Research on the Magnetic Valve Thyristor Controlled Reactor

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ABSTRACT

The magnetic valve thyristor controlled reactor (*MVTCR*) is presented and its configuration and working principle are described in this paper. It is set up for the mathematical models based on equivalent electrical circuit and magnetic circuit by using analytical method to calculate steady-state characteristics. The characteristics of the reactor are showed by numerical simulations. It is revealed some interesting features of *MVTCR* in the paper. As an example, model tests of a prototype of 1*kVA*, 0.4*kV* reactor are performed to support the theoretical results.

Keywords: controllable reactor, magnetic valve, harmonics, dynamic respond, simulation

1 INTRODUCTION

The adjustable reactor is applied in many practical fields. There are mainly four kinds of regulative reactors: tapped coil, adjustable air gap, controllable saturated type and thyristor controlled reactor(*TCR*). Although the *SVC* based on *TCR* is used in power system widely, there are some problems such as: (1)Due to the limitation of manufacturing level of the thyristor valve. TCR can not be installed in power networks over 35*kV* directly, generally it is connected in system with higher voltage grade through a step-down transformer. (2)*TCR* brings about major harmonics and needs additional filters. (3)The thyristor valve requires precise control and complicated protection apparatus for over-voltage and over-current, it may generate direct component while improperly controlled which make the transformer saturated. (4)The thyristor is used to provide the full compensating power, and the high power thyristor is very expensive.

MVTCR overcomes the foibles of *TCR* and keeps its merits at the same time in certain extent. The magnetic circuit of *MVTCR* proposal has a part of reduced transverse section, only the iron core with small area of transverse section is saturated in the whole working range of *MVTCR*, other parts of the magnetic circuits keep unsaturated and remain in linear state.

The capacity of *MVTCR* can be regulated in succession by making use of the DC controlling current to dominate the saturated degree of reduced transverse section, it takes advantage of power source itself to convert voltage through self-coupling winding and to gain exciting source by thyristor rectification without additional windings. The *MVTCR* combines working windings with controlling windings organically to reduce energy loss and simplify construction. Furthermore it generates less

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harmonics, has an approximately linear characteristic of voltage /fundamental current, responds quickly. It can be used in systems with voltage up to 1150*kV* directly as reactive power source.

2 CONFIGURATION AND PRINCIPLE

The main iron-core of *MVTCR* is divided into two parallel limbs which have two stages of varied transverse sections for the limitation of generated harmonics and a group of symmetrically distributed windings with taps (Fig.1). The areas of these varied transverse sections are different. Two windings are arranged individually on the upper and lower parts of each limb. There is a tap with tapping ratio δ in each winding. The windings of different limbs are crossly connected and then two branches of the series windings connected in parallel to be joined of network. Two thyristors and diodes are connected to the taps of the windings. Within one period of the working frequency, the two thyristors are triggered and conducted in turn to provide the reactor with DC biased current. The biased energy is drawn from the network itself by self-coupling of the reactor(Fig.2).

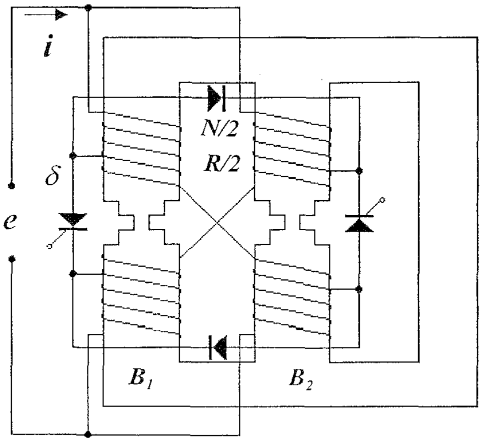


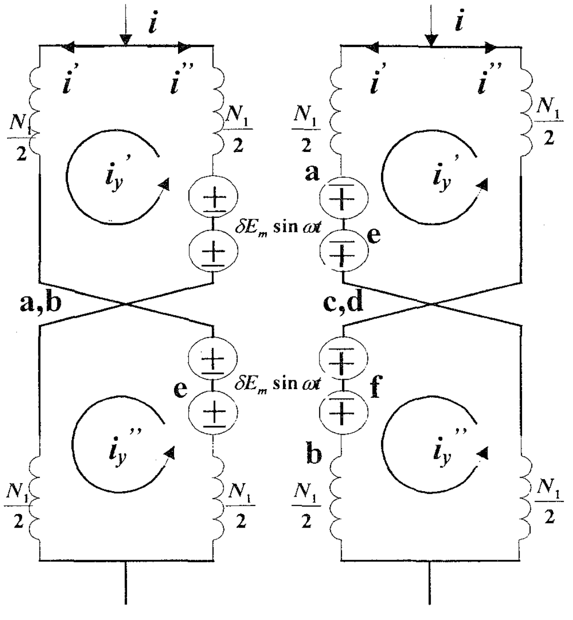
Fig.1 Configuration of the *MVTCR*

Where, N-turns of windings

R-resistance of windings

δ-tapping ratio of windings

B_1, B_2-flux density of two parallel limbs



(a) (b)

Fig.2 Circuit of biased energy

(a)Left thyristor conducted

(b)Right thyristor conducted

The diodes are used for fly wheel current caused by inductive load during the blocking of the thyristors. The current of the reactor is subject to the degree of saturation β which is defined as the electrical angle of each magnetic core during one period of working frequency. The larger the conducting angle of the thyristors, the more the β and the capacity of the reactor. All windings of the reactor play twofold roles, i.e. controlling and working windings, which may help to reduce additional energy losses of the circuits.

Because of the special configuration of the *MVTCR*, the thyristors is connected to the winding tap with tapping ratio δ, and therefore the voltage endured by the thyristor is only a percentage of the rated value put on the reactor. It is not necessary to connect large amount of thyristors in series when the *MVTCR* is used in high voltage system directly. It shows that the power of thyristors needed by *MVTCR* is much less than that of *TCR*.

3 MATHEMATICAL MODEL ANALYSIS

The *MVTCR* has special magnetic circuit which has limbs of varied transverse sections as shown in detail in Fig.3. Because saturation takes place only in the range of reduced section and other parts of the magnetic circuits remain unsaturated, the following relations can be obtained:

$$\begin{cases} B = \left\{ A_1 B_e + \dfrac{\mu_0 (A - A_1)}{l} \left[l_t f(B_t) + (l - l_t) f(B_e) \right] \right\} / A \\ H_e = \left[l_t f(B_t) + (l - l_t) f(B_t) \right] / l \\ B_e = \left[A_2 B_t + \mu_0 (A_1 - A_2) f(B_t) \right] / A_1 \end{cases} \tag{1}$$

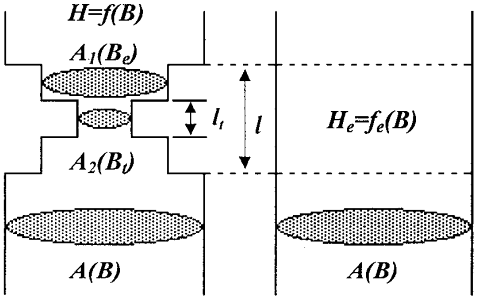


Fig.3 Working part of the magnetic circuit

where μ_0 is the magnetic conductivity of air.

From equations (1), the practical *H/B* characteristic of the iron-core can be converted to the equivalent relation $H_e=f_e(B)$.

The derived equivalent electrical circuit of the *MVTCR* is demonstrated in Fig.4. The equivalent circuit is almost the same as that of a conventional controllable saturated ones. The difference is the DC supply source which is proportional in magnitude to the network voltage itself in the former case.

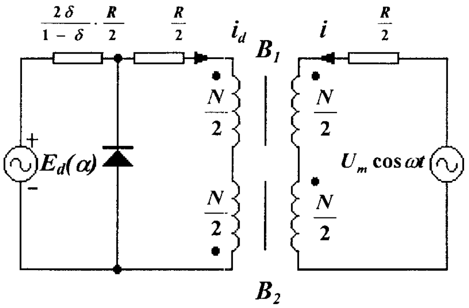


Fig.4. Equivalent electrical circuit of the *MVTCR*

The direct component of the control voltage is given by the following equation:

$$E_d(\alpha) = \frac{1}{\pi} \int_\alpha^\pi \frac{\delta U_m \sin\theta}{1-\delta} d\theta = \frac{\delta U_m (1 + \cos\alpha)}{\pi (1-\delta)} \tag{2}$$

where α is the gating angle of the thyristors.

$$\begin{cases} U_m \cos\omega t = \dfrac{R}{2} \cdot i + NA \left(\dfrac{dB_1}{dt} + \dfrac{dB_2}{dt} \right) / 2 \\ E_d(\alpha) = \left(\dfrac{1+\delta}{1-\delta} \right) \cdot \dfrac{R}{2} i_d + NA \left(\dfrac{dB_1}{dt} - \dfrac{dB_2}{dt} \right) / 2 \\ i \dfrac{N}{2} + i_d \dfrac{N}{2} = l H_{e1} \\ i \dfrac{N}{2} - i_d \dfrac{N}{2} = l H_{e2} \\ H_{e1} = f_e(B_1) \\ H_{e2} = f_e(B_2) \end{cases} \tag{3}$$

Supposed that the supply voltage is $U_m cos \omega t$, the above functions can be obtained.

It can be proved that the difference (B_1-B_2) contains direct and even harmonics at steady-state. Because the working windings of *MVTCR* are connected in parallel, the inducted potential of even harmonics can be circulating freely in short circuit formed by parallel windings and in fact, the even harmonics contained by B_1 or B_2 are very small. Ignoring these higher order harmonics and reserving the direct component $z = (B_1 - B_2) / 2$, it can be gained for the solution from equations (3)

$$i = \frac{l}{N} \left[f_e (B_m \sin\omega t + z) + f_e (B_m \sin\omega t - z) \right] \tag{4}$$

where $B_m = U_m / \omega NA$.

The fundamental component of i is given by

$$i_1 = I_{am} \cos\omega t + I_{bm} \sin\omega t \qquad (5)$$

where

$$\begin{cases} I_{am} = \dfrac{l}{N}\left\{\dfrac{2}{\pi}\int_0^{\pi}\left[f_c(B_m \sin\omega t + z) + f_c(B_m \sin\omega t - z)\right]\cos\omega t d\omega t\right\} \\ I_{bm} = \dfrac{l}{N}\left\{\dfrac{2}{\pi}\int_0^{\pi}\left[f_c(B_m \sin\omega t + z) + f_c(B_m \sin\omega t - z)\right]\sin\omega t d\omega t\right\} \end{cases}$$

z is determined by equations (2) and (3).

4 CHARACTERISTICS SIMULATIONS AND MODEL TESTS

4.1 voltage-Ampere characteristic

The voltage current(fundamental) characteristic of *MVTCR* is calculated from equation (5). The results are shown in Fig.5, the model test results are displayed in dots in Fig.5 too.

In Fig.5, the Y axis is the magnitude of the supply voltage, and the X axis is the fundamental component of the current. The degree are the triggering angle of the thyristors.

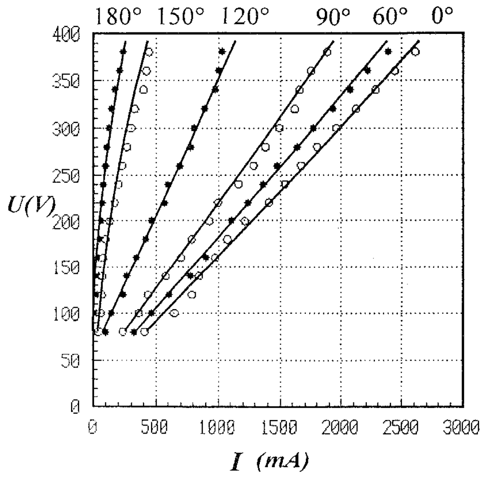
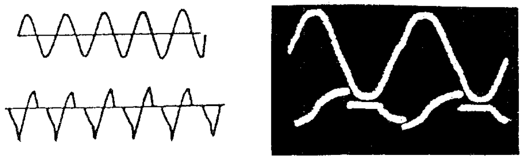


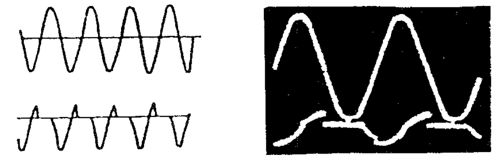
Fig.5 The voltage/fundamental current characteristic

It is seen from the figure that the voltage/ fundamental current characteristic of the *MVTCR* under certain triggering angle of the thyristors is approximately linear which is quite different from that of controllable saturated reactors with separate DC control supply. The working voltage of the *MVTCR* may vary within a considerable range about the rated value which is equal to the phase to phase voltage of the system, the linear voltage/ampere characteristic of *MVTCR* will provide power system with more accurate reactive power support.



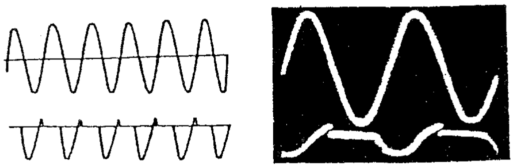
(a) (b)

α=90°



(a) (b)

α=54°



(a) (b)

α=36°

Fig.6 The current(up) of the *MVTCR* and Voltage(down) of the thyristors

(a)Calculating results,(b)Testing results

4.2 Harmonics characteristics

Fig.7 shows the variations of the amplitudes of some of the major (lower order) harmonics with the β of *MVTCR* under rated supply voltage.

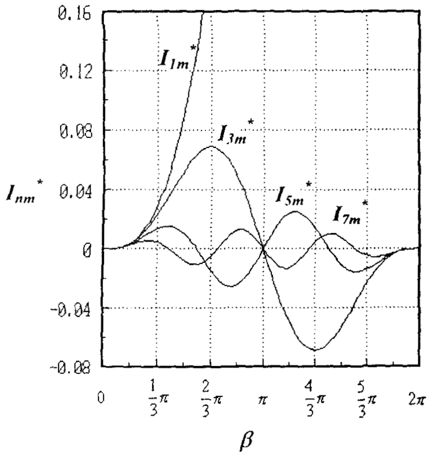


Fig.7. The peak value of harmonics

Each amplitude of the harmonics is expressed as a percentage of the rated fundamental current of the reactor. The calculated harmonics produced by the reactor in Fig.8 is very small within the whole range of the regulation the capacity.

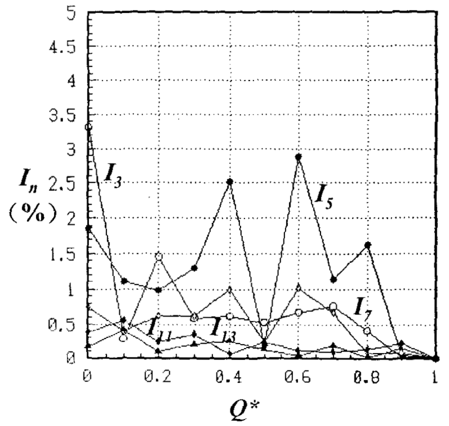


Fig.8 Relations of generated harmonics to the capacity under rated supply voltage

The third harmonic component plays dominant part in the generated harmonics and never exceeds 5% of rated fundamental current under rated supply voltage. The relation of total generated harmonics which is expressed by $\sqrt{I_3^2+I_5^2+I_7^2+I_{11}^2+I_{13}^2}$ to the rated fundamental current within the whole range of regulation is approximately the same as the curve I_3(%) in Fig.8.

4.3 Control law

The effect of increasing of the triggering (controlling) angle is to reduce the fundamental component of the current under rated supply voltage. The relationship of the fundamental component of the current to the controlling angle is shown in Fig.5. The minimum value of the current (capacity) is near zero when the controlling angle is 180° and the maximum value of the current is reached with the angle 0°. The angle corresponding to the maximum value of the current (rated value) is determined by both the resistance in the electrical circuit and the tapping ratio of the windings for DC supply. The experiment results is aslo shown in dots in the figure.

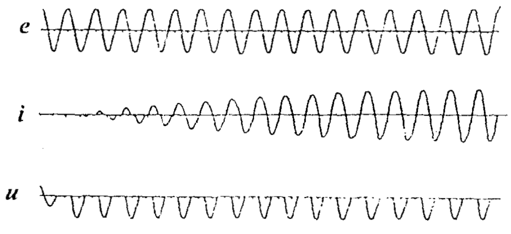
4.4 Respond time of open-loop jump

It can be derived the open-loop jump respond time from equations(2), (3).

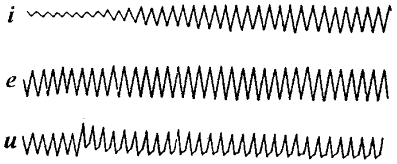
$$\frac{dz}{dt}=\frac{d}{dt}\left(\frac{B_1-B_2}{2}\right)=\frac{2\delta U_m}{(1-\delta)\pi NA} \quad (6)$$

$$n=\frac{1-\delta}{2\delta} \quad (7)$$

where, n is the number of working frequency periods. From equation(7), it can be discovered that n is inverse ratio to the winding tap δ. Fig.9 shows that the calculating and testing results of open-loop jump control from no-load to rated load.



(a)Calculating result



(b)Testing result

Fig.9 Respond time of the *MVTCR*

Where, e-supply voltage, i-current of reactor, u-voltage on thyristor

5 CONCLUSION

The proposed *MVTCR* is simple in construction and has approximately linear voltage/fundamental current characteristic under certain conducting angle of the thyristors. The calculated results show that the generated higher order harmonics are very small and the total of the harmonics is below 5% of rated fundamental current under rated supply voltage within the whole range of regulation. The equivalent electrical and magnetic circuits of the reactor have been obtained for accurate dynamic and steady-state computations. Because of the improved configuration of *MVTCR* , it has excellent operating performances.

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