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Analyses Of the Active Superconducting Fault Current Limiter Simulations and Experimental

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ABSTRACT: In this paper the operation principle of a new type of active superconducting fault current limiter (SFCL) is given. The SFCL consist of an air-core superconducting transformer, a PWM converter and a superconducting magnet. The air-core superconducting transformer primary winding is in series with AC main circuit, and the second winding is connected with the superconducting magnet all the way through a PWM converter. In normal (no fault) operation state, the flux in air core is compensated to zero, so the SFCL has no influence on main circuit. In the case of short circuit, by controlling the amplitude and phase angle of the second winding's current, the limiting impedance which is in series with the AC main circuit can be regulated and the fault current will be limited to a certain level. Using SIMULINK, the simplified model of the active SFCL is created, and simulations validate this SFCL can suppress the fault current efficiently. Also the current-limiting experiment is done with a small conventional transformer. Experimental results are similar as that of simulation results.

KEYWORDS: Active superconducting fault current limiter, PWM converter, Controllable current source, Fault current.

I.INTRODUCTION

Nowadays demand of electrical power increases day by day hence need of power transmission also increasing, due to this increase in transmission demands with the existing circuit breakers there may be possibility that their cut-off ratings can be exceeded by the fault current any times. This increase of the fault current has forced a severe burden on the related machinery in the power system grid, and due to this the stability of power system is also damaged. Application of the FCL [1] in electric power system can suppress the amplitude of the short circuit current as well as improve the stability of power system. In actual, the FCL is basically variable impedance which is in series with a circuit breaker. At the time of short circuit, the impedance of FCL rises to a value where the fault current is correspondingly reduced to a lower level, at which the circuit breaker can handle easily. Many kinds of fault current limiters have been developed in accordance with the development of power electronics techniques, magnetic technologies and superconducting materials [2–5]. Superconducting fault current limiters having features like compactness and low cost have been expected as new power devices for the future electric network. A new type active SFCL is presented here, which can be used in the AC power system as well as in the DC power system. It is an widespread concept for active DC-SFCL [6,7]. The operating principle of SFCL is similar to that of fault current limiter based on flux compensation [8]. In addition, this paper introduces the new concept that controlling the amplitude as well as the phase of the second winding's current, which can finally increase the limiting capacity of SFCL. The circuit arrangement and operation principle of the SFCL have been introduced. Simulations and experimental results can confirm that this type of FCL is well suited for power system.

II. THEORETICAL ANALYSES

2.1. The circuit structure and operation principle

The circuit arrangement of the active SFCL is as shown in Fig. 1, which is consist of an air-core superconducting transformer, a PWM converter and a superconducting magnet. The primary winding of the air-core superconducting transformer is connected in series with AC main circuit, and the second winding is connected with the superconducting magnet through a PWM converter. The air-core superconducting transformer has some advantages such as zero iron losses and no magnetic saturation takes place. In air cored transformer greater possibility of reduction in size and weight than the conventional and the iron-core superconducting transformer [9]. The current in AC main circuit (I_1), the second winding's current (I_2), and the mains voltage (U_s) will be detected in real time. According to the amplitude of

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the detected current, normal or fault state can be determined. Once detecting the fault, let DSP be the core of control circuit and control the PWM converter which will respond within five milliseconds to change the amplitude and phase angle of I_2. In normal (no fault)operating state, the converter works as a rectifier and the energy transfers from the AC side to the DC side, hence the superconducting magnet is get charged.

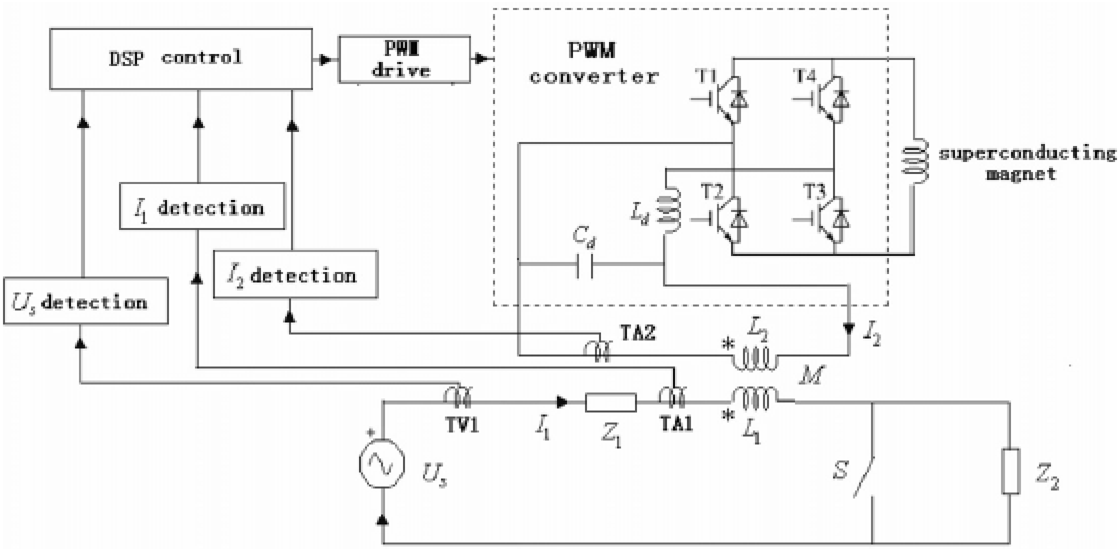

Fig.1: circuit arrangement of the active SFCL

Where U_s: AC voltage source
Z_1 : Circuit impedance
Z_2 : Load impedance
L_1, L_2: Self inductance of two windings
M: Mutual inductance of two windings

The second winding's current will up to a certain value where the flux in air-core is compensated to zero, and the SFCL has no effect on the main circuit. In the case of short circuit, the limiting impedance which is in series with the AC main circuit can be regulated by changing the magnitude and phase angle of I_2, and in this way the fault current will be suppressed. From the viewpoint of energy transferring, now the converter acts as an inverter and the superconducting magnet provides energy to the AC side. As the voltage of the primary winding will increase accordingly, which can compensate the fall of the voltage induced by short circuit. Superconducting magnet which is used for storing as well as providing energy. This superconducting magnet having advantages like low losses, high energy conversion efficiency and rapid response speed, as a result of this increasing the working efficiency of the SFCL. In addition, the losses of this type SFCL come from three parts: superconducting transformer, superconducting magnet, and power transistors. The implementation of superconductors is favourable for reducing losses.

2.2. The equivalent circuit
By neglecting losses of the air-core superconducting transformer, the voltage equation of the transformer is expressed as follows:

$$\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \end{bmatrix} = j\omega \begin{bmatrix} L1 & M \\ M & L2 \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ -\dot{I}_2 \end{bmatrix} \quad \text{--- (1)}$$

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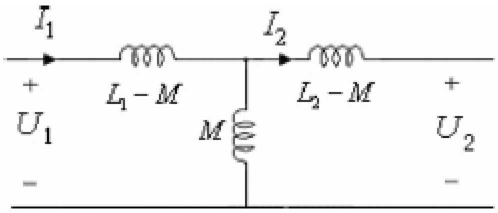

Fig.2: The equivalent circuit of the air-core superconducting transformer.

From Eq. no. (1), the equivalent circuit of the air-cored superconducting transformer is shown as in Fig. 2.The PWM converter's capacity of controlling power exchange is done by regulating its AC side line current. Basically, the PWM converter which is connected with the superconducting coil can be considered as a controllable current source [7]. The equivalent circuit of the active SFCL is shown in Fig. 3. In normal operation state, Eq. no. (2) can be derived from Fig. 3.

$$\dot{U}_s = \dot{I}_1(Z_1+Z_2)+ j\omega\, \dot{I}_1 L_1 - j\omega M \dot{I}_b \text{ ---- (2)}$$

Let $j\omega\, \dot{I}_1 L1 - j\omega M \dot{I}_b = 0$, and the limiting impedance is zero. The original state of the controllable current source $\dot{I}_b$ should be set at Eq.no. (3).

$$\dot{I}_b = \dot{I}_1 L1/M = \frac{\dot{U}_S\, L1}{((Z1+Z2))M} \qquad \text{---- (3)}$$

In the case of short circuit, the current in AC main circuit will rise from $\dot{I}_1$ to $\acute{I}_1$. Replacing $\acute{I}_1$ to $\dot{I}_1$ in Eq.no. (2), and $\acute{I}_1$ can be expressed as Eq.no. (4).

$$\acute{I}_1 = \frac{\dot{U}_S + j\omega M \dot{I}_b}{Z1 + j\omega L1} \qquad \text{---- (4)}$$

Eq.no. (4) points that controlling $\dot{I}_b$ can regulate $\acute{I}_1$. There are three modes of controlling $\dot{I}_b$. Mode 1: Make $\dot{I}_b$ remain the original state. According to the Eqs.no. (3), (4), and Eq.no. (5) can be achieved.

$$\acute{I}_1 = \frac{\dot{U}_S}{Z1 + j\omega L1(1 - {}^{\dot{I}_1}/_{\acute{I}_1})} \qquad \text{---- (5)}$$

From Eq.no. (5), the limiting impedance is shown as $Z_L = j\omega L1(1 - {}^{\acute{I}_1}/_{\dot{I}_1})$

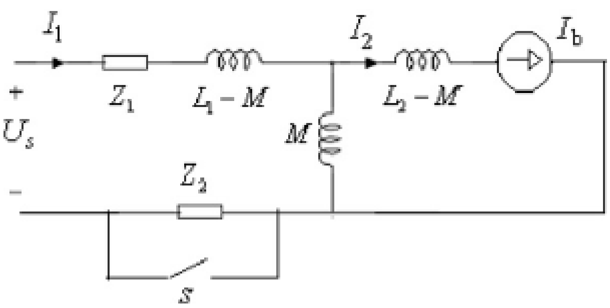

Fig.3: Active SFCL equivalent circuit

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Mode 2: Control the amplitude of $\dot{I}_b$ to zero. The fault current can be written as Eq.no. (6). At this time the limiting impedance can be shown as Z_L=jωL1. As $(1-\acute{I}_1/\dot{I}_1)$< 1, the complex value of limiting impedance in mode 2 is greater than that of mode 1, as a result of the improved limiting effect.

$$\acute{I}_1 = \frac{\dot{U}_S}{Z1+j\omega L1} \qquad \text{---- (6)}$$

Mode 3: Regulate the phase angle of $\dot{I}_b$ to make the phase angle of $j\omega M\dot{I}_b$ lead AC voltage source $\dot{U}_S$180°. According to Eq.no (4), reactance ωL_1 and an inverse voltage with amplitude of $|j\omega M\dot{I}_b|$ is in series with AC main circuit. In this mode, the limiting effect is the best of the three. The equivalent limiting impedance is shown as

$$Z_L = j\omega L1 - \frac{j\omega M\dot{I}_b}{\acute{I}_1}$$

III.MATLAB SIMULATIONS

To calculate the usefulness of this SFCL, the model as shown in Fig. 3 is created in MATLAB. The simulation parameters of the circuit diagram are expressed as: L_1=L_2= 20 mH, M = 19.6 mH, Z1 = (0.19 + 2.16j) Ω, Z2 = 15 + 2j Ω, f = 50 Hz, U_s = 220sinωt V. In this model, an ideal air core transformer is used and the magnetic coupling factor K=M/ $\sqrt{L1L2}$ =0.98. When t = 0.1 s, the switch is closed to simulate the short circuit. According to Eq. (3), the original state of $\dot{I}_b$ can be expressed as

$$\dot{I}_b = \frac{\dot{U}_S\, L1}{(Z1+Z2)M} = 14{:}25 \angle 15{:}3^{o}\text{A}$$

In mode 1, the fault current characteristics waveform is as shown in Fig. 4. Compared with the peak amplitude 175 A without SFCL, it can be limited to 53.5 A after installation of SFCL. The decrease of the expected fault current is 121.5 A.

In mode 2, control $\dot{I}_b$=0 and the peak amplitude of the fault current can be limited to 49.2 A. The reduction of the expected fault current is 125.8 A.

In mode 3, the phase angle of $\dot{I}_b$ leads $\dot{U}_S$ 90°is needed. Regulate $\dot{I}_b$=14.25 ∟90° A, and the peak amplitude can be limited to 38.9 A. So the reduction of the expected fault current is 136.1 A.

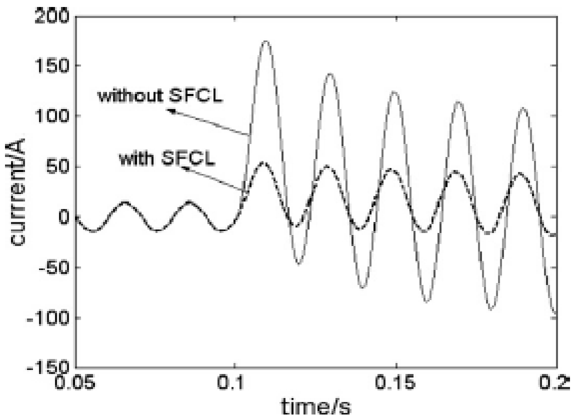

Fig.4: The fault current characteristics waveform (mode 1).

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The comparison of the fault current characteristics in these three modes is shown as follow. In Fig. 5, we can find mode 2 is finer to mode 1. Mode 3, which is based on regulating the phase angle, therefore mode 2 shows the best effect of suppressing fault current.

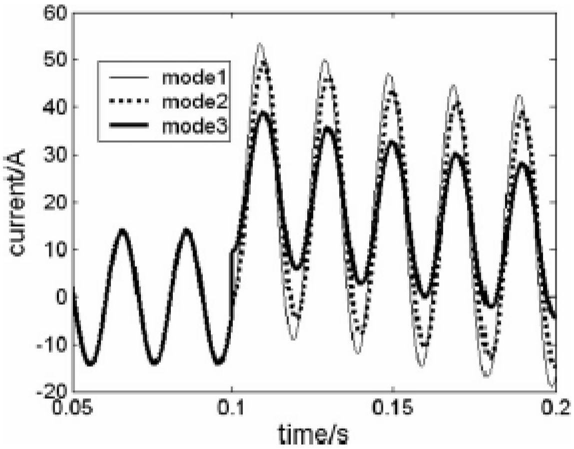

Fig. 5: The fault current characteristics comparison in all three modes.

In addition, in mode 3 the limiting capacity can also be controlled by changing the amplitude of current $\dot{I}_b$. Fig. 6 shows the fault current characteristics comparison under the different amplitudes. When $\dot{I}_b$=6 ∟90^{o}A, 14.25∟90^{o}A and 20∟90^{o}A, the peak amplitude of the fault current will respectively be limited to 44.5 A, 38.9 A and 34.7 A, thus correspondingly the reduction of the expected fault current is 130.5 A, 136.1 A, 140.3 A. Hence it is clear that the higher amplitude level of $\dot{I}_b$, the better limiting effect.

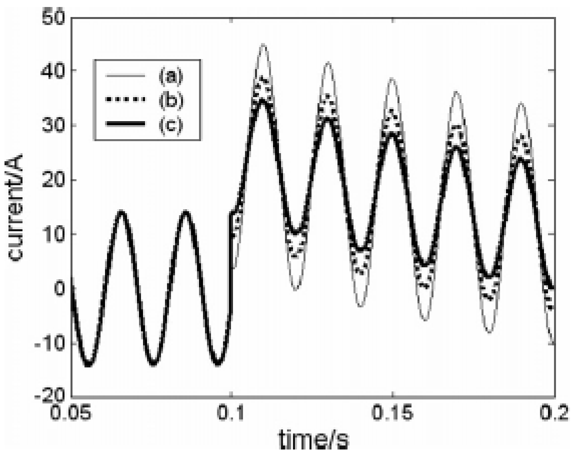

Fig.6: The fault current characteristics comparison under different amplitude

The relationship between the peak amplitude of the fault current and the amplitude of $\dot{I}_b$ is shown in Fig. 7 and the relationship between the peak amplitude of the fault current and the phase of $\dot{I}_b$ (amplitude is constant) is shown in Fig. 8. This waveform is an approximate sinusoidal wave, and when the phase of $\dot{I}_b$is 90^o, this is the best limiting effect. Besides, three points, which response to model 1, 2,3, can also be found in Fig. 8

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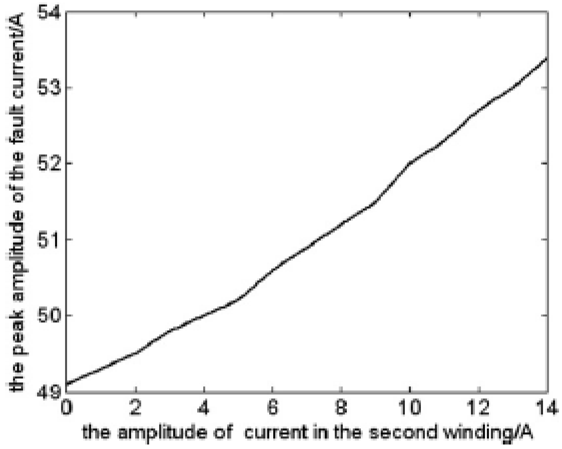

Fig. 7: The relationship between the peak amplitude of the fault current and the amplitude of I_b when the phase is constant.

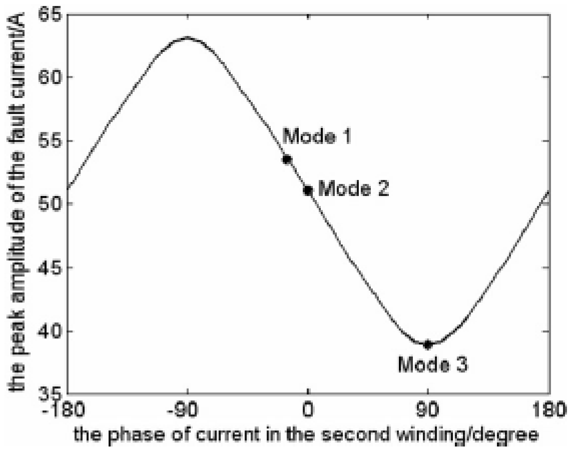

Fig. 8: The relationship between the peak amplitude of the fault current and the amplitude of I_b when the amplitude is constant.

The asymmetries in the waveforms of current of Figs. 4 to 6 can be found, which is due to the presence of natural response. Natural response is an exponential decay DC wave and one component of the fault current. It is due to the initial energy stored in the circuit and the physical characteristics of the circuit, but not concerned with some external voltage or current source. The asymmetries cannot be avoided unless the AC circuit represents pure resistive characteristic after fault happening, at this time natural response is zero and the fault current waveform will be symmetrical. In power system the fault current is asymmetric usually. As the fault would be eliminated quickly, the asymmetric current basically does not effect on the quality of power delivery. It is impossible to remove the asymmetric current only depending on the SFCL. However, by increasing the resistive component of limiting impedance, the natural response will decay more faster.

IV. EXPERIMENTAL RESEARCH

To verify the limiting effect of the SFCL, at first step, the experiment is carried out with a conventional transformer. Fig. 9 shows the experimental circuit of FCL and device parameters. Two voltage sources of equal phase have been used to compensating the flux in the iron core to zero in normal operation state.

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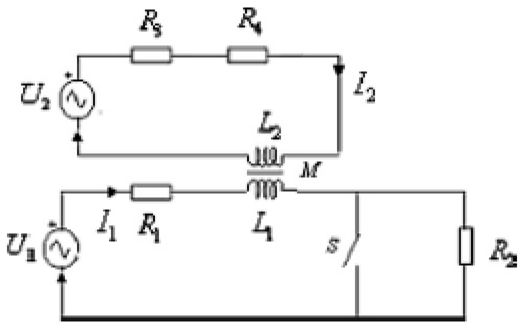

Fig.9: Experimental circuit of the FCL. L_1 = 5.98 mH; L_2 =5.92 mH; M = 5.87 mH; $R_1 = R_3$ = 0.6 Ω; $R_2 = R_4$ = 0.8 Ω; $|\dot{U}_1|=|\dot{U}_2|$=25V.

The fault current characteristics waveform is as shown in Fig. 10. The current can be limited to 25.4 A, as compared to 40 A without FCL. The reduction of the expected fault current is 14.6 A.

At the time of fault, the voltage of the primary winding will increase, which cause effect with the current in the secondary winding. Fig. 11 shows the characteristics of current of seconding winding according to: (a) normal state, (b) fault state. So this experiment is equal to evaluate the mode: when the fault happens, the amplitude of $\dot{I}_2$ is regulated to be higher with the phase angle constant.

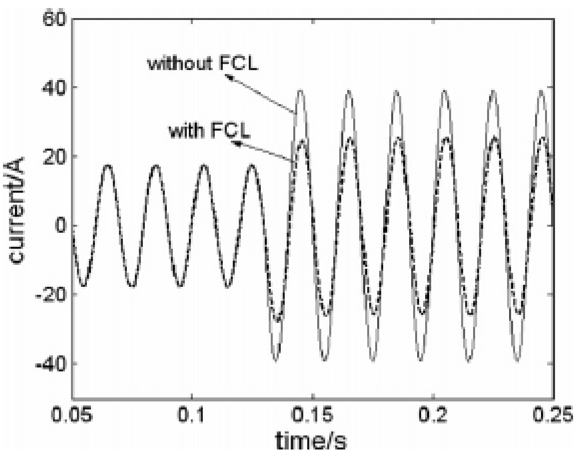

Fig.10: Fault current characteristics waveforms.

Fig. 12 shows primary winding voltage characteristics. Because of the errors in resistance between four resistors and the voltage disturbances, the flux can not completely compensated to zero, which may have some effect on the original state of the AC circuit. However, from the observation of the current characteristics this effect is small enough so that it can be neglected.

Based on above all analyses, it is evident this FCL can limit the fault current rapidly and efficiently. The next step for the experimental research is realizing the concept of regulating the phase angle.

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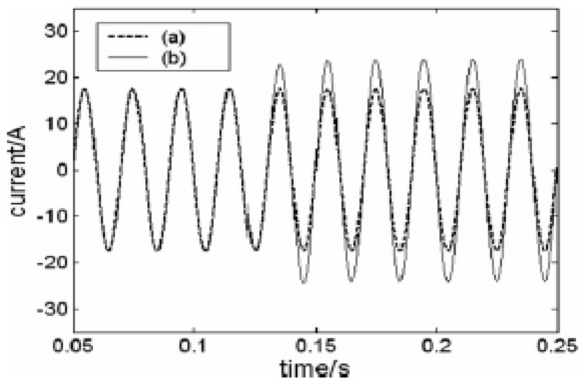

Fig.11: The characteristics of current for the seconding winding according to:(a) normal state and (b) fault state.

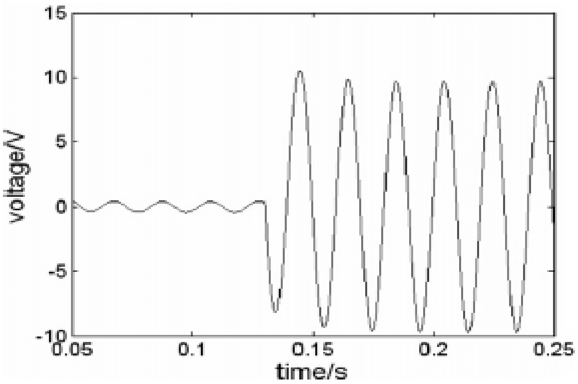

Fig.12: The primary winding voltage characteristics

V. CONCLUSION

In this paper a new active SFCL is presented, and its limiting effect is validated by using simulations. In normal operating state, the SFCL has no influence on main circuit. When short fault happens in the circuit, by regulating the amplitude and phase angle of the current in the second winding, the limiting impedance which is in series with the AC main circuit can be changed, so that the fault current will be controlled to a certain level. In another words, this device is an active impeditive SFCL. The current-limiting experiment is done by using a small conventional transformer, and experimental results are matching well with simulations. However, a lot of problems are needed to be solved, such as the built of real system model, the design of control device, and the analysis of loss. These tasks will be performed in future.

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