A dissertation submitted to
The School of Electrical Electronic and Computer Engineering

of North-West University (Potchefstroom campus)

Research into Specific Numerical Protection Maloperations

In partial fulfilment of the requirements for the degree

Master of Science

in Electrical Engineering

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November 2012

ABSTRACT

High voltage transmission system availability and system security are key performance criteria for electricity utilities worldwide. System disturbances need to be cleared quickly and accurately in order to minimise the impact of faults and to facilitate speedy system restoration. In this context, the South African utility, Eskom has maintained a process of refreshing protective relaying technology as older equipment becomes obsolete and is no longer capable of meeting the utility's requirements.

The difficulties which a process of equipment renewal presents the organisation with include the risk of incorrectly applying the newer technologies within the complex electrical network. The application of new technology is affected by the complexities of the newer technology with respect to the older, more familiar technologies. Some of the difficulties can be addressed with revised commissioning procedures or the use of modern test equipment. Enhanced relay algorithms and settings calculation methodologies can however not be simplified.

Protective relay maloperations cannot always be completely avoided and when they do occur, these must be investigated and addressed to prevent future recurrences.

The research covered by this dissertation focuses on a number of protective relay maloperations on transmission lines using impedance protection algorithms. The research undertaken identifies the previously unidentified causes of the maloperations and describes a relay settings solution for improving the accuracy of the protective relays.

The methodology that was followed in the research covers the following aspects:

- Identification and highlighting of some of the protection relay maloperations that occurred during system faults,
- Review of the fundamental principles involved in system fault analysis,

- Comprehensive study of the theory involved in the calculation of an overhead line conductor self and mutual-inductance, as well as the calculation of the positive, negative and zero sequence impedances of an overhead line,
- Brief evaluation of the effect of load impedance on relay measurements and the impact on fault clearing operation,
- Analysis of the theoretical operation of various numerical relays during single-phase-to-earth faults in radial and meshed (complex) network conditions,
- Mathematical calculations using typical Newton-Raphson methods to study the impact of resistive single-phase-to-earth faults on the voltage and current measurements at the relaying position with the exclusion of the capacitive components between conductors and conductors and earth,
- Comparison and evaluation of mathematical calculations and system studies using network simulation software which included all steady state network parameters,
- Review and analysis of actual system faults that had been previously analysed without definitive conclusion. The faults were re-analysed in an attempt to correlate findings with the hypothesis of the research,
- Comparison of the performance of protective relay impedance charactersitics using positive sequence domain versus loop domain analysis techniques.

This study concluded that significant benefits can be achieved by analysing system faults and relay operation using loop quantities in primary impedance values as opposed to positive sequence or apparent impedance quantities in secondary values. The inherent differences between the positive or apparent impedance characteristics of the relays are nullified when considered in the loop impedance domain, provided that the relays reach settings were calculated correctly.

The study also showed that load current cannot be ignored when calculating settings as it has significant impact on the actual impedance measured during fault conditions. It is therefore crucial that when relays from different manufacturers are being used to protect the same circuit that the differences between the relays and the subsequent measurements are clearly understood and compensated for.

Finally relay setting changes have been proposed for implementation based on the findings of this research. The combination of the theory, network simulations and secondary injections performed on the relays all correlate and therefore validate the research. It is left for the utility and or users of these relays to evaluate the results of this research and implement the necessary changes as applicable.

Key Search Words

- Numerical
- Protection
- Maloperation
- Proposed
- Relay Setting Changes
- Theory
- Network
- Reduction

OPSOMMING

Die beskikbaarheid en sekuriteit van die transmissienetwerk is die sleutelprestasiekriteria vir elektrisiteitsvoorsieningsmaatskappye wêreldwyd. Dit is noodsaaklik dat stelselfoute vinnig en korrek van die stelsel verwyder word om die invloed van sodanige foute te minimaliseer en te verseker dat die stelsel so spoedig moontlik herstel kan word. In hierdie verband het die Suid-Afrikaanse elektrisiteitsvoorsieningsmaatskappy, Eskom, ‘n aaneenlopende proses van hernuwing van beveiligingsrelêtegnologie reeds ‘n geruime tyd in plek ten einde verouderde toerusting, te vervang.

Van die probleme wat deur ‘n proses van hernuwing van toerusting aan die maatskappy gestel was, sluit die risiko in wat gepaardgaan met die foutiewe toepassing van nuwe tegnologie in ‘n reeds komplekse elektriese netwerk. Die toepassing van die nuwe tegnologie word beïnvloed deur die kompleksiteit daarvan in verhouding met die ouer en meer bekende tegnologieë. Sommige van die probleme word aangepreek deur middel van hersiende inbedryfstellingsprosedures en die gebruik van moderne toetsuitrusting. Dit is egter nie so eenvoudig om gevorderde relêalgoritmes en die uitwerking van gepaardgaande instellings te analiseer nie.

Dit is nie altyd moontlik om die foutiewe werking van beveiligingsrelês te voorkom nie, maar dit is van uiterste belang dat wanneer dit gebeur, die oorsaak daarvan deeglik nagevors word ten einde herhaling daarvan te voorkom.

Die navorsing wat in hierdie verhandeling bespreek word, is gefokus op ‘n aantal foutiewe impedansiebeveiligingsrelêwerkings op oorhoofse transmissielyne. Die navorsing is daarop gemik om die oorsake van foutiewe relêwerking wat voorheen nie volledig geïdentifiseer was nie, aan te spreek en bied relêstellingsoplossings wat daarop gemik is om die akkuraatheid van die beveiligingsrelês te bevorder.

Die metodologie wat gevolg is in hierdie verhandeling, hanteer onder meer die volgende aspekte:

- Die identifisering van sommige van die foutiewe beveiligingsrelêwerkings wat plaasgevind het tydens stelsel foute,
- Die hersiening van die fundamentele beginsels met betrekking tot netwerkfoutanalises.
- ‘n Uiteenlopende studie van die teorie rondom die berekening van oorhoofse transmissielyngeleier induktansie en wedersydse induktansie sowel as die bepaling van die positiewe, negatiewe en zero volgorde impedansies.
- ‘n Kort studie om te bepaal wat die uitwerking van die lasimpedansie op relêmeting en die gevolglike relêwerking is, ten einde foute van die stelsel te verwyder.
- Die analisering van die teoretiese werking van verskeie numeriese relês tydens eenfasige foute onder radiale en komplekse netwerktoestande.
- Wiskundige berekeninge met behulp van Matlab-sagteware wat gebruik maak van tipiese Newton-Raphson-metodes, is gebruik om die uitwerking van eenfasige foute op die spanning en stroommetings by die relêverbindingspunt te bepaal. Die kapasitiewe komponente tussen die verskillende fases van die oorhoofse lyn en tussen fases en grond is hier geïgnoreer.
- ‘n Vergelyking van en evaluering van die wiskundige berekeninge en netwerkstudies wat met behulp van netwerksimulasiesagteware uitgevoer is. Alle statiese netwerkparameters is met die simulasiesagteware ingesluit.
- Hersiening en evaluering van werklike netwerkfoute wat voorheen nie tot konkrete gevolgtrekkings gelei het nie. Die foute is heranaliseer in ‘n poging om gevolgtrekkings te maak wat die doelstelling van die hipotese van hiedie navorsing sou ondersteun.
- Vergelykings word getref tussen die doeltreffende analisering van die positiewe volgordekarakteristieke van die relês en die soos voorgestel in ‘n lusdomein.

Die studie het tot die gevolgtrekking gekom dat daar ‘n aansienlike voordeel bestaan wanneer stelselfoute en relêwerking geanaliseer word deur gebruik te maak van primêre impedansielusdomeinwaardes in teenstelling met positiewe volgorde of skyn-impedansies in sekondêre waardes. Die inherente verskille wat tussen die positiewe of skynimpedansiekarakteristieke van die relês bestaan, verdwyn wanneer daarna in die lusdomein verwys word. Die enigste vereiste hier is dat die impedansie bereikinstellings van die relês wat met mekaar vergelyk word, korrek bereken moet wees.

Die studie het ook aangetoon dat lasstroom nie altyd geïgnoreer kan word nie, maar dat dit in ag geneem behoort te word wanneer relêstellings bereken word, aangesien lasstroom ‘n aansienlike invloed kan hê op die relêimpedansiemeting tydens stelselfouttoestande. Dit is daarom belangrik, dat wanneer relês van verskillende vervaardigers gebruik word om dieselfde oorhoofse stroombaan te beveilig, dat die verskille tussen die relês, hul meetalgoritmes en eksterne faktore duidelik verstaan word en die nodige kompensasie toegepas word.

Nuwe relêstellings wat gebaseer is op die bevindinge van hierdie navorsing word voorgestel vir implementering. Die kombinasie van die teorie, netwerksimulasies en sekondêre inspuitingstoetse wat op die relês gedoen is, stem ooreen en kwalifiseer gevolglik hierdie werk. Dit word aan Eskom, die netwerkoperateur, en ander gebruikers van hierdie relês oorgelaat om die resultate van hierdie werk te evalueer en te implementeer waar nodig.

Ken HOM in al jou weë, dan sal HY jou paaie gelyk maak

– (Spreuke 13:6)

ACKNOWLEDGEMENTS

I gratefully acknowledge the support, assistance, guidance and contribution provided to me which have enabled me to reach this point where I am ready to submit my work.

Thank you to…

…God, our Heavenly Father, for giving me the talent and perseverance.

…Charlotte, my wife, my inspiration, for always believing in me.

…Christiaan, Hercules and Bianca, my children, for your understanding
encouragement and for keeping me young.

…Johannes en Helena, my parents, for their continued support.

…William Haw, my father in law, for always keeping me on track.

…My mentor, Prof Jan de Kock for your help and guidance.

…Eskom Transmission System Operations team, with special acknowledgement to
Paul Keller.

…Colleques from Trans Africa Projects, with special thank you to
Tea Mihić, Hantie van der Walt and Peter Diamandes

To all of you whom I have not explicidly mentioned and who have been part of this journey – I appreciate it and will always remember it.

Thank you

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List of Definitions

The definitions of system security and reliability can be summarized as follows (listed alphabetically):

Bundle of conductors (conductor bundle) - a group of conductors grouped closely together so as to minimize the effect of corona, as well as to function together as a single conductor within a single or multi-phase circuit.

Displacement voltage – is defined by relay manufacturer A as the total zero sequence voltage ($3V_0$) that develops during single-phase-to-earth system faults.

Geometric Mean Distance (GMD) - the mn^{th} root of the product of all the distances between two sets of bundle conductors respectively having m and n number of conductors within a bundle [1].

Geometric Mean Radius (GMR), also termed Self Geometric Mean Distance - the n^2 root of the product of the distances from every conductor within the bundle of conductors to itself and to every other conductor within the bundle, n being the number of conductors within the bundle [1].

Resistivity - the ratio of an electic field to the current density [3].

System Minutes – (MW energy lost * Number of Minutes)/(MW Peak of previous year – International Load)

System reliability - the probability to remain in the operating state as a function of time, given that the system started in the operating state at time t = 0 [10].

System security - the ability of the system to refrain from unnecessary operations [10].

List of symbols

α = angle

$\alpha 1$ = angle between strands on same layer with centre strand

β = Source voltage angle

δ = depth from conductor surface

ϕ_E = Phase angle of the short circuit earth current (return current)

ϕ_{IL} = Phase angle of the short circuit phase current

ϕ_L = Phase angle of the short circuit phase current

φ_{Loop} = Resistive fault blinder angle for zone measurement of relay B

ϕ_V = Phase angle of the short circuit voltage

ϕ_{VLL} = Phase angle of the short circuit line voltage

λ_n = Lay length of conductor layer

φ = number flux linkages of a circuit in weber-turns

φ_a = Total flux for phase A

φ_{1p1} = Flux for conductor 1 due to current in conductor 1

φ_{1p2} = Flux for conductor 1 due to current in conductor 2

φ_1 = Total flux for conductor 1

φ_{int} = Total flux linkages inside a conductor

φ_{ext} = Total external flux of a conductor

φ_{mutual} = Mutual flux of conductor

$\varphi_{n,\ outer}$ = Outer magnetic flux associated with each layer

$\varphi_{n,\ inner}$ = Inner magnetic flux associated with each layer

$d\psi$ = Change in flux linkages

$d\varphi$ = Change in flux

$d\varphi/dt$ = rate of change of flux

di/dt = rate of change of current

ε_0 = Permittivity of earth

Ω = Ohm

ρ = Resistivity

ρ_a = Resistivity of non=ferrous material

ρ_{al} = Resistivity of aluminium

ρ_e = Earth resistivity

ρ_m = Mass resistivity

ρ_s = Resistivity of steel or ferrous material

ρ_{20} = Conductor resistivity at temperature of 20° C

μ_0 = Relative permeability of air

μ = Absolute permeability of conductor

μ_r = Relative permeability of conductor

ω = angular frequency of current

ω_0 = Fundamental system frequency

Υ = Star connection

Δ = Delta connection

$>$ = Greater than sign

$<$ = Smaller than sign

List of variables

A = Conductor cross=sectional area

A = Constant in J.R. Carson’s single series expansion

A_s = Cross section area of the steel core

B = Magnetic flux density

C = Degree of series compensation

D = Diameter

d = Diameter of each strand

$D_{aa'}$ …D_{am} = Distances between conductor a in composite conductor X and conductor a’ through to m in composite conductor Y

$D_{a'a}$ …$D_{a'n}$ = Distance between conductor a’ in composite conductor Y and conductor a through n in composite conductor X

$d_{a1ij,jj}$ = distance between strands on same layer

D_e Distance between overhead conductor and its image

D_{eq} = Geometric mean distance between conductors of phases a, b and c

D_{ik} = distance between conductor I and image of conductor k

d_{ik} = distance between conductor I and conductor k

D_n = Geometric Mean Radius of of conductor layer n

D_n = Mean diameter (GMR) of layer n

D_{1n} = Distances between conductors 1, 2, 3,….n

D_p = Mean diameter (GMR) of layer p

D_{1p} = Distance of point P from conductor 1

D_{2p} = Distance of point P from conductor 2

d_{al_Ln} = Product of distances between strands in the n^{th} aluminium layer of conductor, (n $\in$ 1, 2,….m, m $\neq$ n)

d_{Ln_m} = Product of distances between strands between different layers in the conductor, (n $\in$ 1, 2,….m)

$d_{si,j}$ = distance between strands in same layer

d_s = Skin depth

D_s = Geometric Mean Radius for a solid conductor

D_{ss} = Geometric Mean Radius for a single strand

$D^b{}_s$ = Geometric Mean Radius for bundle conductor

di_{L1}/dt = Change in current for a change in time for phase L_1

di_{L2}/dt = Change in current for a change in time for phase L_2

di_{L3}/dt = Change in current for a change in time for phase L_3

di_E/dt = Change in earth current for a change in time

E_a = A-phase source voltage

E_b = B-phase source voltage

E_c = C-phase source voltage

E_{ab} = A-B-phase voltage

E_{bc} = B-C-phase voltage

E_{ca} = C-A-phase voltage

E_r = Resultant parallel source voltage

e = induced voltage

f = Electrical system frequency

F_{sub} = Sub-synchronous frequency

F_{net} = network frequency

H = Magnetic field strength

h_i = average height above earth of conductor i

I_{A1} = First layer current in stranded conductor

I_{A11} = Third layer current in stranded conductor

I_a = A-phase current

I_B = Capacitor bank base current

I_b = B-phase current

I_{b} = Base current

I_c = C-phase current

I_E = Short circuit earth current (rms)

$I_E>$ = Earth current detection threshold value for relay A

I_F = Fault current

I_L = Short circuit phase current (rms)

$I_{L(app)}$ = Load current due to applied voltage

$I_{L(pu)}$ = Load current in per unit

I_{Lu} = Normalised line current

I_N = Rated capacitor bank current, A rms

INBlockPP = Setting for the residual current below which operation of the phase-to-phase fault loops is allowed

I_s = Current in the steel core

I_{TH} = Capacitor threshold rating, A rms

$I_1 \dots I_n$ = Current in the different layers

I_{L1} = Faulted phase current

i_{L1} = Phase current for phase L_1

i_{L2} = Phase current for phase L_2

i_{L3} = Phase current for phase L_3

I_N = Earth return current

I_0 = Zero sequence current

I_1 = Positive sequence current

I_2 = Negative sequence current

J = Current density at depth δ from the conductor surface

J_s = current density at the conductor surface

K = enlarging factor due to remote in-feed

K_{bc}, = Capacitor bank constant

K_F = Impedance enhancement factor

K_{gf1} = Grading factor used with series capacitors

km = Kilometer

K_p = Capacitor bank constant

k_n = Conductor length factor

K_L = Generic earth compensation factor

K_N = Earth loop compensation factor for relay B

K_R = Resistance earth loop correction factor for relay A

K_{trans} = transient factor used with series capacitors

K_X = Reactance earth loop correction factor for relay A

K_0 = Generic relay earth fault compensation factor

k_1 = Coefficient of current concentration (specific to conductor type)

k_2 = Coefficient of current concentration (specific to conductor type)

L = Inductance of conductor

L_a = Inductance per phase

L_{arc} = length of the fault arc in meters

L_{av} = Average inductance per conductor

L’ = conductor inductance to neutral inclusive of skin effect

L'' = total conductor inductance to neutral inclusive of skin and proximity effect

L_e = external conductor inductance to neutral assuming uniform current distribution

L_i = internal conductor inductance assuming uniform current distribution

L_i' = internal conductor inductance inclusive of skin effect

L_{int} = Internal inductance of a conductor

L_{ext} = External inductance of a conductor

L_N = line earth return inductance for high-speed zone of relay B

L_{tot} = Total self-inductance of a conductor

L_1 = Self-inductance of conductor 1

L_2 = Self-inductance of conductor 2

m = Mass

n = Number of layers in a stranded conductor

n_{al} = number of aluminium strands in conductor

n_i = Number of strands in layer i

n_j = number of strands in layer j

n_s = Number of strands in conductor

P, Q = correction terms for earth return

p = per unit value of distance to fault on overhead line

$\bar{p}$ = complex depth

p = Percentage protection relay reduction reach required due to series compensation

R = Resistance

R' = effective ac-resistance inclusive of skin effect

R_{ap} = Apparent resistance measured for protective zone

R'' = Total effective ac-resistance inclusive of skin and proximity effect

RA1 = Fault detector resistive reach limit 1 for relay A

RA2 = Fault detector resistive reach limit 2 for relay A

R_{ac} = ac-resistance

r_d = Frequency dependent resistance

R_{dc} = dc-resistance

R_E, R_C = Equivalent series capacitor resistance

R_E p.u. = per unit series capacitor resistance

R_E/R_L = Resistance ratio

$(R_E/R_L)_{SET}$ = Resistance ratio settings applied to relay A

$R'_{i\text{-internal}}$ = ac-resistance of conductor i in ohm per unit length

R_F = Fault resistance

RFPE = Fault resistance setting for phase-to-earth element of relay B

$R_{Lm\text{-}Ln}$ = Phase-to-phase fault loop resistance measurement

R_m = Measured fault loop resistance for relay B

R_{phs} = Phase Selector resistance measured

R_0 = Resistance of material at base temperature

R0PE = Zero sequence resistance setting for phase-to-earth element of relay B

$R0PE_{ZM}$ = Zone ($_M$) Zero sequence resistance setting for phase-to-earth element of of relay B

R1PE = Positive sequence resistance setting for phase-to-earth element of relay B

$R1PE_{ZM}$ = Zone ($_M$) Positive sequence resistance setting for phase-to-earth element of relay B

R1PP = Positive sequence resistance setting for phase-to-phase element

$R1PP_{PHS}$ = Resistive phase-to-phase setting for phase selector element

RFPE = Phase-to-earth fault loop resistance setting for relay B

$RFPE_{ZM}$ = Zone ($_M$) Phase-to-earth fault loop resistance setting for relay B

$RFPE_{PHS}$ = Zone ($_M$) Phase selector fault loop resistance setting for relay B

RFPP = Fault resistance setting for phase-to-phase element

$RFPP_{PHS}$ = Fault resistance setting for phase selector element

R_{FN} = the loop resistance for high-speed zone of relay B

$R_{Ph\text{-}E}$ = Phase-to-earth resistance fault loop measurement

R_t = dc-resistance at temperature t

r = radial distance of point P, radius of conductor

r_a = dc-resistance from manufacturers conductor tables

r_a' = Geometric Mean Radius of conductor a

r_d = Frequency dependent resistance of the image conductor

r_i = radius of conductor i,

r_s = Conductor strand radius

r_1 = Radius of conductor 1

r_2 = Radius of conductor 2

S = Maximum apparent load MVA

S_b = MVA base

T = Constant for the specific conductor material

T20 = Constant for the specific conductor material at temperature of 20° C

t = Temperature

U_{i1}, U_{i2}, U_{i3} = Induced voltages per layer in stranded conductor

U_E – Zero sequence voltage ($3V_0$)

V_a = A-phase voltage

V_b = B-phase voltage

V_c = C-phase voltage

V_{aF} = A-phase voltage at point of fault

V_{app} = Applied load voltage

V_{a1} = Positive sequence voltage for phase A

V_b = Base voltage

V_{L1} = Faulted phase voltage

$V_{L1\text{-}E}$ = Phase-to-earth voltage for phase L_1

$V_{L2\text{-}E}$ = Phase-to-earth voltage for phase L_2

$V_{L3\text{-}E}$ = Phase-to-earth voltage for phase L_3

$V_{L(pu)}$ = Load voltage in per unit of applied voltage

V_{mov} = voltage across the MOV

$V_{Ph\text{-}E}$ = Short circuit phase voltage (rms)

V_{PF} = Pre-fault voltage

V_0 = Zero sequence voltage

V_1 = Positive sequence voltage

V_2 = Negative sequence voltage

x = factor in per unit of line length

X = the set positive sequence reactance for high-speed zone of relay B

X_c = Series capacitor capacitive reactance

X_F = Fault reactance

$X'_{i\text{-internal}}$ = internal reactance of conductor i

x_{ik} = horizontal distance between conductors i and k

X_{CE}, X_C = Equivalent series capacitor reactance

X_{CE} p.u. = per unit series capacitor reactance

X_E/X_L = Inductance ratio

$(X_E/X_L)_{SET}$ X_L = Inductive reactance ratio settings applied to relay A

$X_{Lm\text{-}Ln}$ = Phase-to-phase fault loop reactance measurement

X_m = Measured fault loop reactance for relay B

X_N = Rated value of the capacitive reactance, A rms

X_{neg} = resulting capacitive reactance of compensated line with fault on remote capacitor terminal

X_{NH} = the set earth return reactance for high-speed zone of relay B

$X_{n,outer}$ = Outer mutual inductive reactance

$X_{n,inner}$ = Inner mutual inductive reactance

X_{nn} = Complex self-inductive reactance of the nn-th layer

$X_{Ph\text{-}E}$ = Phase-to-earth reactance fault loop measurement for relay A

X_{phs} = Phase Selector reactance measured

X_{pq} = Complex mutual inductive reactance of the nn-th layer

X+A = Forward reactive reach limit for relay A

X-A = Reverse reactive reach limit for relay A

X0PE = Zero sequence phase-to-earth element reactive reach setting parameter for relay B

$X0PE_{PHS}$ = Zero sequence phase selector element reactive reach setting parameter for relay B

$X0PE_{ZM}$ = Zone ($_M$) Zero sequence phase-to-earth element reactive reach setting parameter for relay B

X1PE = Positive sequence phase-to-earth element reactive reach setting parameter for relay B

$X1PE_{PHS}$ = Positive sequence phase selector element reactive reach setting parameter for relay B

$X1PE_{ZM}$ = Zone ($_M$) Positive sequence phase-to-earth element reactive reach setting parameter for relay B

X1PP = Positive sequence reactance setting for phase-to-phase element relay B

$X1PP_{PHS}$ = Reactive phase-to-phase setting for phase selector element

X_1 = Overhead line inductive reactance

X_0 = Zero sequence reactance of overhead line

X_1 = Positive sequence reactance of overhead line

X_2 = Negative sequence reactance of overhead line

Y_0 = Zero sequence admittance

Y_1 = Positive sequence admittance

Y_2 = Negative sequence admittance

Y_r = Resultant parallel network admittance

Z_a = A-phase overhead line impedance

Z_{ABC-N} = Three-phase impedance loop

Z_{ap} = Apparent impedance

Z_{A-N} = A-phase-to-earth impedance loop measurement

Z_{B-N} = B-phase-to-earth impedance loop measurement

Z_{C-N} = C-phase-to-earth impedance loop measurement

Z_b = B-phase overhead line impedance

Z_c = C-phase overhead line impedance

Z_E = Earth impedance in parallel with earth wire

Z_{Eii} = Earth contribution term in conductor impedance calculation

Z_{ii} = Self impedance of conductor

Z_{ik} = mutual impedance of conductor

Z_g = Fault impedance to earth in phase=to=phase=to=earth faults

Z_{Gii} = Geometric term in conductor impedance calculation

Z_{gen} = Impedance calculated with generic equation

Z_F = Fault impedance

Z_L = Loop impedance

Z_L AB = Positive sequence impedance for circuit AB

Z_L BC = Positive sequence impedance for circuit BC

Z_{loop} = Loop impedance

$Z_{LOADMIN}$ = Minimum load impedance

Z_{L1-N} = Phase-to-earth loop fault impedance for phase L_1 *(A-phase)*

Z_{L2-N} = Phase-to-earth loop fault impedance for phase L_2 *(B-phase)*

Z_{L3-N} = Phase-to-earth loop fault impedance for phase L_3 *(C-phase)*

Z_n = Neutral-to-earth impedance

Z_N = Earth-return impedance

Z_{phs} = Phase Selector impedance measured

Z_{relA} = Impedance calculated with the equation for relay A

Z_{relB} = Impedance calculated with the equation for relay B

Z_{s1} = Source 1 impedance

Z_{s2} = Source 2 impedance

Z_TA = Transformer A impedance

Z_TB = Transformer B impedance

Z0 = Zero sequence impedance

Z1 = Positive sequence impedance

Z2 = Negative sequence impedance

ΔI = changes in phase current between samples, relay B

ΔR', ΔX' = J.R. Carson's correction terms for earth return effects

Δt = change in time

Z_Y = Star connected load impedance

Z_Δ =Delta connected load impedance

List of abreviations

AAC = Stranded aluminium conductor

AAAC = All aluminium conductors

ACSR = Aluminium conductor steel reinforced

GMR = Geometric Mean Radius

GMD = Geometric Mean Distance

MOV = Metal Oxide Varistor

MOVS = Metal Oxide Varistors

ms = miliseconds

MVA = Mega volt ampere

Mvar = Mega volt ampere reactive

MW = Mega Watt

kV = Kilovolt

s = Seconds