Fuzzy Rule-Based Fault Location Technique for Thyristor-Controlled Series-Compensated Transmission Lines

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Abstract

Estimating the distance of a transmission line with a flexible alternating current transmission system including a thyristor-controlled series compensator is a challenging task. The distance estimation technique based on a fuzzy rule-based system (FRS) in a thyristor-controlled series-compensated transmission line with multi-location faults is investigated in this study. The Haar wavelet current coefficients of the relaying bus are utilized as inputs to accomplish the distance estimation task. The FRS is illustrated through the Mamdani system in the LabVIEW software. The efficacy of the FRS is studied considering the effects of variation with respect to fault parameters. The main characteristic FRS is that it does not involve any two-end communication links because it employs relay terminal measurements only.

Keywords: Fuzzy rule-based system, Multi-location faults, Transmission lines

1. Introduction

Flexible alternating current transmission system (FACTS) controllers are a family of power electronics-based controllers that have become increasingly popular in electrical power and transmission systems. Recently, FACTS controllers have been established as a feasible transmission choice to accomplish effective utility of rights of way and enhanced transmission capacity to meet growing electrical demand. Among the different FACTS controllers, the thyristor-controlled series-compensated transmission line (TCSCTL) is a promising option for transferring control power [1]. It offers various functionalities, such as enhanced damping of power oscillations, active power flow, transient stability, mitigating the sub-synchronous resonance issue, and limiting the short-circuit current. Nonetheless, the protection of TCSCTL is more difficult and complicated than the protection of an uncompensated transmission line because of voltage and current inversions, reaching, and ferroresonance problems. Moreover,

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there are problems with mho relay functionalities in such applications.

TCSCTL is now a main part of the FACTS device group, and it is widely identified as an economical and effective means of solving the issues related to long transmission lines, such as, voltage and transient stability issues and FACTS controllers based optimal power flow control, in deregulation of the electrical power market to reduce losses and improve congestion management in transmission systems. Therefore, it is crucial to identify the specific fault issue in a transmission line so that the FACTS device is leveraged fully.

2. Related Research

Numerous studies have addressed the distance estimation of shunt faults (single location faults) in TCSCTL applications. Some the significant research include neural network-based distance estimation [2,3], genetic algorithm tuned support vector machine and artificial intelligence based faulty classifications [4,5], fuzzy-based section identification [6], fault detection [7], and fault analysis [8,9] for TCSCTL. The majority of studies have been validated on shunt faults, while only a few have addressed the issues related to the multi-location (two-location) faults in TCSCTLs. The popular computational approaches used in the development of multi-location fault models include neural networks [10,11], fuzzy rule-based systems (FRS) [12,13], and support vector machines [14]. Among these methods, FRS is proven to be the most suitable method, followed by support vector machines and neural network techniques.

The most recent fault distance methods based on FRS are reported in [15–18], which draw current from the relay terminal. FRS fault diagnosis for TCSCTLs is reported in studies [19–23]. However, this technique does not locate multi-location faults in TCSCTLs. Furthermore, the techniques mentioned in [19–23] require simplicity. Therefore, a suitable method needs to be investigated with a simple process; however, this is not provided in the abovementioned studies. As a result, our research focuses on the issue mentioned above utilizing FRS in the LabVIEW software. In this context, this study utilizes a concept based on the FRS, whose objectives are stated as follows:

- 1) The main purpose of FRS study is to boost error (%).
- 2) The speed of FRS is very high.
- 3) The FRS has no significant impact on instants (Φ), resistances (R), multi-location faults, and distance in each phase (D1, D2, D3).

- 4) It directly utilizes the current information without performing communication links.

The remainder of this paper is as follows: Section 3 explains the TCSCTL, and technical inputs used for obtaining the distance of multi-location faults. Section 4 describes the FRS technique in detail. In Section 5, the experimental evaluation of FRS using various data samples to verify its performance is illustrated. Finally, the obtained result are summarized in Section 6.

3. Studied System

A schematic representation of the TCSCTL considered in this study is demonstrated in Figure 1. This line operates at 500 kV voltage, 100 km length, and 60 Hz frequency. The TCSCTL consists of one capacitor that is used in the line for compensation. The capacitor is connected in parallel with an air gap arrangement, a metal oxide varistor (MOV) that protects it from overvoltage. Furthermore, it is also in parallel with the series connected inductor and anti-parallel thyristor combination. The 3-phase time-domain currents (IA, IB, and IC) are extracted from the relay terminal. B-1 is considered a relay terminal because here the behavior of the TCSCTL with respect to varying currents is studied, which is simulated using the MATLAB/Simulink software environment. Figure 2 shows a flow chart of the proposed framework.

When a fault occurs in two phases of TCSCTL at two distances simultaneously, is known as a multi-location fault. The TCSCTL is simulated for a simulation time of 200 ms, and the waveform of the instantaneous currents during the multi-location fault situation, that is, the B fault at 58 km and C fault at 15 km, are shown in Figure 3. Here, the 3rd level Haar wavelet transform is used for extracting features from currents obtained via the TCSCTL simulations. To estimate the multi-location fault distance, input signals are simulated according to various fault scenarios. Following feature extraction, a generally suitable computational scheme is adopted by the proposed technique to perform the distance estimation task regarding multi-location faults. The Haar wavelet transforms are the easiest wavelet transforms. The main benefits of the Haar wavelet transform are the investigation of signals with sudden transitions, that is, monitoring of tool failures in machines, and rapid computation. The Haar wavelet transforms can be expressed as

$$\psi(t) = \begin{cases} +1, & 0 \leq t \leq 1/2, \\ -1, & 1/2 \leq t \leq 1, \\ 0, & \text{Otherwise.} \end{cases} \quad (1)$$

Figure 1. TCSCTL connection diagram.

Figure 2. Flow chart of proposed FRS framework.

Figure 3. Current coefficients during multi-location fault.

4. Fuzzy Rule-Based System

Fuzzy logic was introduced by Lofty Zadeh in 1965 based on the theory of “partial truth,” that is the truth values lied between “absolutely false” and “absolutely true”. Fuzzy logic provides a structure to design the uncertainty, perception process, and human way of reasoning. It is also based on natural language, and through a set of IF-THEN rules, an expert system is created, which is a function of fuzzy computations. Fuzzy logic has many benefits: first, it is applicable to many systems; furthermore, it can be understood simply owing to being mostly flexible; and finally, it can be used to design nonlinear functions of arbitrary complexities. The FRS components are depicted in Figure 4.

The FRS used in this study is of the Mamdani type. The input, outputs, and their membership functions are reported in Figure 5. The membership function is obtained by dividing the input

and output gaps into separate parts in a triangular format. The IF-THEN rules have two components: an antecedent component and a consequent component. For each rule in the FRS, Haar wavelet currents are the antecedent of the rule, and the distance in each phase is the consequent. Each rule is then evaluated on these variables using the fuzzy AND operator to produce another value. The number of rules in the FRS scheme used here is 27, as shown in Figure 6. Each output parameter is a crisp value, which indicates the location in a range of 0-100. Here, we used the most applicable method of defuzzification, the center of gravity method, to defuzzify the outputs.

5. Experimental Results

In this section, the adopted FRS scheme is examined on the widely studied 500 V, 60 Hz, TCSCCTL. The FRS scheme has been assessed with respect to different dynamic fault param-

Figure 4. Fuzzy rule-based system.

Figure 5. The input, outputs, and their membership functions.

FRS System IF-THEN Rules

1. IF 'IA' IS 'F1' AND 'IB' IS 'F1' AND 'IC' IS 'F1' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J3'
2. IF 'IA' IS 'F1' AND 'IB' IS 'F1' AND 'IC' IS 'F2' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J2'
3. IF 'IA' IS 'F1' AND 'IB' IS 'F1' AND 'IC' IS 'F3' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J1'
4. IF 'IA' IS 'F1' AND 'IB' IS 'F2' AND 'IC' IS 'F1' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J3'
5. IF 'IA' IS 'F1' AND 'IB' IS 'F2' AND 'IC' IS 'F2' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J2'
6. IF 'IA' IS 'F1' AND 'IB' IS 'F2' AND 'IC' IS 'F3' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J1'
7. IF 'IA' IS 'F1' AND 'IB' IS 'F3' AND 'IC' IS 'F1' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J3'
8. IF 'IA' IS 'F1' AND 'IB' IS 'F3' AND 'IC' IS 'F2' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J2'
9. IF 'IA' IS 'F1' AND 'IB' IS 'F3' AND 'IC' IS 'F3' THEN 'D1' IS 'J3' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J1'
10. IF 'IA' IS 'F2' AND 'IB' IS 'F1' AND 'IC' IS 'F1' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J3'
11. IF 'IA' IS 'F2' AND 'IB' IS 'F1' AND 'IC' IS 'F2' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J2'
12. IF 'IA' IS 'F2' AND 'IB' IS 'F1' AND 'IC' IS 'F3' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J1'
13. IF 'IA' IS 'F2' AND 'IB' IS 'F2' AND 'IC' IS 'F1' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J3'
14. IF 'IA' IS 'F2' AND 'IB' IS 'F2' AND 'IC' IS 'F2' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J2'
15. IF 'IA' IS 'F2' AND 'IB' IS 'F2' AND 'IC' IS 'F3' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J1'
16. IF 'IA' IS 'F2' AND 'IB' IS 'F3' AND 'IC' IS 'F1' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J3'
17. IF 'IA' IS 'F2' AND 'IB' IS 'F3' AND 'IC' IS 'F2' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J2'
18. IF 'IA' IS 'F2' AND 'IB' IS 'F3' AND 'IC' IS 'F3' THEN 'D1' IS 'J2' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J1'
19. IF 'IA' IS 'F3' AND 'IB' IS 'F1' AND 'IC' IS 'F1' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J3'
20. IF 'IA' IS 'F3' AND 'IB' IS 'F1' AND 'IC' IS 'F2' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J2'
21. IF 'IA' IS 'F3' AND 'IB' IS 'F1' AND 'IC' IS 'F3' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J3' ALSO 'D3' IS 'J1'
22. IF 'IA' IS 'F3' AND 'IB' IS 'F2' AND 'IC' IS 'F1' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J3'
23. IF 'IA' IS 'F3' AND 'IB' IS 'F2' AND 'IC' IS 'F2' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J2'
24. IF 'IA' IS 'F3' AND 'IB' IS 'F2' AND 'IC' IS 'F3' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J2' ALSO 'D3' IS 'J1'
25. IF 'IA' IS 'F3' AND 'IB' IS 'F3' AND 'IC' IS 'F1' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J3'
26. IF 'IA' IS 'F3' AND 'IB' IS 'F3' AND 'IC' IS 'F2' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J2'
27. IF 'IA' IS 'F3' AND 'IB' IS 'F3' AND 'IC' IS 'F3' THEN 'D1' IS 'J1' ALSO 'D2' IS 'J1' ALSO 'D3' IS 'J1'

Figure 6. IF-THEN rules.

ters, such as instants (Φ), resistances (R), multi-location faults, and distance in each phase (D1, D2, D3), where a total of 25,000 fault cases have been examined. The effects of varying R, Φ , shunt faults, distances, and types, and corresponding test results are reported in Tables 1-4. The FRS applications in multi-location and shunt faults in the LabVIEW fuzzy software are depicted in Figures 7 and 8, respectively. The error in the distance estimation of multi-location faults is calculated using Eq. (2).

$$\text{Error (\%)} = \left| \frac{\text{Estimated fault location (km)} - \text{Real fault location (km)}}{\text{Line length}} \right| \times 100. \quad (2)$$

Table 1. Effect of varying ϕ in multi-location fault scenario (A fault at 11 km and C fault at 78 km)

Φ (°)	R (Ω)	D1 (km)	D2 (km)	D3 (km)	Error in phase	
					A fault	C fault
10	20	11.101	100	78.083	0.101	0.083
50	20	10.880	100	78.155	0.220	0.155
100	20	11.233	100	77.966	0.233	0.034
150	20	11.147	100	77.801	0.147	0.199
200	20	11.025	100	78.067	0.025	0.067
250	20	10.735	100	78.221	0.265	0.221
300	20	11.254	100	78.011	0.254	0.011
350	20	11.211	100	78.226	0.211	0.226

It is important to test the FRS application for close-in (1-5 km) and remote-end (95-99 km) multi-location faults because

Table 2. Effect of varying R in multi-location fault scenario (A fault at 92 km and B fault at 21 km)

Φ (°)	R (Ω)	D1 (km)	D2 (km)	D3 (km)	Error in phase	
					A fault	C fault
90	10	92.192	20.829	100	0.192	0.171
90	30	92.034	21.186	100	0.034	0.186
90	50	91.943	21.155	100	0.057	0.155
90	70	92.091	21.245	100	0.091	0.245
90	90	92.176	21.043	100	0.176	0.043
90	110	91.803	21.024	100	0.197	0.024
90	130	92.106	21.011	100	0.106	0.011
90	150	92.131	21.162	100	0.131	0.162

Figure 7. The outputs of FRS where phase B is located at 50 km at 46 ms and C is located at 14 km at 46 ms, with the other output A located at 100 km, indicating that there exists a BC multi-location fault.

in such cases the voltage and current magnitudes are different, which leads to relay failures. The results of the FRS for close-in and remote-end multi-location faults are listed in Table 5. The FRS application during close-in and remote-end multi-location faults in the LabVIEW fuzzy software is shown in Figure 9. This confirms that the proposed scheme is not affected by the addition of close-in and remote-end multi-location faults. Moreover, observe that most fault cases are located below the 0.258 error value.

Figure 8. The outputs of FRS where phase A is located at 83 km at 46 ms, with other outputs B and C located at 100 km, indicating that there exists a BC-shunt fault.

Figure 9. The outputs of FRS where phase A (close-in) is located at 3 km at 46 ms and C (remote-end) is located at 99 km at 46 ms, with the other output B located at 100 km, indicating that there exists an AC multi-location fault.

To assess the FRS performance, multi-location fault-based algorithms presented in [3,10–12,14] are chosen. The comparison results support the computational ones presented in Table 6. The

Table 3. Effect of varying distances and types

Φ (°)	R (Ω)	Fault-1	Fault-2	D1 (km)	D2 (km)	D3 (km)	Error in Fault-1	Error in Fault-2
45	75	A-Phase fault at 28 km	B-Phase fault at 83 km	28.134	83.252	100	0.134	0.252
45	75	A-Phase fault at 32 km	C-Phase fault at 67 km	31.981	100	67.240	0.029	0.240
45	75	B-Phase fault at 44 km	C-Phase fault at 15 km	100	43.864	15.066	0.136	0.066
45	75	A-Phase fault at 65 km	B-Phase fault at 26 km	64.953	25.762	100	0.047	0.248
45	75	A-Phase fault at 18 km	C-Phase fault at 94 km	18.213	100	94.125	0.213	0.125
45	75	B-Phase fault at 19 km	C-Phase fault at 06 km	100	19.201	06.161	0.201	0.161

Table 4. Effect of varying shunt faults

Φ (°)	R (Ω)	Type	Distance (km)	D1 (km)	D2 (km)	D3 (km)	Error
180	50	Phase-B fault	9	100	8.926	100	0.074
180	50	Phase-B fault	15	100	15.085	100	0.085
180	50	Phase-B fault	28	100	27.068	100	0.068
180	50	Phase-B fault	36	100	35.891	100	0.009
180	50	Phase-B fault	44	100	44.104	100	0.104
180	50	Phase-B fault	51	100	51.211	100	0.211
180	50	Phase-B fault	60	100	60.282	100	0.282
180	50	Phase-B fault	67	100	66.135	100	0.135
180	50	Phase-B fault	73	100	72.823	100	0.177
180	50	Phase-B fault	82	100	82.292	100	0.292
180	50	Phase-B fault	89	100	89.124	100	0.124
180	50	Phase-B fault	99	100	98.761	100	0.239

Table 5. Effect of close-in and remote-end multi-location faults

Φ (°)	R (Ω)	Fault-1	Fault-2	D1 (km)	D2 (km)	D3 (km)	Error in Fault-1	Error in Fault-2
45	75	A-Phase fault at 1 km	B-Phase fault at 5 km	1.163	99.189	100	0.163	0.189
45	75	A-Phase fault at 2 km	C-Phase fault at 4 km	2.020	100	98.142	0.020	0.142
45	75	B-Phase fault at 3 km	C-Phase fault at 3 km	100	3.863	97.067	0.137	0.067
45	75	A-Phase fault at 4 km	B-Phase fault at 2 km	4.900	96.765	100	0.100	0.235
45	75	A-Phase fault at 5 km	C-Phase fault at 1 km	5.244	100	95.088	0.244	0.088

results of the FRS technique compared to those obtained by the algorithms presented in [3,10–12], achieve excellent distance estimation accuracy and track the output values well for all data sets. The FRS scheme designed in LabVIEW simulations outperforms the benchmark algorithms without planning complex techniques, such as those adopted in [3,10,11,14]. Therefore, we can conclude that more test samples are recommended than those used in [12,14]. To the best of our knowledge, no im-

plementation has described the enhancement of multi-location fault distance estimation in TCSCCTL, as we have in this study.

6. Conclusion

This study presented an FRS technique for the distance estimation of multi-location faults in TCSCCTLs. In addition, the proposed research is independent of the Haar wavelet voltage and communication links. The standard deviation values of the

Table 6. Comparison of FRS to established techniques

Ref	Fault types	Model used	Test samples	Error
[3]	Multi-location faults	Neural networks	-	1
[10]	Multi-location faults	Neural networks	-	1
[11]	Cross-country faults	Neural networks	-	1
[12]	Multi-location faults	FRS	1000	0.5
[13]	Cross-country faults	FRS	20,000	0.41
[14]	Cross-country faults	Support vector machines	14,500	-
[16]	Simultaneous faults	FRS	-	0.4
Proposed FRS	Multi-location faults	FRS	25000	0.25

Haar wavelet current coefficients were considered for distance estimation of TCSC in multi-location faults. The drastic change in different faults provided significant results during the FRS validation. In addition, the FRS achieved high efficacy with respect to errors against line parameters. Furthermore, the enactment of the proposed FRS was compared to that of the other techniques. The proposed FRS scheme detected all types of multi-location faults with cycle time range between 0.01 to 0.46 seconds.

Conflicts of Interest

No potential conflicts of interest relevant to this article was reported.

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