

Controller of Dynamic Reactive Power Compensation based on FPGA

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Abstract

Thyristor switched capacitor (TSC) is a commonly used method of compensation of reactive power on the grid, but problems are that the compensator responses slowly and real-time tracking capability is poor. So software and hardware are developed. The fuzzy-PI controller is adopted to control TSC. And this controller is embedded in the field programmable gate array (FPGA), which can take advantage of FPGA (Field Programmable Gate Array). The detailed analysis is given. Simulation and field test show that the design improves speed, reliability and stability of the controller.

Keywords: Fuzzy-PI, FPGA, reactive power compensation, TSC

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1. Introduction

With the application of new industrial areas of power electronics and various types of non-linear devices, the impact on the power grid is increasingly complex. Outstanding performance is power factor reduction, grid voltage fluctuations, flicker, a large number of harmonics and so on. The taken measures are reactive power compensation device for reactive power compensation. The reactive compensation key is the performance of the reactive power compensation controller.

At present, the more advanced hardware of reactive power compensation controller is DSP, which can achieve dynamic reactive power compensation. However, stability and speed can not fully meet the electricity requirements [1, 2]. FPGA is applied to control Thyristor switched capacitor (TSC) to realize pure hardware control [3]. Fuzzy-PI method is embedded in FPGA, which effectively solves the above problems.

2. Structure and Working Principle of Reactive Power Compensation Controller

2.1. Structure

Reactive power compensation system structure with thyristor switched capacitor (TSC) is shown in Figure 1. It consists of reactive power compensation controller and switching capacitor groups.

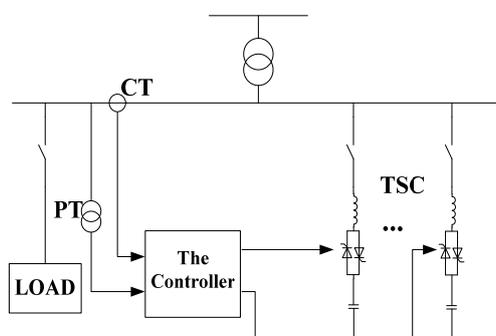


Figure 1. Reactive Power Compensation System Structure with TSC

2.1.1. Reactive Detection

Many ways can achieve real-time dynamic reactive power compensation. Among them, fast instantaneous reactive power detection method is used, namely P-Q theory [4], which is now briefly described as follows:

Suppose three-phase voltage and current instantaneous values are respectively e_a 、 e_b 、 e_c and i_a 、 i_b 、 i_c . To simplify the analysis, the three-phase voltage and current are transformed into an orthogonal coordinate system (Figure 2), the instantaneous voltage, current and its conversion formula are respectively as follows:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = C_{\alpha\beta} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{\alpha\beta} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

Where: $C_{\alpha\beta} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$

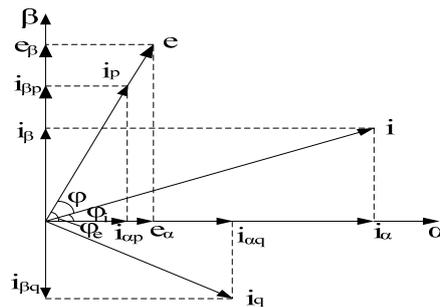


Figure 2. The Voltage and Current Vector in the α - β Coordinate System

Figure 2 shows:

$$\vec{e} = \vec{e}_\alpha + \vec{e}_\beta = e \angle \varphi_e \quad (3)$$

$$\vec{i} = \vec{i}_\alpha + \vec{i}_\beta = i \angle \varphi_i \quad (4)$$

Definition of instantaneous active current i_p and instantaneous reactive current i_q :

$$i_p = i \cos \varphi \quad i_q = i \sin \varphi \quad (5)$$

Three-phase instantaneous active power p and reactive power q can be expressed as:

$$p = ei_p \quad q = ei_q \quad (6)$$

So matrix expression is:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ e_\beta & -e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{pq} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = \frac{1}{e} \begin{bmatrix} p \\ q \end{bmatrix} = \frac{1}{e} C_{pq} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{e} C_{pq} C_{\alpha\beta} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{8}$$

Active power p and reactive power q can be obtained by the Equation (1), (2) and Equation (7), (8):

$$p = e_a i_a + e_b i_b + e_c i_c \tag{9}$$

$$q = \frac{1}{\sqrt{3}} [(e_b - e_c) i_a + (e_c - e_a) i_b + (e_a - e_b) i_c] \tag{10}$$

2.1.2 Switching Strategy

Based on analysis of various control methods and the P-Q theory, a composite control strategy of fuzzy-PI control is presented, in which fuzzy rules plays an important role. Switching control method in Equation (10) is shown in Figure 3. When the reactive deviation is large, fuzzy control is applied to switch large-capacity capacitor bank, in order to improve the response speed. When a small deviation appears, PI control [5] unit is used to switch small-capacity capacitor bank, in order to improve the precision and achieve the desired effect [6-8].

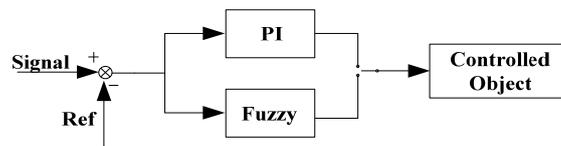


Figure 3. The Strategy of Controller

a) Fuzzy Control Unit

In practice, one-dimensional fuzzy controller with adjustable scale factor (adjusted based on field experience) is used. Membership function is triangle method, and Δu and Δq are divided into nine grades. Their reactive power fuzzy switching control table is shown in Table 1.

Table 1. Reactive Power Fuzzy Switching Control Table

Δu	Δv_u	Δq	Δv_q
-4	3.67	-4	3.67
-3	2.6	-3	2.6
-2	2	-2	2
-1	1	-1	1
0	0	0	0
1	-1	1	-1
2	-2	2	-2
3	-2.6	3	-2.6
4	-3.67	4	-3.67

b) PI Controller

When the deviation is small, the conventional PI control is used, the control schematics shown in Figure 4. Where:

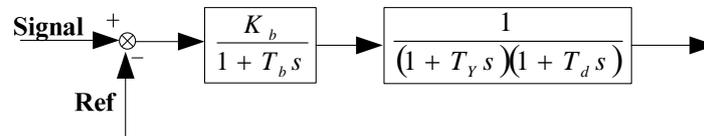


Figure 4. PI Control Schematics

In Figure 4, $\frac{K_b}{1 + T_b s}$ is the transfer function for the PI regulator, $\frac{1}{(1 + T_y s)(1 + T_d s)}$ is SVC's approximate model.

2. Design of Dynamic Reactive Power Compensation Controller

The core part of the design is FPGA, supplemented by the single-chip microcomputer. Because of the pure hardware, FPGA has high speed, parallel and strong anti-jamming capability, applied in the calculation of instantaneous reactive and switching control, which greatly improves the control capability of reactive power compensation. MCS-51 micro controller for LCD display, keyboard management, communications and other functions. Hardware structure of reactive power compensation controller based FPGA is shown in Figure 5.

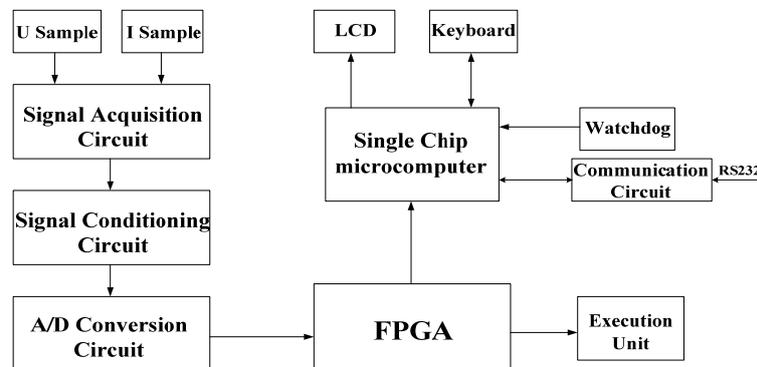


Figure 5. The Diagram of Controller Hardware Structure

2.1. Signal Acquisition Circuit

Voltage and current signal complete the strength transformation of the electrical signal by SPT204A voltage transformer and SCT254 current transformer. Grid voltage and current are converted into 0-0.1V AC voltage and 0-2.5mA current signal respectively, playing the role of the electrical isolation simultaneously. The design is also provided a low pass filter to prevent high-frequency interference.

2.2. Signal Conditioning Circuit [9]

The circuit comprises a signal conversion module, the AC to DC converting module, low-pass filtering module and a signal amplifier module. Because the electrical signal is transmitted only in the form of voltage, current signal is converted to the acceptable voltage signal. Due to AC component in the electrical signal, a DC signal obtained by the AC to DC converter must be in positive interval before they are received. Low-pass filter module is used to

filter out high frequency harmonic wave [10]. Finally, signal amplification circuit enhances the small signal to 0-3.3V voltage signal.

2.3. A/D Conversion Circuit

The controller uses A/D conversion chip MAX1928 of 8 input channels, 10-bit resolution, low power, low noise and fast speed. The conversion clock and the reference voltage can be provided by external or internal circuit. Its communication to master chip is a standard serial interface SPI.

2.4. Execution Unit

A negative pulse is issued by the detection circuit when the zero voltage across the thyristor, which is processed with switching instruction by "and" operation. The result triggers the multivibrator to output pulse sequence to trigger thyristor by a pulse transformer and the respective capacitors is input to the power grid.

2.5. Controller's Workflow

Controller's workflow based on FPGA is shown in Figure 6, including six functional modules of the initialization, the voltage and current instantaneous value of the acquisition, signal conditioning, A / D conversion, parameter processing and switching execution.

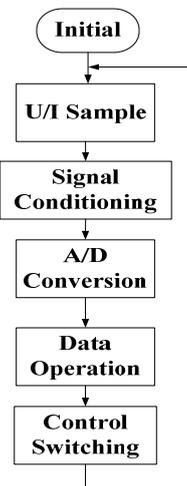


Figure 6. Controller's Workflow

3. System Simulation and Field Test

3.1. System Simulation

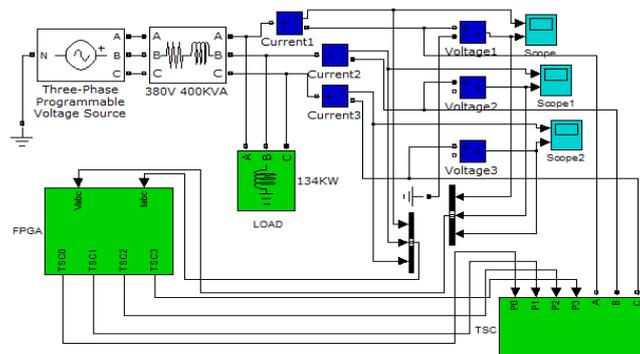


Figure 7. The Simulation of Var Compensation Device on TSC

In order to verify the aforementioned control algorithm in theory, for Figure 1, simpowersystem toolbox is applied to create a simulation model and simulation [11, 12], shown in Figure 7. The simulation conditions are that the power supply is supplied by RL circuit of the short-circuit power of 400kVA, and that load is a 134kW pure inductance circuit, and that the TSC's capacitor group capacity is 45Kvar, and that each phase conveys 15 kinds of reactive power from 1Kvar to 15kvar respectively.

Before and after compensation, the voltage and current waveforms are shown in Figure 8 and Figure 9. So the current lags the voltage before compensation, which represents inductor state, It is clear that the phase of current is the same as that of voltage after compensation. Therefore, it is proved theoretically feasible.

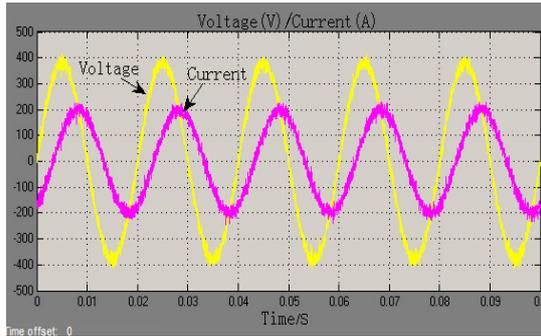


Figure 8. The Voltage and Current before Compensation

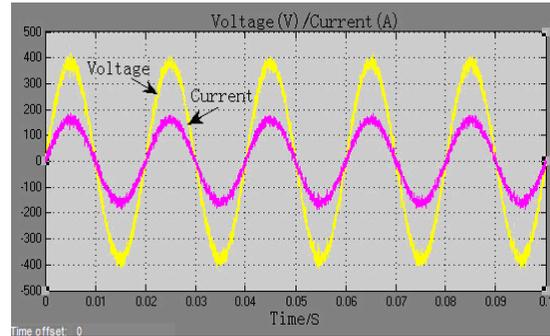


Figure 9. The Voltage and Current after Compensation

3.2. Field Test

Hardware circuit that uses FPGA as the core control part is developed. And with the actual capacitor bank switching cabinet, reactive power compensation control tests is carried out in the field. Power supply voltage of 380v is used, switching capacitor banks are triangle - packet compensation. Capacitors are divided into 12 groups, there are six groups with the large-capacity capacitors of 50Kvar, 4 groups with small-capacity capacitors of 10Kvar and 2 groups with capacitors of 5Kvar.

Capacitor bank switching cabinet is incorporated into load. Before and after capacitor bank switching compensation, the voltage and current waveforms of the load side shown in Figure 10 and Figure 11, which obtained by an oscilloscope record in the field. So the pre-compensation voltage leads current and phase angle is large, that is, the power factor is low, while the compensated phase angle significantly reduces, but there is tiny owed compensation, mainly due to capacitance grading imprecise in the actual capacitor bank switching cabinet. Further, seen from the waveform before and after compensation, With reference to Figure 10, ripples in Figure 11 is smaller, which indicates it also inhibits the higher harmonics. At the same time, the current RMS significantly reduces in the case of same loads. So the effect of reactive compensation is obvious.

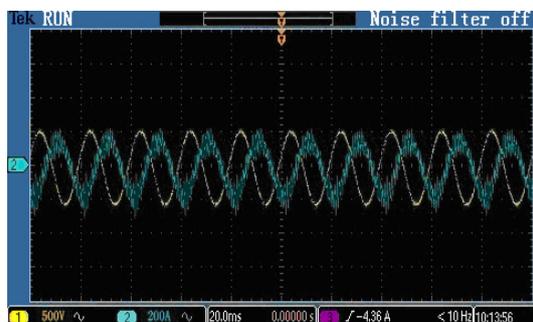


Figure 10. The Measured Waveform before Execution

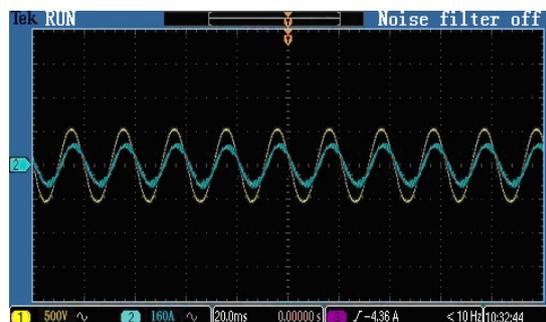


Figure 11. The Measured Waveform after Execution

4. Conclusion

Dynamic reactive power compensation controller with FPGA as hardware and fuzzy-PI algorithm as software is proposed. Simulation and field tests prove the design is feasible. There is tiny owed compensation, mainly due to the actual capacitor bank switching cabinet capacitance grading not fine. Due to the delay of switching capacitor bank, it is hard to measure the time of switching in terms of quick compensation. Therefore, the time data is not specifically given. But in view of the theory of controller realized by hardware only, it is faster than the speed of execution of the DSP software. Therefore, the proposed control scheme will provide the basis for developing a new dynamic reactive power compensation products.

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