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Performance Evaluation of Measurement Algorithms used in IEDs

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Abstract

Many Intelligent Electronic Devices (IEDs) are available for the protection of power systems. These IEDs use a series of mathematical algorithms for fault detection and execute various protection functions. The first and essential mathematical algorithm of any IED is the measurement algorithm. The aim of the measurement algorithm is to estimate the fundamental frequency component (phasor) of input current and voltage signals. Most protection algorithms use the estimated phasor for their executions. The most important factors for the successful use of the protection algorithms in IEDs are accuracy and speed of the phasor estimation by the measurement algorithms.

A fault in a power system produces step changes in the current and voltage phasors recorded by IEDs as well as a variety of nuisance signals. The nuisance signals introduce significant input distortions to measurement algorithms. Measurement algorithms that estimate the fundamental frequency phasor component from the distorted input signals produce some errors. Different measurement algorithms produce different amounts of

error. This is because their design is based on different approaches with different assumptions that result in different performance in the presence of nuisance signals.

It is important to evaluate the performance of measurement algorithms in the presence of nuisance signals. The evaluation is to ensure that measurement algorithms estimate the fundamental frequency component at the required design accuracy and speed. The result of the performance evaluation can be used to select appropriate measurement algorithms for specific protection applications. However, the parameters of nuisance signals are uncertain due to their dependence on unpredictable factors such as fault location and fault impedance. Thus, a methodology for the evaluation of measurement algorithm performance should take into account the uncertainty of the parameters of nuisance signals.

The traditional method of evaluating the performance of measurement algorithms is based on the local sensitivity method using a linear function approximation at a nominal point. The local sensitivity method varies only a single nuisance parameter (factor) while other factors are fixed at their nominal values. The studied factor is varied to observe errors in the output of the measurement algorithm. Such an approach, however, does not provide the overall performance of measurement algorithms. Besides, varying the single factor does not represent realistic scenarios.

This thesis proposes a new methodology to evaluate the performance of measurement algorithms implemented in IEDs. The proposed methodology uses the global uncertainty and sensitivity analysis method. In this method, all factors representing nuisance components are varied simultaneously. Uncertainty analysis measures the uncertainty in output of the measurement algorithm due to the uncertainty of input factors. Sensitivity analysis measures the contribution of all factors and their interactions to output uncertainty.

In general, the global uncertainty and sensitivity method that is based on the Monte Carlo approach requires extensive evaluations. Its implementation can be prohibitive, particularly in practical testing, because the number of factors is large. Thus, a two-stage methodology with a significantly smaller number of evaluations is used. The first-stage is the use of the Morris method as a preliminary (screening of factors) sensitivity analysis and the second-stage is the implementation of the Extended Fourier Amplitude Sensitivity Test (EFAST) technique for comprehensive global uncertainty and sensitivity analysis. A single evaluation involves one run of the IED injection test which can take a few minutes. Thus, it is justifiable to search for the methodology that is uses the smaller number of evaluations.

The proposed methodology contributes to an automated testing method integrating ATP/EMTP, MATLAB and SIMLAB programs as well as the injection test facility. The ATP/EMTP program is used to generate fault test scenarios. The MATLAB program is used to model elements of the IED to calculate performance indices on the output of measurement algorithms and automatically control the process of extensive evaluations (simulations). The main role of the SIMLAB is to analyze the uncertainty and sensitivity of the measurement algorithms outputs.

The proposed methodology has been demonstrated by evaluating the performance of a known measurement algorithm in simulation and an unknown measurement algorithm of a commercial IED (SEL-421). The methodology has been successfully performed in the simulation as well as in practical testing. The results of the analysis indicate that the performance is typically most sensitive to a few parameters out of many possible factors. These important parameters should then be the focus of research for the optimization of measurement algorithms.

Declaration and Publications

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List of Publications

(P1) Ibrahim, M.N.; Zivanovic, R.; "An advanced method for evaluation of measurement algorithms used in digital protective relaying," *Power Engineering Conference, 2009 (AUPEC 2009). Australasian Universities on*, vol., no., pp.1-6, Adelaide, Australia, 27-30 Sept. 2009.

(P2) Ibrahim, M.N.; Rohadi, N.; Zivanovic, R.; "Methodology for automated testing of transmission line fault locator algorithms," *Power Engineering Conference, 2009 (AUPEC 2009). Australasian Universities on*, vol., no., pp.1-4, Adelaide, Australia, 27-30 Sept. 2009.

(P3) Ibrahim, M.N.; Zivanovic, R.; "Impact of CVT transient on measurement algorithms implemented in digital protective relays," *Electrical Energy and Industrial Electronic Systems (EEIES 2009), International Conference on*, vol., no., pp.1-6, Penang, Malaysia, 7-8 December 2009.

(P4) Ibrahim, M.N.; Zivanovic, R.; "Impact of CT saturation on phasor measurement algorithms: Uncertainty and sensitivity study," *Probabilistic Methods Applied to Power Systems (PMAPS 2010), 2010 IEEE 11th International Conference on* , vol., no., pp.728-733, Singapore, 14-17 June 2010.

(P5) Ibrahim, M.N.; Zivanovic, R.; "Factor-Space Dimension Reduction for Sensitivity Analysis of Intelligent Electronic Devices," *TENCON 2011, 2011 IEEE Region 10 Conference on*, Bali, Indonesia, 21-24 November 2011.

(P6) Ibrahim, M.N.; Zivanovic, R.; "A novel global sensitivity analysis approach in testing measurement algorithms used by protective relays," *Journal of European Transactions on Electrical Power*, February 2012. Doi: 10.1002/etep.673.

In Press Publications

(P7) Ibrahim, M.N.; Zivanovic, R.; "Global Uncertainty and Sensitivity Analysis for Evaluation of Measurement Algorithm Performance as Affected by CVT Transients," *Journal of Electric Power Systems Research*. Submitted for review.

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Symbols

ΔV	Voltage amplitude change
C	Equivalent capacitance
$EE_i(X)$	Elementary effect of changing the i^{th} input factor
f_c	Cut-off frequency
$\acute{f}_c$	Frequency response of measurement algorithm
f_{max}	Maximum frequency
f_{min}	Minimum frequency
FRI	Ideal/benchmark frequency response
$\mathrm{F_L}$	Fault location
h_3	Amplitude of third harmonic
h_5	Amplitude of fifth harmonic
G_1, G_2	Equivalent generator 1 and 2
H	The highest harmonic order
j	Integer frequency
L	Equivalent inductance

L_C	Compensation inductance
L_G	Number of grid level
L_M	Magnetizing inductance
L_P	Primary leakage inductance
L_S	Secondary leakage inductance
N	Number of sample per cycle
N_S	Number of simulation
$N1{:}N2$	Turn ratio
O_S	Overshoot
$p(X)$	Probability distribution of X
PI_{DC}	Performance index for DC amplitude attenuation
PI_{FA}	Performance index for fundamental aggregate criterion
PI_{H3}	Performance index for third harmonic amplitude attenuation
PI_{H5}	Performance index for fifth harmonic amplitude attenuation
R	Equivalent resistance
R_F	Fault resistance
R_M	Magnetizing resistance
R_P	Primary winding resistance
R_S	Secondary winding resistance
U_S	Undershoot
s	Scalar variable
$s(k)$	Sample of signals, $k = 1,2,3 \ldots . \infty$
S_j	Imaginary part of the fundamental frequency
S_r	Real part of the fundamental frequency
S_{se}	Steady state error
SI_i	Sensitivity index for $i^{th.}$ factor
$SI_{i,j}$	Sensitivity index for interaction of $i^{th.}$ and $j^{th.}$ factor
$SI_{i,total}$	Total sensitivity index for $i^{th.}$ factor
T_S	Settling time
x_n	$n^{th.}$ nuisance factor
V_i	Variance contributed by $i^{th.}$ factor

$V_{i,j}$	Variance contributed by interaction of i and j factor
$V_{\sim i}$	Variance contributed by other than $i^{th.}$ factor
V_{group}	Variance contributed by a group of factors
V_{total}	Total variance
ω	Angular frequency
$\bar{y}$	Output mean value
ZB	Burden of CT
α	Amplitude of decaying DC offset
τ	Time constant of decaying DC offset
λ	Remanent flux
δf_1	Off-nominal fundamental frequency
β	Fault inception angle
y_{true}	True value of fundamental frequency amplitude
y_{max}	The maximum value of estimated fundamental frequency
y_{min}	The minimum value of estimated fundamental frequency
y_{∞}	Steady state value of fundamental frequency amplitude
μ	Mean of error value
σ	Standard deviation of error
min_{error}	Minimum of error
max_{error}	Maximum of error
Δ	Predetermined pertubation
A_j	Fourier cosine
B_j	Fourier sine
Λ_j	Variance spectrum

Abbreviations

A/D	Analogue to Digital Converter
ATP	Alternative Transient Program
ANOVA	Analysis of Variance
CB	Circuit Breaker
CT	Current Transformer
COMTRADE	Common Transient Data Exchange
CVT	Capacitive Voltage Transformer
DFT	Discrete Fourier Transform
EFAST	Extended Fourier Amplitude Sensitivity Test
EHV	Extra High Voltage
EMTP	Electromagnetic Transient Program
FAST	Fourier Amplitude Sensitivity Test
FIR	Finite Impulse Response
FSC	Ferro-resonant Suppression Circuit
GPS	Global Positioning System
LHS	Latin Hypercube Sampling

IED	Intelligent Electronic Device
IIR	Infinite Impulse Response
LPF	Low Pass Filter
MC	Monte Carlo
OAT	One Factor At A Time
PDF	Probability Distribution Function
PMU	Phasor Measurement Unit
PPE	Percentage peak error
PRMSE	Percentage root-mean-square error
p.u.	Per unit
QMC	Quasi-Monte Carlo
RL	Resistor-Inductor Element
RMS	Root-mean-square
RRTS	Remote Relay Test System
SA	Sensitivity Analysis
SIR	Source to Impedance Ratio
TSM	Taylor Series Method
TVE	Total Vector Error
U	Uniform distribution function
UA	Uncertainty Analysis
VT	Voltage Transformer