Design of the fuzzy PI control system for load voltage in hybrid distribution transformer

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Abstract: Hybrid distribution transformer (HDT) is a novel transformer that has a powerful control on grid current and load voltage, and it is significant for the construction of the smart grid. The load voltage control is the key part in HDT control system. Here, a load voltage control strategy based on fuzzy PI controller is proposed, since the traditional PI controller cannot achieve satisfying dynamic performance under the operation of grid voltage change. The fuzzy controller can respond faster than PI controller for the outputs that is only determined by inputs and independent with time, when the grid voltage rags or swells. While combining the fuzzy controller with the PI controller, the fuzzy control will cover the shortage of PI control in transient process and the PI control ensures that the static performance will not be affected. In the end, the simulation model of HDT is carried out, and the result shows that the load voltage can track the reference faster than the traditional PI controller, which improves the performance of voltage control system.

1 Introduction

With the development of smart grid and the advancement of power electronics, on the one hand, more and more intelligent devices are required in network; on the other hand, it also causes a lot of problems such as voltage sags or swells and power factor degradation [1, 2]. In distribution network, the distribution transformer plays a crucial role. The traditional distribution transformer has no controllability in the grid current and the custom voltage, which cannot meet the demand of smart grid [3, 4].

Hybrid distribution transformer (HDT) is a new type transformer which combines the tradition transformer with the power electronics technology and has great controllability [5–9]. HDT was first proposed by E. C. Aeloaize et al. (2003), Z. Fedyczak et al. (2007), and J. Kaniewski et al. (2009), but it can only control voltage on account of it consisting of traditional transformer and matrix inverter. Then, S. Balá et al. (2012), J. Sastry et al. (2013), J. Burkard et al. (2015), and M. A. Radi et al. (2015) proposed a different structure of HDT, which combines the distribution transformer with the AC–DC converters and thus it can also control the current.

The HDT consists of two converters, of which one is used for grid current control and the other one is used for load voltage control [8]. In general, the PI control is one of the most common control algorithms which can achieve great static performance in load voltage control under the dq synchronous reference frame, but the dynamic performance is not satisfying, especially when the grid voltage changes suddenly.

Fuzzy control is a control method which utilises the human expert knowledge to regulate the control system and is easy to design because it does not rely on the accurate mathematical model of the control system [10]. What’s more, the fuzzy controller has a better dynamic performance than PI controller since there is no inertia in it. Therefore, to achieve better dynamic performance, the fuzzy controller is attached to the PI controller.

This paper is organised as follows. Section 2 presents the circuit topology of HDT and analysis the principle. In Section 3, considering the characteristics of the voltage control of HDT, a Fuzzy-PI controller is designed to improve the dynamic performance. In Section 4, the proposed controller is applied to the control system based on MATLAB/Simulink. Its results are compared with the results under PI control, which proves that the Fuzzy-PI controller is effective in improving the dynamic performance. Finally, Section 5 presents conclusions.

2 Schematic diagram of HDT

The schematic diagram of HDT is shown in Fig. 1, which is the structure analysed here. The subscripts of each variables or symbols in Fig. 1 indicate the corresponding phase (a, b, c), and the subscript k will replace the phase mark in the following description.

There are two voltage-source converters in Fig. 1. One of these converters is CVp and another one is CVt. They have the same topology and share a DC bus that consists of two same capacities valued D. The output port of CVp and CVt are both connected to the transformers through inductance to filter the high-order harmonic components produced by SPWM.

In the schematic diagram, each phase has two transformers, of which one is the main transformer T1 that consists of three windings (W1k, W2k, W3k), and the other one is the isolation transformer T2 that has two windings (W4k, W5k). The main transformer transports the large proportion of load power, and the primary winding W1k is connected to the grid. The power capacity of the secondary winding W2k is equal to the primary winding and the load is connected to the W2k. W3k is the control winding that connected to the CVp through the inductance Lp. According to the magneto motive self-balance principle, the magneto motive force of three windings should keep balance, thus regulating the current i3k by controlling CVt can compensate the reactive and harmonic components produced by harmonic load and the grid current i4k can become symmetric sinusoidal wave and the power factor can be unity.

The isolation transformer only transport small portion power, and it is primary winding W4k is connected to W1k in series and secondary winding W5k is connected to the CVt through the inductance Ls. According to the balance of voltage in grid side, applying an appropriate voltage-control strategy can control the voltage vLk, then the load voltage vLk keep sinusoidal.

3 Design of voltage control system

The function of the voltage control system in practice is making the load voltage steady and keep sinusoidal when the grid voltage
fluctuation. The traditional PI control can realise no static error in \(dq\) synchronous reference frame, and it is because of the integral part. However, the integral also brings inertia into the control system, which will lead to an unsatisfying response time. The fuzzy control system is able to infer the output based on the current input and fuzzy rule base, which is not impacted by previous state, so it has better dynamic performance. In order to improve dynamic performance of control system, combining fuzzy control with PI control will be effective.

In \(dq\) synchronous reference frame, the PI controller can realise no static error. Considering that the \(q\)-axis component is \(\sim 0\) under balanced three-phase situation, the fuzzy controller can be only applied in \(d\)-axis control. The control objective of fuzzy controller is to enhance sensitivity of the control system to grid voltage fluctuation, so it needs to generate extra output when the grid voltage cannot maintain the expected load voltage. Based on the mentioned reasons, the structure of \(d\)-axis controller is shown in Fig. 2. The output of controller is the sum of PI controller and fuzzy controller, and in different situations the different parts play the major role.

The classic pattern of fuzzy controller is shown in Fig. 3. The input of fuzzy controller is the grid voltage and the reference of load voltage. The scaling factor of inputs is determined by the compensation scope of voltage and the number of linguistic expressions of controller. The scope of inputs is both plus or minus 20%, and the number of fuzzy sets of input is five.

There are four parts inside the fuzzy controller. The fuzzifier maps a crisp point to fuzzy sets of inputs, and the defuzzifier maps fuzzy sets of outputs to a crisp point. Both inputs are divided into five linguistic expressions, which are PL (positive large), PS (positive small), ZO (zero), NS (negative small), and NL (negative large). The membership functions for inputs are assumed as gaussmf, which is shown in Fig. 4. Fig. 5 shows the membership function of output. It is divided into nine linguistic expressions, which are PL (positive large), PM (positive medium), PS (positive small), ZO (zero), NS (negative small), NM (negative medium), and NL (negative large).

The fuzzy rule base is the core of fuzzy control. It is from experience of manual and semiautomatic operation, consisting of a series of fuzzy IF-THEN rules. These rules are mainly divided into three parts:

(i) If the grid voltage is approximately equal to the reference of load voltage, the output of fuzzy controller is zero. Only PI control can satisfy the requirements of static performance.
Table 1  Fuzzy rules

| $u_{Ld}$ | $u_{gd}$ | NL | NS | ZO | PS | PL |
|---------|---------|----|----|----|----|----|
| NL      | ZO      | NS | ZO | NM | NL | NLL |
| NS      | PS      | ZO | NS | NM | NL | NLL |
| ZO      | PM      | PS | ZO | NM | NL | NLL |
| PS      | PL      | PM | ZO | NM | NL | NLL |
| PL      | PLL     | PL | ZO | NM | NL | NLL |

(ii) If the grid voltage is larger than the reference of load voltage, the fuzzy controller needs to generate negative output to drop the load voltage.

(iii) If the grid voltage is smaller than the reference of load voltage, the fuzzy controller needs to generate positive output to raise the load voltage.

Based on the principles above, Table 1 is the table of the fuzzy rules in this system. Through this table, the fuzzy inference engine maps from the fuzzy sets of input to the fuzzy sets of output, and finally gets a crisp output point through the defuzzifier.

4 Results

According to the schematic diagram of HDT, the simulation model can be built in the Simulink/MATLAB, and the proposed controller is applied to the control system. To simplify the analysis, the CV is open and has no effect on the control of load voltage. The DC bus consists of two same DC voltage source. The parameters of each element and controller are given as follows:

- The rated grid phase voltage, $U_{SN}$, is $10,000 / \sqrt{3}$ kV.
- The inductance $L_1$ connected with the CV is 2.5 mH and the parasitic resistance of it is 0.1 Ω.
- The filter capacitor in the load side is 62.5 μF and the damping resistance is 1 Ω.
- The $K_P$ and $K_I$ of voltage PI controller are 0.3 and 30, respectively.

To prove the validity of the proposed control, this section uses three parallel simulations. Fig. 6a shows the grid voltage of three phase, which rises from $0.8U_{SN}$ to $1.2U_{SN}$ in steps of $0.1U_{SN}$. In traditional PI control, the error of load voltage in d-axis is shown in Fig. 6b when the reference of load voltage in d-axis is kept 220 V. There are transient processes obviously. Fig. 6c shows the error of load voltage in d-axis under fuzzy-PI control, and the transient processes are virtually eliminated when grid voltage fluctuation. The load voltage of three phases is shown in Fig. 7, and the load voltage is extremely stable.

Fig. 8 shows the results when the grid voltage drops stepwise. The range of variation is from $1.2U_{SN}$ to $0.8U_{SN}$ in step of $0.1U_{SN}$. In traditional PI control, the error of load voltage in d-axis is shown in Fig. 8a when the reference of load voltage in d-axis is kept 220√2 V. There are transient processes obviously. Fig. 8c shows the error of load voltage in d-axis when applying the fuzzy-PI control, and the transient processes are virtually eliminated when grid voltage fluctuation. The load voltage of three phases is shown in Fig. 9, and the load voltage is extremely stable.
HDT is quite significant to building the smart grid. It combines the power electronics with transformer and has strong controllability on grid current and load voltage. The most common control method is PI control, which is applied in the load voltage control system of HDT. This paper designs a fuzzy-PI controller of load voltage to improve the dynamic performance. The proposed controller consists of PI controller and fuzzy controller, and the output of fuzzy controller will make the control system react faster and the static performance will not be affected for the PI controller.

Then, according to the characteristic of HDT, this paper designs the membership functions and fuzzy rules. Finally, the proposed controller is applied in the physical model of HDT, and the performance is compared with the PI control, which verifies the effectiveness of the fuzzy-PI controller.

6 References

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Fig. 10 When the grid voltage changes smoothly
(a) The waveform of the grid voltage, (b) The error of load voltage in d-axis under PI control, (c) The error of load voltage in d-axis under fuzzy-PI control

Fig. 11 Waveform of load voltage under fuzzy-PI control when the grid voltage changes smoothly

Fig. 10 shows the simulation results when the grid voltage changes smoothly. Fig. 10b is the error of load voltage under PI control, which has lower response speed than fuzzy-PI control that shown in Fig. 10c. Fig. 11.