Global Sensitivity Analysis of Impedance Measurement Algorithms Implemented in Intelligent Electronic Devices

by

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Abstract

A novel methodology for testing performance of impedance measurement algorithms used in transmission line protection schemes is developed. Nowadays, impedance measurement algorithms are software functions implemented in the multifunction Intelligence Electronic Devices (IEDs) responsible for overall monitoring, protection and control of transmission lines. Accurate impedance measurement during fault conditions is the key in successful performance of the line protection as well as fault location functions of an IED. This thesis investigates a typical practical situation where only short-term fault records of voltage and current measurements from one side of a transmission line are used as inputs in the impedance measurement algorithm. Current flowing into the fault from the remote terminal of transmission line as well as fault impedance can influence significantly accuracy of impedance measurement. Since these two quantities are not measured, we require a systematic tool which will assess sensitivity of impedance measurement to those factors. At present, these sensitivities are obtained in heuristic and ad hoc manner during application testing done by utilities before commissioning of new IEDs. Situation in practice can be increasingly complex and this kind of unsystematic testing approach can fail. The thesis addresses those practical complex cases in the systematic manner. In these cases we encounter the following configurations of transmission lines with new not measured factors:

- parallel closely spaced lines, where the effect of electromagnetic mutual coupling can be significant;
- series capacitive compensation of transmission line, where capacitance of the compensation device can be unknown;
- three-terminal lines, where measurements on the tapped line are not available.

The proposed systematic sensitivity testing tool comprises of a transmission line electromagnetic simulation module and a Global Sensitivity Analysis (GSA) module. The software packages commonly used by industry are employed to implement those modules: the DIgSILENT software for the line simulation module and the SIMLAB software for the GSA module. The simulation module is used to simulate large number of fault scenarios for all samples in the factor space, while the GSA module is responsible for creating a set of specific samples in the factor space as well as for sensitivity analysis. The commercial multifunctional IED SEL-421 from the Schweitezer Engineering Laboratories has been used to demonstrate the proposed sensitivity analysis tool. The IED functions has been modelled in DIgSILENT environment and integrated into the simulation module. Test automation program has been written using the DIgSILENT Programming Language (DPL) so fully automatic and integrated performance of the simulation and the GSA modules has been achieved. The GSA module relies on the Quasi-Monte Carlo (QMC) technique with the Sobol's quasi random sampling and the Morris method is used in fast factor pre-screening in order to remove non-influential factors before applying the QMC GSA. The results of systematic tests of the impedance measurement algorithm implemented in the SEL-421 IED, for various line configuration cases, are presented in this thesis. The results verify the usefulness of the proposed testing methodology for practical applications.

Statement of Originality

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Glossary of Symbols

$\underline{E}_S$, $\underline{E}_R$, $\underline{E}_T$	source voltage behind terminal S , R, T, respectively	V
$\underline{E}_{1S}$	positive-sequence voltage behind terminal S	V
F	fault location	p.u.
$\underline{I}_1$, $\underline{I}_2$, $\underline{I}_0$	positive-, negative-, and zero-sequence current, respectively	A
$\underline{I}_{1S}$, $\underline{I}_{2S}$, $\underline{I}_{0S}$	positive-, negative-, zero-sequence current at terminal S, respectively	A
$\underline{I}_{AB}$	phase A-B current at the end S during the fault	A
$\underline{I}_{BC}$	phase B-C current at the end S during the fault	A
$\underline{I}_{CA}$	phase C-A current at the end S during the fault	A
$\underline{V}_{AB}$	phase A-B voltage at the end S during the fault	V
$\underline{V}_{BC}$	phase B-C voltage at the end S during the fault	V
$\underline{V}_{CA}$	phase C-A voltage at the end S during the fault	V
$\underline{I}_F$	pure-fault current flowing through the fault resistance	A
$\underline{V}_F$	voltage drop from relaying point to fault location F	V
$\Delta\underline{V}$	random errors of measured voltage distributed value	V
$\Delta\underline{I}$	random errors of measured current distributed value	I
$\underline{I}_S$	total line current at the end S during the fault	A

$\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$	phase-A, Phase-B, Phase-C current at the end S during the fault, respectively	A
$\underline{I}_S^C$	total compensated current at the end S during the fault	A
$\underline{I}_A^C$	phase-A compensated current at the end S during the fault	A
$\underline{k}_0$	zero-sequence current compensation factor	
k_{0M}	zero-sequence current compensation factor of mutual coupling	
$\underline{I}_{0P}$	zero-sequence current parallel line with both lines in active	A
$\underline{I}'_{0P}$	zero-sequence current parallel line with one is switched off and grounded at both sides	A
$\underline{k}_{0(mod)}$	modified of zero-sequence current compensation factor	
p	proportional of the total line from terminal S	p.u.
r	zone reach from terminal S	p.u.
$R_{1L,}$ R_{0L}	positive- and zero-sequence line resistances, respectively	Ω
$R_{1S,}$ R_{1R}	positive -sequence source resistance at station S and R, respectively	Ω
R_F	fault resistance	Ω
X_C	capacitor reactance	Ω
X_L	inductor reactance	Ω
R'_F	resistance and capacitve/inductive reactance	Ω
$\underline{V}_1, \underline{V}_2, \underline{V}_0$	positive-, negative-, and zero-sequence voltage, respectively	V
$\underline{V}_{1S}, \underline{V}_{2S}, \underline{V}_{0S}$	positive-, negative-, and zero-sequence voltage at terminal S, respectively	V

$\underline{V}_S$	total voltage at the line end S during the fault	V
$X_{1L,}X_{0L}$	positive- and zero-sequence line reactance, respectively	Ω
$\Delta\underline{Z}_m$	error calculated in apparent fault impedance on the line at terminal S	Ω
$\underline{Z}_{Ref}$	expected value of apparent fault impedance	Ω
$\underline{Z}_{m(\text{sec.})}$	secondary part of measured impedance on the line at terminal S	Ω
$\underline{Z}_m$	measured fault impedance on the line at terminal S	Ω
$\underline{Z}_{1S}, \underline{Z}_{1R}$	positive-sequence source impedance behind bus S and R, respectively	Ω
$\underline{Z}_{0S}, \underline{Z}_{0R}$	zero-sequence source impedance behind bus S and R, respectively	Ω
$\underline{Z}_{1L}, \underline{Z}_{0L}$	positive- and zero- sequence line impedance, respectively	Ω
$\underline{Z}_S, \underline{Z}_R, \underline{Z}_T$	source impedance behind bus *S,* R, and T respectively	Ω
$\underline{Z}_L$	total line impedance	Ω
$\underline{Z}_{OM}$	mutual impedance of line for the zero-sequence network	Ω
$\underline{Z}_{est}$	estimated impedance of line	Ω
$\underline{Z}_{act}$	actual impedance of line	Ω
$\underline{Z}_{tot}$	total impedance of line (total protected line impedance)	Ω
$\underline{Z}_{012}$	sequence impedance matric	Ω
$\underline{Z}_{E1,}\ \underline{Z}_{E2}, \underline{Z}_{E3}$	equivalent of external line impedance	Ω
θ_L	the angle of maximum reach	deg
$\underline{S}_{Pol}$	polarizing quantity	Ω

$\underline{S}_{op}$	operating quantity	Ω
$\underline{V}^*{}_{pol}$	polarising voltage	V
Θ	impedance relay operation angle	deg
ϕ_i	angle of the measured current	deg
ϕ_V	angle of the measured voltage	deg
$error_{ss}$	error steady state	%
δ_F	pre-fault power flow angle	deg
$\underline{Z}_{1L1,}$ $\underline{Z}_{1L2}$, $\underline{Z}_{1L3}$	positive- sequence line impedance, Line-1, Line-2, and Line-3, respectively	Ω
$\boldsymbol{x}_i$	a number of factors	
$\underline{v}_s(t)$	time varying of measured voltage from terminal S of transmission line	V
$\underline{i}_s(t)$	time varying of measaured line current	A
Δt	sampling interval	s
τ	time constant	s
N	number of samples per period	
Δ	difference	
$H(s)$	transfer function	
s_i	poles of transfer function	
π	mathematical constant	3.14
A	constant value	
$\delta_S, \delta_R, \delta_T$	power flow angle of source impedance in bus S, R, T respectively	deg

x_k	sample of signal with dc-offset	
φ	phase angle	deg
$\underline{V}_{peak}$	maksimum voltage	V
ω	machine angular speed	rad/s
t	time	s
ρ	conductivity of material	Ω.m
l	length of the conductor	m
A	cross sectional area	m^2
R_{dc}	dc-resistance	Ω
L_{int}	internal inductance	H
L_{ext}	external inductance	H
L_{tot}	total inductance	H
R_{t1}	dc-resistance at termperature t_1	Ω
R_{t2}	dc-resistance at termperature t_2	Ω
t_1, t_2	first temperature, second temperature	$°C$
M	temperature constant	
H	magnetic intencity	A/m
B	magnetic dencity	T
λ	flux linkage	Wb-turn/m
$d\emptyset$	differential flux	Wb/m
X_A	inductive reactance of phase A	Ω
$\emptyset_{AB}, \emptyset_{AC}$	flux due to I_B and I_C	Wb

$\underline{Z}_{xy}$	line impedance, xx for self impedance and xy mutual impedance, where $xy = a, b, c$	Ω
$\underline{V}_{AS}, \underline{V}_{BS}, \underline{V}_{CS},$	phase to ground voltage measured from terminal S of	V
$\underline{V}_{AR}, \underline{V}_{BR}, \underline{V}_{CR,}$	phase to ground voltage measured from terminal R of	V
$\underline{V}_{C1}, \underline{V}_{C2}, \underline{V}_{C0},$	sequence voltage of series capacitor	V
$\emptyset_{AA,self},$	self flux in phase A	Wb
$\emptyset_{AA,self}$	another self-flux of phase A	Wb
$\underline{V}_{real}$	real voltage value	V
$\underline{V}_{imag}$	imaginary voltage value	V
$\underline{V}_{mag}$	magnitude voltage	V
$\underline{V}_{angle}$	voltage angle	deg
$\underline{S}_{k}.$	sampled value	
E_i	‘elementary effect’ calculation for Morris method	
d	number of discretization grid levels	
μ	mean	
σ	Standard deviation	
$E\{*\}$	expected operator	
$V\big(f(\mathbf{x})\big)$	Total variance	
S_i	sensitivity indice	
x_i, x_j	two independence factors	

$Re\{\underline{Z}_{0S}\}$, $Re\{\underline{Z}_{0R}\}$	real value of zero-sequence of source impedance in terminal S and terminal R	Ω
$Im\{\underline{Z}_{0S}\}$, $Im\{\underline{Z}_{0R}\}$	imaginary value of zero-sequence of source impedance in terminal S and terminal R	Ω
$Re\{\underline{Z}_{1S}\}$, $Re\{\underline{Z}_{1R}\}$	real value of positive-sequence of source impedance in terminal S and terminal R	Ω
$Im\{\underline{Z}_{1S}\}$, $Im\{\underline{Z}_{1R}\}$	imaginary value of positive-sequence of source impedance in terminal S and terminal R	Ω
$Re\{\underline{Z}_{1L}\}$, $Re\{\underline{Z}_{0L}\}$	real value of positive- and zero-sequence of line impedance	Ω
$Im\{\underline{Z}_{1L}\}$, $Im\{\underline{Z}_{0L}\}$	imaginary value of positive- and zero-sequence of line impedance	Ω
f	non linear complex function	
$\underline{\boldsymbol{P}}_{\boldsymbol{S}}$	group of positive- and zero-sequence sources impedance	
$\underline{\boldsymbol{P}}_{\boldsymbol{E}}$	group of sources of voltage	
$\underline{\boldsymbol{P}}_{\boldsymbol{L}}$	group of positive- and zero-sequence line impedance	
$\underline{V}_{REF}$	reference voltage	V
$\underline{V}_{V}$	voltage drop across the capacitor	V
q	exponent	
P	reference current	A
R'_C	equivalent series resistance	Ω
X'_C	equivalent series reactance	Ω
X_{CO}	capacitor bank reactance	Ω

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Abbreviations

A/D	Analogue to Digital converter
ANOVA	Analysis of Variance
CT	Current Transformer
CVT	Capacitor Voltage Transformer
EMT	Electromagnetic Transient
GSA	Global Sensitivity Analysis
IEDs	Intelligent Electronic Devices
DPL	DIgSILENT Programming Language
QMC	Quasi-Monte Carlo
MCF	Modified Compensation Factor
GMR	Geometric Mean Radius
CB	Circuit Breaker

SCs	Series Capacitors
DFT	Discrete Fourier Transform
MOVs	Metal Oxide Varistors
SA	Sensitivity Analysis
GUI	Graphical User Interface
DSL	Dynamic Simulation Language

List of Publications

[P1] M.N. Ibrahim, **N. Rohadi** and R. Zivanovic, "Methodology for Automated Testing of Transmission Line Fault Locator Algorithms", Australasian Universities Power Engineering Conference (AUPEC 2009), 27-30 September 2009, Adelaide-Australia.

[P2] **N. Rohadi** and R. Zivanovic, "Sensitivity Analysis of Impedance Measurement Algorithms Used in Distance Protection", IEEE TENCON 2011, Bali, Indonesia, November 22-24, 2011.

[P3] **N. Rohadi** and R. Zivanovic, "Sensitivity Analysis of Fault Impedance Measurement Algorithm Used in Protection of Three-Terminal Lines", Australasian Universities Power Engineering Conference (AUPEC 2012), 26-29 September 2012, Bali-Indonesia.

[P4] **N. Rohadi** and R. Zivanovic, " Sensitivity Analysis of a Fault Impedance Measurement Algorithm Applied in Protection of Parallel Transmission Lines", The 9th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM 2012), 18-21 November 2012, Hong Kong

[P5] **N. Rohadi**, R. Zivanovic, "A Method for Sensitivity Analysis of Impedance Measurement Algorithm", Journal of Electrical Engineering, Springer, 2013 (under reviewed).

[P6] **N. Rohadi**, R. Zivanovic, "Sensitivity Analysis of Impedance Measurement Algorithms Used in Series-Compensated Power Transmission Line", Journal of IET Generation, Transmission & Distribution, 2013 (under reviewed)