MVCR Performance Improvement Research Based on ANSYS

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Abstract. Magnetic valve controllable reactor (MVCR) is a kind of reactive power compensation equipment with good control flexibility and high reliability, which as a result making MVCR being applied more and more widely. Therefore it is crucial to improve the performance of MVCR. In this paper, a method is presented for reducing the fringing effect by dividing one single magnetic valve of MVCR into several series-connected parts, which will reduce the corresponding inductance of AC winding. Consequently the equipment will generate more reactive power with the same working voltage and the control voltage as well as improving its performance. By theoretical analysis and simulation with software ANSYS, an optimal separation of MVCR’s iron-core is presented in this paper which calculates the number of magnetic valves and the space length between every two of them. The validity of this design has been fully confirmed by specific experiments that under the same working voltage and control voltage, the current of the AC winding increases by 7.4% when a single magnetic valve is divided into two parts.

1. Introduction
Reactive power compensation device and technology play important roles in the current power system[1]-[2]. Magnetic valve controllable reactor (MVCR) is an important component in the field of static reactive power compensation since it compensates large reactive current flexibly with high reliability[3].

In this paper, an optimum design of MVCR’s iron-core is presented based on the conventional structure by dividing the single magnetic valve of MVCR into several series-connected parts, which effectively reduce the fringing effect of MVCR. Consequently the equipments adopted the optimum design will generate more reactive power than before if given the same working voltage and control voltage, and the performance of MVCR will improve as well. By theoretical analysis and ANSYS simulation, an optimal design is presented in this paper which calculates the effective number of magnetic valves and the space length between every two of them and the validity of this design has been fully confirmed by specific experiments.

2. The structure and working principle of MVCR
Figure.1 shows the profile structure of MVCR according to conventional design which is widely used currently. I and II are the main iron-cores, III is the side yoke [4]. It is known that there are several parts in MVCR’s iron-core possessing smaller cross section than that of the other parts, and these narrow sections are called magnetic valves. It should be noted that within the adjustment scope of the MVCR's capacity, only these sections with smaller cross section will get saturated, while the other
sections are in the unsaturated linear state. Each main iron-core is equipped with an AC winding and a DC winding. Where L1, L2 and L3, L4 present the profile of AC winding 1 and AC winding 2 respectively, L6, L7 and L8, L9 present the profile of DC winding 1 and DC winding 2 respectively. The direction of the current at a certain moment in each winding is shown in Figure 1. During every frequency cycle, these two iron-cores become saturated in turn with the alternation of AC flux’s direction.

3. The analysis of MVCR’s ac winding output reactive power
When the MVCR’s magnetic valve is not saturated, almost all of the magnetic flux lines are within the magnetic valve. In comparison, when the MVCR’s magnetic valve is saturated, some magnetic flux lines will overflow into the air around the magnetic valve instead of staying inside. And with the valve getting more and more saturated, the number of flux lines passing through the air will increase correspondingly. Among these flux lines going through the air, some of them are in a straight path and enter the iron-core vertical to its cross section, while the other bend their path in the air thus cannot enter the valve vertically, which makes the collection of them form the fringing flux.

Assuming that the main core I of MVCR is in a certain state of saturation and the working voltage of AC winding and control voltage of DC winding are kept constant. According to the principle of magnetic circuit, the total permeance of MVCR’s magnetic valve can be expressed as:

\[ \Lambda_1 = \Lambda_i + \Lambda_a = \frac{\mu A_i}{l_g} + \frac{\mu_0 (A - A_i)}{l_g} \]  

Where \( \Lambda_1, \Lambda_i, \Lambda_a, \mu, \mu_0, A_i, A, A - A_i \) and \( l_g \) represent the total permeance of the magnetic valve, the permeance of magnetic valve’s iron-core and the permeance of the air around the magnetic valve respectively, the permeability of magnetic valve after it becomes saturated, the permeability of the air around the magnetic valve, the cross section of magnetic valve, the cross section of the iron-core, the cross section of the air around the magnetic valve and the length of the magnetic valve.

The inductance of AC winding surrounding the main core I can be expressed as:

\[ L = N^2 \Lambda_1 \]  

Where \( N \) represents the number of AC winding turns.

4. The analysis of MVCR’s ac winding output reactive power
Firstly we build MVCR model in ANSYS according to its conventional single-valve structure which has been illustrated in Figure 1. Considering the MVCR’s rated frequency is 50 Hz. The simulation starts from the moment of 0s and the AC working voltage reaches the first peak of sine wave after 0.005s. At this point, if DC control voltage exists, one of the magnetic valves of MVCR will be saturated. The distribution of magnetic flux lines of saturated magnetic valve is shown in Figure 2 considering there is only one magnetic valve in each AC winding.
As is shown in Figure.2, there are a large number of magnetic flux lines overflowing from the saturated magnetic valve and forming the fringing flux. If there is only one magnetic valve in each AC winding, its magnetic resistance can be expressed as:

\[ R_m = \frac{I_g}{\mu A_y} \]  

(3)

According to (3), if the magnetic valve is divided into several parts, the length of each will become smaller, thus the magnetic resistance of each also become smaller. And this change of resistance will let more magnetic flux lines pass inside the iron-core of magnetic valve instead of the air around, which makes the fringing flux decrease. As a result, the corresponding magnetic flux density inside magnetic valve, as well as the saturation degree of magnetic valve increases.

Assuming that one magnetic valve is divided into \( n \) parts of equal length, the magnetic resistance of each part can be expressed as:

\[ R_{mn} = \frac{I_g}{\mu_n A_y} \]  

(4)

Where \( \mu_n \) represents the permeability of each magnetic valve parts after being divided.

Assuming that each of them will still be regarded as an independent magnetic valve and they are connected in series. So the total reluctance of these \( n \) magnetic valves can be expressed as:

\[ R_{tn} = nR_{mn} = \frac{I_g}{\mu_n A_y} \]  

(5)

When taking the permeance of air around each magnetic valve into consideration, the total permeance can be expressed as:

\[ \Lambda_t = \Lambda_{it} + \Lambda_{at} = \frac{\mu_n A_y}{I_g} + \frac{\mu_n (A - A_y)}{I_g} \]  

(6)

Where \( \Lambda_{it} \) and \( \Lambda_{at} \) represent the total permeance of magnetic valve and the total permeance of the air around magnetic valve.

According to the working principle of MVCR and the B-H curve of iron-core, we know that when the magnetic valve is divided, the saturation degree of each magnetic valve will increase, consequently \( \mu_n \) will be less than \( \mu \) mentioned in (1) where there is only one magnetic valve in each AC winding. As a result, the total permeance \( \Lambda_t \) calculated above is less than the total permeance \( \Lambda_t \) calculated in (1).

Therefore, in order to reduce the fringing magnetic flux of MVCR, one single magnetic valve can be divided into several equilong magnetic valves in series. In addition, the length of the several magnetic valves mentioned above summing up together should equal to the length of one single magnetic valve in order to keep the MVCR’s capacity unchanged.

5. The different division of MVCR magnetic valve and the optimal settings

A three-dimensional model of MVCR was built by ANSYS in order to simulate and calculate the AC winding inductance of MVCR accurately. The length of the iron-core and the side yoke is 0.25m. The length of the magnetic valve is 0.04m. The width of the iron-core is 0.05m. The width of the magnetic valve is 0.025m. The width of the side yoke is 0.1m. The length of the upper yoke and the lower yoke is 0.28m. The width of the upper yoke and the lower yoke is 0.05m. AC and DC windings are racetrack coils.

In this model, the voltage of AC winding, the frequency and the voltage of DC winding is set as 220V, 50Hz and 10V respectively. The method of transient analysis is applied in the simulation since it includes AC voltage and DC voltage at the same time. And in order to simulate actual working
condition of MVCR, the field circuit coupled method is used to simulate the external AC and DC voltage.

![Figure 3. The inductance curve of winding 1 with single magnetic valve.](image)

![Figure 4. The flux density when every single magnetic valve is divided into 4 parts at the moment of 0.005s, the space length between two adjacent magnetic valve is 0.03m.](image)

Firstly, set the structure of MVCR to be single magnetic valve and the length of the magnetic valve to be 0.04m. The corresponding inductance of AC winding 1 at different moment is shown in Figure 3. According to Figure 3, we know that the minimum inductance of winding 1 is gained at 0.005s. And at this moment, the current of winding 1 is maximal, the value of magnetic flux inside iron-core which is surrounded by winding 1 is the largest and MVCR’s saturation degree arrives at the peak point. It can be observed that the inductance of winding 1 decreases during the period of 0.001s to 0.005s, and then increase symmetrically during the period of 0.005s to 0.009s, making the moment of 0.005s a symmetrical point. During the period of 0.011s-0.019s, the inductance of AC winding 2 will be the same with what is shown in Figure 3.

Then the model of MVCR with every single magnetic valve divided into four equilong parts is built by ANSYS. Figure 4 shows the flux density at 0.005s with the space length between two adjacent magnetic valves being 0.03m.

When one magnetic valve is divided into n parts, the fringing effect of the flux going across two adjacent parts can be reflected by the permeance of the space around the edges of magnetic valves, which is approximately expressed as follows[5]:

$$\Lambda_{fe} = \mu_0 D (1 + \ln \left( \frac{\pi(2l')}{2l_g} \right)$$

(7)

Where $D$ represents the diameter of iron-core of which the cross section is $A$, $l'$ represents the length of iron-core. It should be noted that $l'$ is expressed as (11), which is shown in figure 5.

$$l' = \left( H_j - n l_c - l_g \right) / 2$$

(8)

Where $H_j$, $l_c$ and $l_g$ represents the space length between the upper and the lower iron yokes, the space length between two adjacent magnetic valves and the total length of magnetic valves.

$l_g'$ represents the space length of two adjacent magnetic valves parts after divided, which can be expressed as:

$$l_g' = l_c + \frac{2}{n} l_g$$

(9)
According to (7), when the space length between two adjacent magnetic valves gradually increases, the permeance \( \Lambda_{f2} \) will gradually reduce and finally comes to 0, which means the magnetic flux lines crossing two or more magnetic valves will gradually disappear. Therefore the corresponding space length acquired at that zero point is regarded as the minimum optimal value. Only when the length is larger than this minimum value will the fringing flux be minimal. Assuming the minimal optimal space length mentioned above is \( l_{eo} \), it can be expressed as:

\[
l_{eo} = \frac{(\pi e/2) H_f - (\pi e/2 + 2/n) l_s}{1 + (\pi e/2)n}
\]

In addition, it can be concluded according to the simulation that when the magnetic valve is divided into 5 parts or more, the change of the inductance is so insignificant that it can be ignored. Taking the manufacturing cost of iron-core into consideration, it would be more appropriate to divide magnetic valve into 4 sections or less. The corresponding inductance of AC winding 1 is shown in Figure 6 when one magnetic valve is divided into n parts with the space length being the minimum optimal value respectively. where n ranges from 2 to 5.

By means of detailed calculation, we came to the following conclusion: after dividing the magnetic valve into 2 to 5 parts, the minimal inductance decreases by 7%, 9.7%, 11.5%, 11.8% respectively comparing to that before dividing.

6. Experimental verification
In order to confirm the theory mentioned above, two MVCRs of the same size are manufactured to carry on specific experiments. One MVCR has only one magnetic valve in each AC winding and the length of them is 0.04m, with the rated voltage and current being 220V and 10A respectively. The other MVCR has two magnetic valves in each AC winding and the length of them is 0.02m. Additionally, the space length between the two valves is 0.09m, which equals to the minimum optimal length. The current in AC winding 1 was measured, which is shown as the waveform in Figure 7. It can be observed from that during the positive half-cycle, the current reached its peak point and had larger amplitude since the iron-core is saturated. In comparison, the amplitude of current is smaller during the negative half-cycle since the core is unsaturated. And the saturation degree of single-valve MVCR is \( \pi / 2 \) under this condition.
reduce the stray loss. It has a positive significance for decreasing MVCR’s loss.

are well elaborated by mathematical analysis and ANSYS simulation, and optimal design equations are given as well. At the same time, the reducing of the MVCR’s fringing magnetic flux can also reduce the stray loss. It has a positive significance for decreasing MVCR’s loss.

When the two MVCR are saturated given the same AC voltage and DC voltage, the reactive current generated by two-valve MVCR was 7.4% more than that generated by single-valve MVCR. The waveforms of current are shown respectively in Figure.8, from which can be observed that the amplitude of current generated by two-valve MVCR is slightly greater than that by single-valve MVCR under the same working condition. And the saturation degree of MVCR with single magnetic valve is $\pi/2$.

7. Conclusion

In this paper, an optimum design of iron-core of MVCR is presented including the method of dividing magnetic valves and the optimal space length between two adjacent valves. Initially keeping the total length of magnetic valves of MVCR unchanged, the experiment results showed that by dividing the single magnetic valve into several series-connected parts and adopting the optimum space length, it can effectively reduce the fringing magnetic flux and cut down the inductance of the AC winding of MVCR. Therefore the MVCR will generate more reactive current under the same working and control voltage, which improving the performance of MVCR. In this paper, the conclusions mentioned above are well elaborated by mathematical analysis and ANSYS simulation, and optimal design equations are given as well. At the same time, the reducing of the MVCR’s fringing magnetic flux can also reduce the stray loss. It has a positive significance for decreasing MVCR’s loss.

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