Exam: Fault detection and location in distribution systems

Testing the Choi-algorithm (patent 5)

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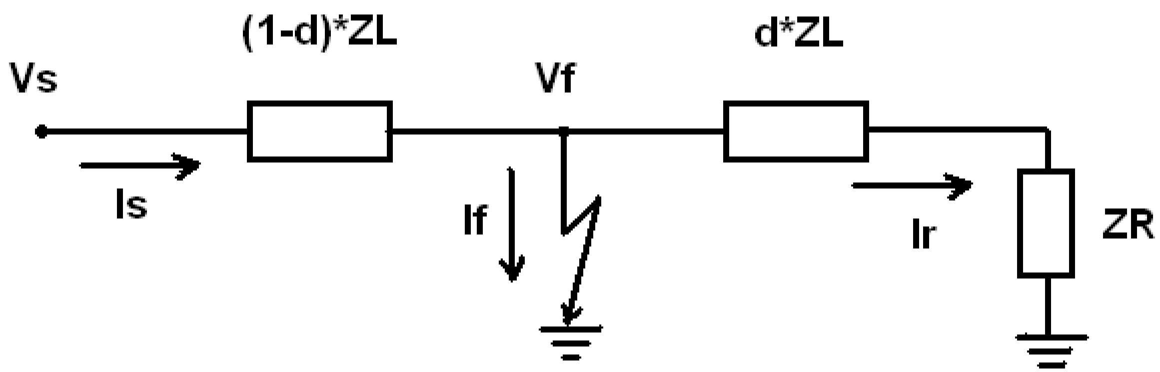
Table of Contents

1. IMPLEMENTING THE PATENTED ALGORITHM IN MATHCAD

1.1. DEFINING A RADIAL TEST FEEDER AND CALCULATING THE FAULT CURRENTS



Fault Location

$d := 0.5$

Source S Voltage

$es := 7071$

Positive Sequence Line Impedance

$Z1L := 10 + 13i$ **Line impedances copied from Creelman case**

Zero Sequence Line Impedance

$Z0L := 30 + 39i$

Load R Positive Sequence Impedance

$Z1R := 200 + 30i$ **Load R is set to correspond "normal" distribution network load**

Load R Zero Sequence Impedance

$Z0R := 0$

Fault Impedances

$INF := 10^{10}$

$ZFA := 0 + j \cdot 0$

$ZFB := INF + j \cdot 0$

$ZFC := INF + j \cdot 0$

$ZFG := 0$ **Fault resistance is set to 0 (this should be the easiest fault to locate)**

CONSTANTS

$a := -0.5 + j \cdot 0.8660254$

$$BAL := \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} \qquad one := \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad zero := \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Three phase voltages at S

$$Vs := es \cdot BAL \qquad Vs = \begin{pmatrix} 7.071 \times 10^3 \\ -3.535 \times 10^3 - 6.124i \times 10^3 \\ -3.535 \times 10^3 + 6.124i \times 10^3 \end{pmatrix}$$

Conversion of positive sequence and zero sequence impedances to Self and Mutual impedances

$$zs(z0,z1) := \frac{2\cdot z1 + z0}{3} \qquad zm(z0,z1) := \frac{z0 - z1}{3}$$

Conversion Matrix Format

$$Z(z0,z1) := \begin{pmatrix} zs(z0,z1) & zm(z0,z1) & zm(z0,z1) \\ zm(z0,z1) & zs(z0,z1) & zm(z0,z1) \\ zm(z0,z1) & zm(z0,z1) & zs(z0,z1) \end{pmatrix}$$

Conversion

$$ZL := Z(Z0L,Z1L) \qquad ZR := Z(Z0R,Z1R)$$

$$ZL = \begin{pmatrix} 16.667 + 21.667i & 6.667 + 8.667i & 6.667 + 8.667i \\ 6.667 + 8.667i & 16.667 + 21.667i & 6.667 + 8.667i \\ 6.667 + 8.667i & 6.667 + 8.667i & 16.667 + 21.667i \end{pmatrix} \quad ZR = \begin{pmatrix} 133.333 + 20i & -66.667 - 10i & -66.667 - 10i \\ -66.667 - 10i & 133.333 + 20i & -66.667 - 10i \\ -66.667 - 10i & -66.667 - 10i & 133.333 + 20i \end{pmatrix}$$

Pre-fault conditions:

$$ZPRE := ZL + ZR \qquad ZPRE = \begin{pmatrix} 150 + 41.667i & -60 - 1.333i & -60 - 1.333i \\ -60 - 1.333i & 150 + 41.667i & -60 - 1.333i \\ -60 - 1.333i & -60 - 1.333i & 150 + 41.667i \end{pmatrix}$$

$$IPRE := ZPRE^{-1}\cdot(Vs) \qquad IPRE = \begin{pmatrix} 32.316 - 6.617i \\ -21.889 - 24.678i \\ -10.428 + 31.295i \end{pmatrix}$$

$$Ia := IPRE_0 \qquad |Ia| = 32.987$$

$$Ib := IPRE_1 \qquad |Ib| = 32.987$$

$$Ic := IPRE_2 \qquad |Ic| = 32.987$$

Line Impedance to the Fault

$$ZSS := (1 - d)\cdot ZL$$

$$ZRR := d\cdot ZL + ZR$$

System Part of the Impedance Matrix

$$ZTOP := augment(augment(ZSS, zero), one)$$

$$ZTOP = \begin{pmatrix} 8.333 + 10.833i & 3.333 + 4.333i & 3.333 + 4.333i & 0 & 0 & 0 & 1 & 0 & 0 \\ 3.333 + 4.333i & 8.333 + 10.833i & 3.333 + 4.333i & 0 & 0 & 0 & 0 & 1 & 0 \\ 3.333 + 4.333i & 3.333 + 4.333i & 8.333 + 10.833i & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$ZMID := augment(augment(zero, ZRR), one)$$

$$ZMID = \begin{pmatrix} 0 & 0 & 0 & 141.667 + 30.833i & -63.333 - 5.667i & -63.333 - 5.667i & 1 & 0 & 0 \\ 0 & 0 & 0 & -63.333 - 5.667i & 141.667 + 30.833i & -63.333 - 5.667i & 0 & 1 & 0 \\ 0 & 0 & 0 & -63.333 - 5.667i & -63.333 - 5.667i & 141.667 + 30.833i & 0 & 0 & 1 \end{pmatrix}$$

$$ZSYS := stack(ZTOP, ZMID)$$

$$ZSYS = \begin{pmatrix} 8.333 + 10.833i & 3.333 + 4.333i & 3.333 + 4.333i & 0 & 0 & 0 & 1 & 0 & 0 \\ 3.333 + 4.333i & 8.333 + 10.833i & 3.333 + 4.333i & 0 & 0 & 0 & 0 & 1 & 0 \\ 3.333 + 4.333i & 3.333 + 4.333i & 8.333 + 10.833i & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 141.667 + 30.833i & -63.333 - 5.667i & -63.333 - 5.667i & 1 & 0 & 0 \\ 0 & 0 & 0 & -63.333 - 5.667i & 141.667 + 30.833i & -63.333 - 5.667i & 0 & 1 & 0 \\ 0 & 0 & 0 & -63.333 - 5.667i & -63.333 - 5.667i & 141.667 + 30.833i & 0 & 0 & 1 \end{pmatrix}$$

Building the voltage Vector:

$$null := \begin{pmatrix} 0 & 0 & 0 \end{pmatrix}$$

$$E := stack\left(Vs, null^T, null^T\right)$$

$$TS := augment(augment(one, zero), zero)$$

$$TR := augment(augment(zero, one), zero)$$

$$TVF := augment(augment(zero, zero), one)$$

Building Fault Part of the Impedance Matrix:

$$ZFAG := ZFA + ZFG$$

$$ZFBG := ZFB + ZFG$$

$$ZFCG := ZFC + ZFG$$

$$ZF := \begin{pmatrix} ZFAG & ZFG & ZFG \\ ZFG & ZFBG & ZFG \\ ZFG & ZFG & ZFCG \end{pmatrix}$$

$$FABCG := augment(augment(-ZF, -ZF), one)$$

$$ZFAG = 0$$

$$ZFBG = 1 \times 10^{10}$$

$$ZFCG = 1 \times 10^{10}$$

$$ZF = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 \times 10^{10} & 0 \\ 0 & 0 & 1 \times 10^{10} \end{pmatrix}$$

$ZABCG := stack(ZSYS, FABCG)$

$YABCG := ZABCG^{-1}$

Fault Currents:

$IABCG := YABCG \cdot E$

$$IABCG = \begin{pmatrix} 379.553 - 488.938i \\ -85.878 + 70.604i \\ -74.416 + 126.578i \\ 58.964 - 94.574i \\ 85.878 - 70.604i \\ 74.416 - 126.578i \\ 0 \\ -4.642 \times 10^3 - 5.896i \times 10^3 \\ -4.336 \times 10^3 + 5.997i \times 10^3 \end{pmatrix}$$

S - End Fault Currents:

$IS := TS \cdot IABCG$

$$IS = \begin{pmatrix} 379.553 - 488.938i \\ -85.878 + 70.604i \\ -74.416 + 126.578i \end{pmatrix}$$

R - End Fault Currents:

$IR := TR \cdot IABCG$

$$IR = \begin{pmatrix} 58.964 - 94.574i \\ 85.878 - 70.604i \\ 74.416 - 126.578i \end{pmatrix}$$

VF fault voltages:

$VF := TVF \cdot IABCG$

$$VF = \begin{pmatrix} 0 \\ -4.642 \times 10^3 - 5.896i \times 10^3 \\ -4.336 \times 10^3 + 5.997i \times 10^3 \end{pmatrix}$$

Line Fault Currents from S Bus

$Iasf := IS_0$ $\quad |Iasf| = 618.968$

$Ibsf := IS_1$ $\quad |Ibsf| = 111.175$

$Icsf := IS_2$ $\quad |Icsf| = 146.833$

Line Fault Voltages at S Bus

$Vaf := Vs_0$ $\quad |Vaf| = 7.071 \times 10^3$

$Vbf := Vs_1$ $\quad |Vbf| = 7.071 \times 10^3$

$Vcf := Vs_2$ $\quad |Vcf| = 7.071 \times 10^3$

1.2. IMPLEMENTING THE PATENTED ALGORITHM

Initial assumptions:

- Faulted phase is known (a)

- Phase voltage (Vsa) during the fault is measured

$Vsa := Vaf$ $\quad Vsa = 7.071 \times 10^{3}$

- Phase currents (Isabc) during the fault are measured

$Isabc := IS$

$Isa := IS_{0}$

$Isb := IS_{1}$

$Isc := IS_{2}$

$$Isabc = \begin{pmatrix} 379.553 - 488.938i \\ -85.878 + 70.604i \\ -74.416 + 126.578i \end{pmatrix}$$

Line and load parameters needed in patended algorithm:

$Zlaa := ZL_{0,0}$ $\quad Zlaa = 16.667 + 21.667i$

$Zlab := ZL_{0,1}$ $\quad Zlab = 6.667 + 8.667i$

$Zlac := ZL_{0,2}$ $\quad Zlac = 6.667 + 8.667i$

$Zraa := ZR_{0,0}$ $\quad Zraa = 133.333 + 20i$

$Zrab := ZR_{0,1}$ $\quad Zrab = -66.667 - 10i$

$Zrac := ZR_{0,2}$ $\quad Zrac = -66.667 - 10i$

Defining C1 and C2:

$C1 := Zlaa \cdot Isa + Zlab \cdot Isb + Zlac \cdot Isc$ $\quad C1 = 1.414 \times 10^{4}$

$C2 := Zraa \cdot Isa + Zrab \cdot Isb + Zrac \cdot Isc$ $\quad C2 = 7.304 \times 10^{4} - 6.914i \times 10^{4}$

Defining ar, ai, br, bi, cr, ci, dr and di:

$ar := Re(C1 \cdot Zlaa)$ $\quad ar = 2.357 \times 10^{5}$

$ai := Im(C1 \cdot Zlaa)$ $\quad ai = 3.064 \times 10^{5}$

$br := Re(Vsa \cdot Zlaa - C1 \cdot Zlaa + C1 \cdot Zraa)$ $\quad br = 1.768 \times 10^{6}$

$bi := Im(Vsa \cdot Zlaa - C1 \cdot Zlaa + C1 \cdot Zraa)$ $\quad bi = 1.296 \times 10^{5}$

$cr := Re[Zraa \cdot (Vsa - C1)]$ $\quad cr = -9.428 \times 10^{5}$

$ci := Im[Zraa \cdot (Vsa - C1)]$ $\quad ci = -1.414 \times 10^{5}$

$dr := \mathrm{Re}(Vsa - C1 - C2)$ $\quad$ $dr = -8.011 \times 10^4$

$di := \mathrm{Im}(Vsa - C1 - C2)$ $\quad$ $di = 6.914 \times 10^4$

Defining second degree polynomial coefficients (a, b and c):

$aa := ar - \frac{dr}{di} \cdot ai$ $\quad$ $aa = 5.907 \times 10^5$

$bb := br - \frac{dr}{di} \cdot bi$ $\quad$ $bb = 1.918 \times 10^6$

$cc := cr - \frac{dr}{di} \cdot ci$ $\quad$ $cc = -1.107 \times 10^6$

Solving the polynomial:

$$d1 := \frac{-bb + \sqrt{bb^2 - 4 \cdot aa \cdot cc}}{2 \cdot aa} \qquad d2 := \frac{-bb - \sqrt{bb^2 - 4 \cdot aa \cdot cc}}{2 \cdot aa}$$

$d1 = 0.5$ $\quad$ $d2 = -3.747$

Accepted $\quad$ **Discarded (negative fault distance not possible)**

Actual fault distance is 1-d1

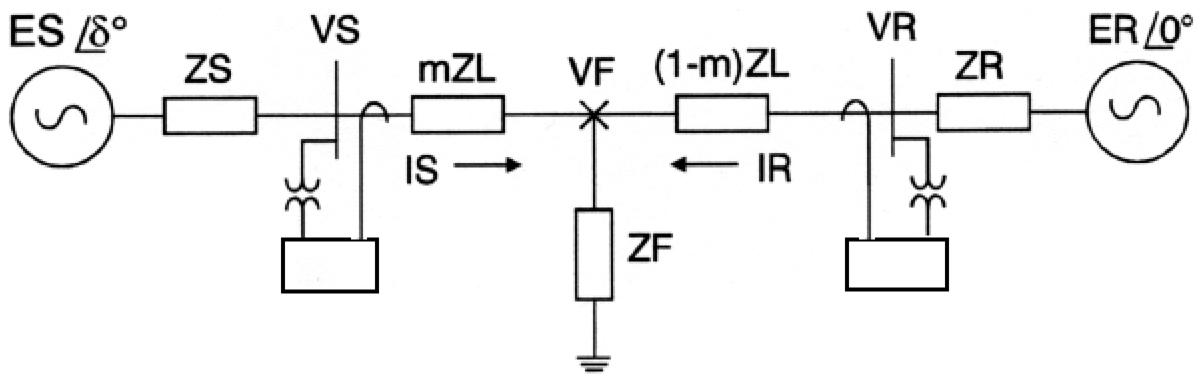
$1 - d1 = 0.5$

The calculated fault distance was correct. This proves that the algorithm works (at least in theory)

The algorithm gives correct results with all values of d in range [0,1[and with all realistic fault resistance values

2. TESTING THE PATENTED METHOD WITH IDEAL 2-SOURCE DATA

2.1. DEFINING THE NETWORK AND CALCULATING THE FAULT CURRENTS



INPUT DATA

$\delta := 0.001$ **Voltage Phase Angle**

$es := 10000 \cdot e^{j \cdot \delta \cdot deg}$ **Source S Voltage**

$er := 0$ **Source R Voltage**

$Z1R := 0.42 + 0.5i$ **Source R Positive Sequence Impedance**

$Z0R := 0$ **Source R Zero Sequence Impedance**

$Z1S := 0.042 + 0.513i$ **Source S Positive Sequence Impedance**

$Z0S := 0.013 + 1.225i$ **Source S Zero Sequence Impedance**

$Z1L := 10 + 13i$ **Positive Sequence Line Impedance**

$Z0L := 30 + 39i$ **Zero Sequence Line Impedance**

Fault Location

$M := 0.5$

Fault Resistance

$ZFG := 0$

Three phase voltages at S and R

$ES := es \cdot BAL$

$ER := er \cdot BAL$

Calculating the impedance matrices

$ZS := Z(Z0S, Z1S)$

$ZL := Z(Z0L, Z1L)$

$ZR := Z(Z0R, Z1R)$

Source and Line Impedances to the Fault

$ZSS := ZS + M \cdot ZL$

$ZRR := ZR + (1 - M) \cdot ZL$

Build System Part of the Impedance Matrix

$ZTOP := \text{augment}(\text{augment}(ZSS, \text{zero}), \text{one})$

$ZMID := \text{augment}(\text{augment}(\text{zero}, ZRR), \text{one})$

$ZSYS := \text{stack}(ZTOP, ZMID)$

Pre-fault conditions:

$ZPRE := ZS + ZL + ZR$

$IPRE := ZPRE^{-1} \cdot (ES - ER)$

Pre_fault voltage at S end

$VSP := ES - ZS \cdot IPRE$

Build the voltage Vector

$E := \text{stack}\left(\text{stack}(ES, ER), \text{null}^T\right)$

$TS := \text{augment}(\text{augment}(\text{one}, \text{zero}), \text{zero})$

$TR := \text{augment}(\text{augment}(\text{zero}, \text{one}), \text{zero})$

Building Fault Part of the Impedance Matrix:

$ZFAG := ZFA + ZFG$

$ZFBG := ZFB + ZFG$

$ZFCG := ZFC + ZFG$

$$ZF := \begin{pmatrix} ZFAG & ZFG & ZFG \\ ZFG & ZFBG & ZFG \\ ZFG & ZFG & ZFCG \end{pmatrix}$$

$\text{FABCG} := \text{augment}(\text{augment}(-\text{ZF}, -\text{ZF}), \text{one})$

FINAL Z MATRIX

$\text{ZABCG} := \text{stack}(\text{ZSYS}, \text{FABCG})$

$\text{YABCG} := \text{ZABCG}^{-1}$

Fault Currents:

$\text{IABCG} := \text{YABCG} \cdot \text{E}$

S - End Fault Currents:

$\text{IS} := \text{TS} \cdot \text{IABCG}$

R - End Fault Currents:

$\text{IR} := \text{TR} \cdot \text{IABCG}$

S - End Voltages

$\text{VS} := \text{ES} - \text{ZS} \cdot \text{IS}$

Line Prefault Load Currents from S Bus

$\text{Ia} := \text{IPRE}_0 \qquad |\text{Ia}| = 571.832$

$\text{Ib} := \text{IPRE}_1 \qquad |\text{Ib}| = 571.832$

$\text{Ic} := \text{IPRE}_2 \qquad |\text{Ic}| = 571.832$

Line Prefault Voltages at S Bus

$\text{Va} := \text{VSP}_0 \qquad |\text{Va}| = 9.752 \times 10^3$

$\text{Vb} := \text{VSP}_1 \qquad |\text{Vb}| = 9.752 \times 10^3$

$\text{Vc} := \text{VSP}_2 \qquad |\text{Vc}| = 9.752 \times 10^3$

Line Fault Currents from S Bus

$\text{Iasf} := \text{IS}_0 \qquad |\text{Iasf}| = 929.021$

$\text{Ibsf} := \text{IS}_1 \qquad |\text{Ibsf}| = 573.339$

$\text{Icsf} := \text{IS}_2 \qquad |\text{Icsf}| = 574.148$

Line Fault Currents from R Bus

$Iarf := IR_0$ $\quad |Iarf| = 215.693$

$Ibrf := IR_1$ $\quad |Ibrf| = 573.339$

$Icrf := IR_2$ $\quad |Icrf| = 574.148$

Line Fault Voltages at S Bus

$Vaf := VS_0$ $\quad |Vaf| = 9.53 \times 10^3$

$Vbf := VS_1$ $\quad |Vbf| = 9.827 \times 10^3$

$Vcf := VS_2$ $\quad |Vcf| = 9.74 \times 10^3$

Generating digital signals of Voltage and Current of the Simulation 4 Cycles with 7680 samples per second

$k := 0 .. 511$

$delT := 0.0001302$

$Van_k := \left|VSP_0\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(VSP_0\right)\right)$

$T1_k := k \cdot delT$

$T2_k := 512 \cdot delT + k \cdot delT$

$T3_k := 1024 \cdot delT + k \cdot delT$

$Vbn_k := \left|VSP_1\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(VSP_1\right)\right)$

$Vcn_k := \left|VSP_2\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(VSP_2\right)\right)$

$Vaf_k := \left|VS_0\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(VS_0\right)\right)$

$Vbf_k := \left|VS_1\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(VS_1\right)\right)$

$Vcf_k := \left|VS_2\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(VS_2\right)\right)$

$Ian_k := \left|IPRE_0\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(IPRE_0\right)\right)$

$Ibn_k := \left|IPRE_1\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(IPRE_1\right)\right)$

$Icn_k := \left|IPRE_2\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(IPRE_2\right)\right)$

$Iaf_k := \left|IS_0\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(IS_0\right)\right)$

$Ibf_k := \left|IS_1\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(IS_1\right)\right)$

$Icf_k := \left|IS_2\right| \cdot \sin\left(2 \cdot \pi \cdot 60 \cdot k \cdot delT + \arg\left(IS_2\right)\right)$

Let us make Normal (4 cycle)+ Fault (4 cycle) +Normal (4 cycle)

$Seg1 := \mathrm{augment}(T1, Ian, Ibn, Icn, Van, Vbn, Vcn)$

$Seg2 := \mathrm{augment}(T2, Iaf, Ibf, Icf, Vaf, Vbf, Vcf)$

$Seg3 := \text{augment}(T3, Ian, Ibn, Icn, Van, Vbn, Vcn)$

$Final := \text{stack}(Seg1, Seg2, Seg3)$

$T := Final^{\langle 0 \rangle}$ $\quad Ia := Final^{\langle 1 \rangle}$ $\quad Ib := Final^{\langle 2 \rangle}$ $\quad Ic := Final^{\langle 3 \rangle}$ $\quad Va := Final^{\langle 4 \rangle}$ $\quad Vb := Final^{\langle 5 \rangle}$ $\quad Vc := Final^{\langle 6 \rangle}$

$Ir := Ia + Ib + Ic$

$Vr := Va + Vb + Vc$

$m := \text{length}(Va)$

$window := 128$

$wind := window - 1$

$$dd := 0 .. \frac{m}{window} - 1$$

$kk := 0 .. m - window$

$$k := 0 .. \frac{m - window}{8}$$

$$k0 := \frac{Z0L - Z1L}{3 \cdot Z1L}$$

$Isa := Ia + k0 \cdot Ir$ $\quad Isb := Ib + k0 \cdot Ir$ $\quad Isc := Ic + k0 \cdot Ir$

$Ua_k := \text{submatrix}(Va, k \cdot 8, k \cdot 8 + wind, 0, 0)$ $\quad Ub_k := \text{submatrix}(Vb, k \cdot 8, k \cdot 8 + wind, 0, 0)$ $\quad Uc_k := \text{submatrix}(Vc, k \cdot 8, k \cdot 8 + wind, 0, 0)$

$Ao_k := \text{submatrix}(Ir, k \cdot 8, k \cdot 8 + wind, 0, 0)$

$Aa_k := \text{submatrix}(Isa, k \cdot 8, k \cdot 8 + wind, 0, 0)$ $\quad Ab_k := \text{submatrix}(Isb, k \cdot 8, k \cdot 8 + wind, 0, 0)$ $\quad Ac_k := \text{submatrix}(Isc, k \cdot 8, k \cdot 8 + wind, 0, 0)$

$Pa_k := FFT(Ua_k)$ $\quad Pb_k := FFT(Ub_k)$ $\quad Pc_k := FFT(Uc_k)$

$Fa_k := FFT(Aa_k)$ $\quad Fb_k := FFT(Ab_k)$ $\quad Fc_k := FFT(Ac_k)$ $\quad Fo_k := FFT(Ao_k)$

2.2. TESTING THE PATENTED ALGORITHM

Initial assumptions:

- Faulted phase is known (a)

- Phase voltage (Vsa) during the fault is measured

$Vsa_k := (Pa_k)_{1,0}$

- Phase currents (Isabc) during the fault are measured

$Isa_k := (Fa_k)_{1,0}$

$Isb_k := (Fb_k)_{1,0}$

$Isc_k := (Fc_k)_{1,0}$

Line parameters needed in patended algorithm:

$Zlaa := ZL_{0,0}$

$Zlab := ZL_{0,1}$

$Zlac := ZL_{0,2}$

$Zraa := ZR_{0,0}$

$Zrab := ZR_{0,1}$

$Zrac := ZR_{0,2}$

Defining C1 and C2:

$C1_k := Zlaa \cdot Isa_k + Zlab \cdot Isb_k + Zlac \cdot Isc_k$

$C2_k := Zraa \cdot Isa_k + Zrab \cdot Isb_k + Zrac \cdot Isc_k$

Defining ar, ai, br, bi, cr, ci, dr and di:

$ar_k := \mathrm{Re}(C1_k \cdot Zlaa)$

$ai_k := \mathrm{Im}(C1_k \cdot Zlaa)$

$br_k := \mathrm{Re}(Vsa_k \cdot Zlaa - C1_k \cdot Zlaa + C1_k \cdot Zraa)$

$bi_k := \mathrm{Im}(Vsa_k \cdot Zlaa - C1_k \cdot Zlaa + C1_k \cdot Zraa)$

$cr_k := \mathrm{Re}\left[Zraa \cdot (Vsa_k - C1_k)\right]$

$ci_k := \mathrm{Im}\left[Zraa \cdot (Vsa_k - C1_k)\right]$

$dr_k := \mathrm{Re}\left(Vsa_k - C1_k - C2_k\right)$

$di_k := \mathrm{Im}\left(Vsa_k - C1_k - C2_k\right)$

Defining second degree polynomial coefficients (a, b and c):

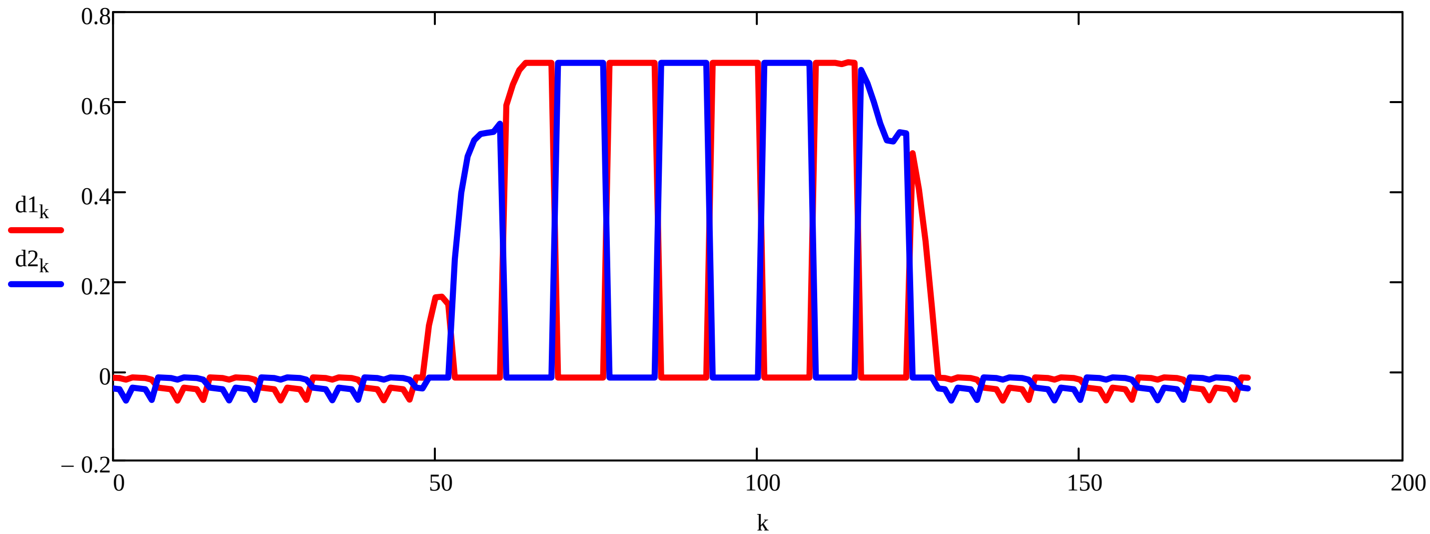
$a_k := ar_k - \frac{dr_k}{di_k} \cdot ai_k$ $\qquad a_{100} = 7.99 \times 10^6$

$b_k := br_k - \frac{dr_k}{di_k} \cdot bi_k$ $\qquad b_{100} = -5.362 \times 10^6$

$c_k := cr_k - \frac{dr_k}{di_k} \cdot ci_k$ $\qquad c_{100} = -8.438 \times 10^4$

Solving the polynomial:

$d1_k := \frac{-b_k + \sqrt{\left(b_k\right)^2 - 4 \cdot a_k \cdot c_k}}{2 \cdot a_k}$ $\qquad d2_k := \frac{\left(-b_k\right) - \sqrt{\left(b_k\right)^2 - 4 \cdot a_k \cdot c_k}}{2 \cdot a_k}$



$d1_{97} = 0.686$

$calculated\_fault\_distance := 1 - d1_{97}$ $\qquad true\_fault\_distance := M$

calculated_fault_distance = 0.314

true_fault_distance = 0.5 ERROR := |calculated_fault_distance − true_fault_distance|

ERROR = 0.186

With the ideal 2-source data the patented algorithm performs quite poorly. The calculated fault distances are somewhat inaccurate. The results are most inaccurate when the fault is in the middle of the line. With small and large fault distances the error is smaller. See Table 1 for calculated fault distances when the actual fault distance varies.

From Table 1 we can also see that the modification to fault distance calculation proposed by Kim (fault distance =2*(1-d)) works only when the fault distance m is between 0 and 0.5

For fault distances larger than 0.5 the formula 1-d/2 works better (doesn't work for distances smaller than 0.5).

The algorithm worked perfectly in Chapter 1, when it was tested with one time domain data (rms values). However, when digitalized values are used, the accuracy of this method is poor. Reason for this is unknown.

Table 1. Calculated fault distances

Actual fault distance	Calculated d	Calculated fault distance 1-d	|error|	Modification proposed by Kim, fault distance = 2*(1-d)	|error|	Modification proposed by Mutanen, fault distance =1-d/2	|error|
0.05	0.976	0.024	0.026	**0.047**	**0.003**		
0.1	0.951	0.049	0.051	**0.098**	**0.002**		
0.3	0.835	0.165	0.135	**0.329**	**0.029**		
0.5	0.686	0.314	0.186	**0.627**	**0.127**		
0.7	0.488	0.512	0.188	1.024	0.324	**0.756**	**0.056**
0.9	0.208	0.792	0.108	1.583	0.683	**0.896**	**0.004**
0.95	0.118	0.882	0.068	1.763	0.813	**0.941**	**0.004**

I was unable to test the patented algorithm with the real fault data, because the impedance ZR is unknown for the CreelmanN system. (I don't even know if the Creelman system is a 2- or 1-source system)