Fault Diagnosis of Transmission Lines with Rogowski Coils as Current Sensors

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ABSTRACT

This paper presents implementation of algorithms developed for fault classification and location detection on transmission lines with data from current & voltage sensors. Rogowski coil as current sensor is gaining importance due to its linearity and wide band width. A lumped parameter model of Rogowski coil is developed and integrated with a power system model in SIMULINK to simulate all types of faults at different locations, fault inception angles and fault resistances. A fault classification scheme based on the evaluation of angles of fault currents and voltages is extended to secondary values obtained from Rogowski coil. Further after estimation of phasors, fault location is detected. The test results show that the proposed algorithm on primary values is equally applicable on secondary values thus offering a fast and reliable technique for fault diagnosis of transmission lines in power systems.

General Terms
Fuzzy logic Fault Classifier (FFC), Fault distance

Keywords
Rogowski coil, lumped parameter model, symmetrical components, toroid, fault inception angle

1. INTRODUCTION
Transmission lines are vital to power systems as they constitute the back bone of power systems. Fault rate is usually much higher in transmission lines as compared to other components. Therefore, effective protection techniques for transmission line are essential. Due to increased complexity in power systems, need for faster fault clearing times, and difficulty in grading time/ over current relays, high speed digital distance relay is a good choice for transmission line protection. Transmission line fault location detection and classification has been a primary concern for high speed protective relaying and single pole auto-reclosures. Fault diagnosis is performed by computation of line impedance through the measurement of voltages and currents on one single end with respect to fault.

Traditional relaying equipment are provided with signals from iron cored voltage and current transformers (CT) having non-linear magnetizing reactance. CT primary currents [1] can change from load currents to high fault currents. To avoid saturation, CTs are designed to operate at load currents on the lower portion of the magnetizing branch of V-I curve's linear region. It is desirable that CTs operate on the linear region without exceeding the saturation voltage even for fault currents. However, since short circuit currents may have a significant DC offset, it may saturate CTs [2] that would not saturate under symmetrical fault conditions.

Rogowski coils (RC) [3][4] are linear and provide advanced solutions for applications in multifunctional protective relaying. These schemes require fewer relays and current sensors than conventional designs, response times to faults are faster and adjustments to load and/or power system configuration changes can be easily made. Since RCs are very accurate and do not saturate, protection levels can be set to lower thresholds increasing the sensitivity of the scheme without affecting reliability of operation. This reduces the stress on protected equipment during faults. The system is immune to external magnetic fields. It is simple, user friendly, requires less wiring and space and can provide metering class accuracy.

MATLAB [5] has powerful high level programming features and tool box for system designing applications. Therefore the protection algorithms can be quickly implemented. Also the fuzzy tool box is used to design a fault classifier [6] based on the symmetrical components [7] of the fault current. SIMULINK [8] provides excellent GUI and block set, that allows flexible and rapid simulation of system models. Communication between MATLAB, SIMULINK and other tool boxes is very simple and doesn't require any change in formatting of the information to be exchanged. The above mentioned excellent advantages make MATLAB/SIMULINK a simple, convenient and interactive tool for simulation and testing of relay algorithm for various fault conditions

In [9], the author presents determination of phase angles of currents for fault classification through fuzzy logic technique. This paper presents a modification on fault classification presented in [10], to classify accurately all the 10 types of faults. Also, it proves the validity of the algorithm developed for fault diagnosis with primary values equally to the secondary values from Rogowski coil sensors.

2. POWER SYSTEM AND ROGOWSKI COIL SIMULATION

2.1 Power System Simulation Parameters
A 345kV power system as shown in Fig. 1 is modeled in SIMULINK to generate fault signals for various faults, fault distances and fault inception angles. The power system details are listed in appendix (1) where S & R represents sending end and receiving end generators and F, the location of fault at a distance 'x' from the sending terminal of a transmission line. The signals so obtained are processed to implement the logic for fault classification.

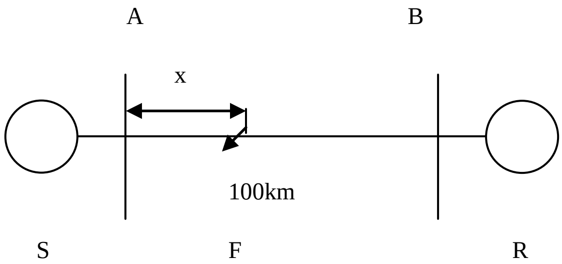


Fig 1: Simulated transmission system

2.2 Rogowski coil Parameters

Rogowski coil (RC) consists of wire wound on a non-magnetic core. The coil is placed around the conductor whose current has to be measured. The construction of RC is shown in Fig. 2 and the geometric characteristics of the circular cross section Rogowski coil [11] [12] are given in Table 1.

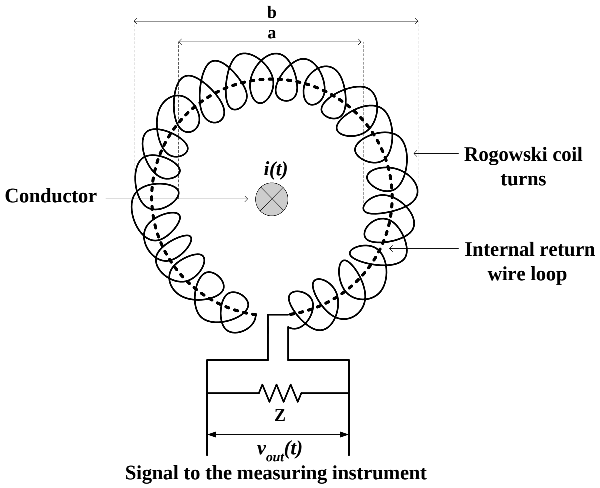


Fig 2: Construction of Rogowski coil

Table 1 Geometric characteristics of RC

Rogowski Coil Dimensions	Specifications
Inner diameter a	162.4 mm
Outer diameter b	191 mm
Transducer diameter d_{rc}	14.3 mm
Length of the wire l_w	25 m
Radius of the wire d	1 mm
Length of the coil l	600 mm

2.3 Rogowski coil Characteristics

The most important characteristics of a Rogowski coil current sensor are:

- Large bandwidth allowing the measurement of current with fast transients as in power distribution and power electronic circuits.
- Large span because with the same coil it is possible to measure few amperes to kilo-amperes
- Good linearity, as the coil is air cored (non-magnetic).
- No saturation, so the coil is not damaged by extra current.
- Galvanic isolation between the primary circuit and measuring circuit.
- The magnetic coupling between the primary and measuring circuit is in nano-henry, hence no charge effect.

Small size, lighter weight, high reliability, low losses and low cost are some more attractive features of Rogowski coils making them the best choice for protection of modern, complex power systems.

2.4 Rogowski coil Simulation

For a toroid coil having circular cross-section, the lumped parameters can be calculated using equations (1), (2) & (3)

$$R_l = \rho_c \frac{l_w}{\pi d^2} \quad (1)$$

$$L_l = \frac{\mu_0 N^2 d_{rc}}{2\pi} \log \frac{b}{a} \quad (2)$$

$$C_l = \frac{4\pi^2 \varepsilon_0 (b+a)}{\log\left[\frac{b+a}{b-a}\right]} \quad (3)$$

Where R_l, L_l, and C_l are the lumped resistance, inductance, and capacitance of the coil respectively. ρ_c is the copper resistivity; μ_0 and ε_0 are the air permeability and permittivity, respectively; and N=431, is the number of turns of the coil [11]. The terminating impedance of the Rogowski coil Z can be approximately calculated as given in reference [11]. The equivalent circuit of the Rogowski coil, based on the lumped parameters, is drawn in Fig. 3, where i is the current flowing in the transmission line, $v_{rc}(t)$ is the induced voltage in the coil, $v_{out}(t)$ is the coil output voltage, and M is the mutual inductance of the coil (200 nH).

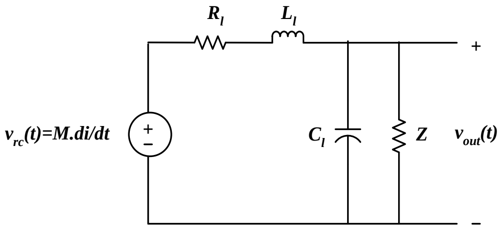


Fig 3: Equivalent lumped circuit of Rogowski coil

Table 2 Measured lumped values of RC

Lumped model parameters	Measured Values
Resistance R_l	0.11Ω
Inductance L_l	0.6 µH
Capacitance C_l	50.3 pF
Terminating Impedance Z	2 KΩ

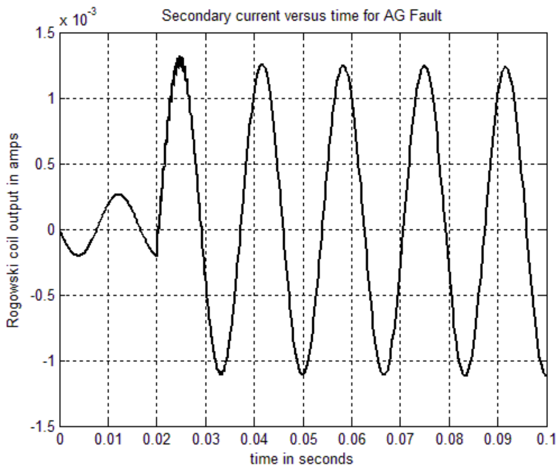
The transfer function (*Vout/Vrc*) of the Rogowski coil lumped parameters model can be calculated as:

$$\frac{V_{out}}{V_{rc}} = \frac{Z}{s^2 L_l Z C_l + s(L_l + R_l Z C_l) + (R_l + Z)} \qquad (4)$$

The Rogowski coil output voltage is proportional to the rate of change of primary current. To obtain secondary current, the coil output voltage must be integrated.

2.5 Fault Current Waveforms with & without Rogowski coil

On simulation of the Rogowski coil in SIMULINK the secondary signal along with the primary current for asymmetric line to ground fault (AG) is shown in Fig. 4. The integrated secondary signal is identical to primary waveform due to linear characteristics.



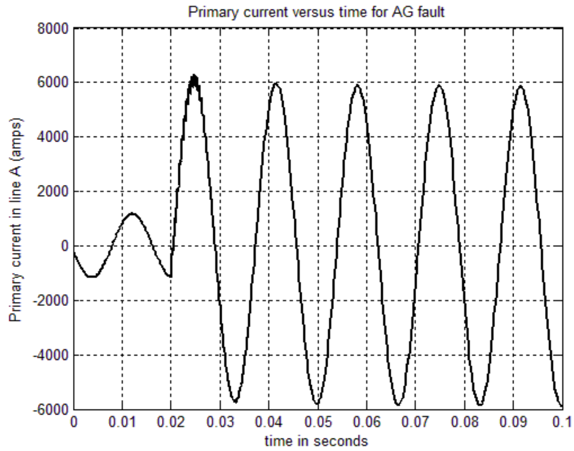


Fig 4: Secondary and primary currents versus time for AG fault.

3. FUZZY LOGIC FAULT CLASSIFIER

The need for accurate fault classification schemes to facilitate rapid fault location is of prime importance for effective and fast protection and system restoration operations. Most of the algorithms used in the past are based on the following techniques:

- Under-impedance
- Torque
- Over-current

A new technique based on the symmetrical components of fault currents is proposed [7] and verified to be 95% better than other fault location packages. The data required is only the three phase fault currents at the substation. The above technique can be implemented using fuzzy logic, neural network or expert system. Due to simplicity fuzzy logic approach [6] is preferred. The new algorithm is based on the angular differences among the sequence components of the fundamental fault current as well as on their relative magnitudes. Based on the three phase fault currents (I_A,I_B,I_C) the zero, positive and negative sequential components with respect to phase a $[I_{a0}, I_{a1}, I_{a2}]$, phase b $[I_{b0}, I_{b1}, I_{b2}]$ and phase c $[I_{c0}, I_{c1}, I_{c2}]$,the phase angle difference between the positive and negative sequence components and the normalized zero sequence and negative sequence currents are evaluated using (5), (6) & (7).

$$\left.\begin{aligned}
\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} &= \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \\
\begin{bmatrix} I_{b0} \\ I_{b1} \\ I_{b2} \end{bmatrix} &= \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_b \\ I_c \\ I_a \end{bmatrix} \\
\begin{bmatrix} I_{c0} \\ I_{c1} \\ I_{c2} \end{bmatrix} &= \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_c \\ I_a \\ I_b \end{bmatrix}
\end{aligned}\right\} \qquad (5)$$

$$\left.\begin{aligned}
&\text{ang_A} = \text{abs (angle } (I_{a1}) - \text{angle } (I_{a2})) \\
&\text{ang_B} = \text{abs (angle } (I_{b1}) - \text{angle } (I_{b2}))
\end{aligned}\right\} \qquad (6)$$

$$\left.\begin{aligned} ang\_C &= abs\,(angle\,(I_{c1}) - angle\,(I_{c2})) \\ R_{of} &= abs\,(I_{a0}/I_{a1}) \\ R_{2f} &= abs\,(I_{a2}/I_{a1}) \end{aligned}\right\} \quad (7)$$

The fundamental relation between angles and current ratios for all asymmetrical faults (AG, BG, CG, AB, BC, CA, ABG, BCG, and CAG) is given in Table 3. For symmetrical fault the zero and negative sequence components do not exist in the system, hence the angles ang_A, ang_B and ang_C are not defined. The values of K and K_1 are defined by equations (8), where Z_2, Z_0 & Z_f are the negative sequence impedance, zero sequence impedance of the line and fault impedance respectively.

The values specified in Table 3 are valid only if the resistance in the fault path is negligibly small.

$$K = {}^{Z_2}\!\big/\left(Z_2 + Z_0 + 3Z_f\right)$$

$$K_1 = \left(Z_2 + 3Z_f\right)/\left(Z_2 + Z_0 + 3Z_f\right) \quad (8)$$

Table 3 Fundamental Relation for Asymmetrical Faults

Type of fault	ang_A	ang_B	ang_C	R_{of}	R_{2f}
AG	0˚	120˚	120˚	1.0	1.0
BG	120˚	0˚	120˚	1.0	1.0
CG	120˚	120˚	0˚	1.0	1.0
AB	60˚	60˚	180˚	0.0	1.0
BC	180˚	60˚	60˚	0.0	1.0
CA	60˚	180˚	60˚	0.0	1.0
ABG	60˚	60˚	180˚	K	K_1
BCG	180˚	60˚	60˚	K	K_1
CAG	60˚	180˚	60˚	K	K_1
SYM	-	-	-	0.0	0.0

3.1 Design of FFC

The properties of the fuzzy logic based fault classifier (FFC) as obtained from Fuzzy Inference System toolbox in MATLAB is given in Table 4. It has five inputs ang_A, ang_B, ang_C, Rof, R2f and an output fault_type (FT), each of the three input variables ang_A, ang_B and ang_C are defined by four fuzzy variables: AZ, AS, AO, AOE (approximately zero, approximately 60˚, approximately 120˚, approximately 180˚) and the other two Rof and R2f are defined by two fuzzy variables: low_Rof, high_Rof, low_R2f, high_R2f. All the fuzzy variables and their ranges are defined in Table 5. It is to be noted that these relationships are valid for faults in an unloaded system.

Table 4 Properties of fuzzy fault classifier

Name	Fault_class1
Type	mamdani
NumInputs	5
InLabels	ang_A, ang_B, ang_C, Rof, R2f
NumOutputs	1
OutLabels	FT
NumRules	10
AndMethod	min
OrMethod	max
ImpMethod	min
AggMethod	max
DefuzzMethod	centroid

Table 5 Fuzzy Variables with their ranges

Fuzzy variable	Triplets		
	A	B	C
approximately 0˚ (AZ)	0˚	0˚	35˚
approximately 60˚ (AS)	35˚	60˚	95˚
approximately 120˚ (AO)	85˚	120˚	155˚
approximately 180˚ (AOE)	145˚	180˚	215˚
Low-R_{of} (low)	0	0	0.26
high-R_{of} (high)	0.26	0.975	1.8
Low-R_{2f} (low)	0	0	0.45
high-R_{of} (high)	0.45	0.975	1.8

A partial rule base for different fault categories is described below:

1. If ang_A is AZ and ang_B is AO and ang_C is AO and Rof is high and R2f is high

Then fault_type is AG

2. If ang_A is AS and ang_B is AS and ang_C is AOE and Rof is low and R2f is high

Then fault_type is AB

3. If ang_A is AS and ang_B is AS and ang_C is AOE and Rof is high and R2f is high

Then fault_type is ABG

4. If Rof is low and R2f is low

Then fault_type is SYM

3.2 Input and Output of FFC with and without Rogowski coil

The typical output of fault classifier with primary and secondary values is listed in Table 6 & Table 7, depending on the pre-fault power level, fault resistance, fault location, fault inception angle(FIA) etc., the values of these five quantities deviate from their corresponding ideal values as in Table 5. The output tabulated is for a fault distance of 50km with respect to S, fault resistance of 1Ω and fault inception angle (FIA) of 0˚.

Table 6 Input & Output of FFC with primary values

Fault	ang_A	ang_B	ang_C	Rof	R2f	o/p
AG	30.93	89.06	150.93	0.8981	0.9316	0.2
BG	152.69	32.69	87.3	0.8889	0.9231	1
CG	87.0	153.01	33.0	0.8625	0.8941	2
AB	74.3	45.69	165.69	4.8e-6	0.9787	3
BC	165.39	74.611	45.39	4.9e-6	0.9821	4
CA	45.4	165.4	74.59	4.9e-6	0.9821	5
ABG	65.2	54.79	174.8	0.283	0.6943	6
BCG	168.9	71.11	48.89	0.2697	0.7096	7
CAG	50.62	170.62	69.377	0.2674	0.766	8
SYM	-	-	-	7.9e-12	0.0852	9

Table 7 Input & Output of FFC with secondary values

Fault	ang_A	ang_B	ang_C	Rof	R2f	o/p
AG	32.65	87.34	152.65	0.8922	0.9112	0.1
BG	152.65	32.65	87.34	0.9128	0.9081	1
CG	86.52	153.49	33.48	0.9496	0.9234	2
AB	74.78	45.21	165.21	5.6e-6	0.9721	3
BC	165.68	74.33	45.67	7.1e-6	0.9733	4
CA	45.41	165.41	74.58	3.5e-6	0.9689	5
ABG	69.62	50.3	170.37	0.2732	0.7196	6
BCG	169.4	70.62	49.38	0.2673	0.7134	7
CAG	49.44	169.44	70.55	0.2768	0.73	8
SYM	-	-	-	3.7e-11	0.0129	9

4. FAULT LOCATION IDENTIFIER

4.1 Fault impedance & distance Calculation

On estimation of current and voltage phasors by applying Fourier transformation as well as the zero sequence current component I_0, the fault impedance for various faults is determined [13]using formulae shown in Table 8.

Table 8 Fault impedance calculation formula on different faults

Fault Type	Formula
AG	$V_A/(I_A+kI_0)$
BG	$V_B/(I_B+kI_0)$
CG	$V_C/(I_C+kI_0)$
AB or ABG	$(V_A-V_B)/(I_A-I_B)$
BC or BCG	$(V_B-V_C)/(I_B-I_C)$
CA or CAG	$(V_C-V_A)/(I_C-I_A)$

Where A, B and C indicates three phases, G is ground, V and I are phasors of voltage and current, k= $(Z_0-Z_1)/Z_1$, Z_0 and Z_1 are zero-sequence, positive-sequence impedances of line respectively. I_0 is zero-sequence current.

Since the impedance of the total line length is a known quantity, the fault distance can be obtained as it is proportional to the evaluated fault impedance according to expression (9),

$$L_f = Z_f / Z_L \times L \tag{9}$$

Where Z_f represents fault impedance, Z_L the total line impedance and L the total line length.

4.2 Error With & Without RC

The % error between actual distance (Actual dist) and measured distance (Measured dist) is calculated as,

$$\%Error = \frac{(\text{Actual dist - Measured dist})}{\text{Actual dist}} \times 100 \tag{10}$$

The distance at which fault is simulated is termed as actual fault distance. For various fault distances the power system simulation is executed to obtain the primary fault currents and voltages by applying Discrete Fourier transformation and hence the fault impedance and fault distance are computed using Table 8 and equation 9 respectively. In the next case, Discrete Fourier transformation is applied on the fault currents and voltages obtained from Rogowski coil. There from, the fault impedance and fault distance are determined from Table 8 and equation (9). This is repeated for various faults like AG, ABG and AB faults. Also the % error using equation (10) is computed and tabulated as shown in Tables 9, 10 & 11. It shows that in worst cases the %error ranges between -3.9 to 1.5 with primary values while with RC it ranges between -0.8 to 2.3 indicating that the fault distance obtained from RC is more accurate hence justifying the usage of Rogowski coils as current sensors instead of current transformers. Tables 9, 10 & 11 are only sample outputs, while the system has been tested for all the types of faults with different FIA and fault resistance.

Table 9 Fault distances and error for AG fault

AG FAULT				
Actual fault distance (km)	distance with pri values (km)	% Error with primary values	distance with RC(km)	% Error with RC
20	19.82	0.9	20.05	-0.25

40	40.26	-0.65	39.84	0.4
60	61.42	-2.36	59.80	0.333
80	79.16	1.05	79.62	0.475

Table 10 Fault distances and error for ABG fault

ABG FAULT				
Actual fault distance (km)	distance with pri values (km)	% Error with primary values	distance with RC(km)	% Error with RC
20	20.31	-1.55	20.04	-0.2
40	39.79	0.525	40.33	-0.825
60	59.78	0.366	59.62	0.633
80	81.41	-1.763	78.40	2.0

Table 11 Fault distances and error for AB fault

AB FAULT				
Actual distance (km)	distance with pri values (km)	% Error with primary values	distance with RC(km)	% Error with RC
20	20.5458	-2.729	20.0356	-0.178
40	39.7373	0.6575	39.067	2.333
60	59.0526	1.579	60.245	-0.408
80	83.1659	-3.957	81.6001	-2.0

5. CONCLUSION

The Fuzzy Fault Classifier logic, designed for primary currents is equally valid with RC output data. Instead if CTs were to be used then, due to core saturation and attenuation, the secondary values would largely differ and hence the logic used in fault identifier would no longer be valid. RC with linear characteristics results in identical secondary and primary signal waveforms as shown in fig 4. Thus Table 6 & 7 is similar. Also as discussed earlier, Table 9, Table 10 and Table 11 show that the % error with secondary values is lesser than that of primary values in worst cases due to accurate computations. Also during study, it is found that adaptive windowing is possible and data sampling for just 5ms from fault inception is enough for fault classification, making it the fastest technique.

Further due to high bandwidth, RC can be used to determine high frequency components to identify various disturbances as well as faults on transmission lines by developing high frequency model of RC. Replacement of CTs with RCs in power system can thus improve power quality as well as its operation, control and protection through accurate measurements over wide range of frequency. It also cuts down the cost of Instrumentation equipment, thus recommending the replacement of all CTs by RCs in stages, a step towards Smart Grid transformation.

6. Appendix 1:

Transmission power system parameters
Voltage rating: 345 kv
System frequency: 60 Hz
Equivalent Voltage per unit:
Es=1∟15˚ (p.u.), Er=1∟0˚ (p.u.)
Equivalent Source Impedance:
Zs1=0.238+5.72(Ω), Zs0=2.738+10(Ω)
Zr1=0.238+6.19(Ω), Zr0=0.833+5.12(Ω)
Length of Transmission Line: 100 km
Line Constants:
R0=0.275(Ω), L0=3.725(mH), C0=6.71(nF)
R1=0.0275(Ω), L1=1.345(mH), C1=9.483(nF)

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