Modeling and Simulation of the Multi-stage Saturable Magnetically Controlled Reactor with Very Low Harmonics

Xuxuan Chen, Baichao Chen, Cuihua Tian, Jiaxin Yuan

Abstract---- **Magnetically controlled reactors (MCRs) as shunt reactors have offered flexible ways regulating the reactive power in the power system. MCRs can be implemented in ultra high voltage power systems and are much more economical and operational than the thyristor controlled reactors (TCRs). However, one remarkable defect of the MCRs is that they will inject great harmonics into the power system. The maximum 3rd and 5th harmonic component of the conventional MCRs are about 7% and 3% of the fundamental current component, respectively.**

In this paper, the structure and the mathematical model of a harmonic free multi-stage saturable MCR (MSMCR) are proposed. The iron cores of this device are designed to more than four stages. Each stage has the same length but with different areas so that the stages are saturated at different time when the dc bias current in the control winding increases, and it will result in that the harmonics created by these stages be compensated for each other. The design uses the particle swarm optimization algorithm (PSO) to decide the areas of the stages based on the harmonics mathematical model of the MSMCR. Since the 3rd harmonic will not be injected to the power systems if delta connected symmetrically, the current harmonics injected to the power system can be limited to as low as 0.8% of the rated output current of the MSMCR, theoretically. A simulation is finally produced to verify the research in PSCAD/EMTDC.

Keywords: magnetization characteristic, harmonic analysis, magnetically controlled reactor (MCR), magnetic variable control, saturable reactor, PSCAD/EMTDC.

I. INTRODUCTION

WIND and solar power generation are becoming the most important renewable energy sources all around the world. However, one of the most important problems to be solved is that the control of generated or consumed reactive power in wind and solar power generation. Nowadays, there already exist several methods to control the reactive power in the power system such as static var compensators (SVC) and the static synchronous compensators (STATCOM). The most common SVCs are thyristor controlled reactors (TCR) [1]. The reactive power control principle of TCR and MCR are similar [2]. They both need capacitor banks in parallel to generate or absorb the reactive power. The working principle of the MCR is similar to the controllable reactor [3]. While it is quite different for STATCOM to generate or absorb reactive power. It depends on the difference between the terminal voltage of the VSC and the AC voltage at the point of connection [4].

The reactive power control of the TCR, MCR and STATCOM is stepless adjustable and the response time is as fast as 20ms. The advantage of the MCRs over TCRs and STATCOM is that MCRs can be connected directly to the ultra high voltage up to 1000 kV without numerous thyristor valves in series [5]. However, MCRs will inject great harmonics into the unbalanced three-phase power system. The maximum 3rd and 5th harmonic component of the conventional MCRs are about 7% and 3% of the fundamental current component, respectively [6].

In order to reduce the harmonics of the MCRs, the core structure and the mathematical model for harmonics analysis of a multi-stage saturable MCR (MSMCR) are proposed in this paper. The cores of the MSMCR are designed to more than four stages only using the same materials as the normal power transformers. The stages will be saturated at different time when the dc bias current in the control winding increases. Then, the harmonics created by these stages can be compensated for each other automatically, and the total harmonics of the MSMCR are reduced. The theoretical results show that the peak values of the current harmonics in single-phase MSMCR are greatly reduced. The peak values of the 3rd, 5th and 7th current harmonics are 2.55%, 0.9% and 0.7%, and RMS values are 1.80%, 0.64%, 0.49%, respectively. The harmonics are much less than the traditional MCRs. The results are tested and verified in PSCAD/EMTDC.

II. MODEL AND PARAMETER DESIGN OF MSMCR

The MCR is based on the working principle of the magnetic magnifier. The working principle of the conventional MCR is detailed in [7]. By controlling the dc current through the control winding, the iron cores of the MCR are deeply saturated, and the reactance of the MCR will be changed depends on the saturation degree of the iron cores.

There is only one stage (magnetic valve) in each iron core of the conventional MCR. The conventional model is shown in Fig. 1. Control windings are coupled by winding taps on each half of the iron cores and thyristors are connected

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between the taps. The turn for each control winding is $N_k/2$. High rated thyristors is not required because the value of N_k/N (δ) is usually 5%. The wind taps results that the voltages upon the thyristors are relatively lower. For a 500 kV power system, there is only 25kV voltage on the thyristors. So the quantities of the thyristors in series are much fewer than the STATCOM.

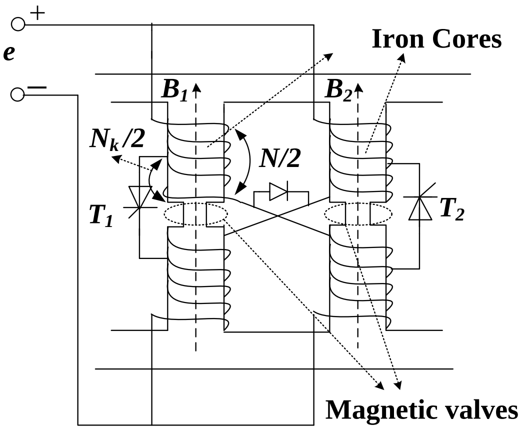
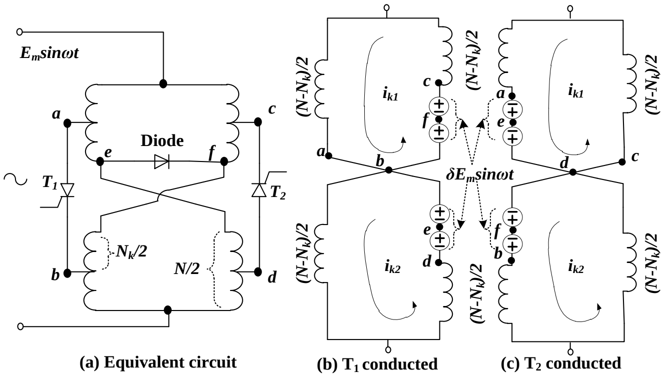


Fig. 1. Model of the conventional MCR

The reactance of the MCR is regulated by controlling the dc current magnitude through the control winding which changes the magnetic field strength in the magnetic valves. The equivalent working circuit of the MCR is shown in Fig.2a. The commutation circuits when thyristors T_1 or T_2 is conducted are shown in Fig.2b and Fig.2c, respectively. The dc control current i_{k1} and i_{k2} can be regulated by changing the switching angles of the thyristors. As the switching angle of the thyristors increases, the dc control current in the control winding decreases and the reactance of the reactor will increase.



(a) Equivalent circuit (b) T_1 conducted (c) T_2 conducted

Fig. 2. Equivalent circuit of the MCR

In this paper, the iron cores of the MCR are specially designed. The magnetic valves consist of more than four stages. The stages are also called the multi-stage saturable magnetic valves. The purpose of the design is to reduce the output harmonics of the MCR. A multi-stage saturable iron core design is shown in Fig.3. A_b is the area of the iron core, A_{s1} is the area of the first stage, A_{s2} is the area of the second stage and A_{sn} is the area of the nth stage. If consider $l_1=l_2=...=l_n$, the B-H characteristic of the iron cores can be described in (1),

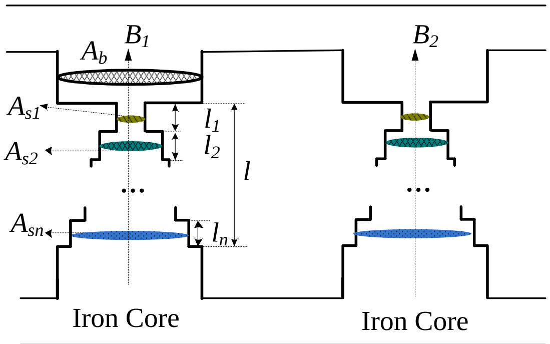


Fig. 3. Design of the multi-stage saturable iron cores

$$H = f(B) = \begin{cases} 0 & |B| < B_{t1} \\ \dfrac{B - \sum_{k=1}^{n-1} \frac{A_{sk}}{A_b} B_{tk}}{\mu_0} & B_{t(n-1)} < |B| < B_{tn} \\ \dfrac{B - \sum_{k=1}^{n} \frac{A_{sk}}{A_b} B_{tk}}{\mu_0} & |B| > B_{tn} \\ \dfrac{B + \sum_{k=1}^{n-1} \frac{A_{sk}}{A_b} B_{tk}}{\mu_0} & -B_{tn} < |B| < -B_{t(n-1)} \end{cases} \tag{1}$$

where B_{t1} and B_{tn} (n=2,3,4…) represent the magnetic flux density when the first and the nth stage begin to saturate, respectively.

In (1), B_{ts} represent the magnetic flux density when the iron cores begin to saturate. The relationship between B_{ts} and B_{tn} can be described in (2),

$$B_{tn} = \frac{A_{sn}}{A_b} B_{ts} \tag{2}$$

The analyses of B_1 and B_2 are the same because the structure of the MSMCR is symmetrical. Taking B_1 in the left iron core as example, as shown in Fig. 4, if the peak value of B_1 is greater than the magnetic flux density B_{tn}, the nth stage begins to saturate then. β_1 and β_n represent the saturation degrees of the first and the nth stage in a power frequency.

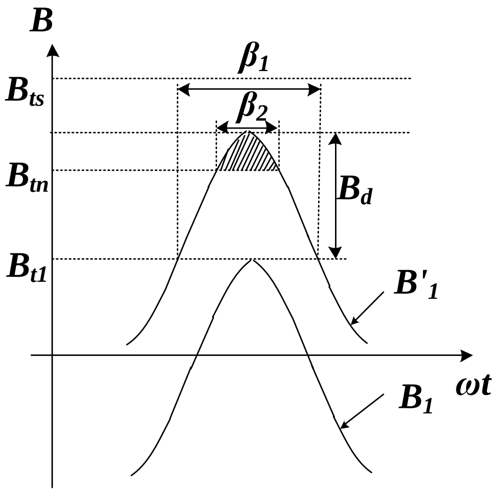


Fig. 4. Schemetic of the magnetic flux density versus particular saturated stages

The mathematical model for current harmonics analysis of the MSMCR is shown in (3),

$$\begin{cases} i_1^* = \sum_{k=1}^{n} \frac{1}{2\pi}(\beta_k - \sin\beta_k) \\ i_{(2m+1)}^* = \sum_{k=1}^{n} \frac{1}{(2m+1)\pi}\left\{ \frac{\sin(m\beta_k)}{2m} - \frac{\sin[(m+1)\beta_k]}{2(m+1)} \right\} \end{cases} \quad (3)$$

$$\beta_n = 2\cos^{-1}\left(\frac{A_{sn}}{A_{s1}} - 1 + \cos\frac{\beta_1}{2}\right)$$

where i_1^* represents peak value of the nominal fundamental current, and $i_{(2m+1)}^*$ (m=1,2,3. . .) represents the peak value of the nominal current harmonics.

The PSO algorithm is chosen to calculate the areas ratios among these stages using (3) and to get the optimization results of the harmonics performance of the MSMCR. PSO is very effective solving this nonlinear optimization problem [8]. The results are shown in Table. I.

TABLE I
AREAS RATIO AMONG THE STAGES IN THE IRON CORES

Stages	Ratios (A_{sn}/ A_b)	B-H curve slopes (μ_n)
1	1.0000	7.000
2	1.6396	3.500
3	1.9874	2.333
4	2.2766	1.750
5	2.6270	1.200
6	2.8924	1.167
7	2.9835	1.000
Iron core	3.0000	1.000

The B-H magnetization the MSMCR is calculated using (4) and the curve is shown in Fig.5. μ_7 equals μ_0 which is the magnetic permeability in the air.

$$H_n = H_{n-1} + \frac{B_{t_n} - B_{t_{(n-1)}}}{\mu_{n-1}} (n \geq 2) \quad (4)$$

In (4), H_1 is equal to zero.

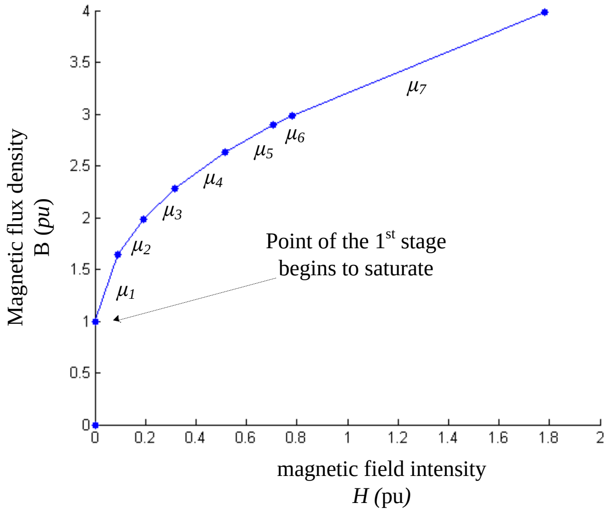


Fig.5. The B-H characteristic of the stages in iron cores

The theoretical results of the current harmonics analyses using (3) are shown in Fig.6. The peak values of the 3rd, 5th and 7th current harmonics are 2.55%, 0.9% and 0.7% of the rated output current, and the RMS values are 1.80%, 0.64%, 0.49%, respectively.

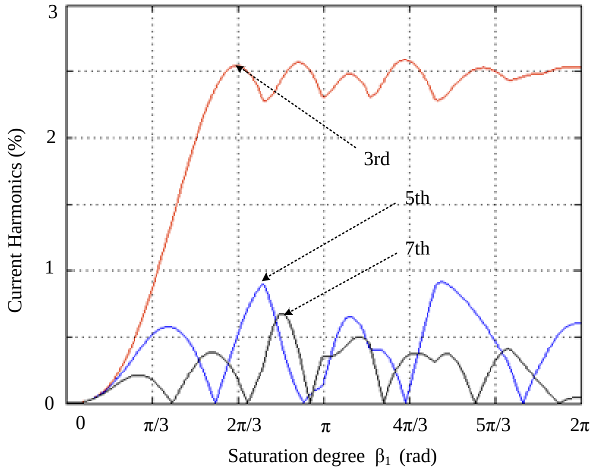


Fig. 6. Peak values of the current harmonics (3rd, 5th and 7th) of MSMCR versus the rated output current

III. SIMULATIONS OF THE SINGLE PHASE MSMCR IN PSCAD/EMTDC

A. *The Circuit of the Single Phase MSMCR*

In order to verify the results of the theoretical harmonics analyses in section II, a transformer module which can simulate the saturation characteristics of the transformers can fulfill the simulation requirement. In this paper, the single-phase MSMCR is modeled using two UMEC transformers model in PSCAD/EMTDC. The simulation can also be done in MATLAB/Simulink or ATPdraw/EMTP, etc.

This paper focuses on the harmonics reduction of the MCR, so the voltage level is not an important factor in the simulation. A low voltage power system is simulated in this paper. However, researchers can adjust the voltage up to 500 kV while need.

The primary windings of the UMEC transformers are connected with different polarity and secondary windings are connected with the same polarity. The dc current controller is composed of a single-phase full-bridge controlled rectifier. The source of the rectifier derives from the ideal transformer of which the tap ratio is 20/1. As the switching angle of the thyristors increasing, the dc control current in the control winding decreases and the reactance of the reactor will increase. Complex controller or control algorithm is not required for this device. The circuit design is shown in Fig.7.

The two voltage sources in the circuit are completely independent which means that the phases of the sources can be different. The line to ground voltage magnitude value is 440 V for both sources. The 0.01 Ω resistors are set to avoid singularity (a zero diagonal) encountered problems in PSCAD/EMTDC.

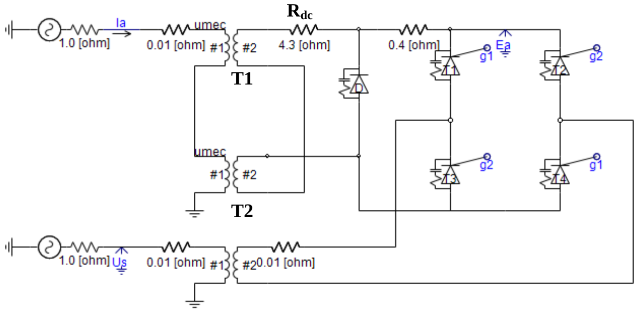


Fig. 7. The Circuit of the single phase MSMCR

B. UMEC Transformer Configurations

The configurations of two UMEC transformers are the same. The primary voltage (RMS) and secondary voltage (RMS) are both 220 V which is a half of the source voltage of the ac side. The apparent power rating of the UMEC transformers are all 2 kVA. The ratio of core yoke length to the core winding-limb length and the ratio of core yoke area to the core winding-limb area are 1.6 and 1, respectively.

The current harmonics of the ac side can be reduced by configuring the saturation characteristics of the UMEC transformers. From Table I, the saturation curve in UMEC transformers can be calculated which is shown in Table II. In this table, the gradients of the lines after point 8 are the same. Actually, the peak value of the magnetic flux in the primary winding can only reach 3 pu.

C. Simulation Results

The stages are saturated one after another when MSMCR begins to output its rated current. Note that, the iron cores of the largest areas in the MSMCR will not saturate which results that the flux in the cores is limited to 3 pu. The limitation can be configured by setting the value of the resistor R_{dc} in the control winding. The flux waveform is shown in Fig.8 when MSMCR output the rated current.

TABLE II
SATURATION CURVE CONFIGURATION IN UMEC TRANSFORMER

Point	Current (%)	Voltage (*pu*)
1	0	0
2	0.1	1
3	9.14	1.6396
4	19.08	1.9871
5	31.47	2.2766
6	51.49	2.6270
7	70.45	2.8924
8	78.26	2.9835
9	178.26	3.98935
10	278.26	4.9835

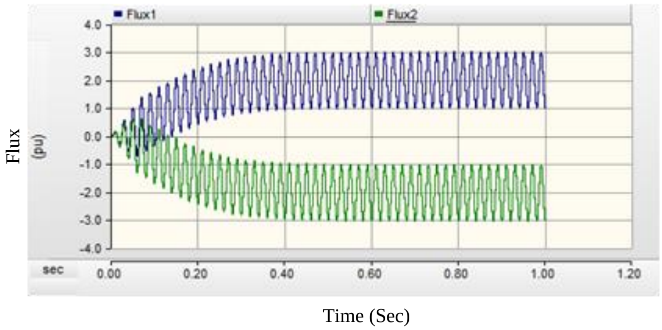


Fig. 8. The flux waveforms of the UMEC transformers

The output current and the RMS value of the MSMCR are shown in Fig.9. The peak and RMS value are 5.05 A and 3.512 A, respectively.

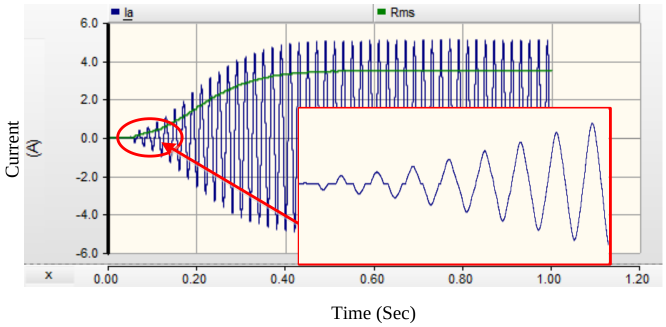


Fig. 9. The output current and the RMS value of the MSMCR

The 3rd, 5th, 7th and 11th harmonics of the output current are shown in Fig.10. The waveform is similar to Fig. 6.The 3rd harmonic is the largest in all harmonics and the peak RMS value is 0.0956 A which is 1.89% of the peak value of the rated output current. The peak values of the 5th, 7th and 11th harmonics are 0.032 A, 0.0195 A and 0.013 A which are 0.63%, 0.39% and 0.26% of the peak value of the rated output current, respectively. The THD of the rated output current is 2.45%. The simulation results are very close to the theoretical results which are 1.80%, 0.64%, 0.49% for the 3rd, 5th and 7th harmonics, respectively.

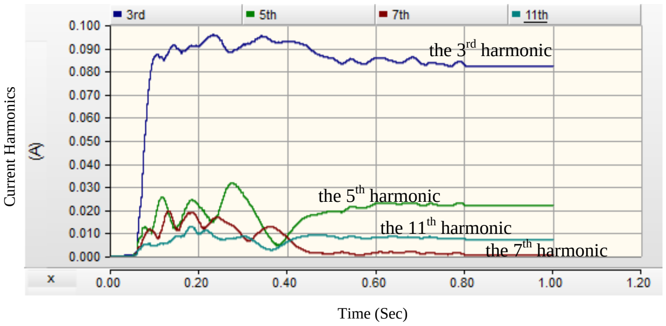


Fig. 10. The 3rd, 5th, 7th and 11th harmonics of the output current

IV. SIMULATIONS OF THE THREE-PHASE MSMCR IN PSCAD/EMTDC

The three-phase MSMCR can be either delta or star-connected to the power system. Because the harmonics results are the same to the single phase MSMCR if delta connected, so we focus on the simulations when MSMCR is the delta connected to the power system in this chapter.

The schematic of the delta connected three-phase MSMCR and its control are shown in Fig.11

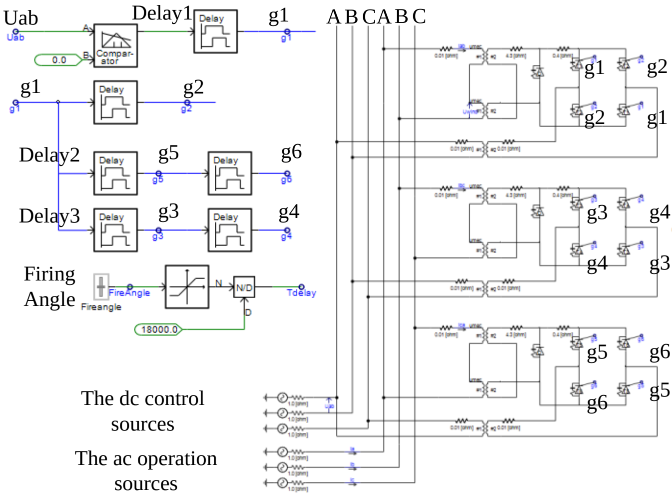


Fig. 11. Schematic of the delta connected three-phase MSMCR

A comparator is used to get a synchronous pulse signal. The comparator outputs 1 when the voltage U_{ab} is greater than zero and outputs zero when U_{ab} is less or equal to zero. A variable named T_{delay} is set as the ON delay time in the first timed on/off logic transition (Delay1). T_{delay} can be regulated through the slider named fire angle of which the value is limited between 0 and 180. The ON delay time of the timed on/off logic transition named delay2 and delay3 are set to 0.00666 s and 0.01333 s. The 6 triggering pulses are generated in this way.

The voltages of the sources are set to 254 V in order to get the same voltage with the star connect method, while the other parameters remain the same with the single phase MSMCR.

The output currents (ac operation source currents) and the RMS value of the MSMCR are shown in Fig.12. The peak and RMS value are 8.69 A and 6.08 A, respectively.

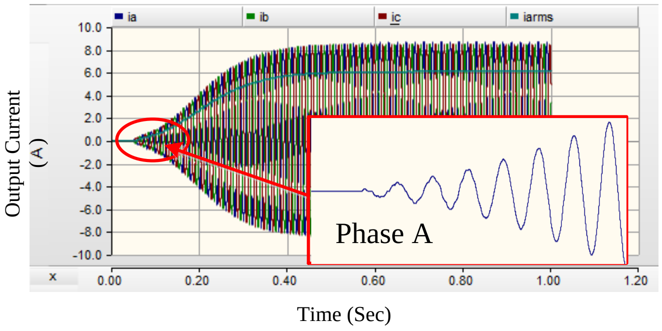


Fig. 12. The output current and the RMS value of the MSMCR

The 3rd, 5th, 7th and 11th harmonics of the output current are shown in Fig.13. The 5th harmonic is the largest in all harmonics and the peak value is 0.0548 A which is 0.63% of the peak value of the rated output current. The peak values of the 3rd, 7th and 11th harmonics are 0.0476 A, 0.0311 A and 0.0206 A which are 0.55%, 0.36% and 0.24% of the peak value of the rated output current, respectively. The THD of the rated output current is 0.8%.

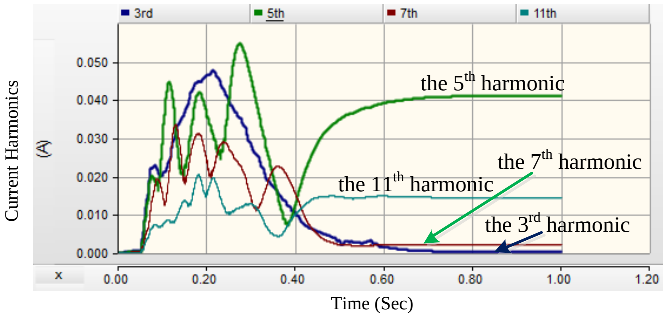


Fig. 13. The 3rd, 5th, 7th and 11th harmonics of the output current

V. AUTOMATIC CONTROL METHOD OF THE MSMCR

The control methods of the single-phase and three-phase MSMCR are almost the same. Both methods need to control the firing angle of the thyristors. The control scheme of the single phase MSMCR is shown in Fig. 14.

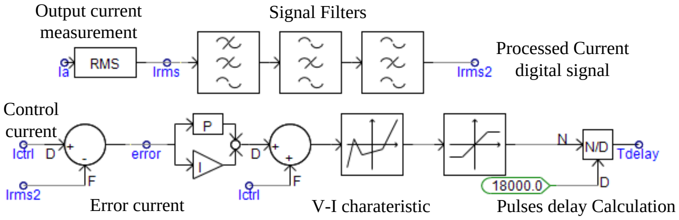


Fig. 14. Single-phase MSMCR control scheme

A current measuring and filtering system is used to get the RMS current value. This system is formed with three second order transfer functions modules including one low pass filter (LPF) and two band-rejection filters(BPF). The parameters of them are shown in Table III.

TABLE III
THE PARAMETER OF THE MEASURING AND FILTERING SYSTEM

	LPF	BRF1	BRF2
Gain	1	1	1
Damping Ratio	0.57	0.16	0.16
Characteristic Frequency	90	120	60

The V-I characteristic of the MSMCR is very important in the control method shown in Fig. 14. Please note that, the data in Table IV will be different when the parameters of the source voltage and the transformer capacity are changed. The V-I characteristic curve can be obtained by manually regulating the firing angle of the thyristors from 0 to 180 degrees. In PSCAD/EMTDC, the V-I characteristic is implemented using the non-linear transfer characteristic module. The characteristic is shown in Table III. In the table, the X axis represents the output current and the Y axis represents the firing angle. The module outputs the firing angle control signal depending on the control current.

The hardlimiter limits the output of the V-I Characteristic between 0 and 180. The PI controller parameters are shown in Table V.

TABLE IV
THE V-I CHARACTERISTIC OF THE MSMCR

Point	X axis (A)	Y axis (Degree)
1	0	180
2	0.149	160
3	0.563	140
4	1.129	120
5	1.793	100
6	2.404	80
7	2.941	60
8	3.301	40
9	3.513	20
10	3.514	10

TABLE V
THE PARAMETER OF THE PI CONTROLLER

	Value
Propoetional Gain	0.5
Integral Time constant	0.5
Maximum Limit	2e-5
Minimum Limit	-2e-5
Initial output of Integrator	0.0

A waveform of the single phase MSMCR output current raises from zero to rated using the automatic control method is shown in Fig. 15. The waveform shows that the transient process is as low as 60ms when the firing pulses signals were given to the thyristors at the time 0.2 s in the simulation. The process time can be less than 60ms by shortly increasing the rectifier source voltage.

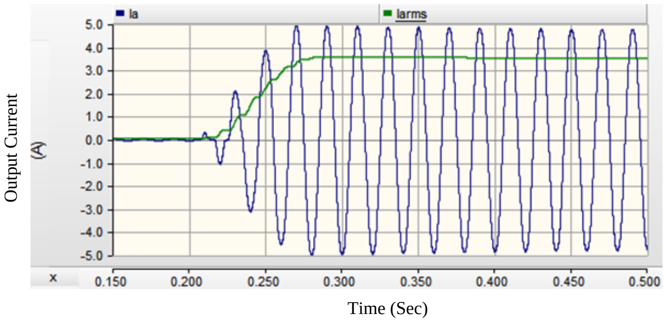


Fig. 15. Output current waveform from 0 to rated

A waveform of the single phase MSMCR output current raises from rated to zero is also shown in Fig.16. The waveform shows that the transient process is as low as 25 ms when the firing pulses signals were given at the time 1s. The process time can be less than 25ms by shortly increasing the resistor R_{dc} value.

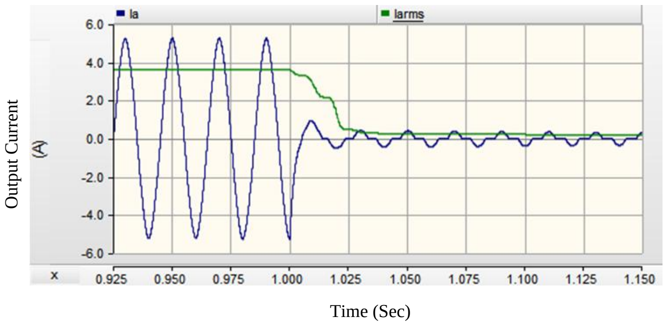


Fig. 16. Output current waveform from rated to zero

VI. CONCLUSIONS

The model and simulations of a harmonic free multi-stage saturable magnetically controlled reactor are proposed in this paper. MSMCR is designed to solve the harmonics problems and provide a more flexible way to control the reactive power in the power system. The peak values of the 3rd, 5th and 7th current harmonics in single-phase MSMCR are 2.55%, 0.9% and 0.7%, and RMS values are 1.80%, 0.64%, 0.49%, respectively. Simulations for single-phase and three-phase MSMCR systems show that the harmonics are much less than the TCR and traditional MCR.

An automatic control method for the MSMCR is also given. The results show that the transient process time is as short as 60 ms in 220 V system and can be shorter in higher voltage systems. Researchers can adjust the voltage up to 500 kV while need.

The research shows that the MCRs have great potential and advantages for power quality control and reactive power compensation and offer much more flexible and economical ways regulating the reactive power in the power systems.

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