FERRORESONANCE IN AN 88KV NETWORK

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2004

DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

25 th day of February 2004

I have chosen to present the work as a technical paper that gives a concise overview of the work undertaken with comprehensive appendices that detailed the computer program, the development of the simulation model and the background of the ferroresonance condition.

FERRORESONANCE IN AN 88KV NETWORK

Abstract: An investigation was conducted on the failures of 88kV line surge arrestors at an Eskom Distribution substation. The surge arrestor failed when one phase of the transmission line was open circuited and all three phases were not isolated by the protection relays. The transformer was lightly loaded and a surge arrestor blocked the neutral path to the ground. The investigation used a modified version of an equivalent circuit proposed by Marti [1]. Transformer magnetising losses, the non-linear resistance of the neutral surge arrestor and the transformer magnetising reactance of the closed-circuit phases were all included. The investigation revealed that the failure of the arrestor was due to the combined volt drops across the open circuited phase of the transformer magnetising reactance and the neutral surge arrestor. A resonance condition lowered the magnetising reactance of the open circuited phase of the transformer and forced the transformer into saturation. This resonance is characteristic of the fundamental frequency ferroresonance condition [2].

Introduction

In recent years, theft of power transmission lines and underground cables in South Africa has increased substantially. Modern power lines and cables consist primarily of aluminium while older cables and substation earthing consists of copper. The result is loss of supply to customers and failure and damage of substation equipment as explained in the paper.

Theft of the transmission lines occurs more frequently because of ease of removing the lines compared to cables. Typically, only one phase and only a few spans (one or two) of the transmission line are stolen at a time leaving the rest of the line intact. This is due to the difficulty of electrically isolating the line and removing the line from the towers. This requires a time range from six hours to a whole day. The assumed process of the theft of lines is explained in Appendix A, Section 1.

Cohen Substation

Cohen substation is an 88 kV Eskom Distribution substation. The substation has two star/delta transformers, the 88/11 kV and the 88/22 kV transformers. The substation serves a semi-rural area with a mixed load, comprising farmers and a few light industries.

At Eskom's Cohen substation a line surge arrestor failed when one phase of an 88kV transmission line was open circuited, possibly due to theft, and this occurred on the 88/11 kV transformer that was lightly loaded. The open circuited phase produced an overvoltage across the surge arrestor. The overvoltage was sufficiently large to cause the surge arrestor to fail thermally, but not large enough to allow the arrestor to operate as a voltage clamp and draw a large current, thereby operating the overcurrent protection. The thermal failure probably took place over a time period ranging from 3 to 27 hours, depending on the actual value of the overvoltage.

The protection relays did not pick up the open circuited phase condition because the relays were set to operate on overcurrent and abnormal voltage conditions were not detected. This paper describes the simulation undertaken to investigate the likely role of resonance between the capacitance of the lines and the magnetizing inductance of the transformer in causing the overvoltages that led to the arrestor failure.

The Problem at Cohen substation

Cohen substation is located in an open, isolated area that gives opportunity for the lines to be stolen (detailed in Appendix A Section 1). At Cohen substation, only one phase of the transmission line was stolen.

The surge arrestor, SAph, that failed is located on the open circuited phase of the transmission line on the HV side of the transformer, shown in Figure 1. The neutral path of the transformer (HV on the star-connected side) to ground is blocked by a neutral surge arrestor, SAn. The neutral surge arrestor prevents the occurrence of large zero sequence fault currents in the transformer.

Technical Explanation of the Problem

When one of the phases from the transmission line is open circuited, there is no direct supply to that phase. The other two phases still have a normal supply and give rise to a voltage onto the open circuited phase through capacitive coupling on the transmission line. Current is fed into the transformer magnetising circuit on the open circuited phase, thereby determining the voltage. Since the open circuit phase is not connected to the power system, the system voltage could not be imposed and the voltage on the open-circuited phase is set by the circuit parameter values.

The voltage appearing across the line arrestor, SAph, in Figure 1 is the phasor sum of the neutral surge arrestor voltage (Vn) and the open circuit winding voltage (V3).

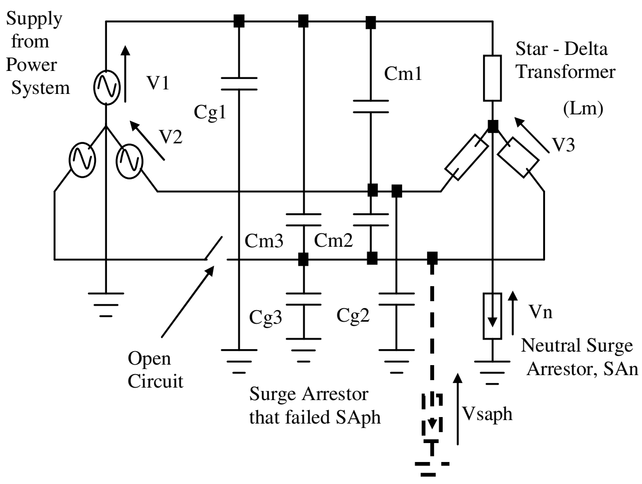


Figure 1: Circuit model for the system with one phase open circuited.

Marti's circuit model [1] only considers the coupling capacitance and the magnetising inductance of the transformer windings. To simulate the situation at Cohen substation, the magnetising resistance, Rm, the non-linear resistance of the neutral surge arrestor, Rn, and the transformer magnetising inductance of the closed circuit phases, L1 & L2, were added to the model as shown in Figure 2 (drawn in red).

Cohen substation is connected to the large interconnected Eskom Power Grid and therefore V1 and V2 (from Figure. 2) represent an infinite busbar. This is in line with the assumptions made in Marti's circuit model [1].

When one of the phases of the transmission line is open circuited, the system at Cohen station becomes unbalanced. Although the currents from V1 and V2 change due to the unbalanced system, the voltage and phase angle values of V1 and V2 remain constant because the current change is relatively small compared to the rated values of the interconnected power system.

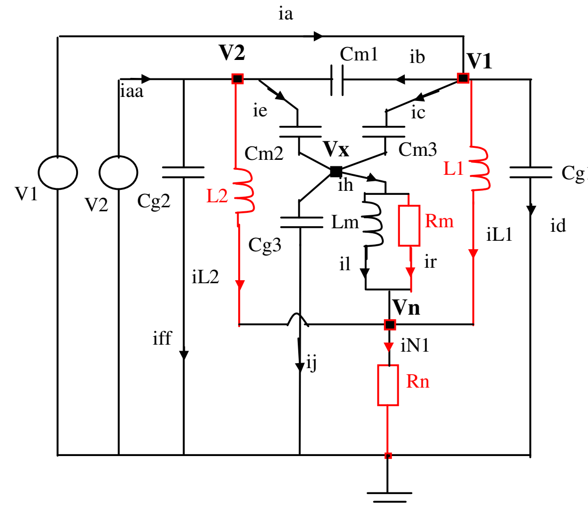


Figure 2: Equivalent circuit with the following parameters,

- Cm1, Cm2 and Cm3 are the mutual capacitances between phases 1 & 2, 2 &3 and 1 & 3 respectively.
- Cg1, Cg2 and Cg3 are the capacitances between phases 1, 2 and 3 to ground.
- Lm is the transformer magnetising inductance.
- V1 is the phase voltage, $50.8\angle 0^{o}$kV
- V2 is the phase voltage, $50.8\angle 120^{o}$kV
- Rm is the transformer magnetising resistance of the open circuit phase.
- Rn is the non linear resistance of the neutral arrestor.
- L1 and L2 are the transformer magnetising inductances of the closed phases.
- Vx and Vn are node voltages.

Transmission Line

The length of the transmission line is 6.6km and uses the H Pole structure (Appendix A, Figure. A1). The transmission line consists of a single circuit, single aluminium stranded conductor of radius 0.02646m.

Only the capacitances of the transmission line were considered and are split into two components, the capacitance between the phases of the transmission line, Cm, and the capacitance between the phase of the transmission line to ground, Cg (calculation detailed in Appendix A, Section 3.1).

The capacitances Cm and Cg are the same for all three phases of the transmission line. Since the open circuit can occur anywhere along the transmission line, the capacitances for the open circuited phase were varied for different lengths of the line in the simulation model.

Transformer

The transformer specifications are listed below,

- 88kV/11kV Star/Delta
- HV Turns : 1340
- LV turns : 205
- Core limb: Height = 1.01 m, Diameter = 0.395 m & Area = 0.1103 m^2

The magnetising resistance, Rm, was calculated to be approximately 200kΩ by assuming a 0.4% iron loss (Pfe) for the transformer output (Appendix A, Section 3.2). The transformer B-H curve was represented by the polynomials below in the Matlab program. Three polynomials were used because of the large range of H values. The polynomials are:

$P1 = 0.2622x^{13} - 0.4186x^{11} + 0.7539x^5 + 6.4407x^2 + 5.9618$
valid for 0<B<1.7 [T] ……..(a)

$P2 = 27.796x^{11} - 133.73x^9 + 269.4247x^6$
valid for 1.7<=B<2 [T] ……..(b)

$P3 = -7300x^{11} + 27370x^{10} - 65070x^8 + 111840x^5$ valid for B>=2 [T] …….(c)

The B/H values calculated by the polynomial equations is plotted against the given B/H values in Appendix A, Section 2.2.

The maximum magnetising current that allows for normal operation of the transformer is 0.72A (Appendix A, Table A2).

The magnetising inductance of the transformer core was calculated using the equation below (derivation in Appendix A, Section 3.2).

$$Lm = \frac{N^2 AB}{H.l} \qquad (1)$$

where:

- B is the magnetic flux density
- H is the magnetic field intensity
- l is the length of the transformer core
- A is the area of the transformer core
- N is the number of HV turns of the transformer winding
- Lm is the transformer magnetising inductance

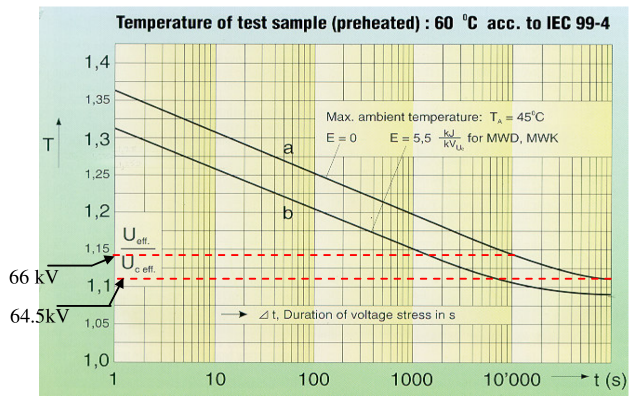
The relationship of the transformer magnetising inductance (Lm) is plotted against the magnetic flux density (B) in Appendix A, Figure A5.

Surge Arrestor

The surge arrestors are metal oxide (MOV) arrestors without spark gaps and are simulated by non linear resistors to dissipate energy from overvoltages [3].

The Transmission Line Surge Arrestor (SAph)

The surge arrestors used were station class, ABB EXLIM R porcelain type arrestor [3]. If a resonant condition led to the arrestor failure, it is likely that an overvoltage was generated which was high enough to lead to thermal overstressing of the arrestor, but not sufficient to cause severe voltage clamping and a large earth current.



<u>Figure 3. Temporary Overvoltage Curve for the Transmission Line Surge Arrestor</u>

The above graph is the Temporary Overvoltage Curve (TOV) [3] of the transmission line surge arrestor (SAph). This graph displays the maximum time allowed for the arrestor to operate at the specified overvoltage, thereafter the arrestor will fail.

The graph contains 2 curves, a and b. Curve a is used if the arrestor had not operated before. Curve b is used if the arrestor had operated for another condition and did not have enough time to cool down.

The voltage that caused the SAph arrestor to fail was deduced using Figure.3 to range from 64.5kV to 66kV using Curve a. The time to failure of the arrestor would then range from 2.7 to 27 hours.

Curve a (Figure.3) was chosen for the model because the probability of the arrestor (SAph) operating prior to the open circuit condition is relatively low.

The Neutral Surge Arrestor (SAn)

The neutral arrestor was an ABB MWK polymer (silicon) type arrestor. The neutral surge arrestor

(SAn) current was assumed to be between 0.25 A (rms) to 1.0 A(rms). According to the peak voltage (8/20µs waveform) versus current graph (Appendix A, Section 2.3) the voltdrop across the arrestor would be 52 kV (rms) and the non linear resistance was calculated to be approximately 90 kΩ .

Simulation Model

The simulation model calculated the circuit parameter values (displayed in Table.1) from Figure 2 by using the SAph voltage range (64.5kV to 66kV from Figure.3, Curve a) as the deciding parameter. The model simulates the open circuit condition as a 'steady state' system.

The circuit shown in, Figure. 2, was solved using 'Nodal Analysis' (Appendix A, Section 4.1) and the resulting equations formed the matrix shown in Appendix A, Section 4.2. The phase voltage 'V1' was used as the reference in the circuit model (Figure 2).

The voltage across the transformer core is given by,

V3 = Vx - Vn

The voltage across the transmission line surge arrestor, SAph, is the phasor addition of the open circuited transformer core volt drop, V3, and the neutral surge arrestor volt drop, Vn.

$$|\text{Vsaph}| = V3 + Vn \qquad (2)$$

Matlab Algorithms

The version of Matlab used was V6.5.0.180913a, Release 13. There were 3 programs developed to create the simulation model. The programs are listed in Appendix A, Section 5.

1. The 'Caps' program calculated the phase and ground capacitances.
2. The 'Magcurve' program developed the polynomial equations to model the transformer B/H values and calculated the transformer magnetizing inductance (Lm) values.
3. The 'Main' program used the capacitance values calculated from the 'Caps' program and the inductance values calculated from the 'Magcurve' program to develop the matrix (Appendix A, Section 4.2). The program calculated the transformer magnetizing voltage (V3), the magnetizing current (il), the neutral surge arrestor voltage (Vn) and current (iN1) and the transmission line surge arrestor voltage (Vsaph).

The 'Main' program varied the open circuited phase length of the transmission line and the 'Magcurve' program varied the magnetizing inductance, Lm, according to the polynomial equations to obtain the required voltage and current values for the open circuit condition. The programs are listed in Appendix B.

Results & Discussion

The simulation has shown that the failure of surge arrestor, SAph, was due to the combined volt drops across the open circuited phase of the transformer core (V3) and the neutral surge arrestor (Vn). The current in the magnetizing branch of the open circuited phase was larger than under normal operating conditions forcing the transformer into saturation and therefore producing the ferroresonance condition.

The voltage of the open circuit phase of the transformer was below the normal operating voltage because the voltage was set by circuit parameters since the transformer winding was disconnected from the power system.

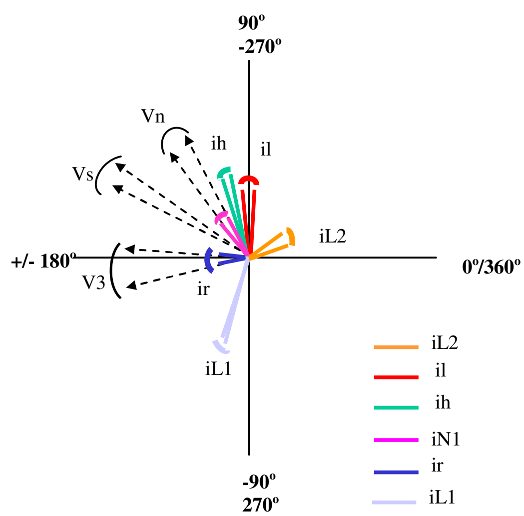


Figure 4: Polar representation of the voltages and currents in the equivalent circuit

Figure 4 shows that Vsaph lies between V3 and Vn and the angle difference between V3 and Vn is approximately 50°. The angle difference between V3 and Vn could not be larger than 90° because the angle of V3 is set by the transformer magnetizing circuit currents, that is il and ir (Figure 2). The vector sum of the voltages will always be additive and result in large Vsaph values.

The voltage across Vn ranged from 24kV to 28 kV. The reason the voltage is lower than the 52 kV voltage predicted is due to the low current, iN1. The current iN1 is the vector sum of iL1, iL2 and ih (Figure 2) but, due to the large angle differences, the current value was reduced.

Increasing the magnetizing resistance, Rm, reduces the volt drop across Vn. Similarly, increasing the neutral surge arrestor resistance Rn, decreases the transformer voltage, V3. This issue was addressed by using the current in the open circuited phase as the defining parameter. This then fixed both the arrestor and winding voltages.

The simulation showed that the close location of the open circuit from the station, 0.5km or less, would cause the arrestor to fail. The close location of the open circuited phase to the substation reduced the capacitance in the open circuited phase (Cg3). A small capacitance would increase the voltage across the open circuit transformer winding and increase the probability of ferroresonance.

The closed circuit transformer windings with magnetizing inductances, L1 and L2 provided other paths for the capacitive current to ground. This reduces the magnetising current in the open circuit transformer winding thereby reducing the depth of saturation of the transformer. The magnetising resistance, Rm, is used to prevent the occurrence of the complete ferroresonance condition that results in extremely large overvoltages that are not relevant to this investigation.

The circuit parameter values that could have resulted in the ferroresonance condition are listed in Table 1.

Table 1. Circuit Parameter Values calculated from the Simulation Model

Circuit Parameter	Magnitude	Angle
V3 [kV]	46.2	176^{o} to 184^{o}
Il [A]	0.48 to 0.59	87^{o} to 94^{o}
Vn [kV]	21.4 to 26	126^{o} to 138^{o}
In1 [A]	0.23 to 0.29	126^{o} to 138^{o}
Vsaph [kV]	62 to 67	161^{o} to 167^{o}
Lm [H]	245 to 300	
Cm [nF/km]	5.04	
Cg [nF/km]	8.5	
B [T]	1.864 to 1.88	

Constants :

- Rn= 90 kΩ
- Rm=200 kΩ
- V1=50.8 kV$\angle 0^{o}$
- V2=50.8 kV$\angle 120^{o}$
- L1 = L2 = 530H
- S = 5.2m
- h = 13.06m
- r = 0.02646m
- l = 6.6 km

where

- S is the spacing between phases of the transmission line [m].
- h is height of the transmission line to ground [m].
- r is the radius of the conductor [m].
- l is the length of the transmission line [km].

Conclusion

The simulation showed that the open circuited phase caused a resonance condition that created the overvoltage that compromised the transmission line surge arrestor, SAph. The 'steady state' ferroresonance condition was identified but did not create the overvoltages as anticipated and was not the sole cause of the overvoltage across the surge arrestor, SAph. The surge arrestor, SAph, failed due to the combined volt drops from the open circuited phase of the transformer and the neutral surge arrestor.

The following assumptions were made in the simulation model,

- The steady state fundamental frequency ferroresonance condition was assumed for the model.
- The transformer series impedance was neglected.
- The magnetising resistance, Rm, was calculated assuming an iron loss was at 0.4% of rated power (Pfe=40kW).
- The transformer had no load.
- The transmission line inductance and resistance were neglected.
- Transmission line conductors were assumed to be a solid circular conductor and not stranded.
- The transformer magnetising resistances of the closed circuit phases were ignored.
- The phase voltages V1 and V2 were assumed to be constant and not affected by the open circuit condition.

The ferroresonance condition is prominent for open circuited phase lengths close to the station (0.5km or less).

Assumptions have been made on the actual circuit from the model and the slight inaccuracy of values does not affect the overall result of the simulation. Ideally the circuit should have been replicated and measurements made in situ but this was not practical due to operational reasons.

A phase protection relay was installed at Cohen substation in July 2003 and there has not been an open circuit condition as yet. When an open circuit condition occurs, the relay would operate and prevent the recurrence of the ferroresonance condition.

References

1. Marti J R, Soudack A C. *Ferroresonance in power systems : Fundamental solutions.* IEE Proceedings-C Vol 138, No 4, July 1991.
2. Teape J W, Slater R D, Simpson R R S, Wood W S. *Hysteresis effects in transformers, including ferroresonance.* IEE Proceedings, Vol 123, No 2, February 1976.
3. Theron R. *Selection of Station Class Arrestors.* Distribution Technology Standard, Eskom Distribution, October 2001.

APPENDIX A

CONTENTS

Appendix A

1. Theft of the Transmission Lines

Ferroresonance for Cohen substation was caused when one phase of the transmission line was open circuited. The phase of the line could be open circuited by,

- one phase of a breaker fails to close,
- the phase is broken by lightning, trees, etc, without falling to ground
- and theft.

The lines that are stolen are assumed to follow the process below.

1. Firstly, a section of the transmission line between two pylons, is chosen.
2. The jumpers from the chosen phase are cut from both pylons rendering the line ‘dead’.
3. Thereafter the ‘dead’ phase is cut, brought down and reeled.
4. This process takes the entire night to accomplish and only one phase can normally be stolen.

2. System Dimensions

The transmission line, surge arrestors and transformer specifications are detailed in the following sections.

2.1 Transmission Line

The length of the transmission line is 6.6km. The line uses the H Pole structure and the dimensions are shown in Figure A1. The transmission line consists of a single circuit, single aluminium stranded conductor with radius 0.02646m and is termed ‘Centipede’ (Eskom use). A solid aluminium core of radius 0.02646m was used in the simulation for simplicity.

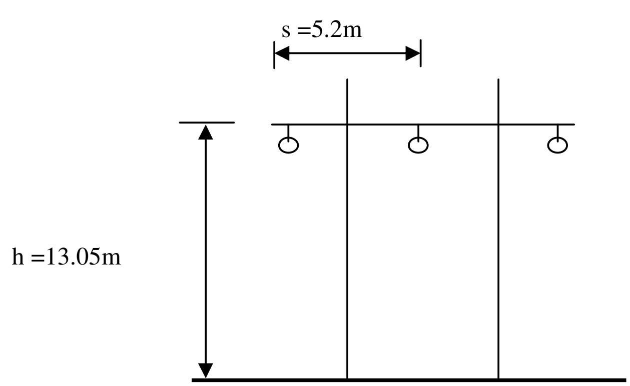


Figure A1. The H Pole structure

2.2 Transformer

The transformer is old and therefore only the following information could be obtained.

The transformer specifications are listed below,

HV : 88 kV Star
LV : 11 kV Delta

HV Turns : 1340
LV turns : 205
Core dimensions (per Limb) : Height : 1.01 m
Diameter : 0.395 m
Area : 0.1103 m^2

The series impedance was obtained from the nameplate to be j9.7 ohms.

The B/H values are,

Magnetic Field Density B [T]	Ampere Turn Balance H [AT/m]	Polynomial
0.4	7	P1
1	13	P1
1.4	26.5	P1
1.5	41	P1
1.6	74.8	P1
1.7	170	P2
1.8	500	P2
1.9	1900	P2
2	10000	P3
2.05	30000	P3
2.1	60000	P3
2.2	130000	P3

Table A1. The B/H values with the corresponding polynomial equation number

The polynomials are,

$P1 = 0.2622x^{13} - 0.4186x^{11} + 0.7539x^5 + 6.4407x^2 + 5.9618$ valid for 0<B<1.7 [T] ……..(a)

$P2 = 27.796x^{11} - 133.73x^9 + 269.4247x^6$ valid for 1.7<B<2 [T] ……..(b)

$P3 = -7300x^{11} + 27370x^{10} - 65070x^8 + 111\,840x^5$ valid for B>2 [T] …….(c)

The B/H curve calculated by the polynomial equations is plotted with the given B/H values below.

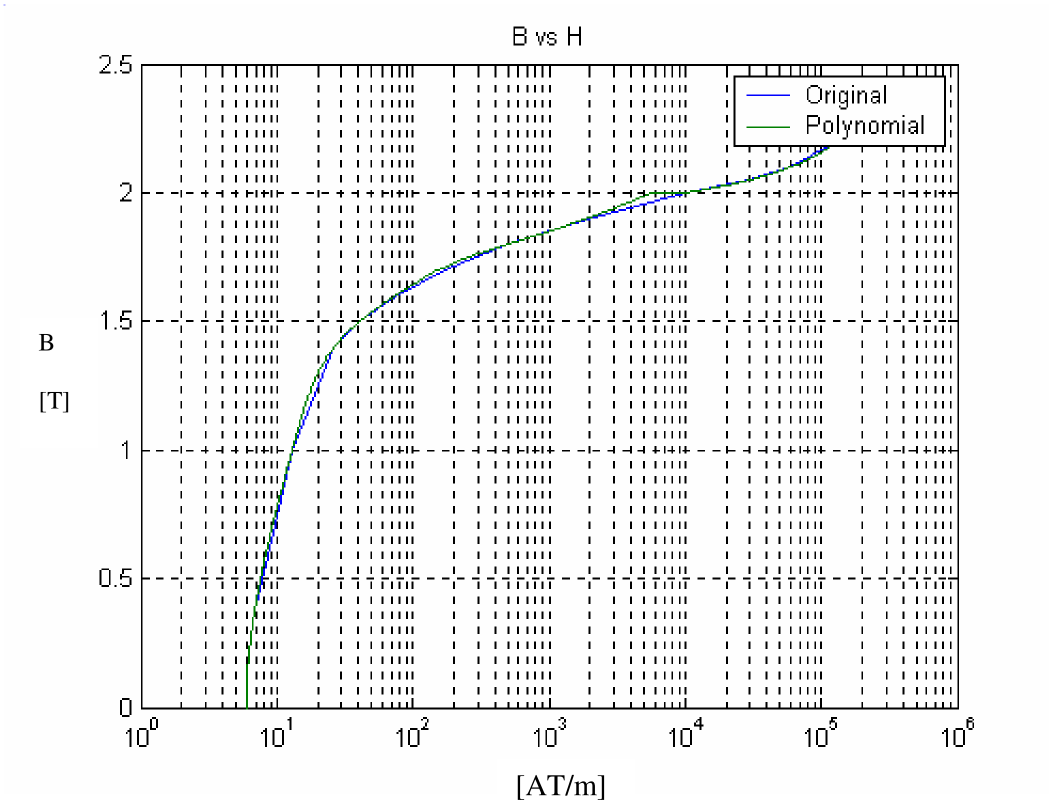


Figure A2. The calculated and given B/H curves

The polynomial curve follows the B/H curve almost identically with a slight deviation at certain points. From the curves above, the transformer enters saturation from 1.8 T onwards. Polynomial P2 calculates H values that are between normal and saturation operating regions. Polynomial P3 calculates the H values when the transformer enters extreme saturation.

Table A2. The transformer saturation voltage, current and time period values

U phase [kV] (V3)	Im rms [A] (il)	Time [s]
50.8	0.31	Infinity
53.3	0.41	Infinity
55.88	0.72	Infinity
58.4	1.93	64800 (18 hrs)
60.9	4.2	1860 (31 min)
66	13.5	61
71.1	25	25
81.2	56	15
91.45	91	10
101.6	129	7

Table A2 compares the phase voltage, the magnetizing current (il) and time period for the transformer to operate before failure at the respective phase voltage and magnetizing current values.

From the Table A2, the magnetising current (il), and time values to obtain ferroresonance were assumed to be between 0.41 A to 0.72 A with the respective voltage and time values. The reason this range was chosen because the transformer was not affected for the open circuit case.

2.3 The Neutral Surge Arrestor (SAn)

The neutral surge arrestor has the same MOV characteristics as the SAph arrestor but was not compromised by the ferroresonance condition. The neutral surge arrestor, SAn, volt drop was obtained from the peak voltage (8/20us waveform) versus current graph in Figure A3. The neutral surge arrestor current values (iN1) obtained from the model varied between 0.5A to 2 A and this results in a 65% to 68 % of the peak voltage (8/20us) value on Figure A3. This results in a peak voltage of approximately 73 kV and the rms voltage expected on the neutral surge arrestor was calculated to be 52kV. The resistance was approximated to be 90 k ohms.

The transformer neutral surge arrestor, SAn, characteristics are,

Upk = 110.5 kV (8/20us wave)
Ur = 36 kV (rms)

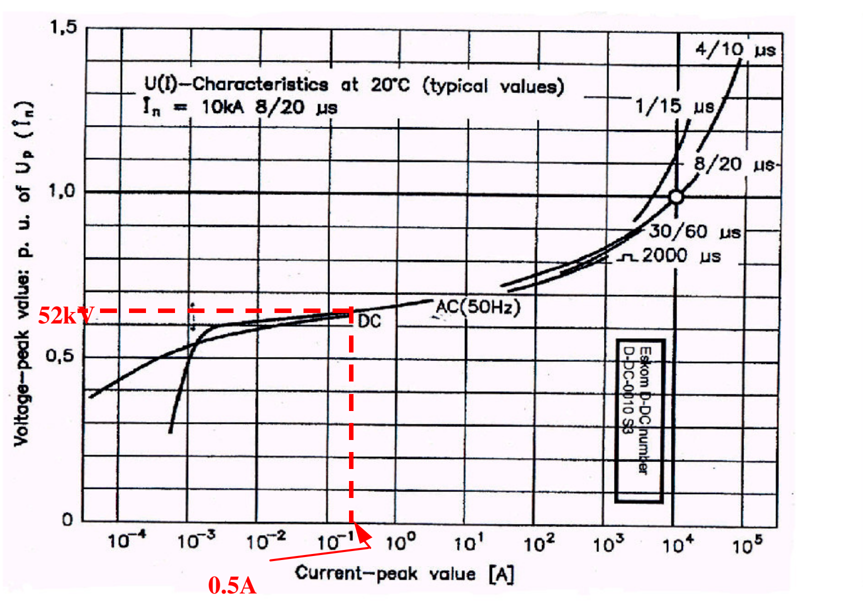


Figure A3. The Peak Voltage versus Current Graph of the Neutral Surge Arrestor

3. Calculations

3.1 Calculation of capacitance

The calculation of the capacitance of the transmission line is split into two components, the capacitance between the phases of the transmission line and the capacitance of the transmission line to ground.

3.1.1 Capacitance between Phases

The capacitance between the phases of the transmission line were calculated using the dimensions from Figure A1.

The equation below was used to calculate the capacitance between phases,

$$Cm = \frac{\pi.\varepsilon.}{\ln \frac{Dm}{Deq}} \qquad (1a)$$

$$\mathbf{Xcm} = \frac{1}{\mathbf{jwCm}} \; [\Omega] \qquad (1b)$$

where $\varepsilon o = 8.85 \times 10^{-12}$ $\left[F/m\right]$(permitivity of vacuum) & $w = 2\pi f$ $\left[rads/s\right]$

Dm is the geometric mean distance between the phases [m] and Deq is the geometric mean radius of the conductor [m].

$$Dm = \sqrt[3]{s \times s \times s} \;\; [m] \qquad (2)$$

Deq = radius of conductor ------(3)

3.1.2 Capacitance between the transmission line and ground

The equation used for the calculation of the capacitance from line to ground is shown in Figure A4.

$$Cg = \frac{2\pi\varepsilon o}{\ln Dm1/Deq} \quad [F] \qquad (4a)$$

$$Xcg = \frac{1}{jwCg} \quad [\Omega] \qquad (4b)$$

Where $2\pi\varepsilon o$ was used because the capacitance calculated was to the neutral (ground) [4].

$$Dm1 = \sqrt{(s\times 2s\times 2h\times x\times y)(s\times s\times x\times 2h\times x)(s\times 2s\times 2h\times x\times y)}$$

$$\overline{(s\times 2s\times 2h\times x\times y)(s\times s\times x\times 2h\times x)(s\times 2s\times 2h\times x\times y)} \quad [m] \quad (5a)$$

$$x = \sqrt{(4h)^2 + s^2} \qquad (5b)$$

$$y = 2\sqrt{h^2 + s^2} \qquad (5c)$$

Deq is the same as in equation (3). Figure A4 displays the dimensions of the transmission line phases to ground to calculate Dm1 (5a).

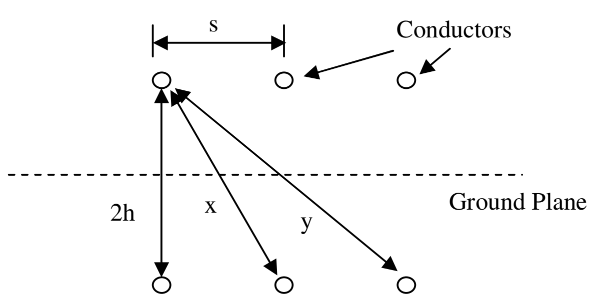


Figure A4. Dimensions of conductor lengths with an imaginary ground plane

The capacitances Cm and Cg are the same for all three phases of the transmission line. Since the open circuit can occur anywhere along the transmission line, the capacitances for the open circuited phase were varied for different lengths of the line in the program model.

3.2 Transformer characteristics

The calculation of the transformer magnetizing inductance (Lm) used the transformer core dimensions and the B/H values calculated using the three polynomials in section 2.2.

The following equations were used to calculate the magnetizing inductance.

$$u = \frac{B}{H} \qquad (6)$$

$$R = \frac{l}{uA} \qquad (7)$$

$$Lm = \frac{N^2}{R} \qquad (8)$$

Where u is the relative permeability [H/m], B is the magnetic field density [T], H is the Ampere Turn Balance [AT/m], l is the length of the transformer core [m], A is the area of the transformer core [m] (section 2.2), N is the number of HV turns of the transformer, R is the reluctance [H^{-1}] and Lm is the transformer magnetizing inductance [H].

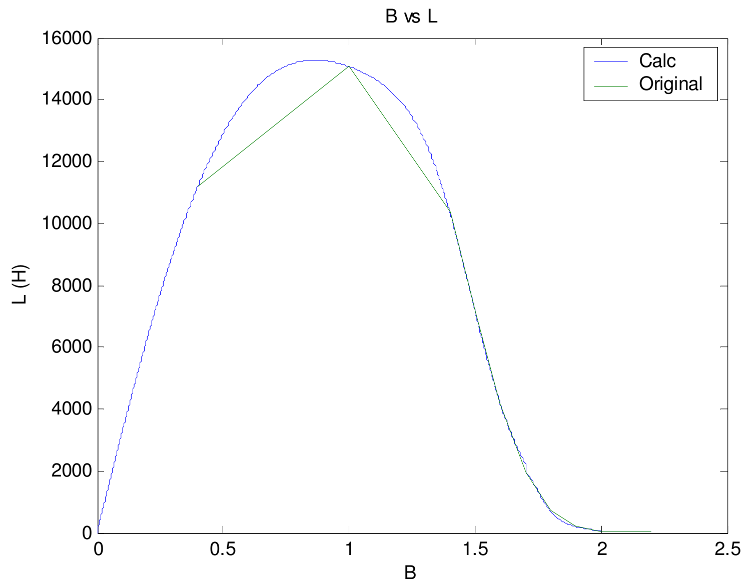
Substituting (6) and (7) into (8) resulted in the equation below,

$$Lm = \frac{N^2.A.B}{H.l} \qquad (9a)$$

$$Xl = jwL \quad [\Omega] \ldots\ldots\ldots..(9b)$$

where $w = 2\pi f$ and $f = 50$ [Hz]

The resulting magnetizing inductance curve related to the magnetic field intensity, B, is shown below, Figure A5.



<u>Figure A5. The Inductance (Lm) curves of the calculated (polynomials) and given values</u>

From the figure, the transformer inductance value, Lm, follows the B/H curve (Figure A2). Therefore, as the transformer moves further into the saturation region, the transformer inductance, Lm, decreases.

The magnetizing resistance was calculated assuming the iron loss, P_{Fe} loss, to be 0.4% of the transformer rated output.

$$P_{fe} = 0.4\% \times 10\mathbf{MVA} = 40\ [\text{kW}] \qquad (10)$$

$$P_{fe} = 3 \times \text{Vp.Ip} = \frac{3.\text{Vp}^2}{\text{Rm}}\ [\text{kW}] \qquad (11)$$

$$\mathbf{Rm} = \frac{3.\mathbf{Vp}^2}{P_{fe}} = 200\ [\text{k}\Omega] \qquad (12)$$

Where Vp is the phase voltage 50.8 [kV], Ip is the phase current [A] and Rm is the magnetizing resistance [Ω].

The magnetizing resistance, Rm, remains relatively constant even if the transformer enters saturation.

4. Simulation Model

4.1 Nodal Analysis

The following equations were developed from Figure 2 (Paper).

X = Grn+GL1+GL2+Glm+Grm (13)

Y = -Gcm2-Gcm3-Gcg3-Glm-Grm (14)

$$\mathbf{Vn} = \frac{1}{\mathbf{x} + \frac{(\mathbf{Glm} + \mathbf{Grm})^2}{\mathbf{y}}}\left[\mathbf{V}1\left(\mathbf{GL}1 - \frac{\mathbf{Glm} + \mathbf{Grm}}{\mathbf{y}}\mathbf{Gcm}3\right) + \mathbf{V}2\left(\mathbf{GL}2 - \frac{\mathbf{Glm} + \mathbf{Grm}}{\mathbf{y}}\mathbf{Gcm}2\right)\right] \quad (15)$$

$$\mathbf{Vx} = \frac{1}{\mathbf{y}}\left[\mathbf{V}1(-\mathbf{Gcm}3) + \mathbf{V}2(-\mathbf{Gcm}2) + \mathbf{Vn}(-\mathbf{Glm} - \mathbf{Grm})\right] \quad (16)$$

Il = V1(Gcm3) + V2(Gcm2) + V3(-Gcm3-Gcg3-Grm-Gcm2)+VnGrm (17)

In1 = V1(GL1) + V2(GL2) + V3 (Glm+Grm) + Vn (-GL2-GL1-Glm-Grm) (18)

Ia = V1(Gcm1+Gcm3+GL1+Gcg1) + V2(-Gcm1) + V3(-Gcm3) + Vn(-GL1) (19)

Iaa = V1(-Gcm1) + V2(Gcg2+GL2+Gcm2+Gcm1) + V3(-Gcm2) + Vn(-GL2) (20)

V1 = 88kV/sqrt(3) $\{0^o\}$ (21)

V2 = V1<120^o = 88kV/sqrt(3) $\{120^o\}$ (22)

4.2 Development of matrix equations

The equations above in section 4.1 formed the matrix below,

$$\begin{bmatrix} il \\ iN1 \\ ia \\ iaa \end{bmatrix} = \begin{bmatrix} Gcm3 & Gcm2 & (-Gcm3 - Gcg3 - Grm - Gcm2) & Grm \\ GL1 & GL2 & (Glm + Grm) & (-GL2 - GL1 - Glm - Grm) \\ (Gcm1 + Gcm3 + GL1 + Gcg1) & -Gcm1 & -Gcm3 & -GL1 \\ -Gcm1 & (Gcg2 + GL2 + Gcm2 + Gcm1) & -Gcm2 & -GL2 \end{bmatrix} \begin{bmatrix} \mathbf{V}1 \\ \mathbf{V}2 \\ \mathbf{Vx} \\ \mathbf{Vn} \end{bmatrix}$$

Where G is the circuit conductances [S]

The voltage across the transformer core is given by,

$$V3 = Vx - Vn \qquad (23)$$

The voltage across the transmission line surge arrestor, SAph, is the vectorial addition of the transformer inductance volt drop, V3, and the neutral surge arrestor volt drop, Vn.

$$|Vsaph| = \mathbf{V}3 + \mathbf{Vn} \qquad (24)$$

5. Matlab Algorithms

5.1 Nominal Algorithms

There were 3 programs developed to create the simulation model. The programs are listed below.

1. The ‘Caps’ program calculated the phase and ground capacitances.
2. The ‘Magcurve’ program developed the polynomial equations to model the transformer B/H values and calculated the transformer magnetizing inductance (Lm) values.
3. The ‘Main’ program used the capacitance values calculated from the ‘Caps’ program and the inductance values calculated from the ‘Magcurve’ program to develop the matrix from section 4.4. The program calculated the transformer magnetizing voltage (v3), magnetizing current (il), the neutral surge arrestor voltage (Vn) and current (iN1) and the transmission line surge arrestor voltage (Vsaph).

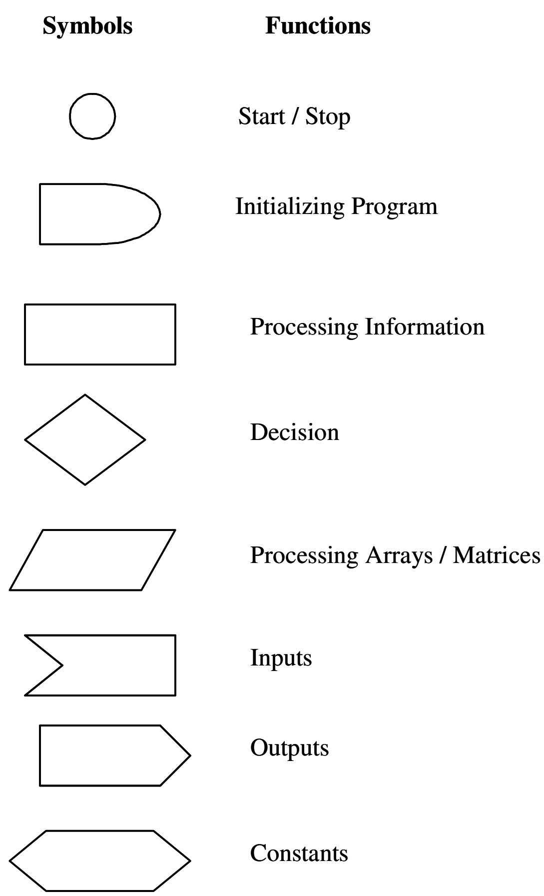


Figure A6. The algorithm shapes

The ‘Main’ program varied the open circuited phase length of the transmission line and the ‘Magcurve’ program varied the magnetizing inductance, Lm, according to the polynomial equations.

The algorithms displayed the structure and the variables of the programs. Different shapes were used to simplify the algorithm and are shown in Figure A6.

The variables, equations, constants and tables displayed in the algorithms are referenced to the report using the respective numbers enclosed in brackets, eg “(3)” represents equation (3). The variables without the brackets are only related to the program.

5.1.1 Caps

The algorithm in Figure. A7a represents the ‘Caps’ Matlab program that calculates the phase and ground capacitances.

The inputs to the program are s,h and r where s is the distance between phases, h is the height between phase and ground, r is the radius of the conductor.

$$\varepsilon o = 8.85\times10^{-12} \quad [\text{F/m}] \text{ and } f = 50 [\text{Hz}] \text{ power frequency}$$

The terms Cm, Dm, Deq, Cg, Dm1, x, y represent equations (1), (2), (3), (4), (5a), (5b) and (5c) in the section 3.1.

The outputs are the values of Cg and Cm sent to the Main program.

5.1.2 Magcurve

The ‘Magcurve’ program does not have any inputs. The constants are obtained from section 2.2,

l = 1.01m length of core
a = 0.1103 m^2 cross sectional area of core
N = 1340 number of turns on transformer HV coil
B = magnetic flux density from Table A1
H = Ampere turn balance from Table A1

There were three polynomial equations to depict the B/H curve because of the large range of H values. The polynomial equations were created to calculate the H values with any corresponding B value. The function ‘Polyfit’ from the Matlab program was used to obtain the polynomial equations. The first polynomial was calculated using the B/H values below,

B11= [0.4 1   1.4   1.5 1.6]
H11= [7   13 26.5 41 74.8]

$$P1 = 0.2622x^{13} - 0.4186x^{11} + 0.7539x^5 + 6.4407x^2 + 5.9618 \quad \text{........(a)}$$

(valid for B<1.7T)

The second polynomial used,

B12 = [1.7   1.8   1.9]
H12 = [170 500 1900]

$$P2 = 27.796x^{11} - 133.73x^9 + 269.4247x^6 \quad \text{........(b)}$$

(valid for 1.7T =<B<2T)

The third polynomial used,

B13 = [2   2.05   2.1   2.2]
H13 = [10000 30000   60000   130000]

$$P3 = -7300x^{11} + 27370x^{10} - 65070x^8 + 111\,840x^5 \quad \text{.......(c)}$$

(valid for B>=2T)

Once the polynomials are created, the program enters a ‘For’ loop. This loop is used to vary B values with a range from 0.1 [T] to 2.2 [T] with steps of 0.01 [T].

The program then enters an ‘If Then Else’ statement used to select the required polynomial to calculate H values according to the B values used (the function ‘Polyval’ was used). If the B value is less than 1.7 T, polynomial (a) is used, similarly if B is greater or equal to 1.7 T and less than 2 T, polynomial (b) is chosen and if B is greater than or equal to 2 T then polynomial (c) is chosen.

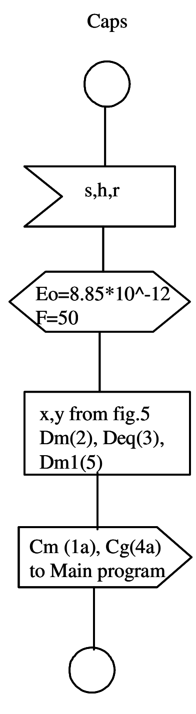
The H values are then used to calculate u, R and Lm values using equations (6), (7) and (8) (from section 3.2) until the cycles of the ‘For’ loop are completed.

The B and Lm values are stored in arrays B2 and L1 respectively and sent to the Main program.

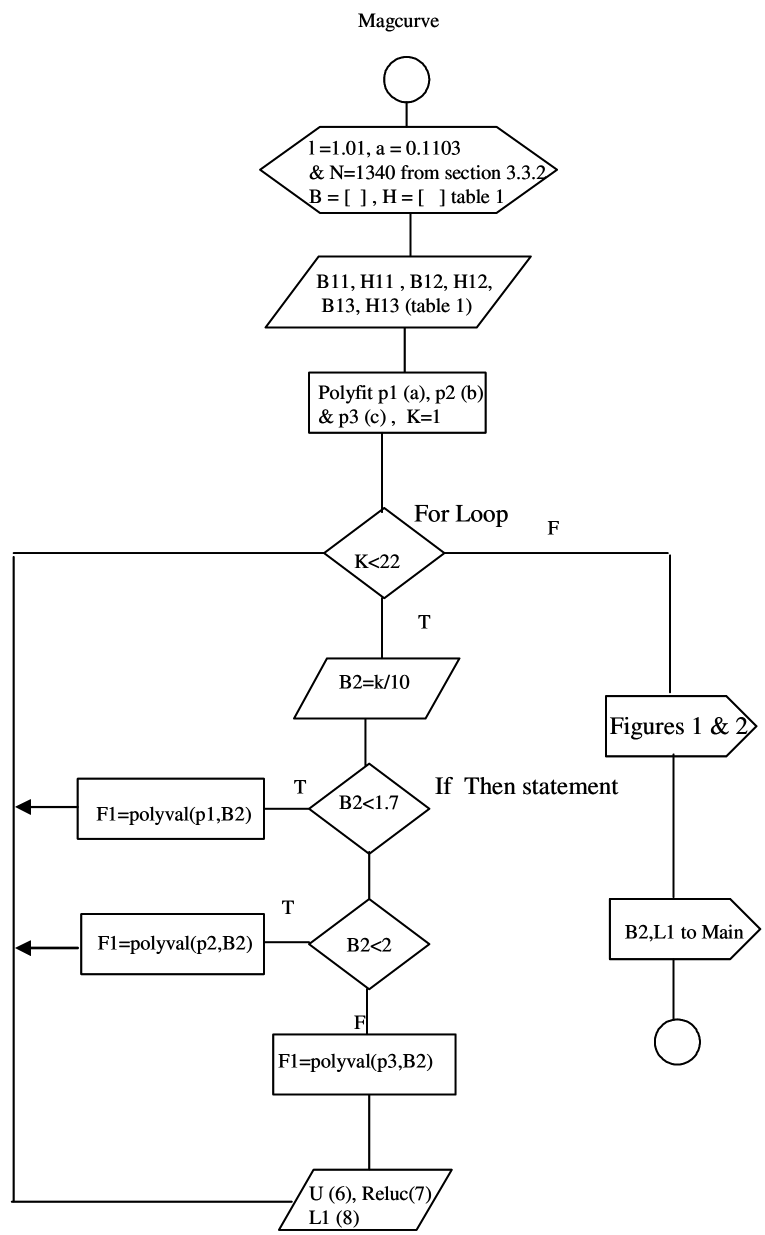
The following part of the program displays the graphs,

Graph 1 – The B and H values from Table A1 are plotted against each other and compared to the B and H values calculated using the polynomial equations.
Graph 2 – The magnetic field density value, B, is plotted against the inductance values, L, calculated using B values from Table A1 and the inductance values, Lm, calculated using the polynomial equations.

Figure (7a) The Capacitance (Cap) Program, Figure. (7b) is the Magcurve Program & Figure (7c) is the Main Program

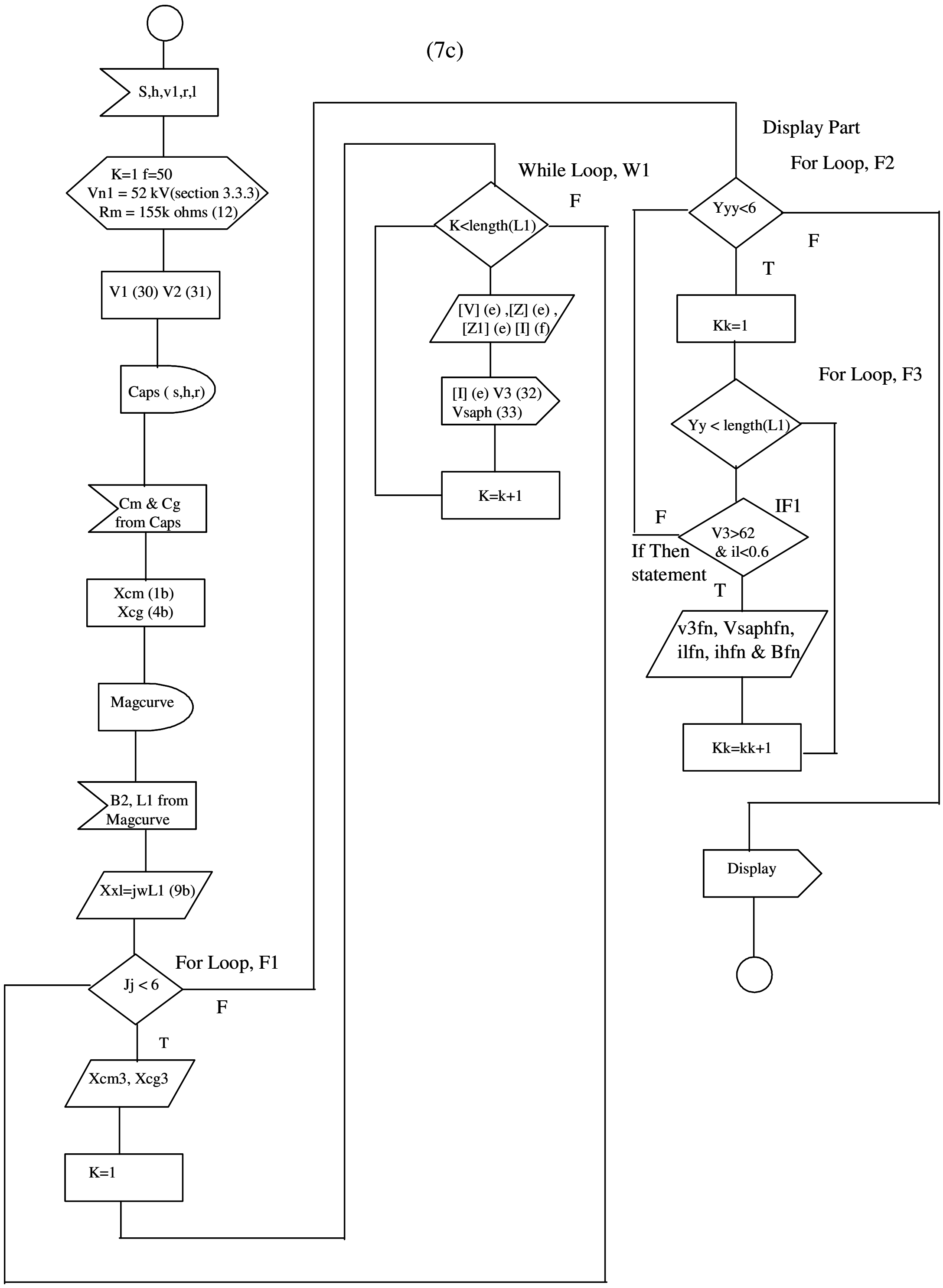


(7a)



(7b)

(7c)


S,h,v1,r,l
K=1 f=50
Vn1 = 52 kV(section 3.3.3)
Rm = 155k ohms (12)
V1 (30) V2 (31)
Caps (s,h,r)
Cm & Cg
from Caps
Xcm (1b)
Xcg (4b)
Magcurve
B2, L1 from
Magcurve
Xxl=jwL1 (9b)
For Loop, F1
Jj < 6
F
T
Xcm3, Xcg3
K=1
While Loop, W1
K<length(L1)
F
[V] (e) ,[Z] (e) ,
[Z1] (e) [I] (f)
[I] (e) V3 (32)
Vsaph (33)
K=k+1
Display Part
For Loop, F2
Yyy<6
F
T
Kk=1
For Loop, F3
Yy < length(L1)
IF1
F
V3>62
& il<0.6
If Then
statement
T
v3fn, Vsaphfn,
ilfn, ihfn & Bfn
Kk=kk+1
Display

5.1.3 Main

The inputs of this program by the user are s, h, V1, r and l where s is the phase spacing (Figure A1), h is the pole height (Figure A1), r is the conductor radius (section 2.1) and l is the length of the line (section 2.1). The value V1 is the phase voltage to ground, 50.8 kV (equation 21). The voltage on the second phase is governed by equation (22). The constants are the power frequency, f = 50 Hz, the neutral surge arrestor resistance (Rn = 90 k ohms from section 2.3) and the magnetising resistance, Rm = 200 k ohms (12).

The program ‘Caps’ is initialized with the respective inputs. The outputs of program ‘Caps’ is Cm and Cg which are accepted as inputs to the Main program. The reactance values Xcm, Xcg and Xxl use equations 1b, 4b and 9b respectively. The program ‘Magcurve’ is initialized and the array outputs B2 and L1 are accepted by Main program.

There is a for loop (F1) structure with 12 loops where each loop increments the length of the open circuited phase by half (0.5) a kilometer. The variables, Xcm3 and Xcg3, represent the reactance of the open circuited phase lengths varied by the for loop structure.

The while loop (W1) structure runs for the number of inductance, L1, values and is nested in the for loop (F1) structure. The arrays ‘v’ and ‘z’ represents [V] and [Z] from the matrix equation (section 3.2). The voltage across the transformer core is designated as ‘V3’ and is calculated using equation (23). The voltage across the transmission line surge arrestor, Vsaph, is calculated using equation (24) and stored in an array. When the while loop (W1) function ends, the for loop (F1) is incremented. When the for loop has completed the required cycles, the display part of the program is initialized.

The display part of the program has two for loops where for loop (F3) is nested in the for loop (F2). The arrays Vn, In1, V3, il, Vsaph, B and Lm are filtered using the ‘If’ (IF1) statement to obtain the required range. The ‘if’ (IF1) statement chooses the transmission line surge arrestor voltage, Vsaph greater than 62 kV, il is less than 0.6A and V3 is greater than 40 kV. This is needed reduce the amount of data produced by the program. The values are then stored in a 2-D array and displayed in the main window.

6. References

[1] Marti J R, Soudack A C. *Ferroresonance in power systems : Fundamental solutions.* IEE Proceedings-C Vol 138, No.4. July 1991.

[2] Teape J W, Slater R D, Simpson R R S, Wood W S. *Hysteresis effects in transformers, including ferroresonance.* IEE Proceedings, Vol 123, No. 2, February 1976.

[3] Theron R. *Selection of Station Class Arrestors.* Distribution Technology Standard, Eskom Distribution. October 2001.

[4] Grainger J J, Stevenson W D (JR). *Power System Analysis.* McGraw-Hill Book Co, Chapter 5, 1994.

APPENDIX B

CAPS PROGRAM

```
function [cm2,cg12]=cap5a(s,h,r)
e=8.85*(10^(-12)); % Permitivity of vacuum [F/m]
f=50; % Power frequency [Hz]
x=sqrt((4*h)^2+s^2); % From eqn (5b) Appendix A section 3.1
y=2*sqrt(h^2+s^2); % From eqn (5c)
Dm=(s*s*2*s)^(1/3); % eqn (2)
Ds=r; % Eqn (3)
cm2=pi*e/(log(Dm/Ds))*1000 % Eqn (1a) [F/km]
Dm1=(s*2*s*2*h*x*y* s*s*x*2*h*x* s*2*s*2*h*x*y* s*2*s*2*h*x*y* s*s*x*2*h*x*
s*2*s*2*h*x*y)^(1/30); % Eqn (5a)
cg12=2*pi*e/(log(Dm1/Ds))*1000 %Eqn (4a) [F/km]

end
```

MAGCURVE PROGRAM

```
function [B2,L1] = magcurve5a

l=1.01; % length of the transformer core [m]
a=0.1103; % area of the transformer core
N=1340; % HV Turns of Transformer
% B & H values of transformer Appendix A Section 2.2
B = [0.4 1 1.4 1.5 1.6 1.7 1.8 1.9 2 2.05 2.1 2.2];
H = [7 13 26.5 41 74.8 170 500 1900 10000 30000 60000 130000];
f=50; % Power Frequency [Hz]
U = 88; % Line voltage [kV]
Uo=[ U 1.05*U 1.1*U 1.15*U 1.2*U 1.3*U 1.4*U 1.6*U 1.8*U 2*U]; % Table A2

% Magnetising Inductance values calculated from given transformer values

for j=1:1:12

   R=(l/a)/(B(j)/H(j));
   L(j)=N*N/R;
end

B1 = [0.4; 1; 1.4; 1.5; 1.6; 1.7; 1.8; 1.9; 2; 2.05; 2.1; 2.2];
H1 = [7; 13; 26.5; 41; 74.8; 170; 500; 1900; 10000; 30000; 60000; 130000];

% Calculating the Polynomial Equations
% Polynomial 1

 B11 = [0.4; 1; 1.4; 1.5; 1.6];
H11 = [7; 13; 26.5; 41; 74.8];
```

```
 p1=polyfit(B11,H11,13);

% Polynomial 2

 B12 =[1.7; 1.8; 1.9];
H12 = [170; 500; 1900];

 p2=polyfit(B12,H12,11);

%Polynomial 3

 B13 = [2; 2.05; 2.1; 2.2];
H13 = [10000; 30000; 60000; 130000];

 p3=polyfit(B13,H13,11);

 lim=round(22);
% Using the Polynomial Equations from above to calculate the H values

 k1=1;
s1=round(0);
 for k=s1:0.1:22%lim %k rep B
     B2(k1)=k/10;
      if B2(k1)<(1.7)

        f1 = polyval(p1,B2(k1));

    elseif B2(k1)<(2)
        f1 = polyval(p2,B2(k1));

    else
        f1=polyval(p3,B2(k1));

    end
        y(k1)=f1;
    R1=(l/a)/(B2(k1)/f1);
    L1(k1)=N*N/R1;
    k1=k1+1;
end

% Figure displays the original and calculated (polynomials) BH curves

figure(1)
semilogx(H,B,'-',y,B2,'-');
 grid on;
 h=legend('Original','Polynomial');
  xlabel('B');
 ylabel(' H');
 title('B vs H');

 % Calculates magnetising inductance using given BH values
```

```
 for j=1:1:12

    R=(l/a)/(B(j)/H(j));
    L(j)=N*N/R;
end

 % Displays Transformer Magnetising Inductances from the Given and
 % Calculated values

figure(2)
 plot(B2,L1,'-',B,L,'-')
 h=legend('Calc','Original');
  xlabel('B');
 ylabel(' L (H)');
 title('B vs L');

end
```

MAIN PROGRAM

```
function SensitivityB3other1(s,h,v1,r,l)

f=50;  %Power Frequency [Hz]
Rm=200000; % Transformer Magnetising Resistance [ohms]
Grm=1/Rm; % conductance Rm [S]
v2ang=120/180*pi; % angle of second phase supply 120 degrees
v2=v1*cos(v2ang)+i*v1*sin(v2ang); % second phase voltage supply
Rn=90000; % Non linear resistance of neutral surge arrestor [ohms]
Grn=1/Rn; % Conductance of Rn

[cm2,cg12]=cap5(s,h,r); % Initialising Caps program & returns Cm & Cg
    Xcm=(-i)/(2*pi*f*cm2*l); % Reactance of Cm
    Xcg1=(-i)/(2*pi*f*cg12*l); % Reactance of Cg
Gcm=1/Xcm; % Conductance of Cm [S]
Gcg=1/Xcg1; % Conductance of Cg [S]

[Bind,L]=magcurve5a; %Initialisation of Magcurve program & returns B & Lm
L2=530; % CLosed Circuit Transformer Limb Inductance L1=L2 [H]
XL1=i*2*pi*50*L2; % Reactance of L1/L2
GL1=1/XL1; % Conductance XL1

Xxl=i*2*pi*f*L; % Reactance of Lm
Xll=shiftdim(Xxl,1);

for jj=1:1:12
   k=1;
     %Reactance of open circuit phase Capacitances Cm & Cg in relation to the
   % location of the open circuit from the station

   Xcm3=(-i)/(2*pi*f*cm2*jj/2);
   Gcm3=1/Xcm3; % Conductance Cm3
   Xcg3=(-i)/(2*pi*f*cg12*jj/2);
   Gcg3=1/Xcg3; % Conductance Cg3
```

```
    while k <= length(Xxl)

       Xl=Xxl(k);
       Glm=1/Xl;

       x=Grn+ GL1+GL1+Glm+Grm; % from eqn (13) in Appendix A
       y=-Gcg3-Gcm-Gcm3-Glm-Grm; % from eqn (14)

       vn=(1)/(x+((Glm+Grm)^2)/y)*( v1*(GL1-(Glm+Grm)/y*Gcm3)+ v2*(GL1-
(Glm+Grm)/y*Gcm)); % eqn (15)
       vx=(1)/y*(v1*(-Gcm3)+v2*(-Gcm)+vn*(-Glm-Grm)); % (16)

       % Matrix from Appendix A Section 4.2
       v=[v1;v2;vx;vn];
       z=[Gcm3 Gcm (-Gcm3-Gcg3-Grm-Gcm) Grm; GL1 GL1 (Glm+Grm) (-GL1-GL1-
Glm-Grm); (Gcm+Gcm3+GL1+Gcg) -Gcm -Gcm3 -GL1; -Gcm (Gcg+GL1+Gcm+Gcm) -
Gcm -GL1];
       cur=z*v; % [I]=[Z]x[V]


    il(k,jj)=(cur(1)); % open circuit magnetising current il
    iln(k,jj)=angle(il(k,jj))/pi*180; % angle of il
     iN1(k,jj)=(cur(2)); % Neutral Surge arresto current
     iN1n(k,jj)=angle(iN1(k,jj))/pi*180; % angle of In1

     ia(k,jj)=(cur(3));
     iaa(k,jj)=(cur(4));
     v3l(k,jj)=vx;
     v3n(k,jj)=angle(v3l(k,jj))/pi*180;

     v3x(k,jj)=vx-vn; % Volt drop of open circuit trfrm  core V3
     v3xn(k,jj)=angle(v3x(k,jj))/pi*180; % angle V3
      vnl(k,jj)=vn; % neutral surge arrestor volt drop Vn
      vnn(k,jj)=angle(vnl(k,jj))/pi*180; % angle of Vn
      vs(k,jj)=v3x(k,jj)+vn;  % Volt drop of transmission line surge arrestor (Vsaph)
      vsn(k,jj)=angle(vs(k,jj))/pi*180; % angle of Vsaph
      Bs(k,jj)=Bind(k); % Magnetic Field Density of trfrm [T]
      Ls(k,jj)=L(k); % Inductance Lm [H]

      % Currents relate to Fig.2
      ir(k,jj)=(vx-vn)*Grm;
      irn(k,jj)=angle(ir(k,jj))/pi*180;
      iL1(k,jj)=(v1-vn)*GL1;
      iL1n(k,jj)=angle(iL1(k,jj))/pi*180;
      iL2(k,jj)=(v2-vn)*GL1;
      iL2n(k,jj)=angle(iL2(k,jj))/pi*180;
      k=k+1;
  end
end

% The procedure below displays the open circuit phase length [km], the
% neutral surge arrestor voltage and angle Vn, the neutral surge arrestor
```

```
% current and angle iN1, the magnetising current & angle il, the transformer
% open circuit volt drop V3, the transmission line surge arrestor volt
% drop Vsaph, the magnetising inductance Lm and magnetic field density B
 jk=1;
    jj=length(Bind);
 jj=length(Bind);

 for yyy=1:1:12
    kk=1;
    jkn=1;
   lngt=yyy;
    for yy=1:1:jj
% the data is filtered for 62kV > Vsaph > 78 kV, il < 0.6A and V3> 40kV
       if abs(vs(yy,yyy))<78000

           if   abs(vs(yy,yyy))>62000 && abs(il(yy,yyy))<0.6 && abs(v3x(yy,yyy))>40000

               % Certain parameter values were divided by large number to
               % cater for the resolution of other small magnitude
               % parameters

               displayfn(jk,1)=lngt;
              displayfn(jk,2)=abs(vnl(yy,yyy))/1000000;
               displayfn(jk,3)=vnn(yy,yyy);

              displayfn(jk,4)=abs(iN1(yy,yyy));
              displayfn(jk,5)=iN1n(yy,yyy);
               displayfn(jk,6)=abs(il(yy,yyy));
              displayfn(jk,7)=iln(yy,yyy);
              displayfn(jk,8)=abs(v3x(yy,yyy))/1000000;
              displayfn(jk,9)=v3xn(yy,yyy);
              displayfn(jk,10)=abs(vs(yy,yyy))/1000000;
              displayfn(jk,11)=vsn(yy,yyy);
              displayfn(jk,12)=Bs(yy,yyy);
             displayfn(jk,13)=Ls(yy,yyy)/1000;

              jk=jk+1;
              jkn=jkn+1;
          end
      end
  end
end
displayfn % displays matrix of results
end
```