Research of Non-contact Compensation AC Voltage Regulator Based on Fuzzy Strategy

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Abstract. The non-contact compensation type AC voltage regulator possesses the advantages of small size, high efficiency, low cost, etc. due to its simple structure and convenient control, and is widely used in the field of AC voltage regulation technology field. However, the non-contact compensation type AC voltage regulator belongs to the class of voltage regulation. And the characteristics of the discontinuous system has the disadvantages of low control precision and weak system reliability. Fuzzy control strategy, through fuzzification and approximate reasoning, can solve the problem of such discontinuous control systems. Some research work shows that using the fuzzy membership strategy to optimize the switching rules of the control system can greatly improve the control precision of the voltage regulation, that is, can improve the regulation accuracy of the AC voltage regulator. The experiment results verify that the regulation accuracy of the system after optimizing the switching rule is 5-10 times pre-set, which proves the effectiveness of the improvement.

1. Introduction

Since the founding of cybernetics by mathematician Norbert Wiener (1894-1964), control science has been developing rapidly and continuously under the research of various scholars and institutions. Discontinuous control system is one of the earliest control methods. Although the development of discontinuous control system is not mature due to its complexity and diversity of control methods, its universality, discontinuous control is still used in many occasions. Non-contact compensated AC regulator is a switching system utilizing discontinuous control system. The device switches the subsystem, namely, gears according to the state variables to complete the function of voltage regulation and stability. But most of the research on Non-contact compensated AC regulator is only about the optimization of its structure and components [1-3], such as the optimization of AC switching devices and structures, the optimization of isolation measures between power grid and compensation circuit. Part of the research which involves the design of switching system is only lists the switching rules of switching system according to the input and output voltage state of the device and the ability of compensating voltage [4,5]. Such considerations can improve the voltage stabilization effect and reliability of the device, but its optimization is often accompanied by the increase of cost, and the accuracy of voltage control is still unsatisfactory. In this paper, the working principle of a non-contact compensated AC regulator is studied and analysed, and its switching rules are deduced. The switching rules are optimized by using the fuzzy membership function. Finally, the effectiveness of the optimization design is verified by simulation experiments.

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2. Overview of the Working Principle of Voltage Regulator

2.1. Analysis of Compensation Principle

The topology of the non-contact compensated AC regulator is shown by Figure 1.

![Figure 1. Topology of Non-contact compensation AC voltage regulator.](image)

The device is a three-phase regulated power supply, which regulates the three-phase voltage separately, and the principle of each phase is identical. Three-phase voltage regulators are $E_A$, $E_B$ and $E_C$ respectively. Each phase is composed of small medium and large, three different ratio voltage regulator transformers $T_1$, $T_2$, $T_3$ and their respective thyristor components $TH_{SCR1}$, $TH_{SCR2}$ and $TH_{SCR3}$, the device main switch $K_S$, bypass switch $K_{BP}$, high voltage side fuse $FU$ of voltage regulator and device monitoring system. The thyristor components are composed of reverse parallel thyristor $TH_1$, $TH_2$, $TH_3$, $TH_4$ and the $H$ bridge composed of their resistance-capacitance absorption module $RC_1$, $RC_2$, $RC_3$, $RC_4$, high-voltage side short-circuit thyristor $TH_S$, and its resistance-capacitance absorption module $RC_S$ as well as short-circuit resistance $RS$.

Set the total compensation rate of the device is $X$, the highest total compensation rate for the device is $A$ times of compensation loop input voltage $U_{BP}$ ($A$ is positive), the lowest total compensation rate is $B$ times of $U_{BP}$ ($B$ is negative), compensation circuit generated compensation voltage is $\Delta U$, system input voltage is $U_i$, output voltage is $U_o$. According to the different energy taking position of the device, that is, whether the bypass switch $K_{BP}$ operates or not, its compensation effect on voltage can be divided into the following two situations:

Step 1: taken energy from the input end of the device, bypass switch $K_{BP}$ does not operate. Since the compensation loop takes energy from the input end of the device, there is:

$$\frac{\Delta U = U_{BP} \times X}{U_{BP} = U_i}$$

In this case, the output voltage $U'_o$ of the device can be shown as follows:

$$U'_o = U_i + \Delta U = U_i \times (1 + X)$$

(2)

When the system input voltage $U_i$ is at the lowest point $U_{imin}$, the $U_{BP}$ value is $U_{imin}$, the device compensates the highest voltage, the value of $X$ is $A$, and the output voltage $U'_{omin}$ is expressed as:

$$U'_{omin} = U_{imin} \times (1 + A)$$

(3)

When the input voltage of the system is at the highest point $U_{imax}$, the $U_{BP}$ value is $U_{imax}$, the value of $X$ is $B$, the output voltage $U'_{omax}$ of the device can be calculated by:

$$U'_{omax} = U_{imax} \times (1 + B)$$

(4)
Step 2: take energy from the output end of the device and bypass switch $K_{BP}$ action. Since the compensation loop takes energy from the output end of the device, the value of $U_{BP}$ will be superimposed with the compensation voltage in the link after the device's voltage compensation. $U_{BP}$ value changes, and will change the device compensation voltage, to carry out cyclic superposition, set its superposition times for $n$ ($n$ for positive integer), the new compensation voltage delta $\Delta U(n)$ generated by the device each cycle is:

$$\begin{align*}
\Delta U(0) &= U_{BP}(0) \times X \\
\Delta U(1) &= U_{BP}(0) \times X^2 \\
& \quad \ldots \\
\Delta U(n) &= U_{BP}(0) \times X^{n+1}
\end{align*}$$

(5)

For $U_{BP}$, there are:

$$\begin{align*}
U_{BP}(1) &= U_{BP}(0) + \Delta U(0) \\
U_{BP}(2) &= U_{BP}(1) + \Delta U(1) \\
& \quad \ldots \\
U_{BP}(n) &= U_{BP}(n-1) + \Delta U(n-1)
\end{align*}$$

(6)

where the value of $U_{BP}(0)$ is depended on the value of the system input voltage. Combining equations (5) and (6), an important equation can be derived as follows:

$$U_o' = U_{BP}(0) \times \sum_{i=0}^{n-1} X^i$$

(7)

Because the compensation circuit takes energy from the output end of the device, the output voltage $U_o$ of the device should be the same value as the iterative $U_{BP}$, the iterative process of the voltage is endless, so there are:

$$U_o = U_{BP}(0) \times \lim_{n \to \infty} \frac{1 - X^{n+1}}{1 - X}$$

(8)

When the input voltage $U_i$ of the system is at the lowest point of $U_{\text{imin}}$, the value of $U_{BP}(0)$ is $U_{\text{imin}}$, the device carries out the highest compensation for the voltage, the value of $X$ is $A$, and the output voltage $U_{\text{omin}}$ of the device is expressed as:

$$U_{\text{omin}} = U_{\text{imin}} \times \lim_{n \to \infty} \frac{1 - A^{n+1}}{1 - A}$$

(9)

When the input voltage of the system is at the highest point of $U_{\text{imax}}$, the $U_{BP}$ value is $U_{\text{imax}}$, the device carries out the lowest compensation, and the value of $X$ is $B$. Currently, the output voltage $U_{\text{omax}}$ of the device is derived as:

$$U_{\text{omax}} = U_{\text{imax}} \times \lim_{n \to \infty} \frac{1 - B^{n+1}}{1 - B}$$

(10)

The voltage compensated by the compensation device will not be greater than its rated voltage value, the absolute value of the total compensation rate $A$, $B$ is less than 1, that is:

$$\begin{align*}
0 & \leq A < 1 \\
-1 & < B \leq 0
\end{align*}$$

(11)

2.2. Switching System Design

Taken the nominal value of the output voltage, i.e., $U_N$, as the reference value, the rated working voltage of the device is 1pu. It is known that its working range is 0.6pu~1.4pu, the allowable range of output
voltage is 0.95pu~1.05pu, the variation ratios of the three compensation transformers are 0.015, 0.045 and 0.135 respectively. The voltage and voltage control strategy of the device is as follows: the input voltage and output voltage of the voltage stabilizing power supply are detected in the whole process, when the input voltage $u_{IN}$ is in the range of voltage regulation and voltage stabilization (0.6pu−0.95pu or 1.05pu−1.4pu), the device begins to adjust the voltage. According to the value of $u_{IN}$, the energy position of the device compensation loop is determined, and then a compensation rate which can compensate the output voltage $u_L$ to the nominal value $U_N$ (0.95pu~1.05pu) is determined by calculation, and then the device is controlled to adjust the corresponding switching action or reverse parallel thyristor switching, so as to change the energy position and compensation rate of the device compensation circuit. If the $u_{IN}$ changes and the calculated $u_L$ cannot be stable within the nominal value $U_N$ under this compensation scheme, then redetermine another Compensation scheme and implement it.

The switching system is designed as follows:

$$y(x) = a_{\sigma(x)}x \quad (12)$$

where $y \in R$ is the output of the system, that is, the output voltage of the device $u_L$; $x \in R$ is the input of the system, that is, the input voltage of the device $u_{IN}$; $\sigma(\cdot): R \rightarrow \{1, 2, ..., 27\}$ is a piecewise constant switching signal based on $u_{IN}$, the change of $\sigma$ value represents the switching of device compensation scheme, and $a_i$ is the system parameter of the $i^{th}$ subsystem, that is, the ratio of output voltage to input voltage under each compensation rule. When $u_{IN} <0.95pu$, positive compensation is carried out, and the device compensation loop takes energy from the output end of the system, there is:

$$L_{IN}1_{1}ua uX = \frac{1}{1-X} \quad (13)$$

When $u_{IN} <1.05pu$, negative compensation is carried out, and the device compensation loop takes energy from the input end of the system, there is:

$$L_{IN}1_{1}uaX u = 1 + X \quad (14)$$

All value of $a_i$ can be obtained. The device requires that the output voltage $u_L$ of the system be stabilized within the range of the nominal value $U_N$, that is:

$$0.95U_N \leq a_{\sigma(x)}u_{IN} <1.05U_N \quad (15)$$

3. Overview of Optimal Strategy of Switching System

Fuzzy control strategy is a kind of theory which is caused by the conflict between practical problems and data analysis. It can transform the practical problems into concrete values, to realize quantitative control.

When a specific value of $\sigma$ is calculated by the nominal value $U_N$ according to the allowable range of output voltage of the device, there is obvious overlap in the range of input voltage $u_{IN}$. Under the condition that the range of values overlaps greatly, the switching system will not be able to determine the specific adjustment coefficient, which will lead to the failure of the system. So here, according to the concept of membership degree of fuzzy set, in addition, the domain $\Psi=[0.6, 1.4]$, use $Z_\sigma$ to represent 27 fuzzy sets, and the compensation effect is the best in each region, that is, the $u_{IN}$ can make the system output value 1pu is the centre, where $u_{IN}$ can be shown as:

$$a_{\sigma(x)}u_{IN} = 1 \quad (16)$$

Then design the “triangle” membership function $\mu_{Z_\sigma}(x)$ of the switching signal. When $\sigma=1$, there are:
\[
\mu_{Z_1}(x) = \begin{cases} 
0, & 0 \leq x < u_{IN1\text{min}} \\
\frac{x - u_{IN1\text{min}}}{u_{IN1\text{max}} - u_{IN1\text{min}}}, & u_{IN1\text{min}} < x \leq u_{IN1} \\
\frac{x - u_{IN1}}{u_{IN1\text{max}} - u_{IN1}}, & u_{IN1} < x \leq u_{IN2\text{max}} \\
1, & u_{IN2\text{max}} \leq x \leq 1.4 
\end{cases}
\]

When \(1 < \sigma < 27\), there are:

\[
\mu_{Z_\sigma}(x) = \begin{cases} 
0, & 0 \leq x < u_{IN\sigma\text{min}} \text{ and } u_{IN\sigma\text{max}} \leq x \\
\frac{x - u_{IN\sigma\text{min}}}{u_{IN\sigma\text{max}} - u_{IN\sigma\text{min}}}, & u_{IN\sigma\text{min}} \leq x < u_{IN\sigma} \\
\frac{x - u_{IN\sigma}}{u_{IN\sigma\text{max}} - u_{IN\sigma}}, & u_{IN\sigma} < x \leq u_{IN\sigma\text{max}} 
\end{cases}
\]

The relational expression covers all domains and has a maximum value, i.e., 1. It is a standard “triangle” membership function and belongs to a normal fuzzy set. The selection rule of designing \(\sigma\) is as follows: for the input quantity \(x\), select the \(\sigma\) that maximizes the degree of membership value \(\mu_{Z_\sigma}(x)\). Namely:

\[
\sigma(x) = \text{arg}_{\sigma} \left( \mu_{Z_\sigma}(x) \right)
\]

### 4. Experiment

The key parameters of the simulation are listed in Table 1. The power supply is selected as variable AC power supply, and set the power supply increases linearly from 132Vrms to 308Vrms within 8s. The reference value is set to 220Vrms, so the range of allowable output voltage, i.e. nominal value \(U_N\), should be 209Vrms~231Vrms.

| Device label | Device parameters |
|--------------|-------------------|
| T1           | 220Vrms: 30Vrms   |
| T2           | 220Vrms: 10Vrms   |
| T3           | 220Vrms: 3Vrms    |
| AC           | 50Hz              |
| R_S1         | 1\(\Omega\)       |
| R_S2         | 1\(\Omega\)       |
| R_S3         | 1\(\Omega\)       |
| R_L          | 20\(\Omega\)      |

The experimental conditions are now described as follows: a 30kVA three-phase isolation transformer is used to connect to the mains to provide the input voltage of the device. Adjust the transformer so that its output voltage is increased from 240Vrms to 540Vrms, one gear per 20Vrms, each gear is kept for 1min, the input voltage and output voltage of the device are monitored, and the output of the device is star-connected in parallel. A 50\(\Omega\)/2kW power resistor acts as a load. The experimental results are shown in Table 2.

During the experimental process, the device is connected to 240Vrms voltage, the main switch KS, the bypass switch KBP and the power-off switch KGP act, and the device starts to compensate. When the voltage rises to 540Vrms, the main switch KS is disconnected, and the output of the device is returned zero. The allowable input voltage range of the device is 361Vrms~399Vrms. It can be seen from Table 2 the device is performing voltage compensation when the input voltage is between 240Vrms and 520Vrms. When the input voltage is between 320V and 500Vrms, the output voltage is average. It is in
the allowable output range; when the voltage rises to 540Vrms, the device is powered off due to input overvoltage. The compensation effect on the voltage fully satisfies the design request.

Table 2. Experimental result.

| Input voltage / Vrms | Output voltage / Vrms |
|----------------------|------------------------|
| 240                  | 296.6                  |
| 260                  | 317.8                  |
| 280                  | 339.1                  |
| 300                  | 360.3                  |
| 320                  | 374.6                  |
| 340                  | 375.2                  |
| 360                  | 375.7                  |
| 380                  | 374.6                  |
| 400                  | 375.2                  |
| 420                  | 374.5                  |
| 440                  | 373.2                  |
| 460                  | 375.6                  |
| 480                  | 377.4                  |
| 500                  | 395.5                  |
| 520                  | 435.4                  |
| 540                  | 0                      |

5. Conclusion

Based on the concept of membership degree in fuzzy mathematics, the control system of a non-contact compensated AC regulator is optimized. The membership function is used to optimize the switching rules of the device switching system, which not only ensures that there is no interference between the subsystems of the optimized switching system, but also improves the overall control accuracy of the device, which provides an idea for the later researchers to optimize the control system.

Of course, there is still a lot of follow-up work to be completed, need to consider the other inputs of the device, and fuzzified, integrated into the switching system, aiming at the stability of the switching system optimization design. Further optimize the voltage stabilization accuracy and reliability of the device.

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