Study on harmonic characteristics and optimization of multi-stage magnetic valve controllable reactor

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Abstract. This paper proposes a multi-stage magnetic valve controllable reactor based on the traditional magnetic valve controllable reactor (MCR). According to the structural characteristics of multi-stage magnetic valve, the mathematical model of harmonic characteristics of multi-stage MCR device is established, and the cross-section parameters of each magnetic valve are optimized by immune algorithm. The results show that after the number of magnetic valve stages exceeds 3, the optimization of total harmonics is reduced, and both are lower than the national common harmonic standard. Finally, the established mathematical model is verified by simulation. The results show that the three-stage and above magnetic valve structure can control the harmonic current under the national standard. The four-stage MCR can suppress the harmonics well and improve the power quality input to the distribution network.

1. Introduction

Reactor plays an indispensable role in improving reactive power and various performance of electric energy. Especially on the basis of traditional reactor function, magnetron reactor has the advantages of continuous and smooth adjustment of its own capacity, less complex manufacturing process, high flexibility, reliability and low cost, and is widely used in rural distribution network [1]. However, when the magnetron reactor works in a saturated state, it will inevitably produce harmonic current and cause harmonic pollution [2]. The national power harmonic standard requires that each harmonic content is less than 4%. Therefore, how to reduce the harmonic current of magnetron reactor has become a research hotspot [3-5].

In [4], Tian Cuihua first proposed a two-stage magnetically saturated core structure. The third harmonic current content of this structure is less than 1% under the condition of semi-limit saturation of the core, but the third harmonic current content reaches 4.6% in the process of dynamic adjustment. In [5], Chen Xuxuan put forward the structure of multi-stage magnetic valve controllable reactor. The third harmonic current output of the structure is less than 3.1% in the whole dynamic regulation process, but the cross-section parameters of the multi-stage magnetic valve are not optimized. Therefore, it is necessary to cooperate with the passive filter in practical application and increase the construction cost. At present, most of the MCR devices used in distribution network are still single-stage magnetic valve structure, which has poor harmonic characteristics and low power quality [6].
However, the structure of multi-stage magnetic valve reactor needs further optimization [7-8]. Therefore, it is very important to design and improve the structure of magnetron reactor to optimize the harmonic characteristics for the application of MCR in distribution network [9-11].

In order to control the harmonic current content under the national harmonic standard and improve the power supply quality of distribution network, this paper puts forward a method of improving the power supply by applying a multi-stage magnetic valve controllable reactor with saturated magnetic valves to the distribution network. The results show that the device can suppress harmonics and improve the power quality of distribution network. Finally, the mathematical model is validated by simulation, and the waveform obtained is consistent with the theory.

2. Multi-stage MCR harmonic characteristics

2.1. Multi-stage MCR harmonic mathematical model

MCR is a reactor with the core saturation as the working principle. During the dynamic adjustment process, high-order harmonics are generated, which causes pollution to the distribution network. Multi-stage MCR devices are currently generally used to reduce harmonic currents injected into the grid. As shown in figure 1, the overall structure of the multi-stage magnetic valve type controllable reactor is composed of two identical and symmetric main iron core columns and side yokes [5]. \( B_1 \) and \( B_2 \) represent the magnetic induction strength in two core columns. \( A_b \) is the cross section area of core column. For multi-stage magnetic valve controllable reactor, the magnetic valve of its core column is composed of several different size magnetic valve cross sections \( A_{sn} \), and the corresponding length \( l_n \) is different.

\[
B_1 = A_{s1} B_1, \quad B_2 = A_{s2} B_2
\]

Figure 1. Core cross-section structure of the multi-stage MCR.

\( B_1 \) and \( B_2 \) are affected by magnetic induction intensity \( B_d \) produced by DC excitation during dynamic regulation. The relationship between saturation \( \beta_n \) and saturation \( B_{1n} \) and \( B_{2n} \) of magnetization curve of section 1 and \( n \) is:

\[
\beta_n = 2ar \cos \frac{B_{2n} - B_d}{B_{1n}} \quad (1)
\]

The magnetic induction intensity of each section is only related to the area of each section when the multi-stage magnetic valve controllable reactor is saturated.

\[
k_n = \frac{A_{sn}}{A_{s1}} = \frac{3A_{sn}}{A_b} = \frac{B_{2n}}{B_{1n}} \quad (2)
\]

\( k_n \) is the ratio of cross-sectional area. Formula (1) (2) can be deduced:

\[
\beta_n = 2ar \cos (k_n - 1 + \cos \frac{\beta_{1n}}{2}) \quad (3)
\]

The segmented core column is equivalent to an integral body of length \( l \), magnetic field intensity \( H_e \), and the current flowing through the winding is:

\[
\cdots
\]
\[ N_i l = H_i l = \sum_{k=1}^{n} H_k l_k \]  

(4)

In the formula, \( N \) is the number of turns of the core winding, \( H_k \) is the magnetic field strength of the \( k \) section, \( l_k \) is the length of the \( k \) section.

The flux through the core is equal to the sum of the flux of each cross section and the corresponding air gap section of the cross section:

\[ \phi = B_{an} A_{sn} + B_{on} (A_n - A_m) \]  

(5)

In the formula, \( B_{an} \) and \( B_{on} \) are the magnetic induction intensities of the core with the \( n \)-th cross section and the corresponding air gap.

If the magnetic field strength of the section and the corresponding air gap section are equal, then

\[ B_{on} = \mu_0 H_n \]  

(6)

The magnetization characteristics of the magnetic valve section of core column 1 can be obtained:

\[ H_s = \begin{cases} 0 & |B_i| < B_{s1} \\ B_s + \sum_{k=1}^{n-1} A_k B_k / \mu_0 l_k & B_{s(n-1)} < |B_i| < B_s \\ B_s > |B_i| > B_{sn} \\ -B_s < |B_i| > -B_{s(n-1)} \end{cases} \]  

(7)

The multi-stage MCR consists of two completely symmetrical core columns, so the total current \( i \) output to the distribution network is the sum of the current output from two core windings:

\[ i = \frac{l}{2N} (H_{e1} + H_{e2}) \]  

(8)

\( H_{e1} \) and \( H_{e2} \) are equivalent magnetic field strengths of two core columns.

According to the above formulas, the mathematical model of multi-stage MCR harmonic current characteristics is as follows:

\[ \begin{align*} 
\iota' & = \sum_{k=1}^{n} \frac{l_k}{2\pi l} (\beta_k - \sin \beta_k) \\
\iota'_{(2m+1)} & = \sum_{k=1}^{n} \frac{l_k}{(2m+1)\pi l} \left( \frac{\sin(m\beta_k)}{2m} - \frac{\sin((m+1)\beta_k)}{2(m+1)} \right)
\end{align*} \]  

(9)

In the formula, \( \iota' \) is the standard unitary value of fundamental current and \( \iota_{(2m+1)}' \) is the standard unitary value of odd harmonic current.

2.2. Section parameter optimization

According to formula (9), it is known that the current harmonic component of multistage magnetron reactor is related to series \( n \), section area \( A_{sn} \) and length \( l_n \), and the parameters of output harmonic are proportional to series. The area and length of each section play a decisive role in saturation and harmonic current. The current quality of reactor output can be improved by optimizing it. Therefore, immune algorithm is applied to optimize the calculation. The principle of immune algorithm is to simulate the biological immune system. It is a heuristic parallel search algorithm. In the process of calculation, the antigen evolves continuously in the solution space through immune operation until the optimal solution is found, which has the ability of fast convergence and global optimization [12].
In this paper, the aim of immune algorithm is to minimize the total harmonic distortion of excitation current of multi-stage magnetic valve core structure. In the optimization process, the antibody is the cross-sectional area and length parameters of all levels of magnetic valves, the antigen is the harmonic calculation function of multi-level magnetic valves, and the chromosome is the coding combination of cross-sectional area parameters and length parameters of all levels of magnetic valves. In the initial calculation, the cross-sectional area and length of all levels of magnetic valves can be set to be 1. After more than one calculation, the optimization results were selected as the next optimization of vaccine injection. Then the reciprocal of the total harmonic distortion rate of the excitation current is used as the fitness to optimize the calculation. The flow chart of immune algorithm optimization is shown in Fig. 2.

**Figure 2.** Immune algorithm optimization flow chart.

The optimization results of multi-stage magnetic valve structure immune algorithm are shown in Fig. 3.

**Figure 3.** Immune algorithm optimization result of the multi-stage MCR.

Figure 3 shows that the fewer the series of magnetic valves, the fewer the optimization parameters and the faster the optimization speed. The structure of two-stage magnetic valve only needs about 10 generations to get the best result, while the structure of five-stage magnetic valve needs about 230 generations. In addition, when the series of magnetic valves increases, the effect of harmonic optimization will gradually decrease. Due to the limitation of the core manufacturing process of reactor, the series of core magnetic valves of magnetic valve type controllable reactor should not exceed 4 stages. Therefore, the results of immune optimization for magnetic valves of stage 2, 3 and 4...
are listed in Table 1 only. The ratios $A'_n$ and $l'_n$ of the parameters $A_n$, $l_n$ and the first magnetic valve parameters $A_{s1}$ and $l_1$ optimized by immune algorithm are shown in the table below.

| parameter | Two-stage | Three-stage | Four-stage |
|-----------|-----------|-------------|------------|
| $A'_1$    | 1         | 1           | 1          |
| $l'_1$    | 1         | 1           | 1          |
| $A'_2$    | 1.9213    | 1.7108      | 1.7019     |
| $l'_2$    | 1.7451    | 1.3028      | 1.2760     |
| $A'_3$    | -         | 2.2369      | 2.2236     |
| $l'_3$    | -         | 1.6866      | 1.6980     |
| $A'_4$    | -         | -           | 2.7445     |
| $l'_4$    | -         | -           | 1.3230     |

From Table 1, when the series of magnetic valves exceeds 3, the optimum range of fitness decreases, that is, the optimum range of total harmonic distortion rate also decreases. Based on the data of Table 1, the theoretical distribution of each harmonic can be calculated.

3. Simulation analysis of multi-stage MCR

The magnetic valve of multistage MCR is saturated by segments in the dynamic regulation process, so it is necessary to adjust the general MCR simulation model according to the magnetization characteristics of the magnetic valve segments in the simulation process [13-14], and at the same time, the established mathematical model can be verified.

The number of segments of the magnetization characteristic curve of multistage MCR device is the same as that of its magnetic valve series. According to the established mathematical model, the parameters in the simulation model are set as follows: The B-H curve parameters of saturated reactor used in single stage magnetic valve structure is [0;0;0.001,1;1.001,2]; the parameters of the two-stage structure is [0, 0; 0.002, 1; 0.338, 1.919; 1.338, 2.919]; the parameters of the three-stage structure curve is [0, 0; 0.0019, 1; 0.1794, 1.7087; 0.4834, 2.2332; 1.4834, 3.2332]; the parameters of the four-stage structure curve is [0,0;0.0019,1;0.1334, 1.6998;0.3578,2.2199;0.7482, 2.7393; 1.7482, 3.7393]. The magnetization characteristic curve of multi-stage magnetic structure can be obtained as shown in Fig. 4.

![Figure 4](image)

Figure 4. Magnetic characteristics for multi-stage MCR.

It can be seen from Fig. 5 that the slope of the last straight line of the B-H curve of the different-stage magnetic valve structure is equal to the air permeability, that is, the value is 1. Based on the above magnetization characteristics, the harmonic current curves of different series MCR can be obtained by substituting them into the simulation model, as shown in Fig. 5.
Harmonic content

Time/s

Seventh
Third
Fifth

(a) One-stage

(b) Two-stage

(c) Three-stage

(d) Four-stage

Figure 5. Harmonic current curve of multi-stage MCR device.

Table 2. Multi-stage MCR device harmonic current amplitude.

| Harmonic amplitude (%) | One-stage | Two-stage | Three-stage | Four-stage |
|------------------------|-----------|-----------|-------------|------------|
| Third                  | 9.8       | 4.6       | 2.9         | 2.4        |
| Fifth                  | 3.7       | 1.7       | 1.6         | 1.4        |
| Seventh                | 1.8       | 0.9       | 0.7         | 0.7        |

The third harmonic amplitude of the two-stage magnetic valve is 4.6% higher than that of the national standard. When three or more magnetic valves are used, the third harmonic current amplitude is always less than 3.0%, which meets the requirements. After 0.45s, the harmonic amplitude of four-stage magnetic valve structure is less than 1.5%. The amplitude of the 5th harmonic is less than 1.5% and that of the 7th harmonic is less than 1.0% during the whole working process, which are well suppressed. That is to say, by using three-stage or more magnetic valve structure, the harmonic optimization of the core magnetic valve structure is realized, which can greatly reduce the harmonic caused by the magnetic valve structure and improve the quality of the output current. When the installation site has higher requirements for equipment harmonic, the four-stage magnetic valve structure can be considered. (Table 2)

4. Conclusion

In this paper, a multi-stage magnetron reactor with piecewise saturation of magnetic valve is proposed, and its harmonic characteristics are studied. The main conclusions are as follows:

(1) According to the structural characteristics of multi-stage magnetic valve controllable reactor, a mathematical model of harmonic analysis is established, and the structural parameters such as core cross-section area and length are optimized by immune algorithm. According to the results, the optimum amplitude of the total harmonics decreases when the series of magnetic valves exceeds three stages.

(2) According to the simulation results, the harmonic current can be controlled by three-stage or more magnetic valve structure under the national standard, and the four-stage magnetic valve-controlled reactor can suppress each harmonic and improve the power quality input to the distribution network.
5. References

[1] M.Z.Yu, B.C.Chen, Z.H.Cao, Automat Electron Power Sys .32,87(2008)
[2] J. X. Yuan, J. W. Zhou, C.T, Yu, et. al, IEEE Trans. Magn. 51,233(2015)
[3] X.M.Tian, X.An, D.S.Yuan, Power sys techno. 38, 217 (2014)
[4] C.H.Tian, B.C.Chen, Trans Chin Electron Soc. 21, 19(2006)
[5] X.X.Chen, C.H.Tian, B.C.Chen,Trans Chin Electron Soc. 26,57(2011)
[6] F .Mao,S.Y.Liao,High Voltage Appar.48,256(2016)
[7] D.M.Gao, H.W. Yuan,Y.B.Zhang, High Voltage Appar .44,389(2008)
[8] D.M.Song, Electric Power Tehno.6,33(2010)
[9] X.Y. HE, Lin L, High Voltage Appar .54,117(2018)
[10] J.Yang, H.X.Chen, X.Zhang, J. North China Electr. Power Univ.43,38 (2016)
[11] X.L.Dai, Power sys techno. 6,11 (1999)
[12] R.B.Xiao, L.Wang, Chin.J. Comput .12,1281(2002)
[13] X.X.Tian, Q.F.Qing, Trans Chin Electron Soc .6, 64 (2003)
[14] X.X.Tian, Q.F.Qing, Trans Chin Electron Soc .4, 18 (2002)