Fault Current Waveform Analysis of a Flux-Lock Type SFCL According to LC Resonance Condition of Third Winding

Sung-Hun Lim†

Abstract – The flux-lock type superconducting fault current limiter (SFCL) can apply the magnetic field into the high-T_C superconducting (HTSC) element by adopting the magnetic field coil in its third winding. To apply the magnetic field into the HTSC element effectively, the capacitor for LC resonance is connected in series with the magnetic field coil. However, the current waveform of third winding for the application of the magnetic field is affected by the LC resonance condition for the frequency of the source voltage and can affect the waveform of the limited fault current. In this paper, the current waveform of the third winding in the flux-lock type SFCL according to LC resonance condition during a fault period was analyzed. From the differential equation for its electrical circuit, the current equation of the third winding was derived and described with the natural frequency and the damping ratio as design parameters. Through the analysis according to the design parameters of the third winding, the waveform of the limited fault current was confirmed to be influenced by the current waveform of the third winding and the design condition for the stable fault current limiting operation of this SFCL was obtained.

Keywords: Fault Current Limiter (SFCL), Fault Current Limiting Operation, Flux-lock Type Superconducting, High-T_C Superconducting (HTSC) Element, LC Resonance.

1. Introduction

The rise in the demand for electric power has increased the short-circuit current of the electric power system and has surpassed the available cut-off ratings of the existing circuit breaker. The continuous efforts to suppress the increase of the short-circuit current have resulted in the development of various types of superconducting fault current limiters (SFCL) in many countries [1-3]. Among the developed SFCLs, the flux-lock type SFCL, one of the SFCLs using magnetic coupling between two coils, has been reported to have several merits [4-7]. The merit of the flux-lock type SFCL is that the current limiting capacity of the SFCL and the normal resistance of the high-TC superconducting (HTSC) element can be adjusted higher or lower than that of the resistive type SFCL operated with the HTSC element alone [7].

In addition, the normal resistance of the flux-lock type SFCL can be increased through the application of the magnetic field into the HTSC element by adopting the magnetic field coil in its third winding. To apply the magnetic field effectively into the HTSC element, the capacitor for LC resonance is connected in series with the solenoid type magnetic field coil [4-5].

However, the current waveform in the third winding during the fault period is affected by the LC resonance condition between the capacitor and the inductance of the magnetic field coil for the frequency of the source voltage, and it affects the waveform of the limited fault current in the flux-lock type SFCL.

In this paper, the current waveform of the third winding in the flux-lock type SFCL according to the third winding of the LC resonance condition was investigated. Through the analysis for the current equation of the third winding, which was derived from the electrical equivalent circuit, the design conditions for the stable fault current limiting operation of the flux-lock type SFCL were derived and its effectiveness was confirmed from its fault current limiting experiments.

2. Analysis of Third Winding's Current due to Circuit Condition

The structure of the flux-lock type SFCL using the magnetic field coil in its third winding is shown in Fig. 1. The detailed operational principle is described in Ref. [4-7]. To make the magnetic field application into the HTSC element more effective, during the fault period, the capacitor (Cr) is connected in series with the magnetic field coil (Lr) [4-5]. Immediately after the magnetic field within the iron core is generated at the fault occurrence, the voltage of the third winding including the primary and the

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secondary windings is induced and thus, the current flows into the third winding for the application of the magnetic field. However, the current waveform of the third winding is dependent on the LC resonance condition between the magnetic field coil and the series capacitor.

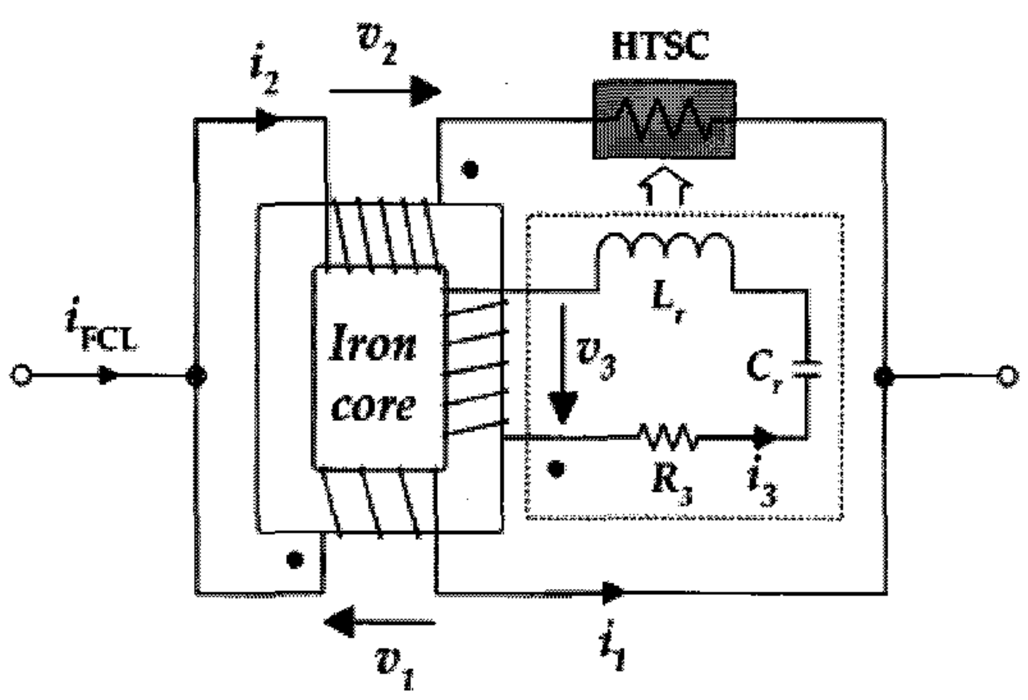

Fig. 1. Schematic configuration of the flux-lock type SFCL using magnetic field coil in the third winding.

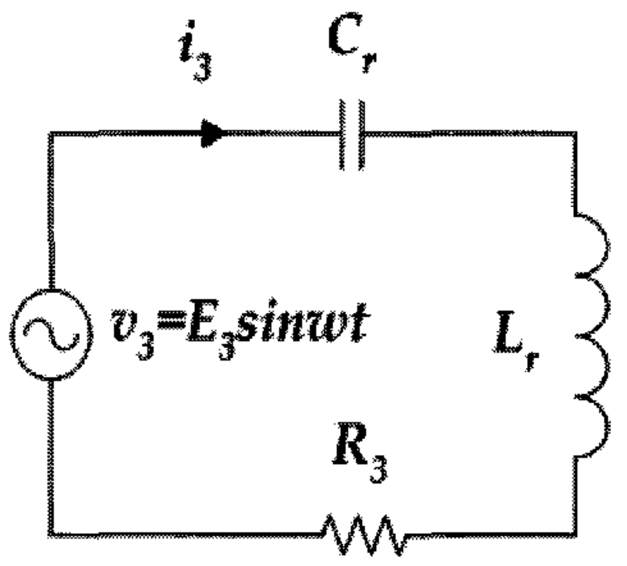

Fig. 2. Equivalent circuit of the third winding part in the flux-lock type SFCL.

To investigate its dependence on the LC resonance condition, the current of the third winding can be derived from the equivalent circuit of the third winding part in the flux-lock type SFCL shown in Fig. 2. From its equivalent circuit, the circuit equation to derive the current of the third winding can be drawn as follows:

$$\frac{\omega E_3 \cos\omega t}{L_r} = \frac{d^2 i_3(t)}{dt^2} + 2\varsigma\omega_n \frac{di_3(t)}{dt} + \omega_n{}^2 i_3(t) \tag{1}$$

where ω is the angular frequency of the source voltage. The natural frequency (ω_n) and the damping ratio (ς) in Equation (1), which are the primary design parameters to determine the current waveform of the third winding during the fault time, are defined as Equation (2).

$$\omega_n = (L_r C_r)^{-0.5}, \qquad \varsigma = 0.5 R_3 (C_r / L_r)^{0.5} \tag{2}$$

From the differential Equation (1), the current of the third winding, which is divided into the transient component (i_h(t)) and the steady state component (i_p(t)), can be derived as expressed in Equation (3).

$$i_3(t) = i_p(t) + i_h(t) \tag{3}$$

where

$$i_p(t) = \frac{\omega E_3}{L_r} \frac{(\omega_n{}^2 - \omega^2)\cos\omega t + (2\varsigma\omega_n\omega)\sin\omega t}{(\omega_n{}^2 - \omega^2)^2 + (2\varsigma\omega_n\omega)^2}$$

$$i_h(t) = e^{-\varsigma\omega_n t}\left(Ae^{\omega_n\sqrt{\varsigma^2-1}t} + Be^{-\omega_n\sqrt{\varsigma^2-1}t}\right)$$

where A and B represent the arbitrary constants, which can be determined from the initial circuit condition. From Equation (1), the current of the third winding during the fault period can oscillate either with attenuation or with non-attenuation in its amplitude, which is determined from whether the damping ratio has a positive value or zero value. If the damping ratio is positive, the transient component in the current of the third winding attenuates and the steady state component only remains as the fault period passes as seen in Equation (3).

If the damping ratio is zero, on the other hand, the transient component in the current of the third winding no longer attenuates and can make the resonance or the beats, which affects the fault current's waveform of the flux-lock type SFCL. Assuming that the natural frequency of the circuit has the same value as the angular frequency of the source voltage, the current of the third winding can resonate and can be approximated as follows:

$$i_3(t) \approx \frac{\omega E_3}{2L_r\omega_n} t \sin\omega_n t \tag{4}$$

As seen in Equation (4), the current of the third winding increases continuously as the fault time passes, and this causes the fault current of the flux-lock type SFCL to increase gradually.

If the natural frequency of the circuit has a value different from the angular frequency of the source voltage, the current of the third winding can make beats and can be drawn as follows:

$$i_3(t) = \frac{2\omega E_3}{L_r(\omega_n{}^2 - \omega^2)} \sin\left(\frac{\omega_n + \omega}{2}\right)t \cdot \sin\left(\frac{\omega_n - \omega}{2}\right)t \tag{5}$$

From Equation (5), the current of the third winding is confirmed to oscillate with two angular frequencies.

3. Simulation and Experiment Results

3.1 Simulation results

The simulation for the analysis of the third winding's

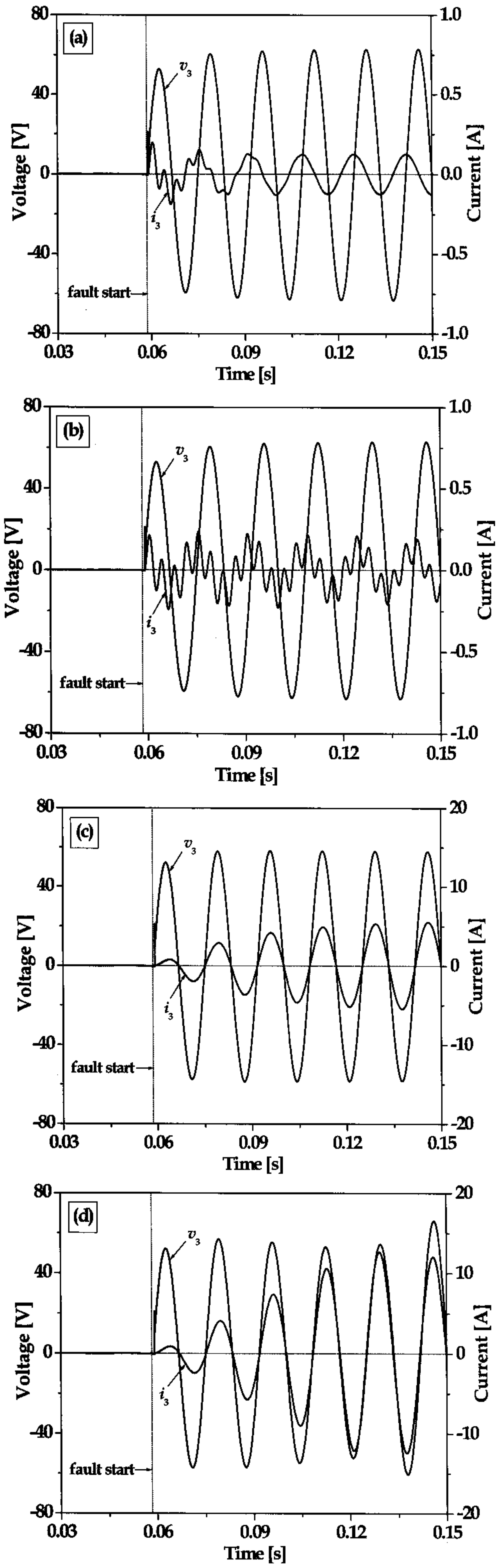

Fig. 3. Simulated current and voltage waveforms of the third winding according to the circuit design parameters. (a) ς=0.042, ω_n=1678.4 (L_r=71 mH, C_r =5 uF, R_3=10Ω). (b) $\varsigma \approx 0$, ω_n=1678.4 (L_r=71 mH, C_r=5 uF, R_3=1uΩ). (c) ς=0.094, ω_n=375.3 (L_r =142 mH, C_r=50 uF, R_3=10Ω). (d) $\varsigma \approx 0$, ω_n=375.3 (L_r=142 mH, C_r=50 uF, R_3=1uΩ).

current due to the circuit design parameters was executed using the PSPICE program. Fig. 3 shows the simulated current and voltage waveforms of the third winding according to the damping ratio and the natural frequency. The damping ratio for the analysis was selected with both positive value and zero value. The natural frequency, another circuit design parameter, was chosen as two values: one is 375.3, similar to the angular frequency of the source voltage (377) and the other is 1678.4, different from the angular frequency of the source voltage.

As seen in Figs. 3(a) and 3(c), in case that the damping ratio is the positive value, the transient component of the third winding's current, which appears at the initial fault time, gradually decreases as the fault time passes and thus, only its steady state component remains. The simulated results in this design condition are consistent with the analyzed ones in Equation (3). From Figs. 3(b) and 3(d) in which the damping ratio is close to zero, it can be observed that the current waveform of the third winding either oscillates with two angular frequencies (Fig. 3(b)) or increases with the oscillation of the non-attenuation (Fig. 3(d)). These simulated results can be confirmed to agree with the expressions of Equations (4) and (5).

3.2 Experiment results

To apply more effective magnetic field into the HTSC element, the current generated in the third winding during the fault period should increase sufficiently and be synchronized with the secondary current of the flux-lock type SFCL. Therefore, as analyzed in the simulation, if the natural frequency is designed to be a similar value to the angular frequency of the source voltage, the current of the third winding can be synchronized with the secondary current and therefore increased. Fig. 4 reveals the experimental current and voltage waveforms of the third winding in case that the natural frequency is close to the angular frequency of the source voltage. As seen in Fig. 4, the damping ratio can be observed to determine the transient component of the third winding's current. Like Fig. 4(a), if the damping ratio is designed to be higher than zero, the transient component of the current in the third winding gradually decreases and disappears. This design condition allows the current of the third winding to approach the constant value, which corresponds to its steady state component and leads to the stable operation of the SFCL. On the other hand, if the damping ratio is designed to be close to zero value as seen in Fig. 4(b), the continuous increase in the current of the third winding occurs, which is called resonance.

The current limiting waveforms of the flux-lock type SFCL dependent on the damping ratio are shown in Fig. 5 in case that the natural frequency is designed to be close to

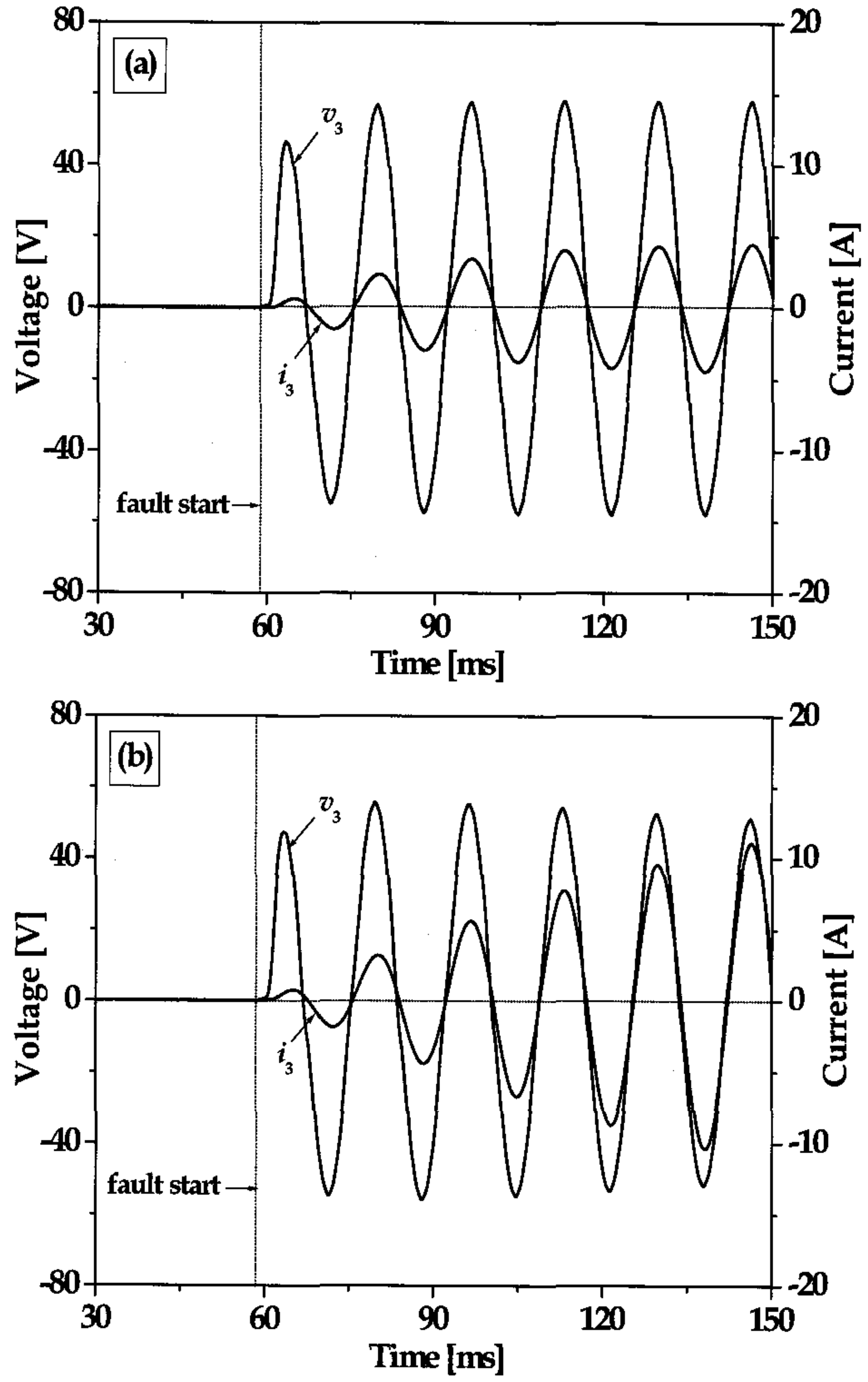

Fig. 4. Experimental current and voltage waveforms of the third winding in case that the natural frequency is designed to be close to the angular frequency of the source voltage. (a) ς = 0.1053, ω_n=366.4 (L_r = 149 mH, C_r = 50 uF, R_3 = 11.5 Ω). (b) ς = 0.0137, ω_n=366.4 (L_r = 149 mH, C_r = 50 uF, R_3 = 1.5 Ω).

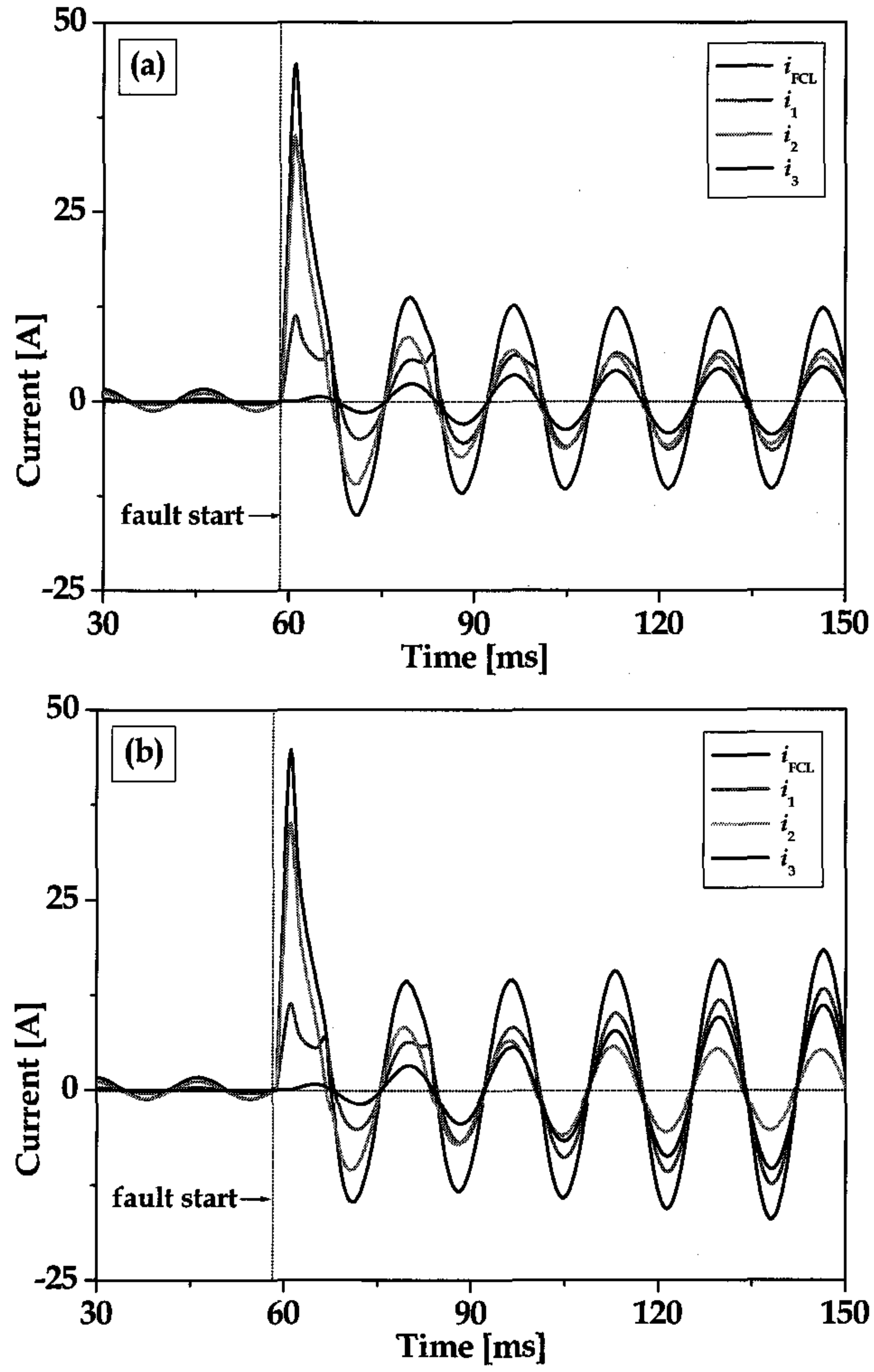

Fig. 5. Experimental current limiting waveforms of the flux-lock type SFCL in case that the natural frequency is designed to be close to the angular frequency of the source voltage. (a) ς = 0.1053, ω_n=366.4 (L_r = 149 mH, C_r = 50 uF, R_3 = 11.5 Ω). (b) ς = 0.0137, ω_n=366.4 (L_r = 149 mH, C_r = 50 uF, R_3 = 1.5 Ω).

the angular frequency of the source voltage. As expected in Fig. 4, the stable current limiting operation can be seen in Fig. 5(a) where the damping ratio is chosen to be higher than zero value. Conversely, in Fig. 5(b) where the damping ratio is designed to be closer to zero value than that in Fig. 5(a), the limited fault current is seen to increase continuously.

4. Conclusions

In this paper, the current waveform of the third winding in the flux-lock type SFCL according to the LC resonance condition of third winding during a fault period was analyzed. The current equation of third winding, which was derived from the differential equation for its electrical circuit, was expressed with the natural frequency and the damping ratio as design parameters. Through the computer simulated analysis according to the damping ratio, the current waveform of the third winding was confirmed to oscillate with attenuation or with non-attenuation in its amplitude. Especially, if the damping ratio was designed to be close to zero value, the current of the third winding was shown to resonate or make beats according to whether the natural frequency had the similar value to the angular frequency of the source voltage or not. It was confirmed from its fault current limiting experiments that the current waveform of the third winding as well as the limited fault current waveform of the SFCL was affected by the damping ratio and the natural frequency and that the designed condition for the stable fault current limiting operation of the SFCL was valid.

Acknowledgements

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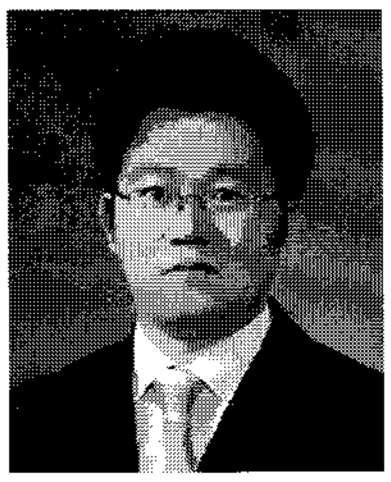

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