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Zero Magnetic Flux Short-circuit Current Limiter Based on Passivity Control

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Abstract

According to the basic principle of zero flux short-circuit current limiter, the control method of the space vector control was applied to the inverter to generate a tracking current which is to compensate the magnetic flux. Based on the theory of passivity control, the energy formation and damping injection method was used into designing the control part. In the environment of MATLAB/SIMULINK, a simulation model was established for short-circuit current limiter and passivity control. Compared with the traditional control method, short-circuit current limiter under passivity control showed a better steady state response.

Keywords: *short-circuit current limiter, flux compensating, passivity control, current tracking, SVPWM*

1. Introduction

With the development of power systems, electrical network structure becomes more and more complex; users of electric power quality and reliability of supply security requirements are increasing. But with the constant expansion of the power system, distributed power increases, making the short circuit current levels greatly increased. When a short-circuit fault on the circuit breaker of the capacity requirements greatly increased, while for the transmission lines and power systems also have a great impact on the secondary device. To protect the power system equipment, reducing the circuit breaker capacity, the need to limit the short circuit current level within a certain range.

Short-circuit current limiter (Fault Current Limiter-FCL) is one of the most important devices in modern power system. Under the normal load conditions, the protection of the FCL presents a low impedance, however, when short circuit occurs, the protection of the FCL action will be showing a large impedance to limit the short circuit current. It has the following advantages: (1) Reduce the direct breaking load of the circuit breaker. (2) Reduce the line voltage generator step-loss and the probability of the system angle stability, voltage stability and frequency stability can be effectively improved. (3) Control the rapid and flexible, allowing the action more often, low cost, small size, etc [1-3].

With the development of fault current limiter, there have been appearing various types of short-circuit current limiter including short-circuit current limiter resistor, inductor-type short-circuit current limiter resonant circuit current limiter, the flux and ultra-short-circuit current limiter conductivity-type short-circuit current limiters. As technology continues to mature, as well as the flux-type resonant circuit current limiter in the power system has been widely used.

In this paper, the short circuit current limiter zero flux passivity proposed control methods, which is based on the short circuit current limiting flux limiter. And through the simulation, compared with hysteresis control and PI control, the results show that the control can be obtained through passivity good response effect.

2. Basic Principle of FCL

2.1. Working Principle of Zero Magnetic Flux Short-circuit Current Limiter

Short-circuit current [4] limiter based on zero flux is the primary side of transformer is connected to system。T type equivalent model of transformer as shown in Figure 1.

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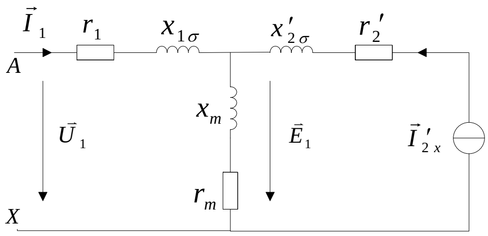

Figure 1. The T Type Equivalent Circuit of the Transformer

When the system work, into the secondary side current and the current at the primary side of the reverse side of the secondary side of the transformer, the secondary side current generated magnetic field will be produced with the primary side current magnetic field offset, If it meet the conditions of $F = \omega_1 \dot{I}_1 + \omega_2 \dot{I}_{2x} = 0$ [4, 5], then the magnetic field will compensate for the 0, and the transformer impedance in access system only for the transformer primary side impedance. Equivalent model of transformer as shown in Figure 2:

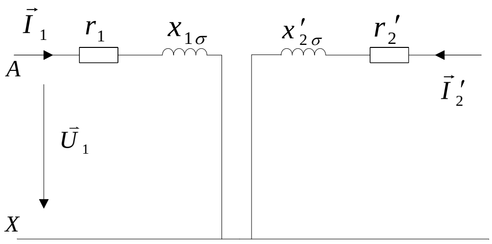

Figure 2. The Equivalent Circuit of the Compensating Transformer

As the series into the system primary side of transformer impedance is small, there is no influence in the normal operation of the system.

When the system occur short circuit fault, cutting off the secondary side compensation current of transformer, stopping the magnetic flux compensation, the access to the impedance of transformer in power network as the primary side excitation impedance and impedance. Equivalent model of transformer as shown in Figure 3:

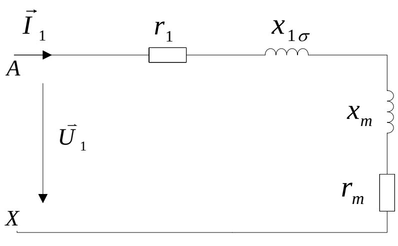

Figure 3. The Equivalent Circuit of the No Compensating Transformer

2.2. The Model of Short Circuit Current Limiter Working Circuit

Using space vector control technology control inverter producing the current which can track current phase of the transformer primary side, the relationship between the amplitude and the amplitude of the primary side current for $k\dot{I}_{2x} = -\dot{I}_1$, k is the ratio of transformer, meeting the conditions of $F = \omega_1 \dot{I}_1 + \omega_2 \dot{I}_{2x} = 0$ can change the magnetic flux compensation transformer to zero. Circuit topology as shown in Figure 4:

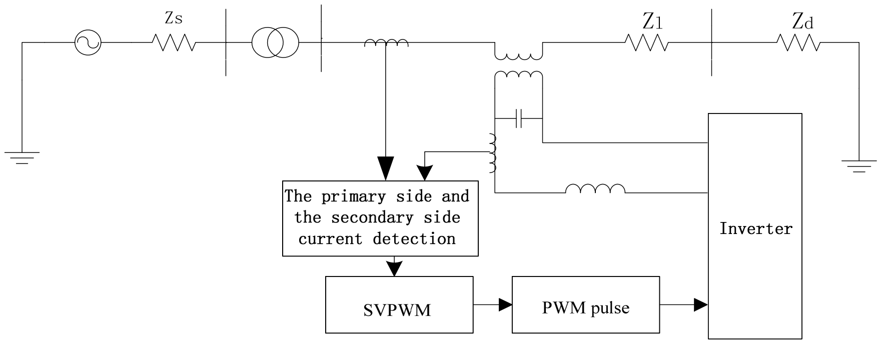

Figure 4. The Topological Graph of the FCL

Taking Single-phase as an example, sampling value tracking current will be the primary side current transformer system current and transformer secondary side current generated by the inverter, processing it into SVPWM Signal instructions, it produces PWM pulse to control inverter working.

3. The Design of Control method

3.1. Zero Flux of Short Circuit Current Limiter Mathematical Model

Zero flux current limiter circuit generates the tracking current from the inverter circuit, take the inverter as a control target, and the control volume is the current track, which is injected to the secondary side of the transformer secondary side. The topological graph of the inverter is shown in Figure 5 [6-8]:

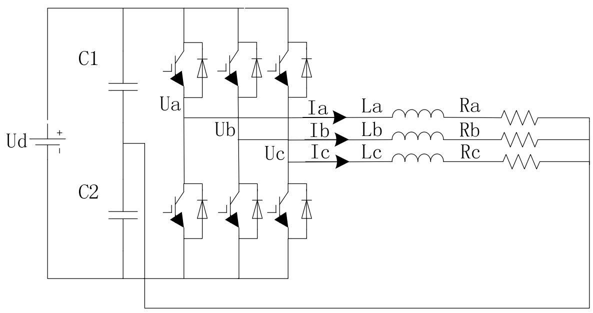

Figure 5. The Topological Graph of the Inverter

According to Figure 5 above, Kirchhoff's current law can be obtained by the following equation of state:

$$\begin{cases} L\dfrac{dI_a}{dt} = -RI_a + U_a \\ L\dfrac{dI_b}{dt} = -RI_b + U_b \\ L\dfrac{dI_c}{dt} = -RI_c + U_c \end{cases} \tag{1}$$

We can get two-phase rotating coordinate system from the transformation the matrix, coordinate the mathematical model of the inverter as formula (2) as follows:

$$\begin{cases} L\dfrac{dI_d}{dt} + RI_d - \omega LI_q - U_d = 0 \\ L\dfrac{dI_q}{dt} + RI_q + \omega LI_d - U_q = 0 \end{cases} \tag{2}$$

ω is the angular velocity of voltage of the system; I_d、I_q are the current component in *d*, *q* axis; U_d、U_q are the voltage component in *d*, *q* axis. *L* is the filter inductance, and *R* is the transformer and inverter equivalent resistance.

3.2. The Traditional Closed Loop PI Control Strategy

The type of three-phase voltage inverter's output loading is used as the secondary side of the short circuit current limiter's transformer, when carries on the magnetic flux compensation, according to the transformer's equivalent circuit shown in Figure 2, the inverter output load equal to the transformer secondary side. Because the secondary side of the transformer impedance value is very small, the R in the formula (2) can be ignored:

$$\begin{cases} U_d = L\dfrac{dI_d}{dt} - \omega LI_q \\ U_q = L\dfrac{dI_q}{dt} + \omega LI_d \end{cases} \tag{3}$$

According to the SVPWM voltage command obtained from the formula (3), we can use the PI regulator controller to obtain a block diagram of the control just as Figure 6 shows:

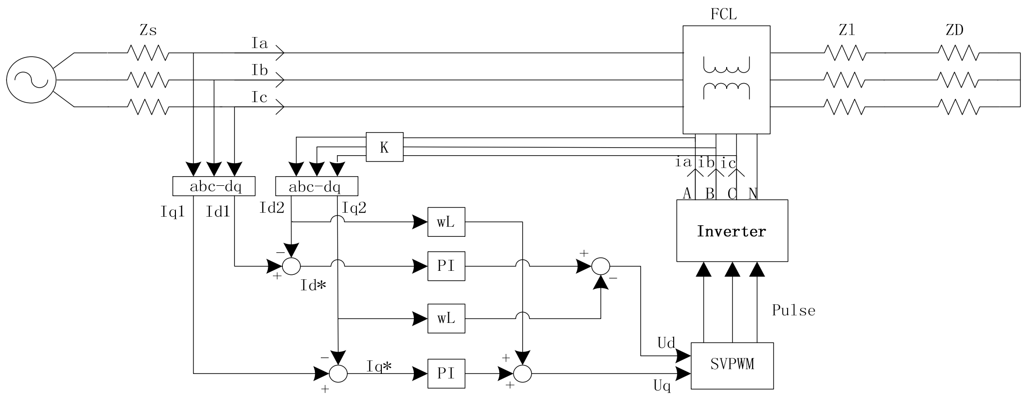

Figure 6. The Control Block Diagram

3.3. Passive Control Strategy

The concept of passive first comes from the network, to deal with the relative order number that equal to or less than 1 rational transfer function that consists of a resistor [9], capacitor and inductor. For a system, if we can define a positive definite function represents the energy, making a value of zero is necessary and sufficient condition for the system of all state variables are zero, and its value is always less than the sum of the external energy input, in that way the system is stable. If the energy of the system is always less than or equal to the initial moment of the system's energy and the energy of the externally supplied, then such a system is passive.

For the zero flux current limiter circuit of the inverter control system, the mathematical model as formula (2).

Passive control is designed as follows [10]:

The formula (2) into Euler-Lagrange system standard model forms:

$$M\dot{x} + Jx + Rx = F \tag{4}$$

In the formula, $x = \begin{bmatrix} I_d & I_q \end{bmatrix}^T$ is the state variable, $M = \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix}$ is the inertia matrix is positive definite, and it satisfy the formula $M = M^T$, $J = \begin{bmatrix} 0 & -\omega L \\ \omega L & 0 \end{bmatrix}$ is the interconnection matrix with skew symmetric properties; $R = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix}$ is the matrix of energy dissipation; $F = \begin{bmatrix} U_d & U_q \end{bmatrix}^T$ is the external voltage source type matrix.

So the total energy function is: $H = \frac{1}{2} x^T M x$.

The total available energy function H derivative:

$$\dot{H} = x^T M\dot{x} = x^T \left(F - Jx - Rx\right) = x^T F - x^T Rx \tag{5}$$

So,

$$H(t) - H(0) + \int_0^t x^T Rx dt = \int_0^t x^T F dt \tag{6}$$

From the (6) we can see that the energy change rate of the system $\left(H(t) - H(0)\right)$ is always less than the rate of change of externally supplied energy sum $\int_0^t x^T F dt$, and the two differences for the dissipation of energy $\int_0^t x^T Rxdt$. So the system is passive.

Passivity control to adjust the use of energy function and dissipation function: (1) To adjust the system energy function, so that in the desired operating point to be tracked on a global and unique minimum. (2) Adjust dissipation function is the system asymptotically stable at the desired operating point.

Define $x^* = \begin{bmatrix} I_d^* & I_q^* \end{bmatrix}$ as expect working point, the error variable is $\hat{x} = x - x^*$, so the error of the system dynamics is:

$$M\dot{\hat{x}} + J\hat{x} + R\hat{x} = F - \left(M\dot{x}^* + Jx^* + Rx^*\right) \tag{7}$$

To the formula (7) is added to make the system asymptotically stable damping matrix to x^* . Thus, the dissipation of the system matrix of the desired is:

$$R_D = R + R_a \tag{8}$$

$R_a = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix}$ is injection of damping matrix. After adding R_a , the new system dynamics for the error is:

$$M\dot{\hat{x}} + J\hat{x} + R_D\hat{x} = F - \left(M\dot{x}^* + Jx^* + Rx^* - R_a\hat{x}\right) = \zeta \tag{9}$$

A new energy function for the system is:

$$H_D = \frac{1}{2}\hat{x}^T M\hat{x} \tag{10}$$

For the new total energy functions H_D available:

$$\dot{H}_D = \hat{x}^T M\dot{\hat{x}} = \hat{x}^T\left(\zeta - J\hat{x} - R_D\hat{x}\right) = \hat{x}^T\zeta - \hat{x}^T R_D\hat{x} \tag{11}$$

Therefore, just let the disturbance quantity $\zeta = 0$, then there must be a specific positive real number γ , making establish. Therefore from Lyapunov stability theorem we can know, formula (12) as shown in the error dynamics is exponentially asymptotically stable (x will converge to x^*).

In order to ensure disturbance quantity $\zeta = 0$, we should satisfy the following formula:

$$\dot{H}_D = -\hat{x}^T R_D\dot{\hat{x}} \le -\gamma H_D < 0 \tag{12}$$

$$M\dot{x}^* + Jx^* + Rx^* - R_a\hat{x} = F \tag{13}$$

By the formula (13) can be controlled passivity SVPWM control instructions are as follows:

$$\begin{cases} U_d = L\dfrac{dI_d^*}{dt} + RI_d^* - \omega LI_q^* + r_1\left(I_d - I_d^*\right) \\ U_q = L\dfrac{dI_q^*}{dt} + RI_q^* + \omega LI_d^* + r_2\left(I_q - I_q^*\right) \end{cases} \tag{14}$$

4. The Simulation Results

Set up zero flux simulation model of short circuit current limiter in MATLAB/SIMULINK environment based on SVPWM, and analysis the simulation [11, 12]. Table 1 shows the simulation parameters of system.

Table 1. Simulation Parameters of System

parameter	data
L	$1\times10^{-4}H$
ω	$50Hz$
Line voltage of the first U	$6.3Kv$
The next level load rated voltage U_D	$6.3Kv$
Active power at the next lower level load P_D	$1.2MW$
line impedance X_L	3Ω

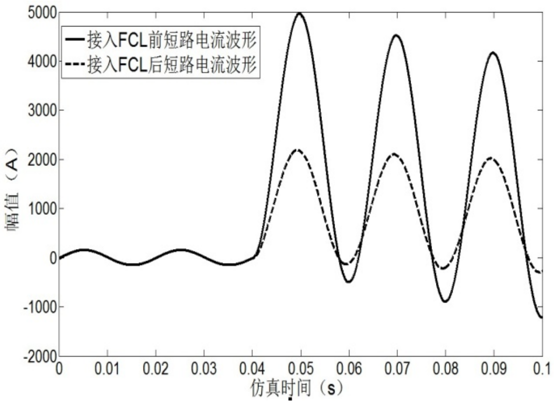

Figure 7. Waveforms of the Short Current

By comparison in Figure 7, we can see the effect of the short circuit current limiter is obviously, short circuit fault occurs in 0.04s, and short circuit current limiters rapid action, the short circuit current is limited to half of the original level of the short circuit current.

In case of failure did not occur, we should control the secondary side of output current to compensate transformer magnetic flux, making the accessing grid impedance is zero, and doesn't affect the normal work. When adopt the conventional PI control strategy, the comparison of the secondary side of the compensation current and the current of the primary side shown in Figure 8, and when we take the passive control strategy, the compared current waveform is shown in Figure 9.

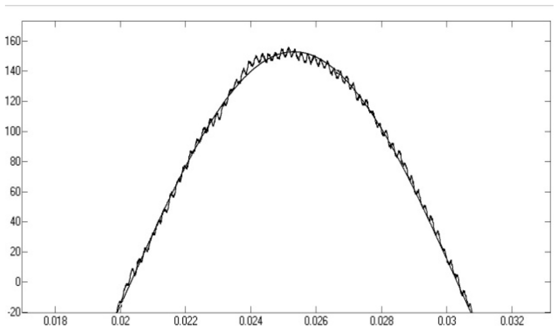

Figure 8. Waveforms of the Tracking Current Based on PI Control

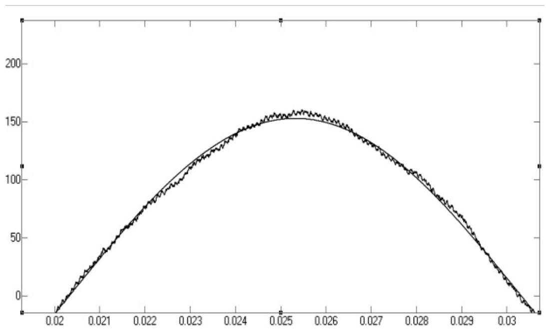

Figure 9. Waveforms of the Tracking Current Based on Passivity Control

Contrast Figure 8 and Figure 9, we can see that compared with the conventional PI control strategy, the current tracking error of the passive control strategy is smaller, the compensation effect is more excellent, so that the access to the system impedance decreases, the impact to the system and the loss of the short-circuit current limiter is smaller too.

5. Conclusion

The proposed zero flux of short circuit current limiter effect is obvious. The compensation for the magnetic flux is controlled by the two different control methods. When take the conventional PI control strategy, the current tracking error is large, resulting in greater impedance access system, and increased loss. However when we take the passive control policy, the current tracking error is decreased significantly, and flux compensation obviously improved. At last it reduces the loss of the short circuit current limiter connected to the grid.

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