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Simulation Analysis of Control System in an Innovative Magnetically-Saturated Controllable Reactor

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Abstract

Controllable saturation reactors are widely used in reactive power compensation. The control system of controllable saturation reactor determines adaption speed, accuracy, and stability. First, an innovative type of controllable saturation reactor is introduced. After that the control system is designed, and a self-tuning algorithm in PID controller is proposed in the paper. The algorithm tunes PID parameters automatically with different error signals caused by varied loads in power system. Then the feasibility of the above algorithm is verified by Simulink module of Matlab software. The results of simulation indicate that the control system can efficiently reduce adaption time and overshoot.

Keywords

Controllable Saturation Reactor; Parameter Self-Tuning; PID Controller; Reactive Power Compensation

1. Introduction

Reactive compensation apparatus are used in power system to reduce losses in power transmission line, to ensure stability of voltage, and to adjust power factor [1]. The Magnetic valve type magnetically-saturated controllable reactor (MCR) is a main type of reactive compensation apparatus [2]. However, the saturation position of Magnetic valve type MCR is in the main limbs of the iron core, which causes unsatisfactory heat dissipation performance. And Magnetic valve type MCR is three-phase six-limb structure, which costs a number of materials [3]. An innovative controllable reactor, side-limes and side-yokes magnetic-saturation type controllable reactor (SSMCR), was proposed by researchers at Chinese Academy of Sciences, Institute of Electrical Engineering. The saturation position of SSMCR is changed to side limbs and side yokes, which efficiently improves heat dissipation performance and reduces material cost [4].

Control system of MCR plays the key role. PID controller and DC-DC converter are applied in SSMCR to control its reactance. DC-DC convertor uses only one IGBT. PID controllers are extensively used in industrial

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automation. However, when applied in nonlinear, high order and time-delayed linear systems, conventional PID controller may cause long adjusting time, big overshoot, and even system out of control [5]. And what's more, extremely complicated and fuzzy systems have no precise mathematical models. To solve the problems, various modified conventional PID controllers such as expert control were developed [6], and Non-conventional PID controllers based on fuzzy logic and genetic algorithm have been designed as well [7]-[9]. Due to frequent drastic variation of loads and nonlinearity of SSMCR, a self-tuning PID control algorithm is proposed in this paper. Then the simulations are conducted to demonstrate its feasibility and effectiveness.

2. Control System Design

Figure 1 illustrates the outline of SSMCR. Compared with the magnetism valve type MCR, SSMCR changes its saturation position to side-limes and side yokes. DC exciting windings are installed at side-limes. When Φ_A, Φ_B and Φ_C are sine AC magnetic flux, the Φ_1, Φ_2, Φ_3 and Φ_4 are not standard sine wave and contain odd harmonics.

Figure 2 is the vector diagram, where Φ_1, Φ_2, Φ_3 and Φ_4 are fundamental waves.

If the side-limb windings are excited by DC current, the DC flux will flow through side limbs and yokes. Therefore, magnetic saturation level of side limbs and yokes are changed and its magnetic resistances are changed as well. As a result, the reactance of SSMCR is changed. Its reactance can be calculated as follow:

$$X_M = \frac{2\pi f W^2}{R_\delta + R_c} = 2\pi f W^2 \mu_0 S_F \left(\frac{\mu_r}{a\mu_r + l} \right) \tag{1}$$

where W is number of turns of AC winding, R_δ is magnetic resistance of air gap, R_c is magnetic resistance of side limbs and yokes, S_F is cross-section area of side limbs and yokes. α is a constant related with length of air gap, cross-section area of core. μ_r is relative permeability which reflects the saturation level of material.

In conclusion, the reactance of SSMCR can be controlled by the DC current in side-limbs winding. μ_r is changed with I_{DC}, the equation of $\mu_r = f(I_{DC})$ cannot be given because of its particular complexity and nonlinearity. The relationship $I_{DC} - X_M$ of SSMCR shows in **Figure 3**. The result is obtained by experiments under U = 380 V.

Figure 4 shows a typical power grid situation applied SSMCR and **Figure 5** is the scheme diagram of control system. ATT7022 is used for as data acquisition equipment (DAE) to collect data of power grid system such as

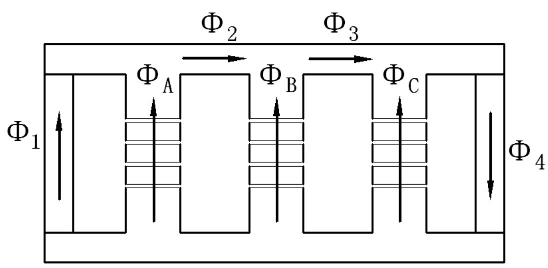

Figure 1. Construction and magnetic circuit of SSMCR.

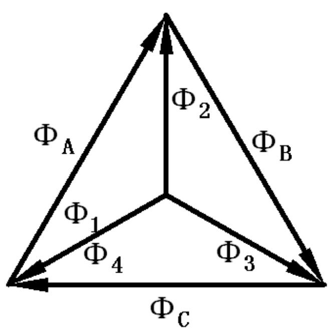

Figure 2. Vector diagram of magnetic flux.

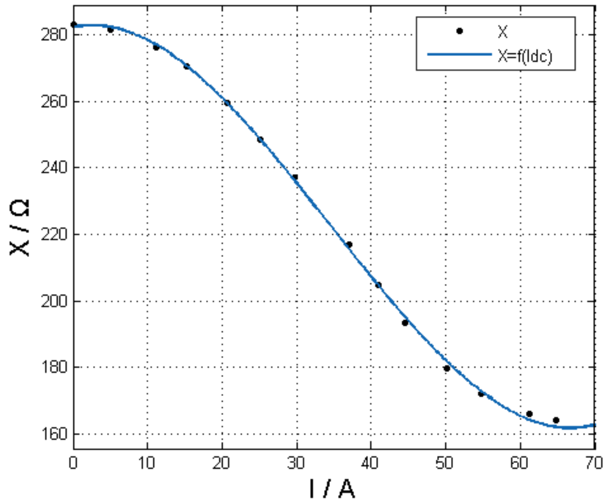

Figure 3. Relationship between DC current and reactance.

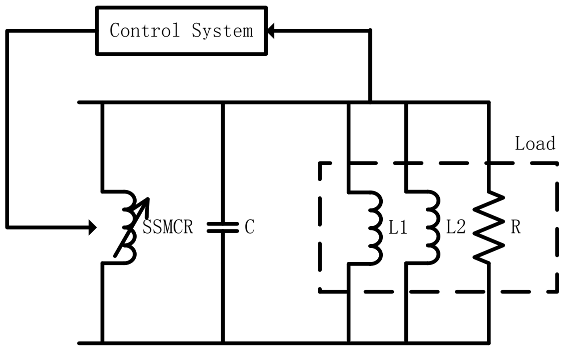

Figure 4. Typical power grid situation applied SSMCR.

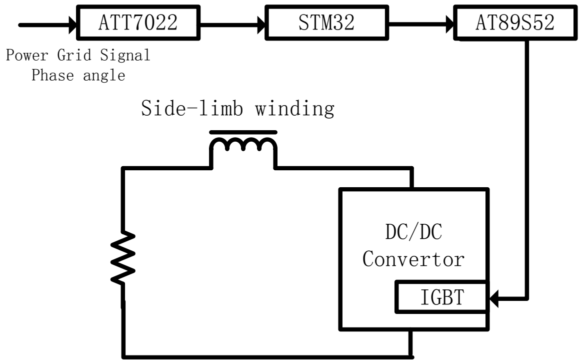

Figure 5. Scheme diagram of control system.

power factor and phrase angle. STM32 is used as the PID controller which controls the phrase angle (or power factor) of SSMCR to a certain set-point. And the AT89S52 is used as executor to drive the IGBT. In our system, the control system adapts the reactance of SSMCR in terms of phrase angle.

3. Self-Tuning PID Control Algorithm

PID controller controls the system based on error signal between set-point and system output. **Figure 6** illustrates the PID controller of SSMCR.

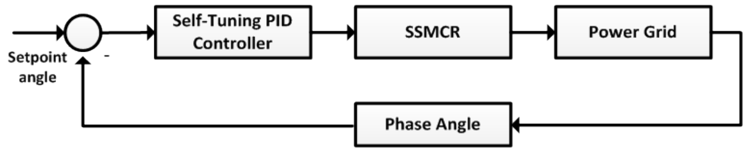

Figure 6. Schematic diagram of PID controller.

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{d}{dt} e(t) \tag{2}$$

$$e(t) = s_{out}(t) - s_{setpoint}(t) \tag{3}$$

where K_P, K_I and K_D are proportional, integral and derivative parameters. K_P depends on the present error, K_I depends on the accumulation of past errors, and K_D is a prediction of future errors, based on current change rate [5].

A classification method of error signal $|e(t)|$ (or $|e'(t)|$ when it comes to derivative) is given as R_i:

$$a_i M \le |e(t)| < a_{i+1} M \tag{4}$$

$$a_i M' \le |e'(t)| < a_{i+1} M' \tag{5}$$

where $0 \le a_i < a_{i+1} \le 1$, $0 < i \le N$, $N \in Z^*$. M and M' is the maximum of expected error.

Based on classification of error signals, parameters tuning principle is designed as: when error signal $|e(t)|$ (or $|e'(t)|$) rises, proportional should rise, integral should decrease, and derivative should rise. Parameter adaption rules are given (R_i):

$$P_{new} = P_{old} + \Delta P_i \cdot P_0 \tag{6}$$

$$I_{new} = I_{old} + \Delta I_i \cdot I_0 \tag{7}$$

$$D_{new} = D_{old} + \Delta D_i \cdot D_0 \tag{8}$$

where P_{new}, I_{new} and D_{new} are the results of parameter tuning. P_{old}, I_{old} and D_{old} are values before parameter tuning. P_0 is the original value of PID controller. ΔP is adaption rate and $|\Delta P| < 1$. ΔP is regarded as the adaption speed of proportional.

When SSMCR is working, the parameters are changed frequently by the controller based on the proposed algorithm. In terms of different classification of error signals, ΔP_i can be found in the rule-table which is given based on SSMCR. Therefore, parameters can be changed in different speeds. Part of rule-table is given in the **Table 1**.

4. Simulations

The feasibility and effectiveness of the proposed algorithm are simulated on Matlab. Input is random step signal and outputs are produced by conventional PID controller and self-tuning PID controller. According to output curves (**Figure 7**), the overshoot produced by conventional PID controller is 7.3% of input variation in average and adaption time is 0.91 s in average. Compared with conventional PID algorithm, the self-tuning PID algorithm can efficiently reduce adaption time to 0.13 s and overshoot to zero.

The model of SSMCR is built as follow. The result is produced by curve fitting based on data in **Figure 3**.

$$X_M = 0.001212 I_{DC}^3 - 0.1272 I_{DC}^2 + 1.489 I_{DC} + 273.1 \tag{9}$$

where X_M is reactance of SSMCR and I_{DC} is exciting DC current.

In order to simulate the self-tuning PID algorithm in typical power grid situation in terms of **Figure 4**, the resistance (R) and inductance (L) of load, and capacitance (C) of compensation capacitor should be chosen properly for building the simulation model. When C and L are fixed and R varies, the **Figure 8** shows the controllable zone of SSMCR. And **Figure 9** is on the situation that R and L are fixed and C varies. Controllable zone is the area between the two curves (maximum curve and minimum curve of system phrase angle).

According to **Figures 8** and **9**, we chose R = 1000 Ω and C = 20 μF. On this situation, the controllable zone shows in **Figure 10**.

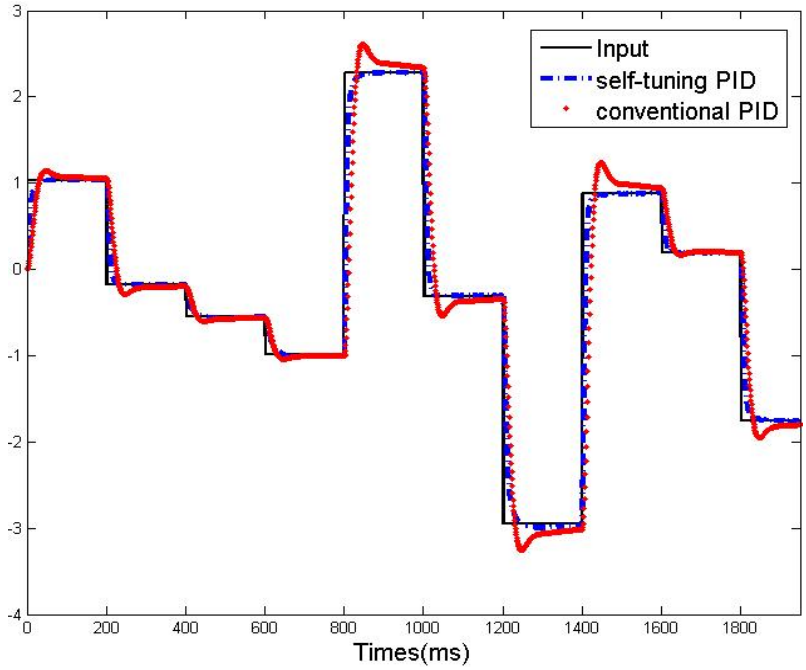

Figure 7. Outputs of conventional and self-tuning algorithm.

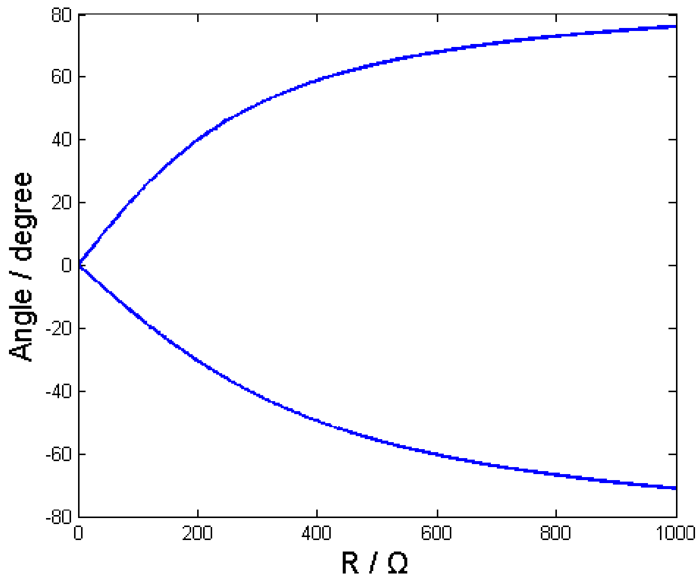

Figure 8. Controllable zone with resistance of loads.

Table 1. Part of rule-table of proportional.

Interval	Proportional		
	Δ	Min	Max
[0, 0.25)	0.480	1.00	3.00
[0.25, 0.5)	0.270	1.00	3.00
[0.5, 0.65)	0.150	1.00	3.00

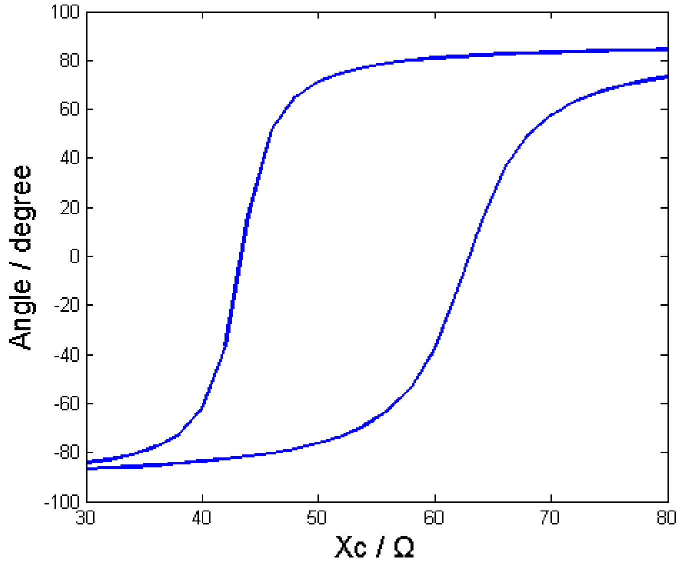

Figure 9. Controllable zone with capacitance of capacitor.

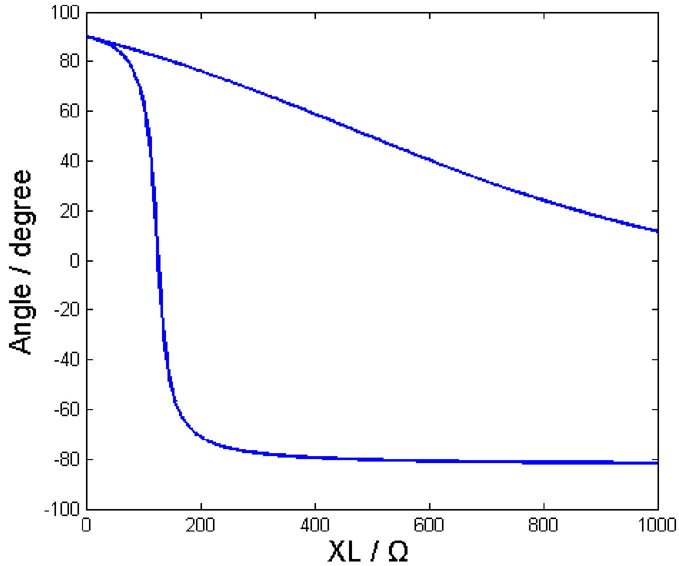

Figure 10. Controllable zone with inductance of loads.

According to **Figure 10**, when 150 Ω < X_L < 800 Ω, the phrase angle of system can be controlled from −43.2˚ to 32.0˚. Therefore, we chosen L = 2.86 H.

The system model is built in Simulink as shown in **Figure 11**. In system simulation, input voltage is 380 V and set-point is set to 18.2 (namely cosφ = 0.95). L_1 and L_2 are switched off and switched on in turns to change the structure of load. According to **Figures 8-10**, the controller could control the phase angle of system to set-point. **Figure 12** shows the control result of PID controller and **Figure 13** shows the I_{DC} curve.

SSMCR with self-tuning PID algorithm can reduce the adaption time to 0.08 s. The overshoots of both phase angle and DC exciting current are zero.

5. Conclusion

An innovative controllable reactor, side-limes and side-yokes magnetic-saturation type controllable reactor (SSMCR) is introduced in the paper.

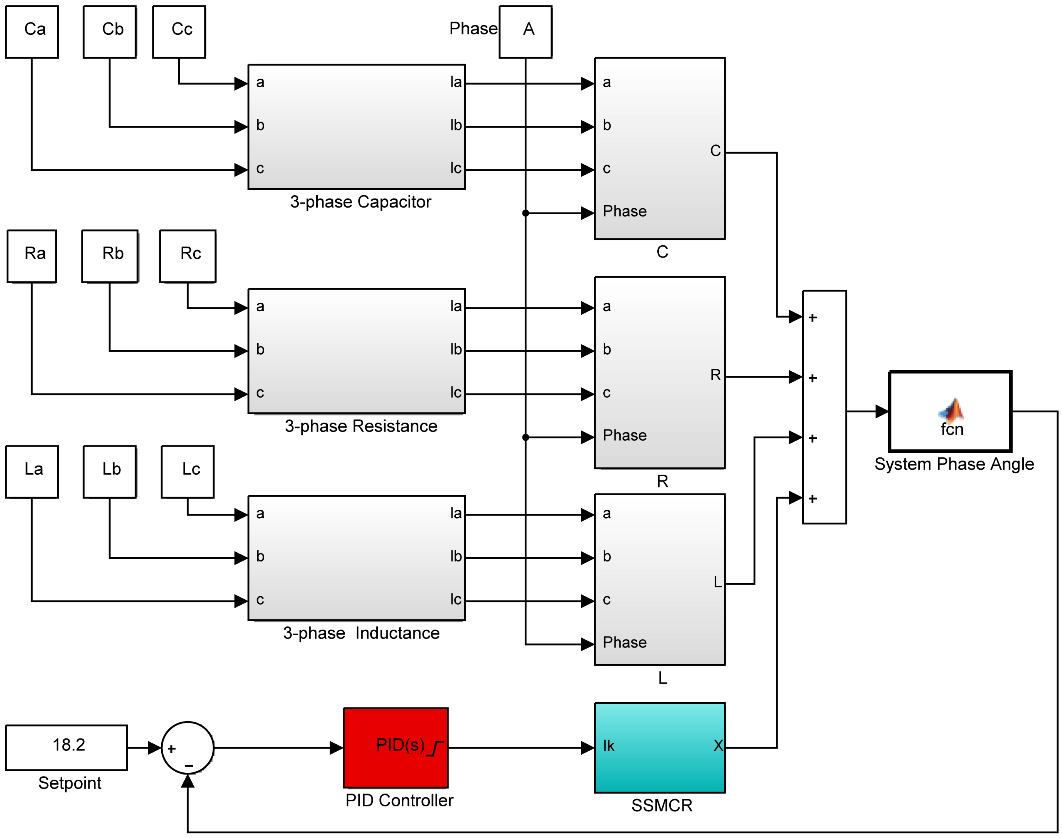

Figure 11. Simulink schematic diagram of system.

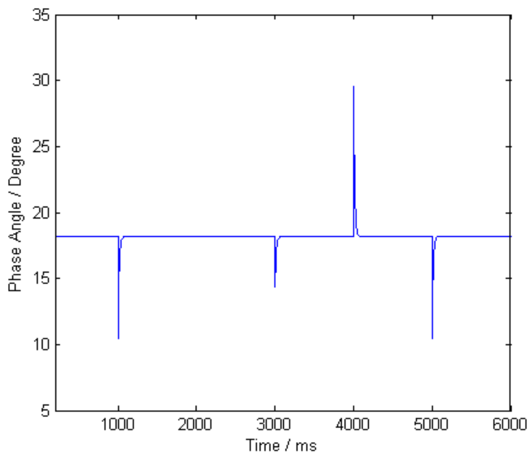

Figure 12. Control result of PID controller.

A control system with PID controller and DC-DC converter is designed, and a PID self-tuning algorithm is proposed. At first, in algorithm simulation, when the sudden changes of input occurs, conventional PID controller gives long adaption time (0.91 s) and big overshoot (7.3% of input variation), while the adaption time and overshoot of self-tuning PID algorithm is 0.13 s and zero. After that loads and compensation capacitor of system are calculated in Matlab to build the system model. Finally, the simulation based on the system model indicates that SSMCR with self-tuning PID algorithm can efficiently reduce the adaption time to 0.08 s and overshoot to zero. In conclusion, the control system we designed can control SSMCR with quick response and perfect smoothness.

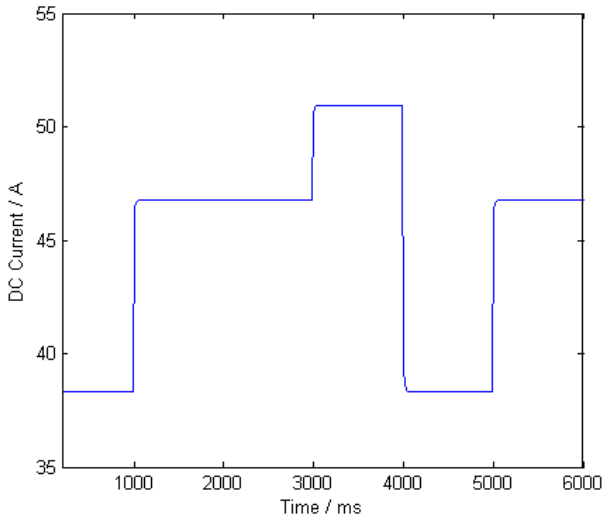

Figure 13. DC exciting current curve.

Since the control system and power grid model are simulated successfully, the experiments will be conducted in next stage based on the simulation data.

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