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Research on Fast Response Characteristic of Magnetic Control Reactor

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Abstract: This paper analyzes the mechanism of the fast response characteristic of a magnetically controlled reactor and response characteristic of magnetically controlled reactor in semi-limit saturated. A model of fast response is established based on pulse width modulation technology, and the simulation analysis is completed. The simulation results show that the response speed of magnetically controlled reactor is two cycles faster than ordinary, based on pulse width modulation technology from rated to no-load or vice versa. Thus, it verifies that the control strategy of fast response of magnetically controlled reactor's correctness and feasibility is based on pulse width modulation technology.

Keywords: Power system, magnetically controlled reactor, fast response.

1. INTRODUCTION

With the rapid development of industrial modernization, high-voltage, high-power and ultra high-power motor has been widely used in electric power, metallurgy and metal rolling transmission, electric locomotive, coal, petrochemical and other industries [1]. This kind of load will cause great active and reactive power impact on the power grid. The grid voltage will not be stable and harm from reactive power and harmonics will occur to power grid's safe and reliable operation [2]. Thus, we must use various types of equipments to compensate reactive power, harmonic suppression and adjust the voltage stability. The excellent performances of magnetically controlled reactor (MCR) in compensation of reactive power, harmonic suppression and adjustment of the voltage stability are regarded highly by the experts. However, although the voltage of the thyristor is very small in MCR (about 1% of the supply voltage), it increases the MCR excitation process, and reduces the dynamic response speed of the control device [3]. Therefore, it is necessary to adopt some measures to improve the dynamic characteristic of MCR. The dynamic response characteristic of MCR will improve by means of the single phase voltage type PWM rectifier inverter circuit.

2. IMPROVING QUICK RESPONSE METHODS OF MCR

In general, there are four ways to improve magnetically controlled reactor fast response, such as increasing DC control voltage of control winding, producing oscillatory discharge of control circuit through charging capacitor, using DC pre bias magnetic and short out control winding etc.

(1) Increasing the DC control voltage

According to the principle of the magnetic control reactor, the capacity of reactor is proportional to the DC component B_d of core magnetic induction intensity, namely the capacity of reactor is increased with increasing of DC component B_d, and vice versa. There is direct contact between the gradient of DC component and the DC control voltage. The relation is presented as follows [4]. javascript:void(0);

$$\frac{dB_d}{dt} = \frac{E_k}{NA_b} \quad (1)$$

Equation (1) shows, in the two core of controlled reactor, the rate of change, which shows the change of the DC component of magnetic induction intensity, is proportional to DC control voltage of the control winding. This proportion relationship is drawn under the different DC control voltage, and it is as shown in Fig. (**1**).

It can be observed that, under the condition of dc voltage, control is larger and the time will be shortened when the DC component of the magnetic induction intensity rises to a certain value. It is important to note that using the method of enhancing control winding DC voltage control to speed up the magnetic control reactor response, needs large capacity of DC control power.

(2) By charging capacitor to the control loops oscillation discharge

When control circuit voltage is constant, the response time of the magnetic valve type controlled reactor depends upon the DC circuit inductance of the reactor [5]. It is due to the existence of the inductance that the DC current response time slows down.

In the control circuit of the magnetic control reactor, the capacitor, which is filled with a certain initial voltage in

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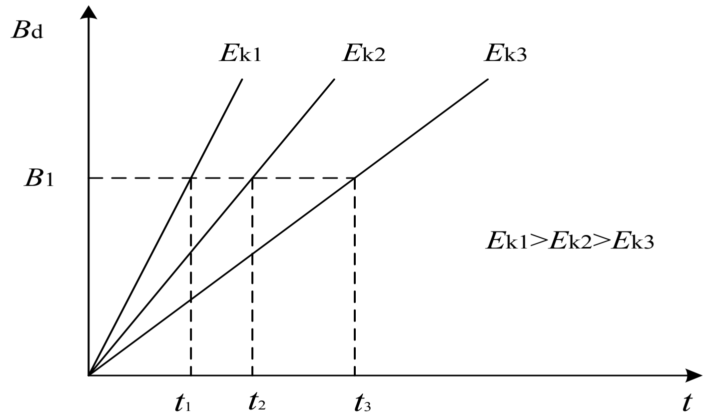


Fig. (1). DC components change of magnetic induction intensity under different DC control voltage.

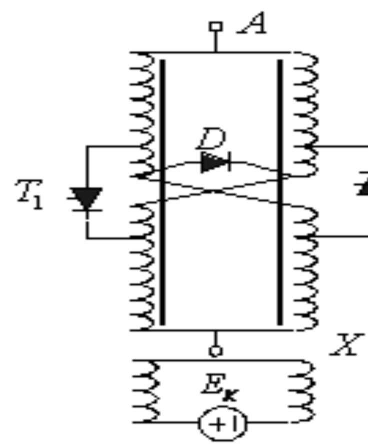


Fig. (2) Compound type structure of the controllable reactor.

advance, is in series. When line has fault, capacitor discharges towards control circuit, the control current is established quickly in L-C oscillation circuit, so as to improve the response speed of the controllable reactor. Selecting the appropriate capacitors and initial parameters can adjust the discharge voltage oscillation frequency and amplitude, so as to control the first peak time of the magnetic induction intensity, and at the same time maintain the control current in the process of the capacitor discharge.

(3) Using DC pre bias magnetic

With DC bias magnetic, namely, suddenly impose a sinusoidal AC voltage on both ends of the work winding. Generally, adopts compound excitation structure, it is used in the arc suppression coil. Its working principle is, when the system is in normal operation, and by joining a small additional control winding DC control power supply then the arc suppression coil impedance gets very large and, moves away from the resonance point. Once the arc suppression coil voltage rise suddenly, the reactor power instantaneously increases under the action of small DC excitation source. At the same time, starting the thyristor T_1 and T_2, cutting off separately excited DC excitation source, and turning excitation source into the self-couple excitation mode then its power will increase without inertia moment and it will improve the response speed of the controllable reactor,as shown in Fig. (**2**).

(4) To increase turns ratio of the coil

By the principle of magnetic control reactor fast response speed, the dynamic response time of the reactor depends on turn ratio δ of reactor coil. By increasing δ, the dynamic response t will be reduced. Therefore, by changing the turn ratio of the reactor coil it can be possible to change the speed of dynamic response of the reactor. Implementation method is illustrated in Fig. (**3**). On the basis of previous magnetic control reactor increased the auxiliary switch K_3, K_4 and diode D_1, D_2. Triggering K_1 and K_3, will operate the reactor and because the reactor has self-coupling effect, electric potential of point *a* is higher than point *c*. After K_1 and K_3 are triggered, point *c* potential is greater than the potential of point *b*. Due to D1's reverse voltage, D_1 is shut down. When the power is negative half cycle, trigger K_2 and K_4, D_2 is close. Both of the above processes, increases the δ, and improves the response time of the reactor. After the achieving fast response, the current of reactor meets the requirements,

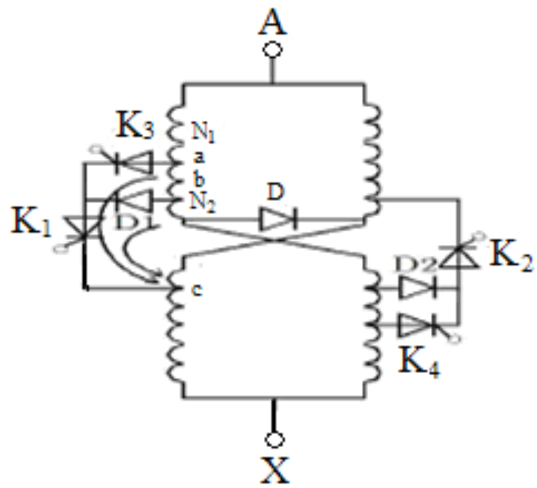


Fig. (3). Quick response circuit.

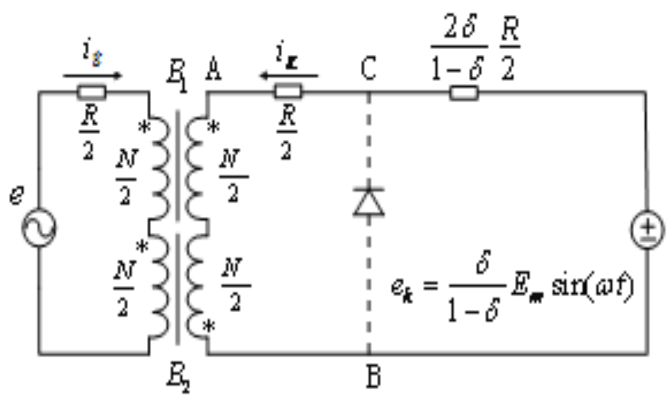


Fig. (4). Equivalent circuit of MCR.

and then terminate K_3 and K_4. When K_1 is triggered at a certain conduction angle, the electric potential of point *b* is higher than point *c*, D_1 is switched on, and the turn ratio δ maintains a small value at the moment.

3. RAPID RESPONSE MECHANISM OF MCR

The dynamic response of MCR includes two kinds of situations. One is the capacity adjustment process from no load to rated (magnetic assist). The other is capacity adjustment process from rated to no-load (demagnetization). In order to improve dynamic response performance of MCR, the reactor will produce the DC control current as soon as possible, form magnetic field in DC controlled, when the reactor was connected to the circuit. But, the reactor will soon remove current from DC controlled and magnetic field in DC controlled gets eliminated and speeds up the dynamic response speed of the reactor [6].

Equivalent control circuit of MCR is as shown in Fig. (**4**).

For the control voltage $e_k = \dfrac{\delta}{1-\delta} E_m \sin\omega t$ can be reduced as follows.

$$P = k_n\left(\frac{E_1}{k}\right)^2 \frac{1}{f} + k_c\left(\frac{E_1}{k}\right)^2 + k_e\left(\frac{E_1}{k}\right)^{1.5} \tag{2}$$

Among them, when the thyristor of MCR is turned on, $K(t)=1$. When the thyristor of MCR is turned off, $K(t)=0$. Therefore, when the thyristor of MCR is connected separately, the equivalent DC control power E_k (including AC component) provides electricity to the control circuit. If the triggering angle of controllable reactor is α, DC component of control voltage E_k is as follows.

$$B = B_r r + B_z z \tag{3}$$

Control DC component is expressed as follows.

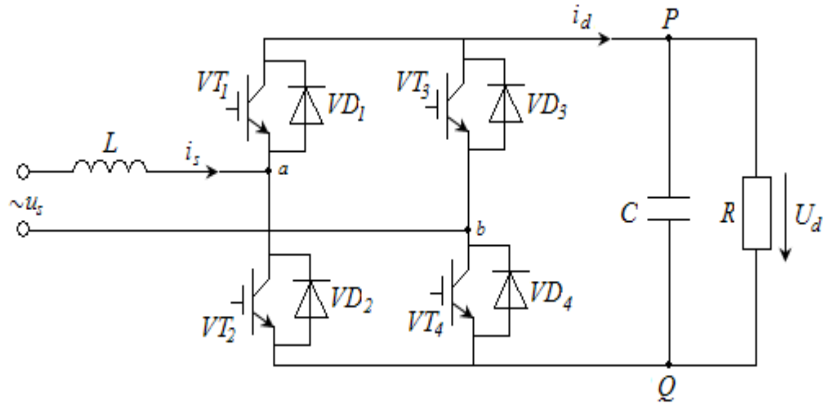


Fig. (5). Voltage type PWM rectifier circuit of single phase bridge.

$$I_k = \frac{E_k}{(1+\frac{2\delta}{1-\delta})\frac{R}{2}} = \frac{2\delta E_m}{\pi(1+\delta)R}(1+\cos\alpha) \tag{4}$$

And, by the control characteristic of the reactor, relational expression can be drawn between the triggering angle α and magnetic saturation β. It is as shown in formula (5).

$$\cos\alpha = \frac{2}{\pi}(\sin\frac{\beta}{2} - \frac{\beta}{2}\cos\frac{\beta}{2}) - 1 \tag{5}$$

Therefore, the relationship between the control current and the magnetic saturation is as shown below.

$$I_k = \frac{1}{\pi}(\sin\frac{\beta}{2} - \frac{\beta}{2}\cos\frac{\beta}{2}) \tag{6}$$

Thus it can be viewed. I_k is proportional to β. With the increase of control current, magnetic saturation β increased [7]. Therefore, this paper presents a new control strategy, namely single-phase voltage type PWM reversible converter control. PWM rectifying circuit generates DC current, DC magnetic field control is established, making the reactor reach the semi-limit saturated quickly, when the reactor is connected to the circuit. And when the reactor is disconnected, change of PWM rectifier mode occurs, the inverter circuit removes the DC current as soon as possible and DC magnetic field energy absorption also occurs. Thus it speeds up the DC reactor's additional magnetic and demagnetization process of MCR. Current transient process of MCR can be shorted, and the purpose of improving response speed of MCR is achieved.

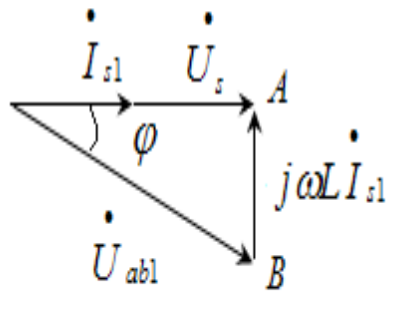
4. PRINCIPLE ANALYSIS OF SINGLE-PHASE VOLTAGE SOURCE PWM REVERSIBLE TRANSDUCER

In the thyristor controlled rectifier device, the power factor of AC circuit is reduced because of the increase of the thyristor triggering angle. So it not only increases the harmonic content of the power grid, but also increases the reactive power consumption of the power grid. A reversible PWM converter is composed of full-controlled device by means of pulse width modulation technology. Through the proper control PWM reversible converter, its work mode and work timing are changed, and the phase and size of the AC current can be adjusted. So, AC current is close to the sine wave, it does not only effectively improve the harmonic problems, but also improves the power factor of AC side.

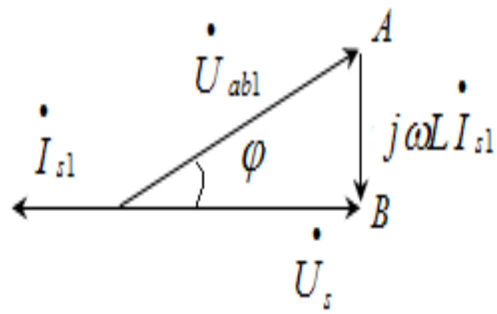
Single phase voltage PWM rectifier circuit of bridge type structure is as shown in Fig. (**5**). A full controlled devices and the antiparallel rectifier diode make a bridge arm. L is for AC inductance. u_s is a sine wave voltage of power grid. U_d is the DC output voltage of the rectifier. u_{ab} is the rectifier input voltage of side, its fundamental wave frequency is the same as the u_s, and its amplitude and phase is adjustable. i_s is current of PWM rectifier, it is from the grid to absorb the current. i_d is the PWM rectifier output current. The AC power can be passed to the DC side through diode VD_1~VD_4. DC side energy can reverse into AC energy through fully-controlled bridge VT_1~VT_4, and the AC energy can go back to the grid. So, energy transformation is reversible for the single-phase voltage source PWM rectifier. The circuit is in the rectifier model or in the inverter model based on pulse width modulation of the VT_1~VT_4.

Assume that the fundamental component of i_s is i_{s1}, and the fundamental wave voltage of u_{ab} is u_{ab1}, equation (7) is gained. The vector diagram, which is under different working conditions, is as shown in Fig. (**6**). It reflects the operation mode of rectifier circuit [8].

$$\dot{U}_s = \dot{U}_{ab1} + j\omega L \dot{I}_{s1} \tag{7}$$



(a) Condition of rectifier



(b) Condition of inverter

Fig. (6). Vector diagram of different working condition for single phase reversible PWM converter.

Defining the power supply voltage, then $u_s(t)$ is expressed as follows.

$$u_s(t) = U_m \sin \omega t \quad (8)$$

So, the modulation wave will be obtained.

$$u_g(t) = U_g \sin(\omega t - \phi) \quad (9)$$

Assuming that amplitude of triangular carrier wave is u_c, $u_{ab}(t)$ is a single polarity SPWM wave, and sine pulse width modulation ratio is $m = U_g / U_c$, then equation (10) can be obtained.

$$u_{ab1}(t) = mU_d \sin(\omega t - \phi) \quad (10)$$

From Fig. (**6**) and equation (10), it can be seen that under the invariable condition of u_s, the circuit, which is working in rectification state (φ=0), or working in inverter state (φ=π), can realize converter power flow through adjusting the amplitude and phase of the u_{ab}.

In Fig. (**5**), according to the principle of power balance, the circuit's power balance expression is as follows.

$$U_s I_s = U_d C \frac{dU_d}{dt} + \frac{U_d^2}{R} \quad (11)$$

As Fig. (**5**) show that the circuit is under steady-state condition, Equation (11) can be written as equation (12) approximately.

$$\frac{dU_d}{dt} = \frac{U_s I_s}{CU_d^*} - \frac{U_d}{RC} \quad (12)$$

In equation (12), the DC reference voltage is set as U_d^*, Laplace transformation is carried out on equation (12). The transfer function, that is expressed from the power supply to DC U_d, is available, and it is as follows [9].

$$W_0(s) = \frac{U_d(s)}{I_s(s)} = \frac{U_s R}{U_d^*(1 + RCs)} \quad (13)$$

In general, switching frequency of PWM rectifier circuit is quite high. So, an inertial link is placed instead of current hysteresis link. Assuming that equivalent time constant of current hysteresis link is T_i, then the transfer function, that is expressed from I_s^* to I_s, is as follows.

$$W_i(s) = \frac{1}{(1 + T_i s)} \quad (14)$$

Increased the low-pass filter can effectively inhibit second ripple of DC output. Assuming that the cutoff frequency of first-order low-pass filter is under 1/2 base wave frequency, the filter transfer function can be represented as follows.

$$G(s) = \frac{1}{1 + T_c s} \quad (15)$$

For PI regulator, proportionality coefficient is k_p, and integral time constant is of τ, then its transfer function can be indicated as follows.

$$R_v(s) = k_p \frac{\tau s + 1}{\tau s} \quad (16)$$

From the above analysis, PWM converter control block diagram can be obtained, and it is shown in Fig. (**7**). The control strategy will be using DC control. The difference value between DC output voltage U_d and reference DC voltage, which is filtered secondary ripple through low-pass filter, can eliminate static error of the control system by PI regulation. After multiplying with sinusoidal synchronization signal, reference current signal i_{sref} is formed. After reference current is compared with net side current, then the current deviation signal is produced. Add current

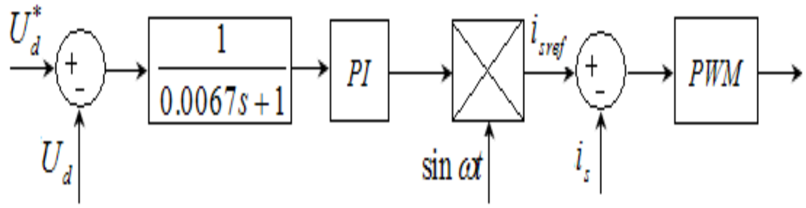


Fig. (7). Diagram of the direct current control strategy for single-phase voltage type PWM converter.

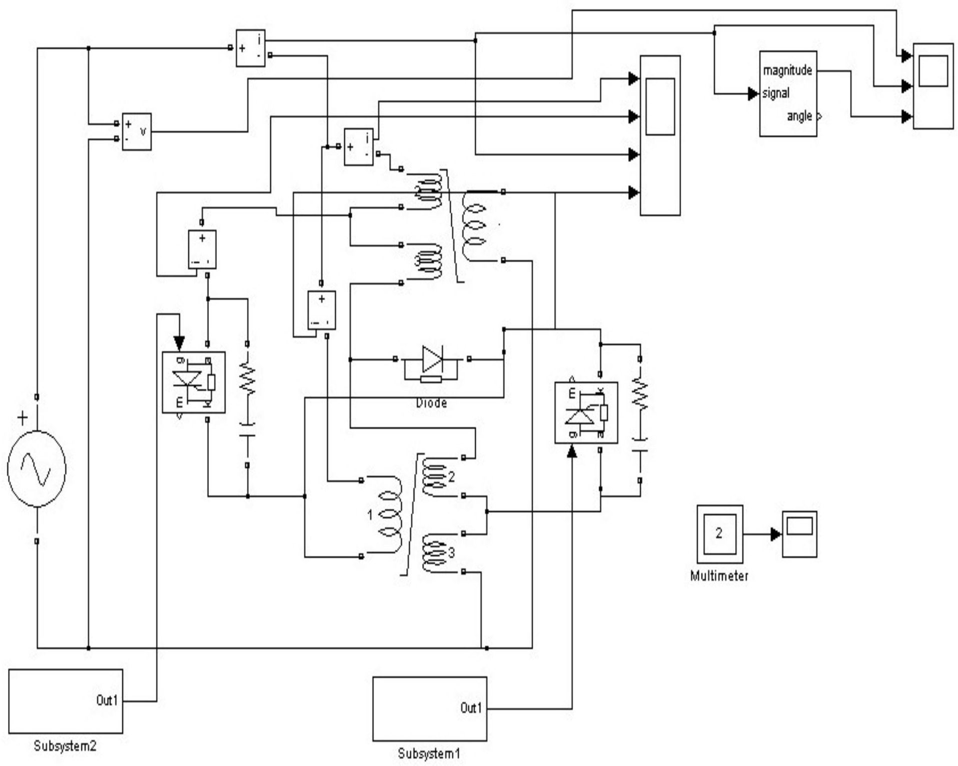


Fig. (8). Simulation model of MCR.

deviation signal to the PWM module, the converter will generate a switch pulse [10].

5. RESPONSE CHARACTERISTIC SIMULATING FOR MCR

According to the characteristics of magnetically controlled reactor, we take two saturation transformers that have three windings. Magnetization curves will use the lesser slope curve model. Setting the MCR capacity as 300e6VA. The frequency is 50Hz. The magnetically controlled reactor's state is semi-limit saturated. The simulation circuit model is shown in Fig. (**8**).

The simulation end time is set to 1.8s. Select the ode23tb algorithm simulation, the magnetic flux curve of the MCR and the output current of two cores of MCR are gained.

From Figs. (**9** and **10**), it can be seen that the timing starts from 0.2s, when it begins to send out pulse, output current of ordinary MCR rises slowly from no load to rated condition, and takes 0.4s or so, after 20 cycles output current tends to stabilize.

When capacity vary from the rated to no-load transition, common MCR disadvantage of slow response is more obvious. At time 1.5s, capacity begins to decrease. At 1.8s, after 15 cycles, the reactor outputs relatively large current, and the response speed is very slow.

6. RAPID RESPONSE SIMULATION OF MCR BASED ON PWM TECHNOLOGY

Magnetically controlled reactor based on PWM technology is a fast response circuit, as shown Fig. (**11**). On the

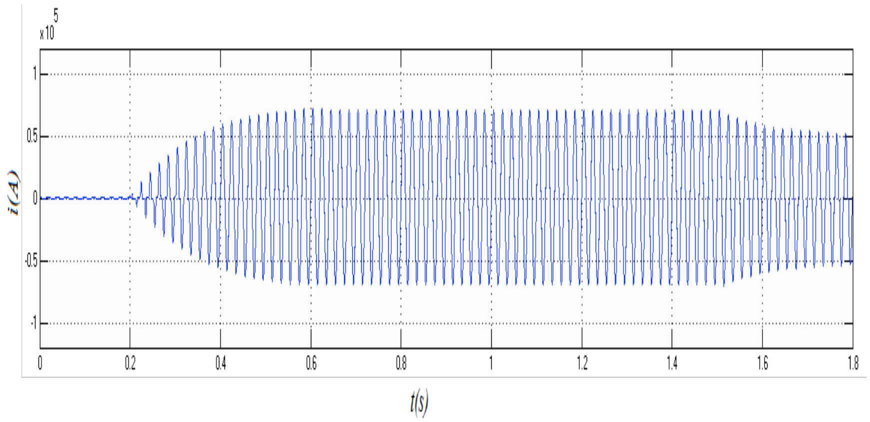


Fig. (9). The output current waveform of MCR.

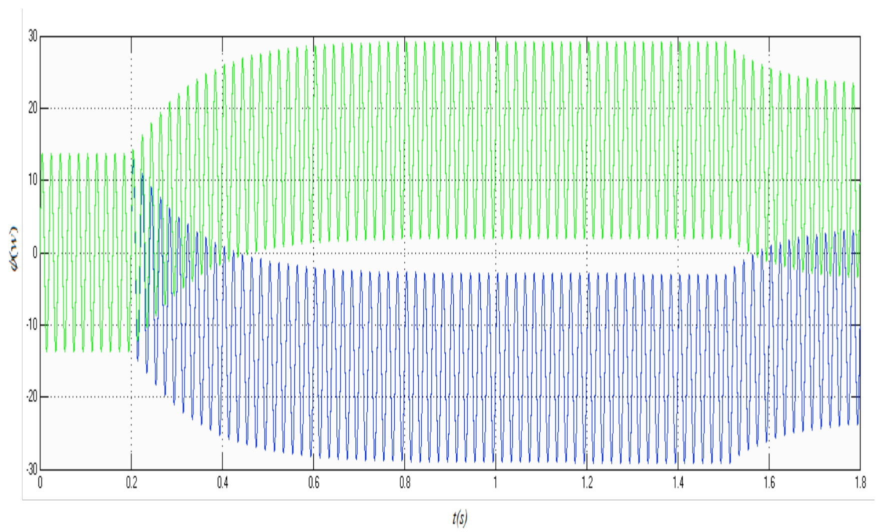


Fig. (10). Flux curve of two cores of MCR.

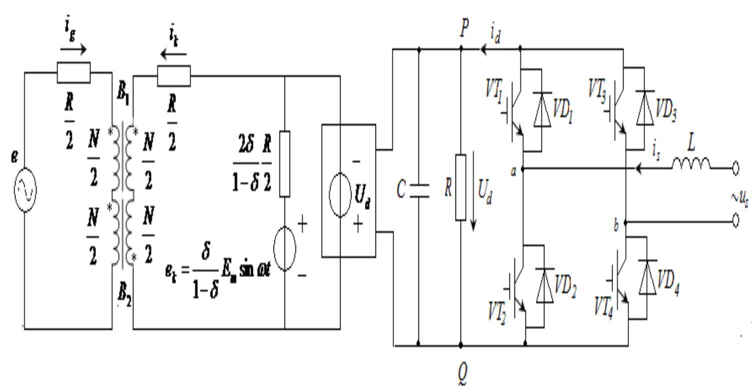


Fig. (11). Fast response circuit of magnetically controlled reactor.

left is magnetically controlled reactor control loop equivalent circuit, and on the right is the PWM converter. The rapid response simulation circuit model is as shown in Fig. (**12**).

Fig. (**12**) shows the simulation model, PWM converter replaces freewheeling diode of MCR. The simulation parameters are as follows. $L = 0.1mL$, $C = 800uF$, $R = 10\Omega$, $U_{\max} = 311V$, $K_p = 2.3$ and $K_i = 48$. MCR output current

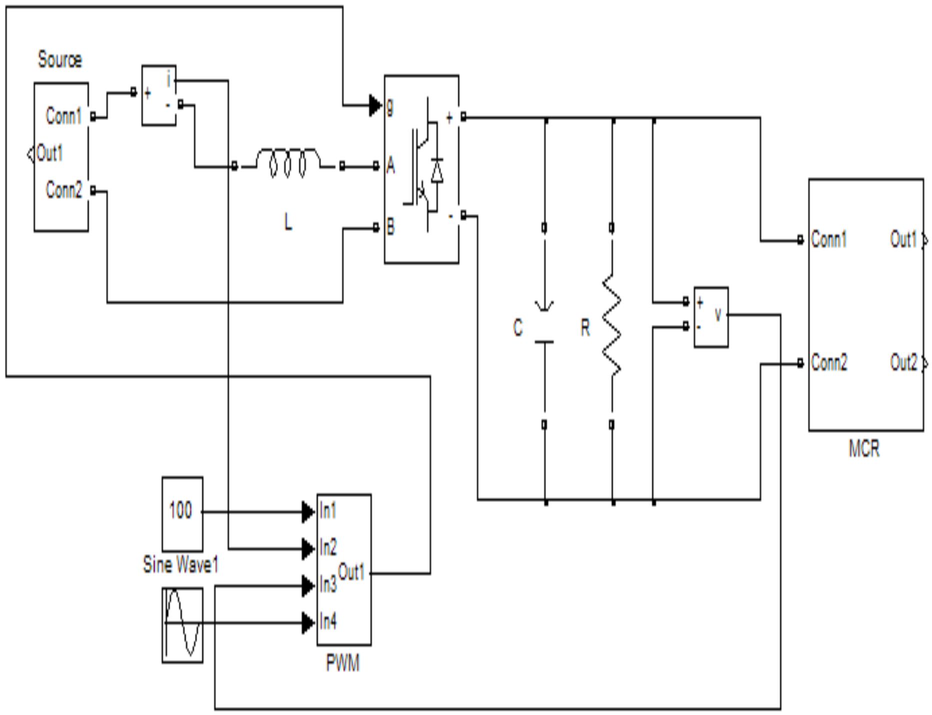


Fig. (12). Fast response MCR simulation circuit model based on PWM converter.

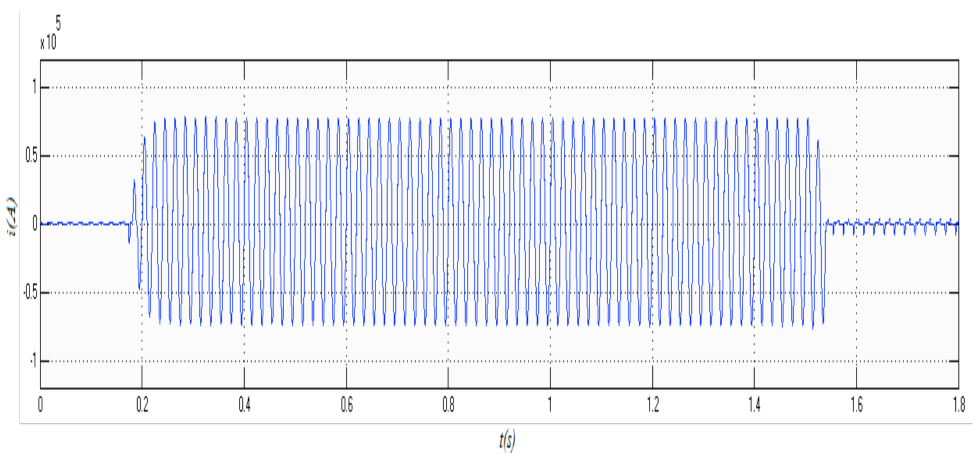


Fig. (13). Output current waveform of fast response MCR.

waveform and flux curves of two cores are illustrated in Fig. (**13** and **14**).

As the Fig. (**13** and **14**) shows, MCR starts working at 0.2s. Considering the DC side capacitor with a charging time, PWM rectifier access to circuit from 0.16s, reactor output current (capacity) from no load to rated condition rise faster, takes about 0.04s, and after 2 cycles it reaches steady state.

When the MCR changes from rated to no-load, from 1.5s rectifier mode is changed into the inverter mode, reactor output current capacity begins to decrease, After only two cycles, namely 0.04s, reactor will reach no-load steady state, dynamic response speed is fast. DC side capacitor of the PWM converter exist, in the condition of no-load DC side capacitor has a DC voltage, and this voltage being very small it won't have any influence on the magnetic control reactor.

CONCLUSION

Through the above analysis, rated capacity of magnetic control reactor is 300000kVA. In case of emergency, due to the rectifier role of PWM circuit, MCR can provide

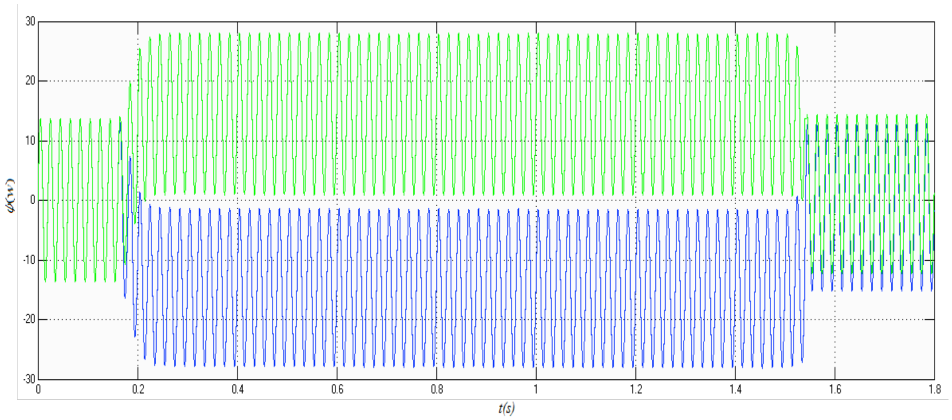


Fig. (14). Flux curve of two cores for rapid response MCR.

300000kVA reactive power in 0.04 seconds. MCR can meet the needs of the electrified railway traction power supply system reactive power and voltage regulation and stability improvement. Similarly, when MCR is from rated to no-load condition, PWM converter circuit plays the role of inverter, output current from the ratings drops to zero quickly, the transition process is very short, the response time is only 2 cycles, thus it achieves the desired rapid response purposes.

CONFLICT OF INTEREST

There is no any potential conflict of interests regarding the publication of this article.

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