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

by

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Doctor of Philosophy

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Faculty of Engineering, Computer, and Mathematical Sciences
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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

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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To my friends, and research partners, thank you very much for your support during this research. The completion of this project would not have been possible without support from you.

Nanang Rohadi, June 2013
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<thead>
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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_S, E_R, E_T$</td>
<td>source voltage behind terminal S, R, T, respectively</td>
<td>V</td>
</tr>
<tr>
<td>$E_{1S}$</td>
<td>positive-sequence voltage behind terminal S</td>
<td>V</td>
</tr>
<tr>
<td>$F$</td>
<td>fault location</td>
<td>p.u.</td>
</tr>
<tr>
<td>$I_1, I_2, I_0$</td>
<td>positive-, negative-, and zero-sequence current, respectively</td>
<td>A</td>
</tr>
<tr>
<td>$I_{1S}, I_{2S}, I_{0S}$</td>
<td>positive-, negative-, zero-sequence current at terminal S, respectively</td>
<td>A</td>
</tr>
<tr>
<td>$I_{AB}$</td>
<td>phase A-B current at the end S during the fault</td>
<td>A</td>
</tr>
<tr>
<td>$I_{BC}$</td>
<td>phase B-C current at the end S during the fault</td>
<td>A</td>
</tr>
<tr>
<td>$I_{CA}$</td>
<td>phase C-A current at the end S during the fault</td>
<td>A</td>
</tr>
<tr>
<td>$V_{AB}$</td>
<td>phase A-B voltage at the end S during the fault</td>
<td>V</td>
</tr>
<tr>
<td>$V_{BC}$</td>
<td>phase B-C voltage at the end S during the fault</td>
<td>V</td>
</tr>
<tr>
<td>$V_{CA}$</td>
<td>phase C-A voltage at the end S during the fault</td>
<td>V</td>
</tr>
<tr>
<td>$I_F$</td>
<td>pure-fault current flowing through the fault resistance</td>
<td>A</td>
</tr>
<tr>
<td>$V_F$</td>
<td>voltage drop from relaying point to fault location F</td>
<td>V</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>random errors of measured voltage distributed value</td>
<td>V</td>
</tr>
<tr>
<td>$\Delta I$</td>
<td>random errors of measured current distributed value</td>
<td>I</td>
</tr>
<tr>
<td>$I_S$</td>
<td>total line current at the end S during the fault</td>
<td>A</td>
</tr>
</tbody>
</table>
$I_A$, $I_B$, $I_C$  
phase-A, Phase-B, Phase-C current at the end S during the fault, respectively

$I_S^C$  
total compensated current at the end S during the fault

$I_A^C$  
phase-A compensated current at the end S during the fault

$k_0$  
zero-sequence current compensation factor

$k_{0M}$  
zero-sequence current compensation factor of mutual coupling

$I_{0P}$  
zero-sequence current parallel line with both lines in active

$I_{0P}'$  
zero-sequence current parallel line with one is switched off and grounded at both sides

$k_{0(mod)}$  
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

$V_1, V_2, V_0$  
positive-, negative-, and zero-sequence voltage, respectively  
V

$V_{1S}, V_{2S}, V_{0S}$  
positive-, negative-, and zero-sequence voltage at terminal S, respectively  
V
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_S$</td>
<td>total voltage at the line end S during the fault</td>
</tr>
<tr>
<td>$X_{1L}, X_{0L}$</td>
<td>positive- and zero-sequence line reactance, respectively</td>
</tr>
<tr>
<td>$\Delta Z_m$</td>
<td>error calculated in apparent fault impedance on the line at terminal S</td>
</tr>
<tr>
<td>$Z_{Ref}$</td>
<td>expected value of apparent fault impedance</td>
</tr>
<tr>
<td>$Z_{m(\text{sec})}$</td>
<td>secondary part of measured impedance on the line at terminal S</td>
</tr>
<tr>
<td>$Z_m$</td>
<td>measured fault impedance on the line at terminal S</td>
</tr>
<tr>
<td>$Z_{1S}, Z_{1R}$</td>
<td>positive-sequence source impedance behind bus S and R, respectively</td>
</tr>
<tr>
<td>$Z_{0S}, Z_{0R}$</td>
<td>zero-sequence source impedance behind bus S and R, respectively</td>
</tr>
<tr>
<td>$Z_{1L}, Z_{0L}$</td>
<td>positive- and zero- sequence line impedance, respectively</td>
</tr>
<tr>
<td>$Z_S, Z_R, Z_T$</td>
<td>source impedance behind bus S, R, and T respectively</td>
</tr>
<tr>
<td>$Z_L$</td>
<td>total line impedance</td>
</tr>
<tr>
<td>$Z_{OM}$</td>
<td>mutual impedance of line for the zero-sequence network</td>
</tr>
<tr>
<td>$Z_{est}$</td>
<td>estimated impedance of line</td>
</tr>
<tr>
<td>$Z_{act}$</td>
<td>actual impedance of line</td>
</tr>
<tr>
<td>$Z_{tot}$</td>
<td>total impedance of line (total protected line impedance)</td>
</tr>
<tr>
<td>$Z_{012}$</td>
<td>sequence impedance matrix</td>
</tr>
<tr>
<td>$Z_{EF1}, Z_{EF2}, Z_{EF3}$</td>
<td>equivalent of external line impedance</td>
</tr>
<tr>
<td>$\theta_L$</td>
<td>the angle of maximum reach</td>
</tr>
<tr>
<td>$S_{Pol}$</td>
<td>polarizing quantity</td>
</tr>
</tbody>
</table>
$S_{pp}$ operating quantity $\Omega$

$V_{pol}^*$ polarising voltage $V$

$\theta$ impedance relay operation angle deg

$\phi_i$ angle of the measured current deg

$\phi_V$ angle of the measured voltage deg

$error_{ss}$ error steady state %

$\delta_F$ pre-fault power flow angle deg

$Z_{1L1}, Z_{1L2}, Z_{1L3}$ positive-sequence line impedance, Line-1, Line-2, and Line-3, respectively $\Omega$

$x_i$ a number of factors

$v_s(t)$ time varying of measured voltage from terminal S of transmission line $V$

$i_s(t)$ time varying of measured line current $A$

$\Delta t$ sampling interval $s$

$\tau$ time constant $s$

$N$ number of samples per period

$\Delta$ difference

$H(s)$ transfer function

$s_i$ poles of transfer function

$\pi$ mathematical constant $3.14$

$A$ constant value

$\delta_S, \delta_R, \delta_T$ power flow angle of source impedance in bus S, R, T deg respectively
\( x_k \) sample of signal with dc-offset
\( \varphi \) phase angle \( \text{deg} \)
\( V_{\text{peak}} \) maksimum voltage \( \text{V} \)
\( \omega \) machine angular speed \( \text{rad/s} \)
\( t \) time \( \text{s} \)
\( \rho \) conductivity of material \( \Omega \cdot \text{m} \)
\( l \) length of the conductor \( \text{m} \)
\( A \) cross sectional area \( \text{m}^2 \)
\( R_{\text{dc}} \) dc-resistance \( \Omega \)
\( L_{\text{int}} \) internal inductance \( \text{H} \)
\( L_{\text{ext}} \) external inductance \( \text{H} \)
\( L_{\text{tot}} \) total inductance \( \text{H} \)
\( R_{t1} \) dc-resistance at termperature \( t_1 \) \( \Omega \)
\( R_{t2} \) dc-resistance at termperature \( t_2 \) \( \Omega \)
\( t_1, t_2 \) first temperature, second temperature \( ^\circ \text{C} \)
\( M \) temperature constant
\( H \) magnetic intencity \( \text{A/m} \)
\( B \) magnetic dencity \( \text{T} \)
\( \lambda \) flux linkage \( \text{Wb-turn/m} \)
\( d\varphi \) differential flux \( \text{Wb/m} \)
\( X_A \) inductive reactance of phase A \( \Omega \)
\( \varphi_{AB}, \varphi_{AC} \) flux due to \( I_B \) and \( I_C \) \( \text{Wb} \)
$Z_{xy}$ line impedance, $xx$ for self impedance and $xy$ mutual impedance, where $xy = a, b, c$ Ω

$V_{AS}, V_{BS}, V_{CS},$ phase to ground voltage measured from terminal S of V

$V_{AR}, V_{BR}, V_{CR},$ phase to ground voltage measured from terminal R of V

$V_{L1}, V_{L2}, V_{L0},$ sequence voltage of series capacitor V

$\phi_{AA, self},$ self flux in phase A Wb

$\phi_{AA, self}$ another self-flux of phase A Wb

$V_{real}$ real voltage value V

$V_{imag}$ imaginary voltage value V

$V_{mag}$ magnitude voltage V

$V_{angle}$ voltage angle deg

$S_k$ sampled value

$E_l$ ‘elementary effect’ calculation for Morris method

d number of discretization grid levels

$\mu$ mean

$\sigma$ Standard deviation

$E\{\ast\}$ expected operator

$V(f(x))$ Total variance

$S_i$ sensitivity indice

$x_i, x_j$ two independence factors
\( \text{Re}\{Z_{0S}\} \), real value of zero-sequence of source impedance in terminal S and terminal R

\( \text{Re}\{Z_{0R}\} \)

\( \text{Im}\{Z_{0S}\} \), imaginary value of zero-sequence of source impedance in terminal S and terminal R

\( \text{Im}\{Z_{0R}\} \)

\( \text{Re}\{Z_{1S}\} \), real value of positive-sequence of source impedance in terminal S and terminal R

\( \text{Re}\{Z_{1R}\} \)

\( \text{Im}\{Z_{1S}\} \), imaginary value of positive-sequence of source impedance in terminal S and terminal R

\( \text{Im}\{Z_{1R}\} \)

\( \text{Re}\{Z_{1L}\} \), real value of positive- and zero-sequence of line impedance

\( \text{Re}\{Z_{0L}\} \)

\( \text{Im}\{Z_{1L}\} \), imaginary value of positive- and zero-sequence of line impedance

\( \text{Im}\{Z_{0L}\} \)

\( f \) non linear complex function

\( \underline{P}_S \) group of positive- and zero-sequence sources impedance

\( \underline{P}_E \) group of sources of voltage

\( \underline{P}_L \) group of positive- and zero-sequence line impedance

\( V_{\text{REF}} \) reference voltage

\( V_{\text{V}} \) voltage drop across the capacitor

\( q \) exponent

\( P \) reference current

\( R'_c \) equivalent series resistance

\( X'_c \) equivalent series reactance

\( X_{CO} \) capacitor bank reactance
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## Abbreviations

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>A/D</td>
<td>Analogue to Digital converter</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
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<tr>
<td>CT</td>
<td>Current Transformer</td>
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<tr>
<td>CVT</td>
<td>Capacitor Voltage Transformer</td>
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<td>EMT</td>
<td>Electromagnetic Transient</td>
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<td>GSA</td>
<td>Global Sensitivity Analysis</td>
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<td>IEDs</td>
<td>Intelligent Electronic Devices</td>
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<td>DPL</td>
<td>DIgSILENT Programming Language</td>
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<td>QMC</td>
<td>Quasi-Monte Carlo</td>
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<td>MCF</td>
<td>Modified Compensation Factor</td>
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<td>GMR</td>
<td>Geometric Mean Radius</td>
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<td>CB</td>
<td>Circuit Breaker</td>
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<td>SCs</td>
<td>Series Capacitors</td>
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<td>DFT</td>
<td>Discrete Fourier Transform</td>
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<td>MOVs</td>
<td>Metal Oxide Varistors</td>
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<td>SA</td>
<td>Sensitivity Analysis</td>
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<td>GUI</td>
<td>Graphical User Interface</td>
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<td>DSL</td>
<td>Dynamic Simulation Language</td>
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List of Publications


