

Design of a TCPST Fuzzy Logic Controller for Improving Power System Transient Stability (Postprint)

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Abstract

Transient stability is one of the major stability issues currently encountered in power systems. Owing to the fast switching capabilities of FACTS devices such as the Thyristor Controlled Phase Shifting Transformer (TCPST), they can be utilized to enhance power system dynamic and transient stability. Conventional TCPST fuzzy logic controllers are designed with the deviation and rate of change of deviation of the controlled variable as inputs, directly employing the TCPST phase shift angle as the control output. This paper proposes a fuzzy logic controller capable of dynamically adjusting the gain of the conventional TCPST first-order dynamic controller during transient processes. The fuzzy logic controller outputs the gain of the conventional TCPST first-order dynamic controller, thereby indirectly achieving TCPST control. Finally, the effectiveness of the proposed fuzzy logic controller is validated using the Anderson 3-machine 9-bus test system.

Full Text

Designing a Fuzzy Logic Controller for TCPST to Enhance the Transient Stability of Power System

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Abstract

Transient stability represents one of the most critical challenges in modern power systems. Thyristor Controlled Phase Shifting Transformers (TCPST), as a key FACTS device, exhibit rapid response characteristics that make them effective

for improving power system transient stability. Conventional TCPST fuzzy logic controllers typically employ error and change in error as inputs while directly outputting the phase shift angle. This paper proposes a novel fuzzy logic controller that dynamically adjusts the gain of a first-order dynamic TCPST controller during transient events. The fuzzy controller uses the conventional TCPST controller as its output mechanism, thereby completing the TCPST control action. The effectiveness of this approach is validated through case studies on the Anderson 3-machine 9-bus system.

Keywords: Thyristor Controlled Phase Shifting Transformer, fuzzy logic control, power system, transient stability

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1. Introduction

Interconnected power systems offer significant advantages including improved economic efficiency, enhanced power quality, and increased operational flexibility. However, their transmission capacity is fundamentally constrained by transient stability limitations, which prevents full realization of these benefits. Consequently, various control devices have been integrated into power systems to enhance transient stability and have been deployed across diverse dynamic control applications.

Thyristor Controlled Phase Shifting Transformers (TCPST), as essential components of Flexible AC Transmission Systems (FACTS), possess rapid response characteristics that enable their use not only for steady-state power flow control but also for suppressing system oscillations and improving transient stability. Traditional TCPST controllers typically utilize first-order dynamic control strategies based on linear control theory. Since the steady-state operating point varies substantially under disturbances, causing significant deviation from the equilibrium condition, controllers designed using linear theory at a specific equilibrium demonstrate limited effectiveness. Furthermore, system nonlinearities, operating range variations, and uncertainties compromise the robustness of such linear controllers.

Fuzzy Logic Control (FLC) offers inherent robustness against these challenges. Reference [6] proposed a fuzzy logic controller for TCPST in an infinite bus system, utilizing generator speed deviation Δ and acceleration deviation as input signals. The controller output was proportional to the phase shift angle, which was then processed through a first-order linear link with gain to produce the final control signal. This design incorporated 27 IF-THEN rules and validated effectiveness through experimental testing. The present study initially explored

using the deviation and rate of change of the controlled variable (typically the active power on the TCPST-installed line) as controller inputs, with the TCPST phase angle serving as direct output. However, this approach risks inducing output oscillations.

To mitigate this issue, this paper proposes a hierarchical control structure where the conventional TCPST first-order dynamic controller serves as the controlled object and the fuzzy logic controller acts as a supervisory regulator. During transient events, the fuzzy logic controller dynamically adjusts the gain of the conventional TCPST controller, thereby completing the control action. Since conventional TCPST first-order dynamic controllers are simple and already widely implemented in practice, investigating fuzzy logic-based gain adjustment holds significant practical value for TCPST applications.

2. TCPST Mathematical Model

The TCPST impedance is denoted as Z_T , with corresponding admittance $Y_T = 1/Z_T = g_T + jb_T$. Typically, the TCPST resistance is negligible, and for simplified power flow calculations, the conductance is neglected ($g_T = 0$).

[Figure 1: see original paper] illustrates the TCPST equivalent circuit. The relationship between the series-injected current and node voltages is:

$$I = Y_T(V_i - V_j e^{j\phi})$$

The conventional first-order dynamic TCPST controller is shown in [Figure 2: see original paper]. The controller input is typically the active power P_{ij} transmitted through the TCPST-installed line, with reference active power P_{ref} representing the steady-state power flow under normal operating conditions. K_{PS} denotes the controller gain, T_{PS} the time constant, and θ_{max} and θ_{min} represent the phase angle limits.

The conventional controller transfer function is:

$$T_{PS} = \frac{K_{PS}}{1 + sT_{PS}}(P_{ref} - P_{ij})$$

In traditional implementations, the gain K_{PS} of the TCPST first-order dynamic controller remains fixed. The fuzzy logic controller proposed in this paper dynamically adjusts K_{PS} during system transients according to fuzzy logic principles.

3.1 Fuzzy Sets

Fuzzy logic extends classical logic by enabling the description of concepts that lack precise definitions, thereby overcoming the limitations of conventional logical systems.

Definition 3.1: For a universe of discourse U , a fuzzy set A is defined by a mapping $A: U \rightarrow [0,1]$, $x \rightarrow \mu_A(x)$. The function $\mu_A(x)$ is called the membership function of fuzzy set A , with its value range in $[0,1]$.

Similar to classical logic, fuzzy logic incorporates “AND,” “OR,” and “NOT” operations.

Definition 3.2: For fuzzy sets A and B belonging to the same universe U , the intersection $A \cap B$, union $A \cup B$, and complement \bar{A} are defined by the following membership functions for all $x \in U$:

$$\mu_{A \cap B}(x) = \min[\mu_A(x), \mu_B(x)]$$

$$\mu_{A \cup B}(x) = \max[\mu_A(x), \mu_B(x)]$$

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x)$$

3.2 Basic Structure of Fuzzy Logic Controller

As derived from the above equations, the fuzzy logic controller depicted in [Figure 3: see original paper] implements a nonlinear mapping. Given a precise numerical input x , the controller produces a precise numerical output y through this nonlinear transformation.

A fuzzy logic controller comprises four primary components: fuzzification, fuzzy rule base, fuzzy inference engine, and defuzzification, as illustrated in [Figure 3: see original paper].

The fuzzy rule base typically contains m IF-THEN rules formulated from expert knowledge and experience. The rule structure includes l rules of the form: IF x_1 is A_1 AND x_2 is A_2 AND \dots AND x_n is A_n THEN y is B

The fuzzification stage converts crisp physical inputs into fuzzy inputs recognizable by the inference system using appropriate membership functions, thereby transforming physical quantities into fuzzy sets. The fuzzy inference engine processes these fuzzy inputs according to the established rule base to generate fuzzy outputs. Finally, defuzzification converts the fuzzy outputs back into crisp signals suitable for practical control implementation. This study employs triangular membership functions, Mamdani inference, and centroid defuzzification.

4.1 Framework of TCPST Fuzzy Logic Controller

Existing TCPST fuzzy logic controllers in literature typically utilize direct control, where the phase angle serves as the controller output. This paper proposes a novel approach where fuzzy logic dynamically adjusts the gain of the conventional TCPST first-order dynamic controller. The overall control structure is presented in [Figure 4: see original paper].

The controller inputs are the error e between reference power P_{ref} and actual power P , and the error change rate Δe , where s represents the differential operator. To ensure universality, the inputs e and Δe are scaled by coefficients K_e and $K_{\Delta e}$ such that $|e|$ and $|\Delta e|$ are limited to a maximum value of 1, thereby completing the normalization process.

Rather than directly actuating the TCPST phase angle δ , the controller output modifies the gain K_P of the conventional first-order dynamic controller. During transient conditions, the fuzzy logic controller adjusts K_P within the range $[K_{Pmin}, K_{Pmax}]$ based on system operating conditions, thereby accomplishing the TCPST control objective.

4.2 Fuzzy Subset Partitioning

The core of fuzzy logic controller design lies in establishing the IF-THEN rule base. Since these rules are constructed upon fuzzy sets, we first define the fuzzy subsets for the input variables.

As described in Section 4.1, after normalization, $|e|$ and $|\Delta e|$ are constrained to a maximum of 1. Consequently, the universe of discourse for e and Δe is defined as $[-1,1]$ and partitioned into seven fuzzy subsets: LP (Large Positive), MP (Medium Positive), SP (Small Positive), VS (Very Small), SN (Small Negative), MN (Medium Negative), and LN (Large Negative). These subsets utilize triangular membership functions as depicted in [Figure 5: see original paper].

For the LN subset of e , the membership function is defined as:

$$\mu_{LN}(e) = \begin{cases} 1 & e \leq -1 \\ -3e - 2 & -1 < e \leq -2/3 \\ 0 & e > -2/3 \end{cases}$$

Similar membership function definitions apply to the remaining subsets.

The fuzzy logic controller output is the normalized gain K_P^* . To ensure universality, the actual gain K_P is first normalized:

$$K_P^* = \frac{K_P - K_{Pmin}}{K_{Pmax} - K_{Pmin}}$$

Similar to the inputs, K_P^* is defined over the universe $[0,1]$ and partitioned into seven subsets: ZE (Zero), VS (Very Small), S (Small), SB (Small Big), MB (Medium Big), B (Big), and VB (Very Big), with triangular membership functions shown in [Figure 6: see original paper].

4.3 Fuzzy Logic Controller Strategy

The output K_P^* is determined through fuzzy rules of the form: IF e is A AND Δe is B THEN K_P^* is C

The control strategy adheres to the following principles: 1. The controller should achieve minimal overshoot and settling time. 2. Control actions should be avoided when deviations stem from measurement noise or system dead zones. 3. To maintain power flow within operational limits, controller output should be appropriately limited when approaching boundaries to prevent excessive control actions. 4. The controller must maintain robust performance across varying operating conditions.

Based on these principles and the defined membership functions, the fuzzy inference system establishes the mapping between inputs e , Δe and output K_P^* , as illustrated by the input-output surface in [Figure 7: see original paper]. After obtaining K_P^* , the actual controller gain is calculated as:

$$KP = KP_{min} + KP^*(KP_{max} - KP_{min})$$

5. Case Study Analysis

The Anderson 3-machine 9-bus system, shown in [Figure 8: see original paper], is employed for validation studies. System parameters are adopted from reference [9]. Real-time digital simulation is utilized to verify the effectiveness of the proposed controller.

The controller utilizes the active power deviation and its rate of change on the TCPST-installed line as input signals. The steady-state gain is set to $K_{P0} = 15$, with the gain range defined as $[8,25]$ ($K_{Pmin} = 8$, $K_{Pmax} = 25$) and time constant $T_P = 0.2$ s.

5.1 Simulation Case I

A three-phase fault is applied on line 7-8, cleared after 100 ms by disconnecting line 5-7, which is subsequently reclosed after 500 ms. Three scenarios are compared: (1) no TCPST installed, (2) one TCPST (PS1 on line 8-9), and (3) two TCPSTs (on lines 8-9 and 4-5). The power angle swing curves for generators 2 and 1 are presented in [Figure 9: see original paper].

Without TCPST, the system exhibits sustained oscillations. With a single TCPST, stability is maintained but damping remains relatively slow. With two TCPSTs, the system maintains stability while achieving significantly more effective oscillation suppression.

5.2 Simulation Case II

With one TCPST installed (PS1 on line 8-9), the fuzzy P-type controller is compared with the conventional P-type controller under identical fault conditions, as shown in [Figure 10: see original paper].

Simulation results demonstrate that the fuzzy P-type controller provides superior damping of generator angle oscillations compared to its conventional counterpart. As illustrated in the phase angle and gain response curves, during large oscillations the fuzzy controller automatically increases the proportional gain K_P to produce larger phase shifts for enhanced control action. As oscillations diminish, the controller reduces the gain to maintain small phase angles near zero.

Overall, the proposed fuzzy logic controller exhibits superior control performance across various simulation scenarios compared to conventional P-type controllers.

6. Conclusion

Existing TCPST fuzzy logic controllers in literature typically employ direct phase angle control. This paper proposes a novel fuzzy logic controller that adjusts the gain of the conventional TCPST first-order dynamic controller. This approach integrates fuzzy logic with conventional linear control, using the gain K_P as output to accomplish TCPST control.

Simulation studies on the Anderson 3-machine 9-bus system demonstrate that the proposed controller effectively enhances power system transient stability and rapidly damps transmission line power oscillations. However, potential oscillations in the output K_P require further investigation and refinement.

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Note: Figure translations are in progress. See original paper for figures.

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