simulation analysis considering various fault conditions, i.e. fault locations (at the receiving end and the bus of feeders F1 to F6), fault voltage phases (0~150°) and fault levels (1% to 100%).

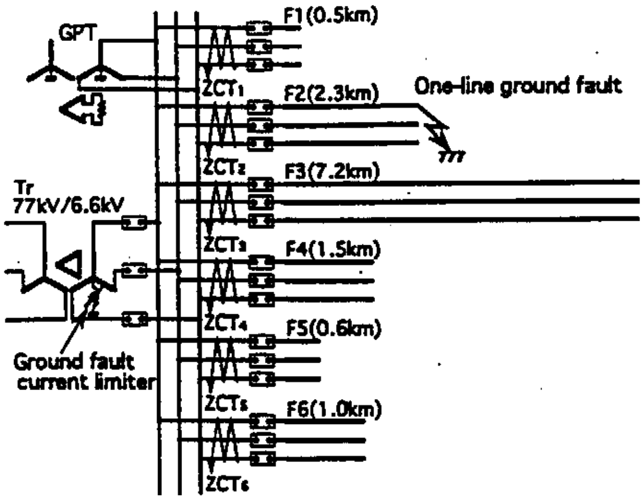


Fig. 5. Analysis model of power distribution system.

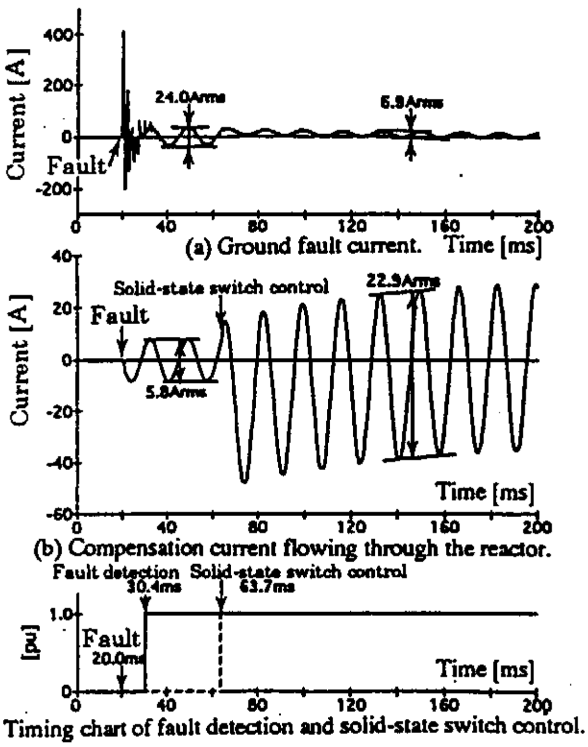


Fig. 6. Fault protection of 100% ground fault at the receiving end of feeder F2 (Case-1).

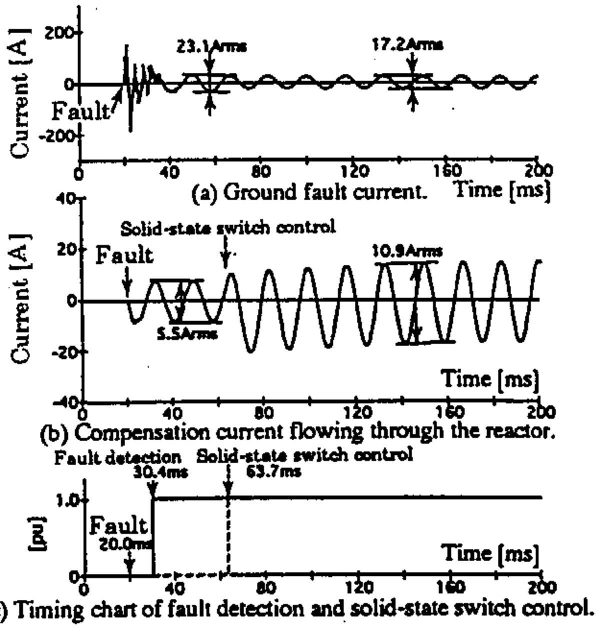


Fig. 7. Fault protection of 100% ground fault at the receiving end of feeder F3 (Case-2).

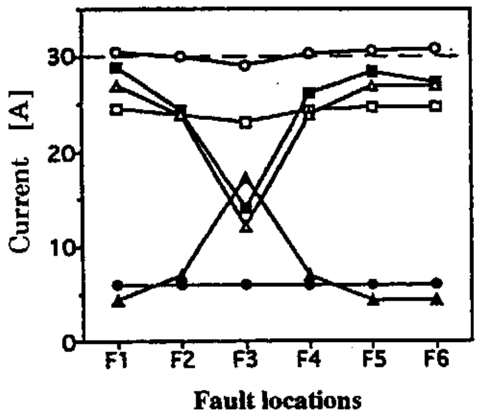
4. ANALYTICAL RESULTS AND EVALUATIONS

4.1 Operating Waveforms

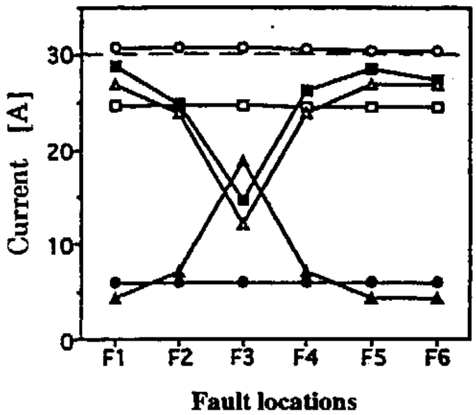
Fig. 6 shows analytical results when protecting from a one-line ground fault occurrence on feeder F2. Feeder F2 has an intermediate length in the model system of Fig. 5. This analytical case is case-1. Fig. 6(a) shows the simulation results of arithmetic computations on the ground fault current; Fig. 6(b), the compensating current flowing through the compensating reactor; and Fig. 6(c), the ground fault detection/control signals from the controller. When a ground fault occurs at 20ms, a transient overcurrent occurs, followed by a ground fault current of 24.0Arms. At this time, the compensating reactor is compensating for the ground fault current corresponding to an initial compensation level of 6.0Arms. When this TGCL is not used, the ground current becomes about 30Arms. Ground fault detection and directional judgment end 10.4ms after the fault occurrence (i.e. at 30.4ms). Two cycles after the fault detection (63.7ms), a computed compensation level of 24.4A is output. In response to tap-changing on the solid-state switches, the compensating current is increased to 22.9Arms. Consequently, the ground fault current drops from 24.0Arms to 6.9Arms. Still, the values of the compensation current in Fig. 6(b) differ from the initial compensation level of 6A and an ex post facto compensation level of 24A, because the compensation reactor has a component of resistance.

By the way, the circuit breakers interrupt the fault current and clear the fault within 1.0sec after the fault occurrence. TGCL can cope with multiple ground faults on the same phase, because TGCL continues to compensate until the fault is cleared.

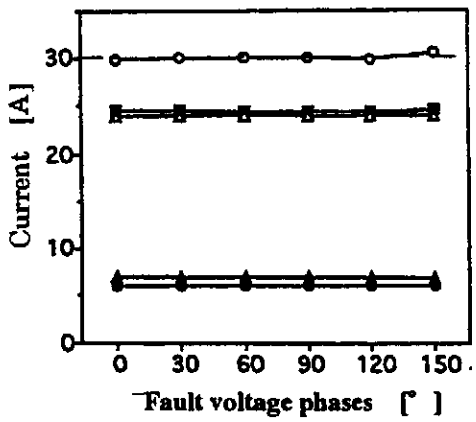
Fig. 7 shows analytical results when a one-line ground fault occurs on feeder F3. Feeder F3 has the longest length in the model system of Fig. 5. This analytical case is case-2. When a ground fault occurs, the ground fault current is 23.1Arms in Fig. 7(a). This value is smaller than the ground fault current in Fig. 6(a), because resistance and reactance of feeder F3 are larger than those of feeder F2. Ground fault detection and directional judgment are done in the same way as case-1. The computed compensation level of 12.0A is output. This value is smaller than that of feeder F2. Because the length of feeder F3 is longer than that of feeder F2, the charging current of the capacitance of feeder F3 is larger, and the uncompensated charging current in all feeders is larger. In response to control of the compensating reactor, the compensating



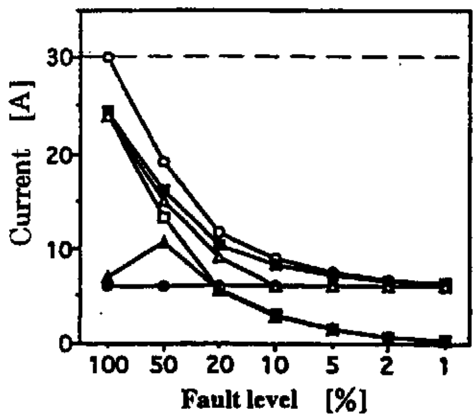
(a) Protecting characteristics to fault locations (Case-1).
(Fault level 100%, Fault voltage phase 90° at the receiving end.)



(b) Protecting characteristics to fault locations (Case-2).
(Fault level 100%, Fault voltage phase 90° at the bus side.)



(c) Protecting characteristics to fault voltage phases.
(Fault level 100% at the receiving end of feeder F2.)



(d) Protecting characteristics to fault level.
(Fault voltage phase 90° at the receiving end of feeder F2.)

○ : Charging current (Detected value)	□ : Initial ground fault current	△ : Inserted reactor value
● : Initial compensation level	■ : Computed compensation level	▲ : Ground fault current after compensation

Fig. 8. Protecting characteristics of the ground fault current limiting system.

current is increased from 5.5Arms to 10.9Arms, and the ground fault current drops to 17.2Arms.

These results indicate that the TGCL can detect a ground fault, compute its compensation level, and control the solid-state switches within 50ms after the fault occurrence. Therefore, the ground fault current can be limited to lower than 20A.

4.2 Protecting Characteristics

Fig. 8 shows the protecting characteristics of the TGCL which are obtained by simulation analysis considering various fault conditions. Fig. 8(a) shows the protecting characteristics when a one-line ground fault occurs at the receiving end of feeders F1 to F6. Ground fault currents in all cases are about 24Arms. Therefore, considering an initial compensation level of 6Arms, the charging current of capacitance to ground becomes about 30Arms. The ground fault current on each feeder is uneven about 1A, because resistance and reactance of the cable are different for each feeder. When a ground fault occurs on feeder F1, a computed compensation level of 28.8A is output toward the ground fault current of 24.6A. This computed level includes an initial compensation level of 6.0A. The tap of the compensating reactor is changed to 27A and the ground fault current drops to 4.4A. In a similar way, it is confirmed that the TGCL can restrain the ground fault current on feeders F2 to F6. The computed compensation level of the TGCL controller is different for the each feeder, because the charging current of the capacitance to ground of the fault line remains uncompensated.

Fig. 8(b) shows the protecting characteristics when a one-line ground fault occurs at the bus side of each feeder. Comparison of Fig. 8(b) and (a) shows the computed compensation level and the selected compensating reactor of the former agree well with those of the latter on each feeder. These results indicate that TGCL can restrain the ground fault current at all positions on the feeder (from the bus side to the receiving end).

Fig. 8(c) shows the protecting characteristics when a one-line ground fault occurs at the receiving end of feeder F2. In this figure, the voltage phase of the ground fault occurrence is changed. In all phases, the tap of the compensating reactor is changed to 24A and the ground fault current is limited to below 7A. For the TGCL, the voltage phase of the ground fault occurrence does not affect its protecting characteristics.

Fig. 8(d) shows the protecting characteristics to ground fault level when a one-line ground fault occurs at the receiving end of feeder F2. The ground fault level is decided by ground fault resistance. The dead ground fault is expressed as 100%. The TGCL can detect fault occurrence and can judge internal and external faults from 100% to 1% of the ground fault level. At less than 10% of the ground fault level, the computed compensation level of the TGCL controller is smaller than the minimum value 9A of the changing tap, so the TGCL compensating reactor has been kept the initial compensation level of 6.0A. This result indicates that the TGCL has a effective limiting function for large ground fault currents.

As mentioned above, the protecting characteristics of the TGCL are confirmed by simulation analysis considering various fault conditions. In this method, the charging current (several amperes) of the capacitance to ground of the fault line remains uncompensated. The advantage of the TGCL is that there is little effect on the setting of present DGs.

5 . CONCLUSION

In this paper, the protecting characteristics of the thyristor controlled ground fault current limiting system (TGCL) were estimated by simulation analysis considering various fault conditions, i.e. fault locations, fault voltage phases and fault levels. Results showed that the TGCL had a good protecting potential in all conditions. Control was ensured by an in-phase control method for zero-phase sequence voltage and current. The TGCL would detect and reduce the one-line ground fault current to below 20A within 50ms after a fault occurrence. The advantage of the TGCL was that there was little effect on the setting of present DGs. These findings indicated that the TGCL would be a valuable protection system for high ground fault current distribution systems.

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