Spring 2009

# The assessment of winding forces due to inrush current in large transformers with heavily saturated cores

Richard Howard Palmer

other; thus the fields are non-uniform. Therefore the high voltage and tap winding coil objects were divided into symmetrical compartments to allow for an average resultant flux magnitude and direction to be determined based on the current flowing through each compartment object.

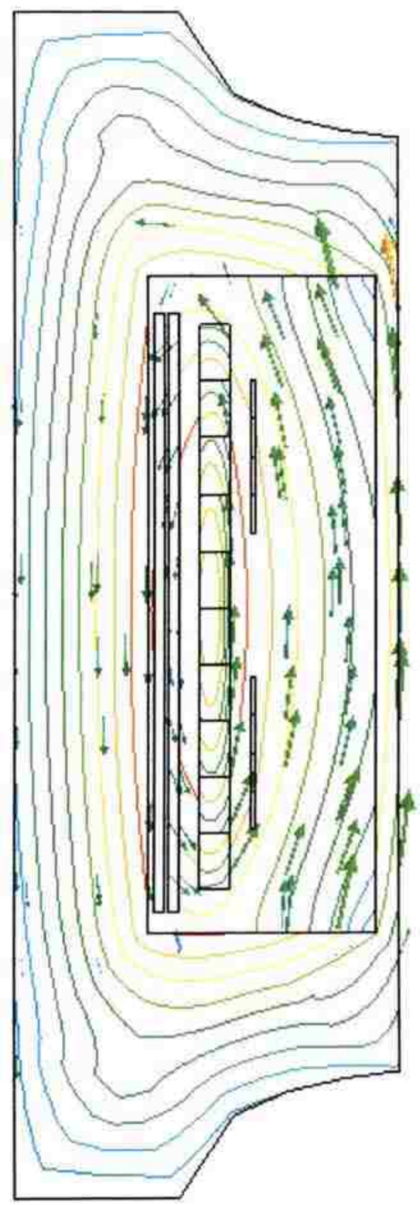


Figure 3.3. Example FEA model object flux line plot
(Transformer $Tx_A$ illustrated)

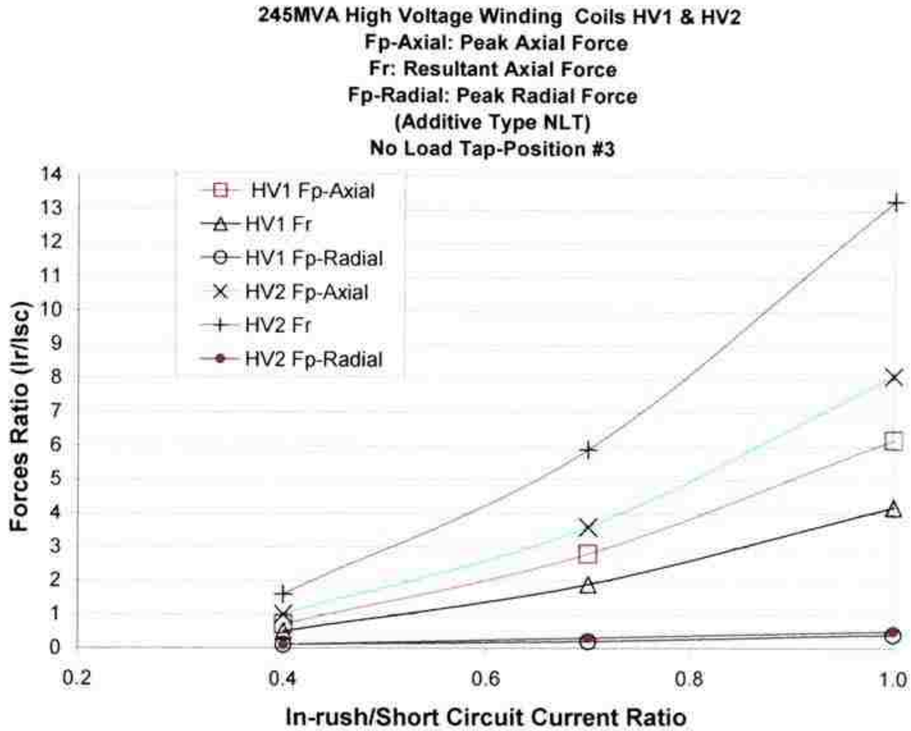



Figure 4.1. Transformer $Tx_{A(Additive)}$: High voltage winding forces

The lower tap winding (TC1) inrush ($I_{IR}$) current-produced peak axial ($F_{P\text{-}ax}$) and resultant axial ($F_R$) forces exceeded those due to short-circuit ($I_{SC}$) current when $I_{IR}$ currents were greater than 80% of the $I_{SC}$ current. At $I_{IR}$ equal to $I_{SC}$ the $F_R$ and $F_{P\text{-}ax}$ forces were 2 times the $I_{SC}$ $F_R$ and $F_{P\text{-}ax}$ forces. Results are illustrated in Figure 4.2 and presented in Appendix D.

The tap windings TC1 and TC2 inrush current-produced peak radial ($F_{P\text{-}rad}$) forces exceeded those due to short-circuit ($I_{SC}$) current. At $I_{IR}$ equal to $I_{SC}$ the TC1 $F_{P\text{-}rad}$ force was nearly 14 times the $I_{SC}$ $F_{P\text{-}rad}$ force and the TC2 $F_{P\text{-}rad}$ force was greater than 34 times the $I_{SC}$ $F_{P\text{-}rad}$ force. Results are illustrated in Figure 4.3 and presented in Appendix D.

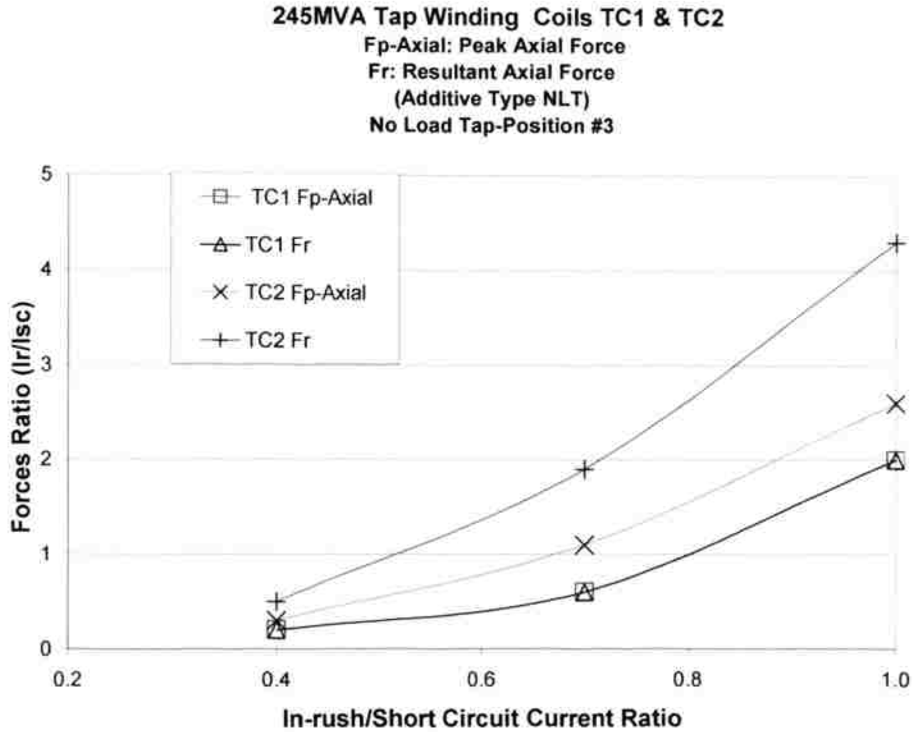



Figure 4.2. Transformer $Tx_{A(Additive)}$: Tap winding axial forces

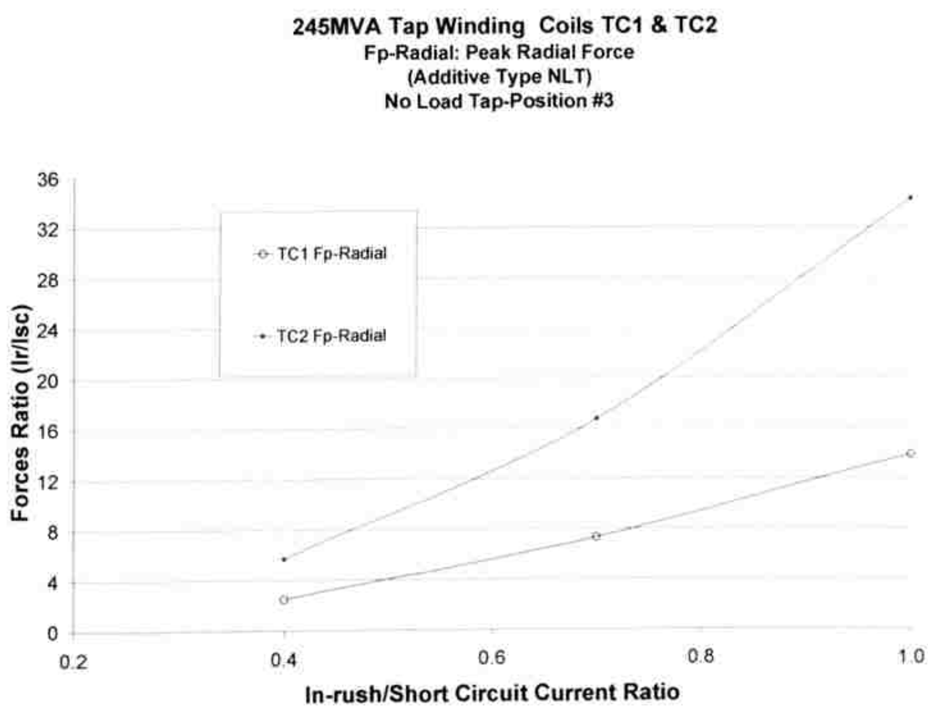



Figure 4.3. Transformer $Tx_{A(Additive)}$: Tap winding radial forces

forces were 1.1 times the $I_{SC}$ $F_R$ and $F_{P\text{-}ax}$ forces. Results are illustrated in Figure 4.5 and presented in Appendix D.

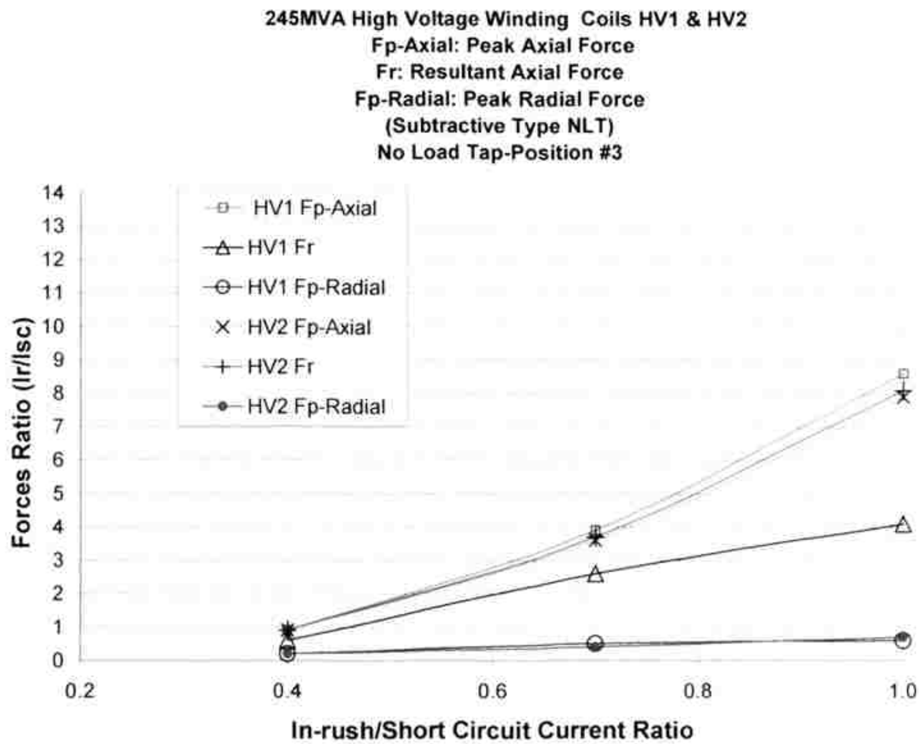



Figure 4.4. Transformer $Tx_{A(Subtractive)}$: High voltage winding forces

The tap windings TC1 and TC2 inrush current-produced peak radial ($F_{P\text{-}rad}$) forces exceeded those due to short-circuit current. At $I_{IR}$ equal to $I_{SC}$ the TC1 $F_{P\text{-}rad}$ force was nearly 12 times the $I_{SC}$ $F_{P\text{-}rad}$ force and the TC2 $F_{P\text{-}rad}$ force was greater than 8 times the short-circuit $F_{P\text{-}rad}$ force. Results are illustrated in Figure 4.6 and presented in Appendix D.

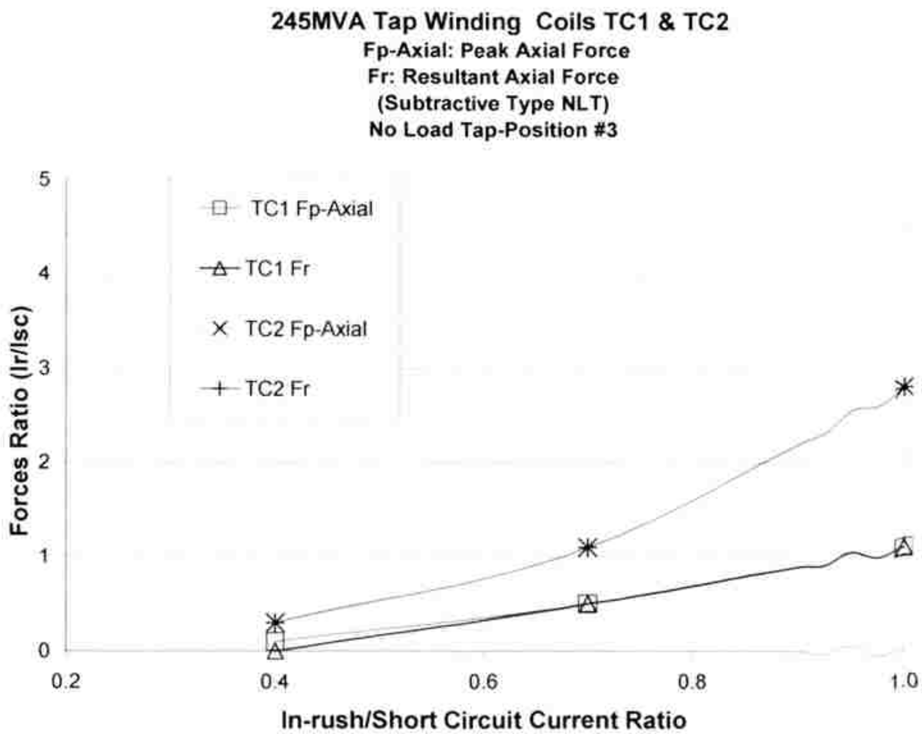



Figure 4.5. Transformer $Tx_{A(Subtractive)}$: Tap winding axial forces

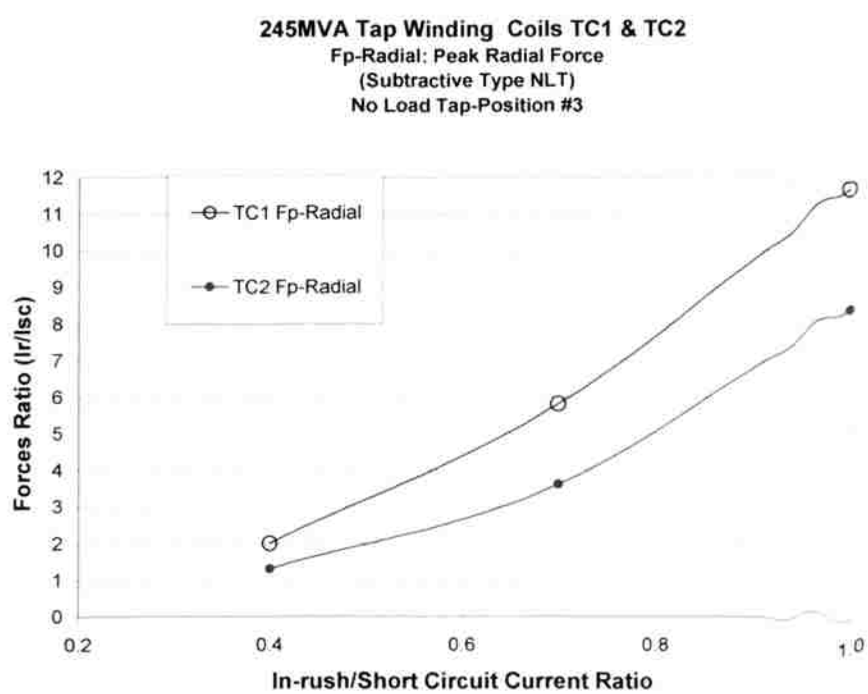



Figure 4.6. Transformer $Tx_{A(Subtractive)}$: Tap winding radial forces

The lower high voltage winding (HV1) inrush ($I_{IR}$) current-produced peak axial ($F_{P\text{-}ax}$) and resultant axial ($F_R$) forces exceeded those due to short-circuit ($I_{SC}$) current when $I_{IR}$ currents were near or 50% of the $I_{SC}$ current. At $I_{IR}$ equal to $I_{SC}$ the $F_{P\text{-}ax}$ and $F_R$ forces were near or greater than 4 times the $I_{SC}$ $F_{P\text{-}ax}$ and $F_R$ forces. The inrush current peak radial ($F_{P\text{-}rad}$) forces were at or less than 27% of the short-circuit $F_{P\text{-}rad}$ forces. Results are illustrated in Figure 4.8 and presented in Appendix D.

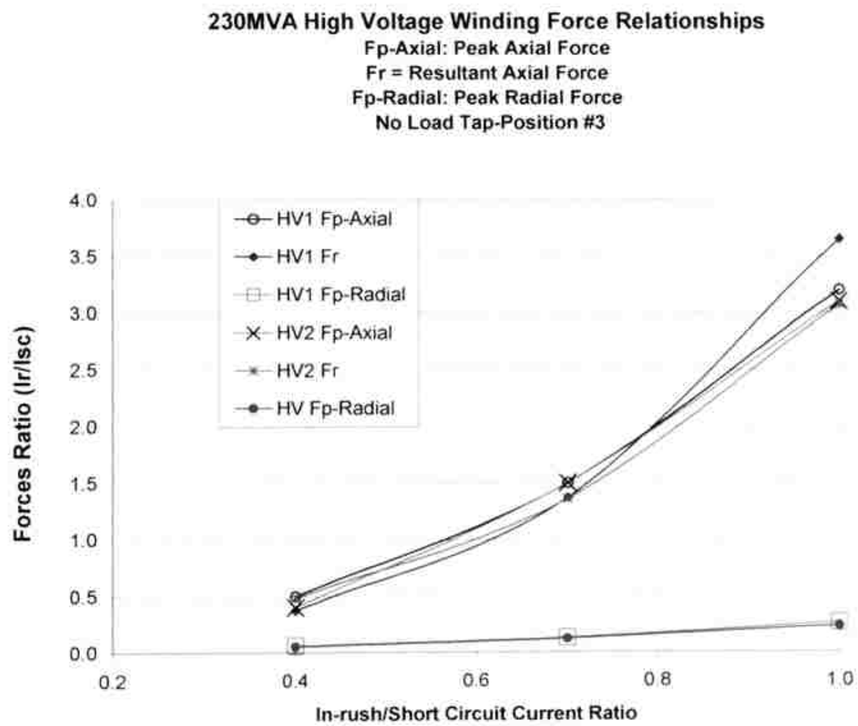



Figure 4.7. Transformer $Tx_{B(Additive)}$ (Center Entry): High voltage winding forces

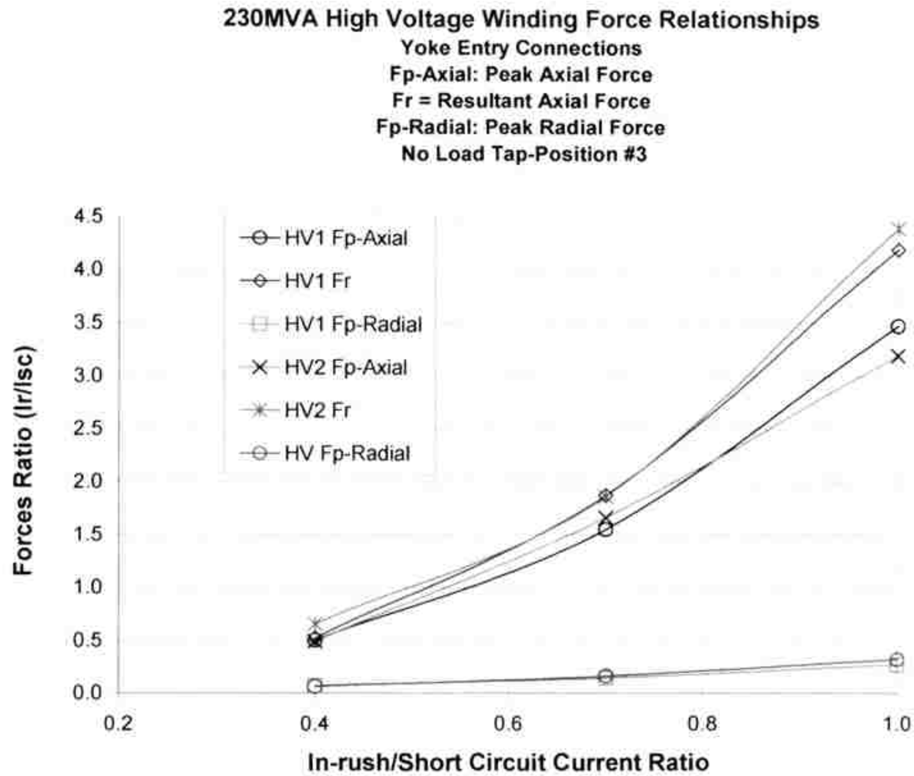



Figure 4.8. Transformer $Tx_{B(Additive)}$ (Yoke Entry): High voltage winding forces

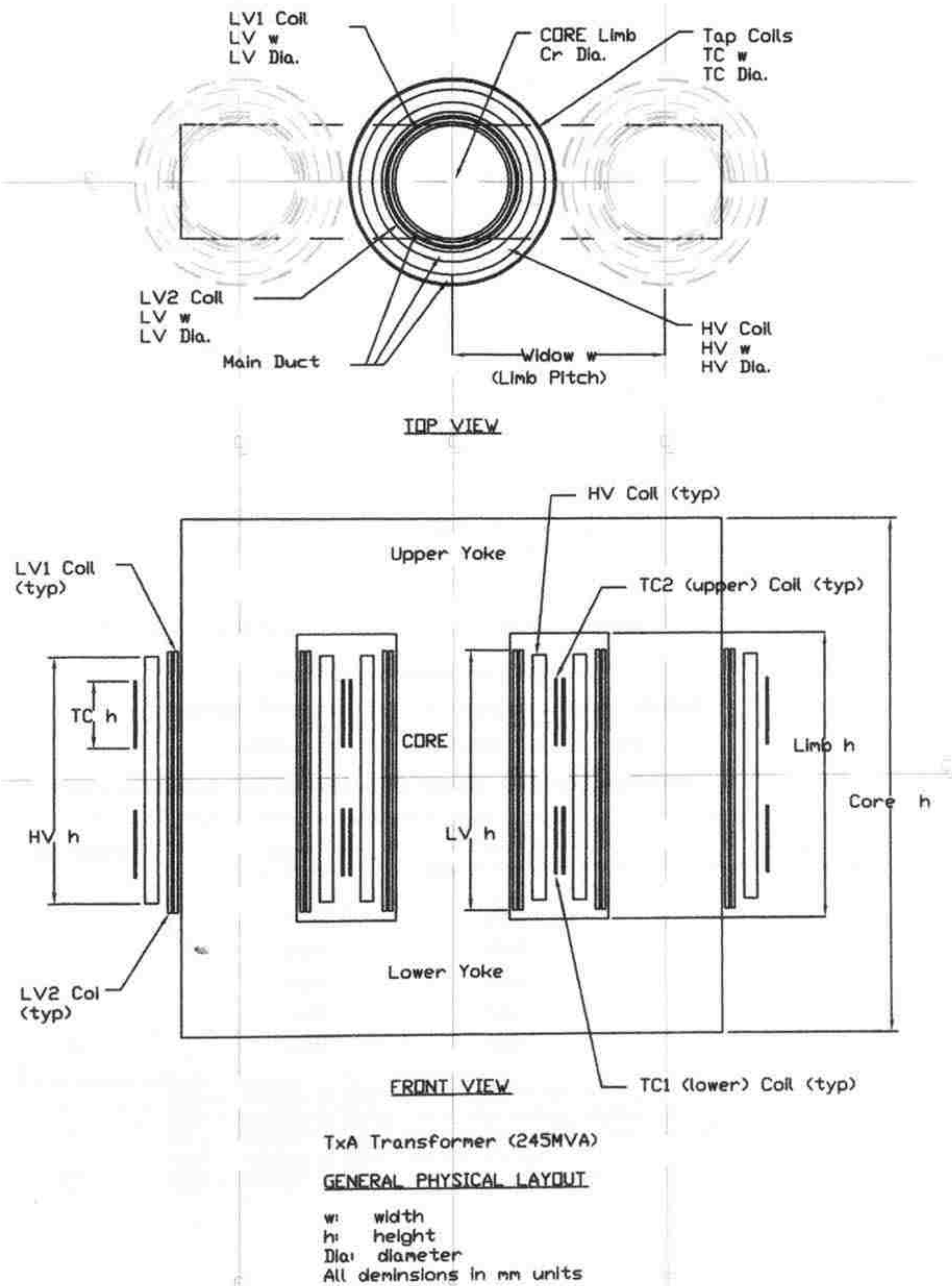



Figure A.1. 245MVA ($Tx_A$) transformer general physical layout.

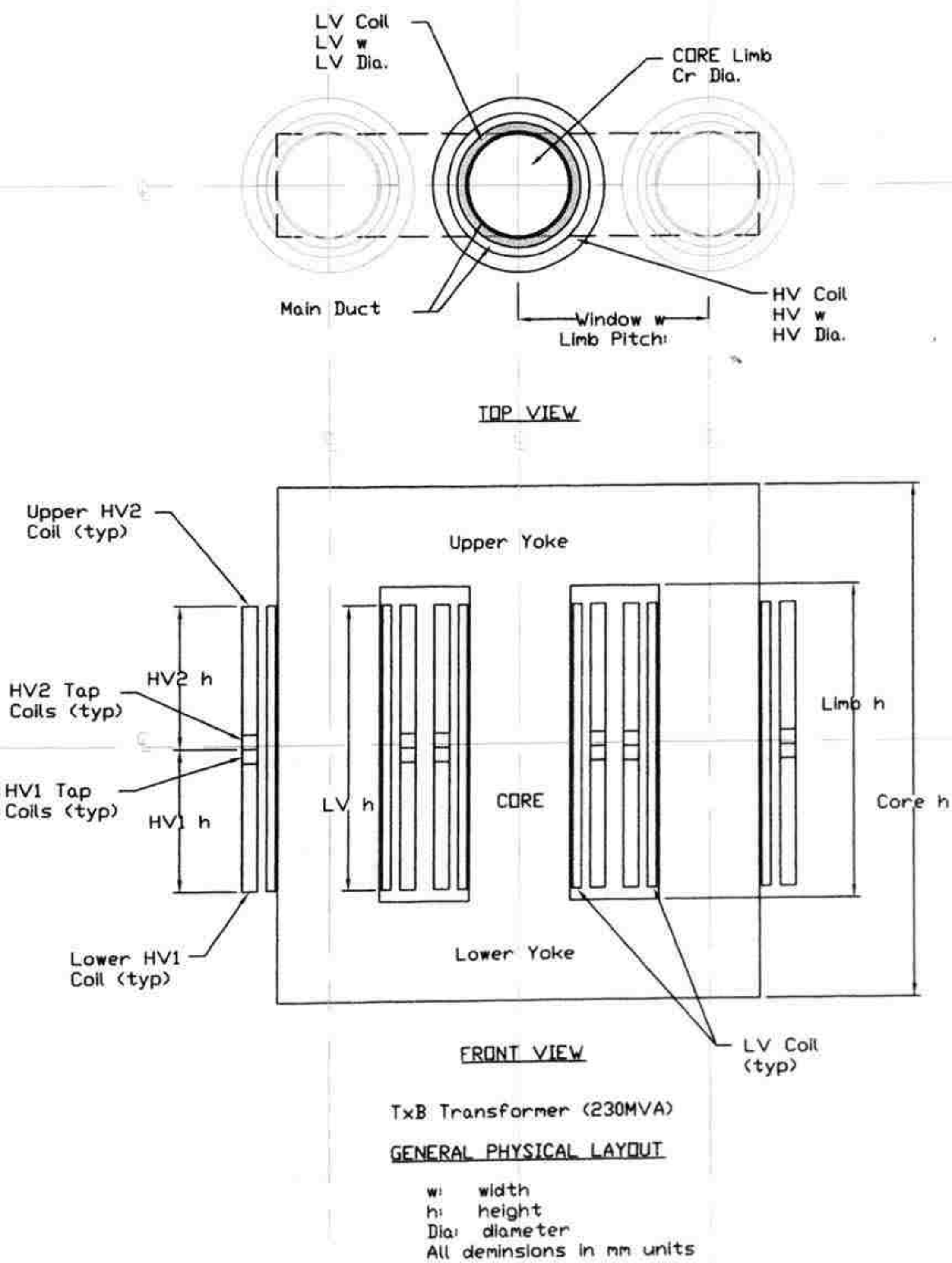



Figure B.1. 230MVA ($Tx_B$) transformer general physical layout.

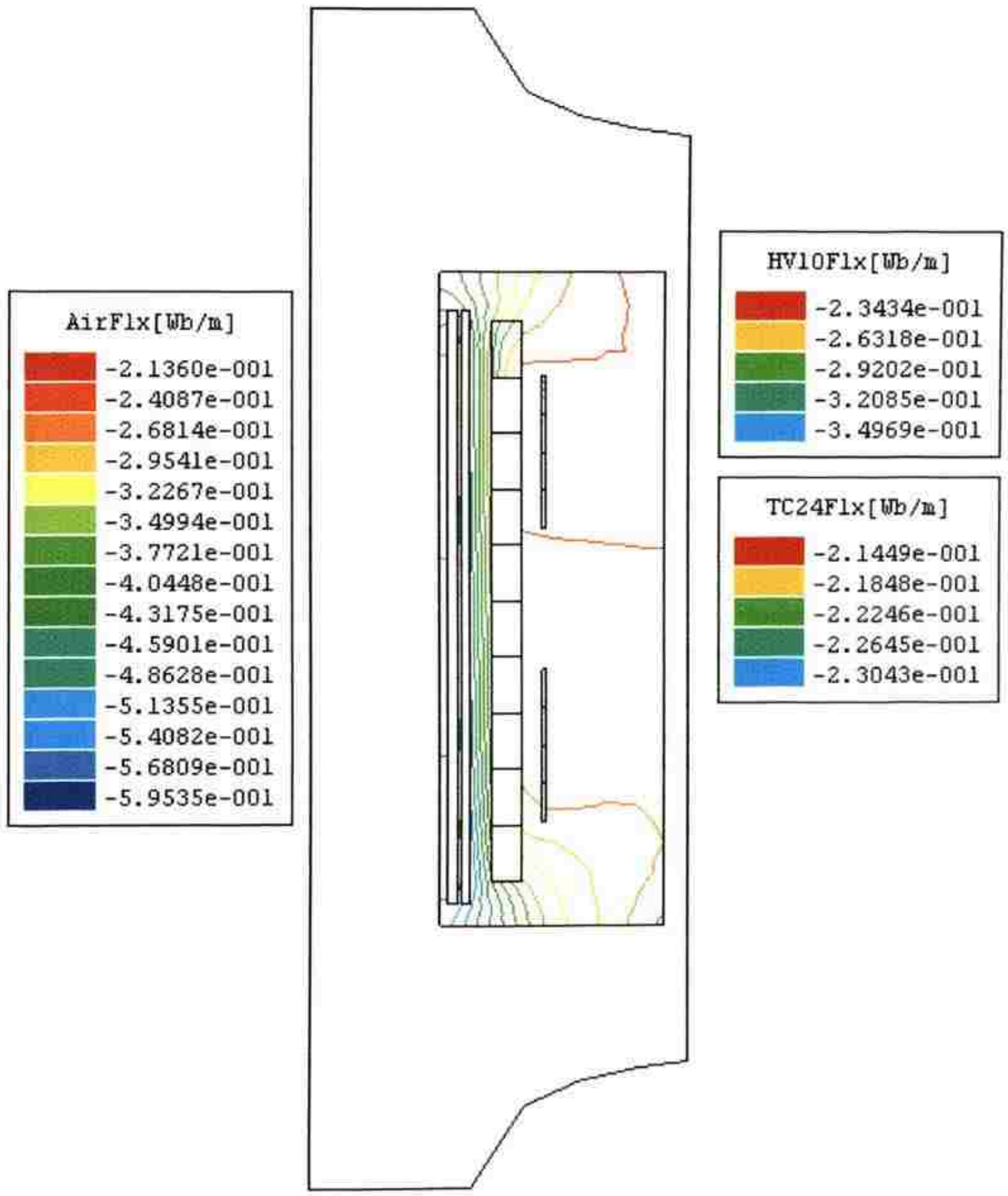



Figure C.4. Transformer $Tx_{A(Additive)}$: Air gap, high voltage (compartment HV10) winding, and upper tap (compartment TC24) winding flux line plots during short circuit conditions.

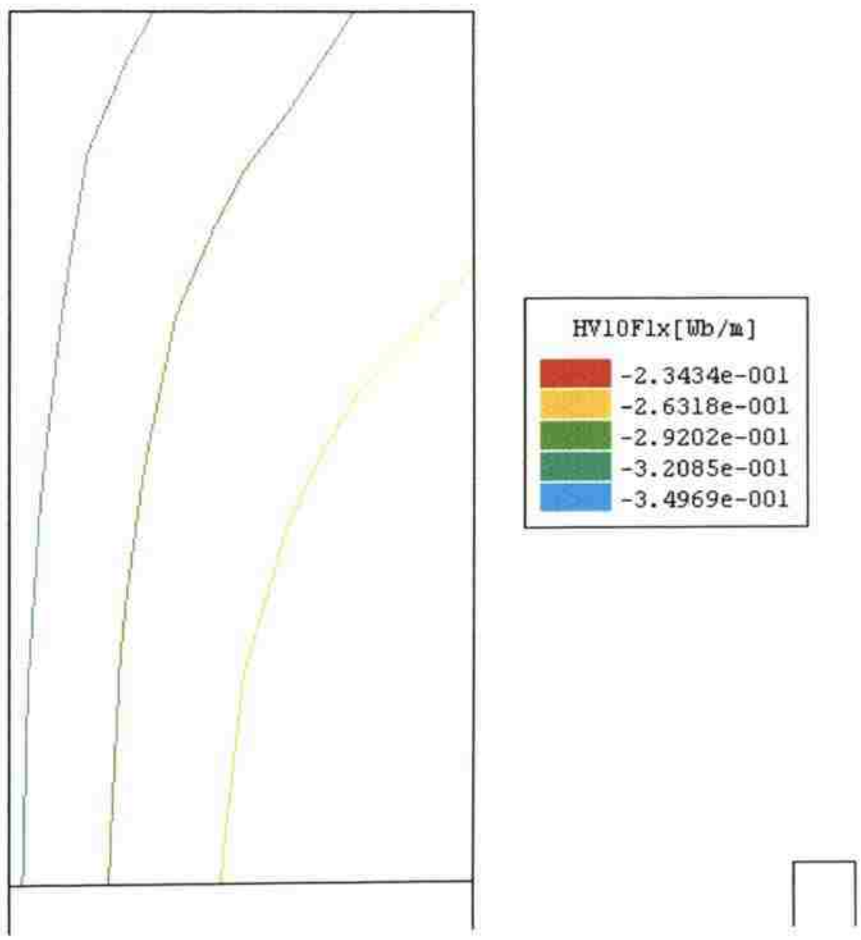



Figure C.5. Transformer $Tx_{A\ (Additive)}$: High voltage (compartment HV10) winding flux line plots during short circuit conditions.

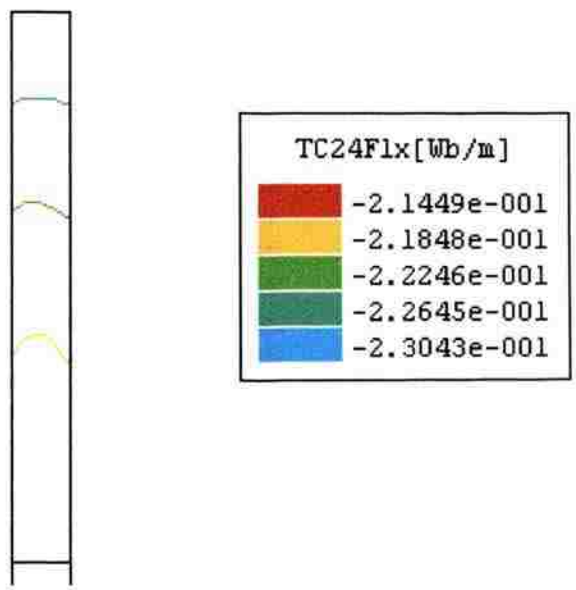



Figure C.6. Transformer $Tx_{A(Additive)}$: Upper tap (compartment TC24) winding flux line plots during short circuit conditions.

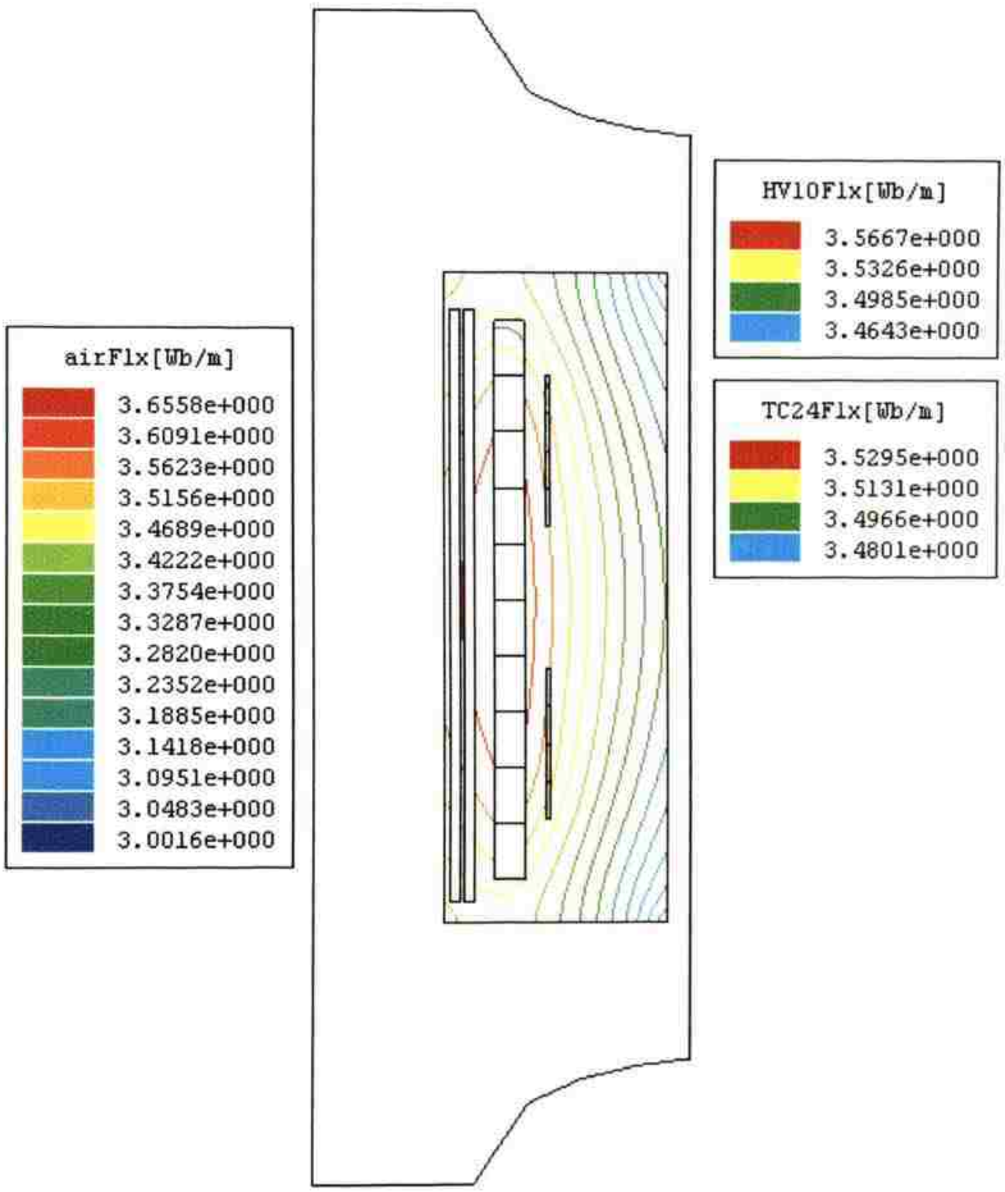



Figure C.7. Transformer $Tx_{A(Additive)}$: Air gap, high voltage (compartment HV10) winding, and upper tap (compartment TC24) winding flux Line plots during inrush current conditions (Inrush current equals 70% of short circuit).

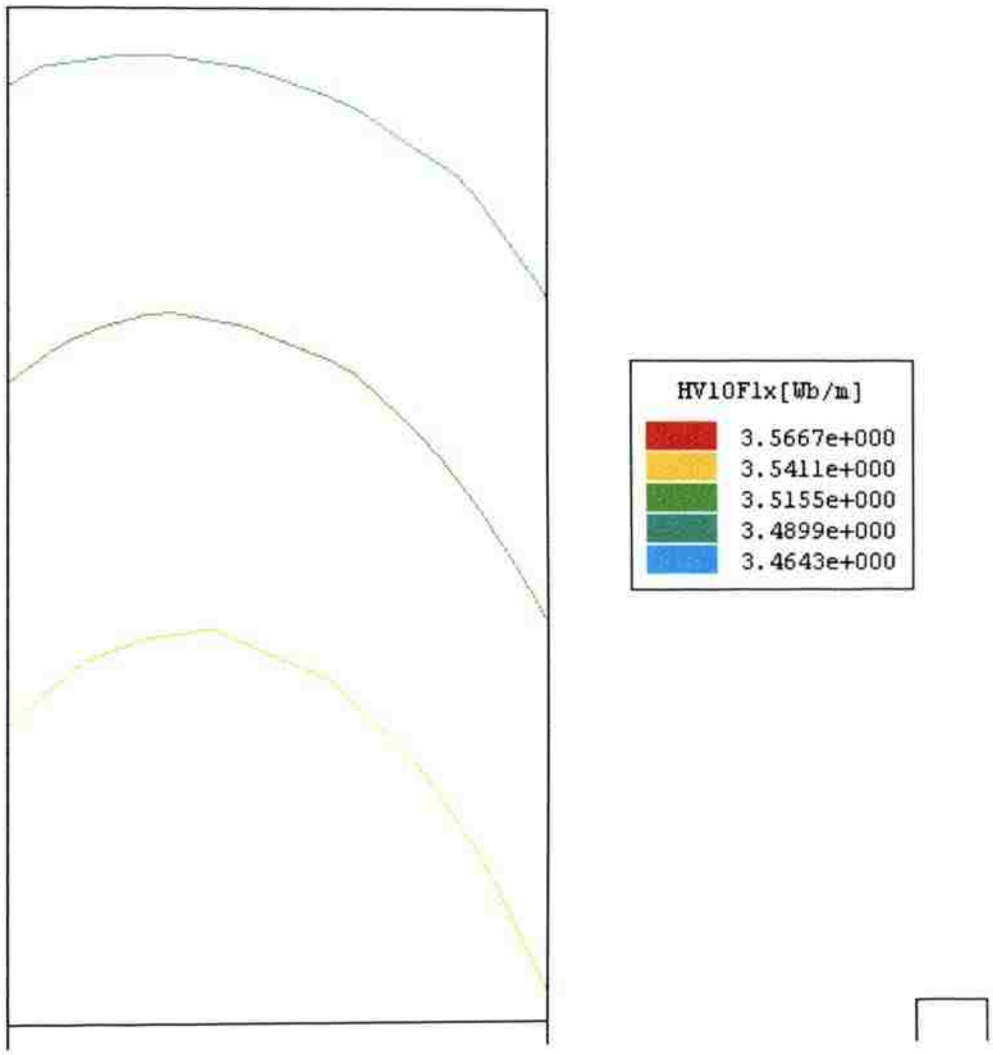



Figure C.8. Transformer $Tx_{A(Additive)}$: High voltage (compartment HV10) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

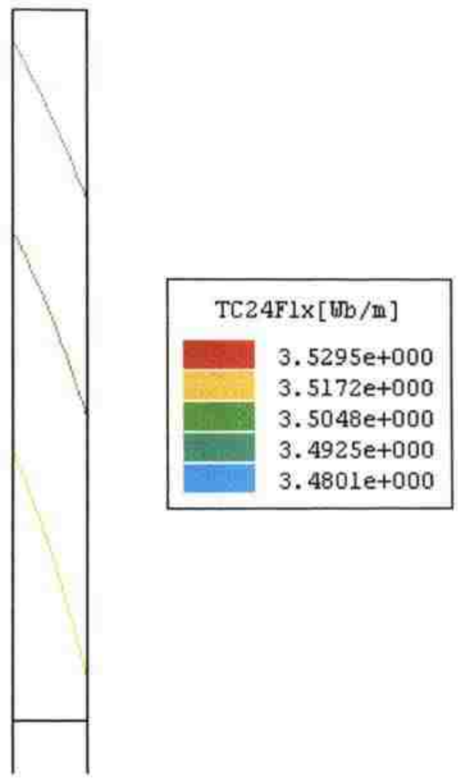



Figure C.9. Transformer $Tx_{A(Additive)}$: Upper tap (compartment TC24) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

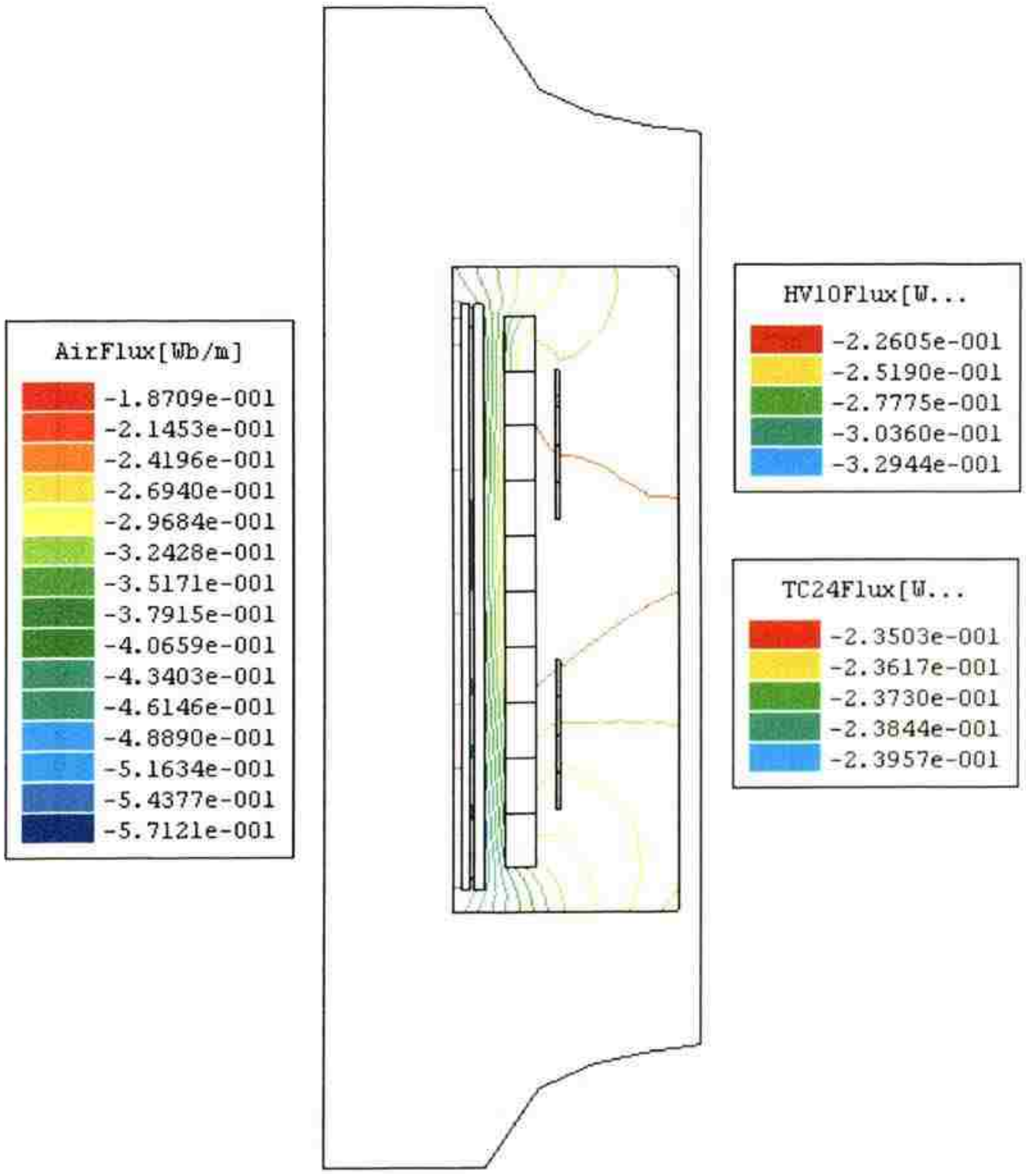



Figure C.10. Transformer $Tx_{A(Subtractive)}$: Air gap, high voltage (compartment HV10) winding, and upper tap (compartment TC24) winding flux line plots during short circuit conditions.

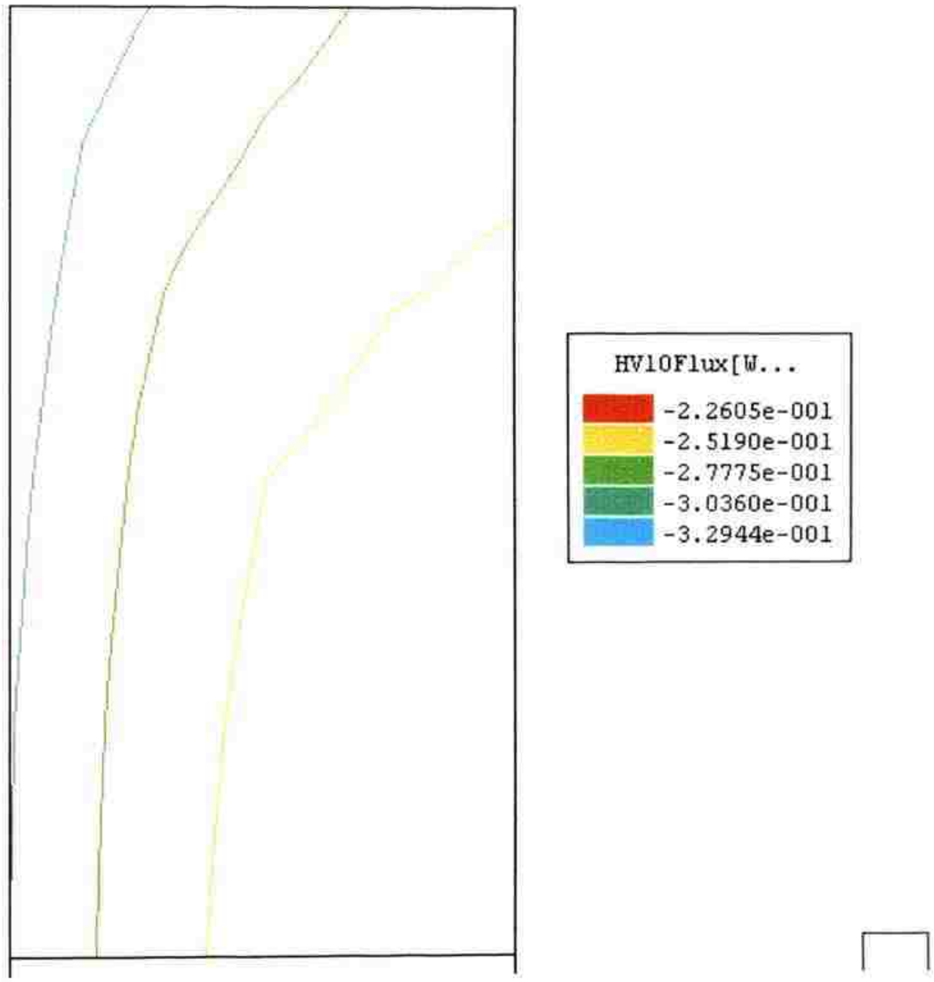



Figure C.11. Transformer $Tx_{A\ (Subtractive)}$: High voltage (compartment HV10) winding flux line plots during short circuit conditions.

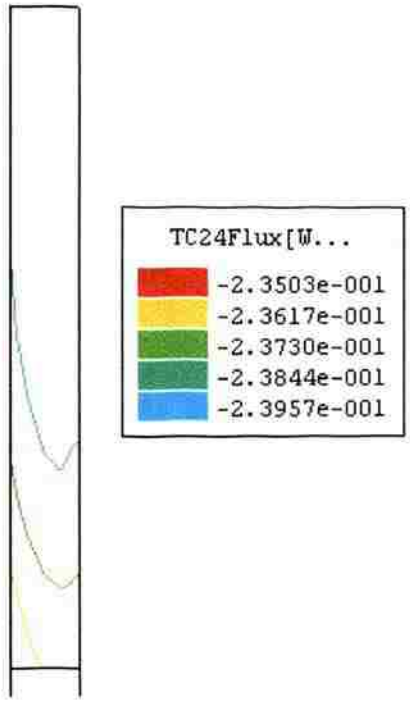



Figure C.12. Transformer $Tx_{A(Subtractive)}$: Upper tap (compartment TC24) winding flux line plots during short circuit conditions.

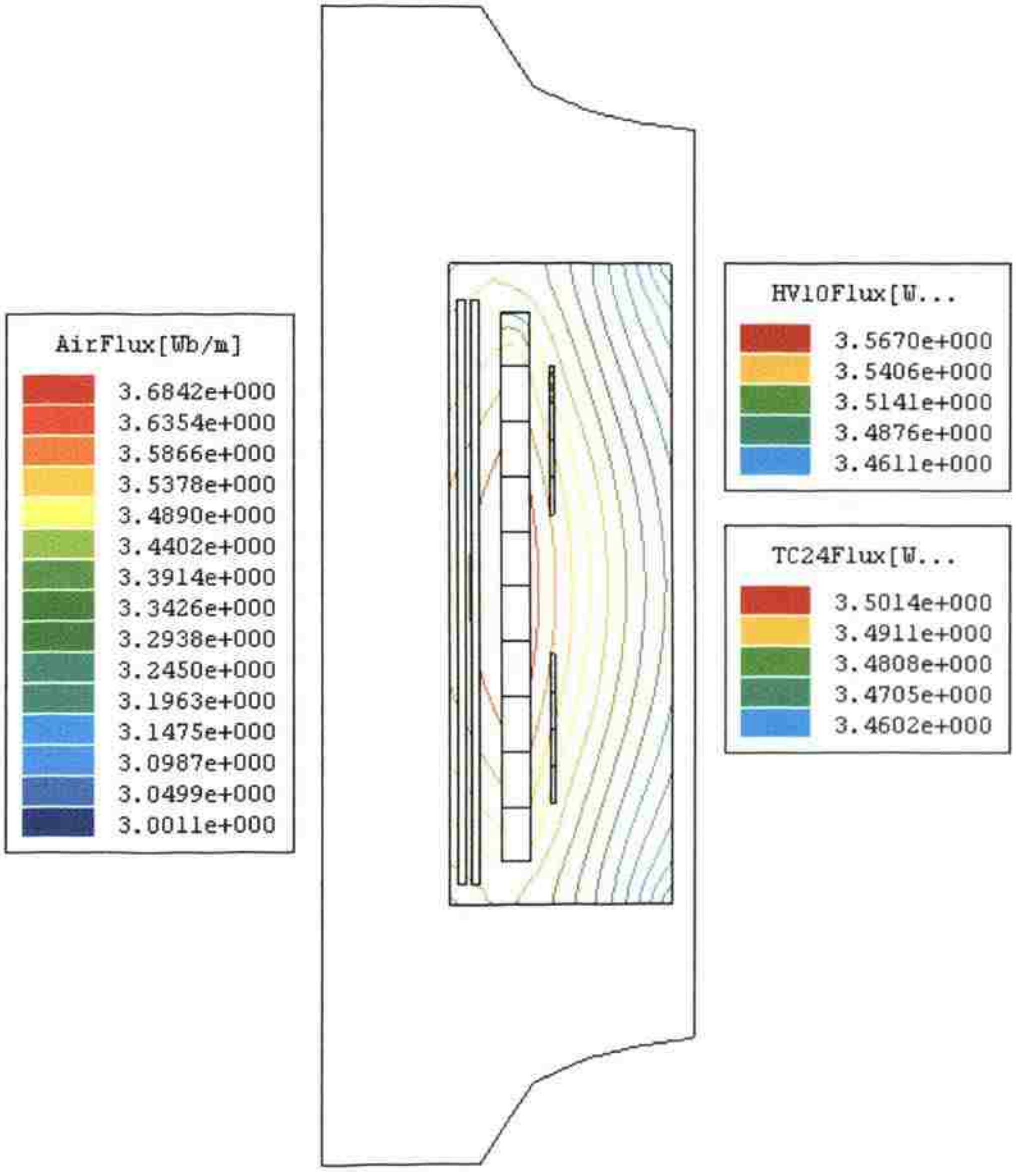



Figure C.13. Transformer $Tx_{A(Subtractive)}$: Air gap, high voltage (compartment HV10) winding, and upper tap (compartment TC24) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

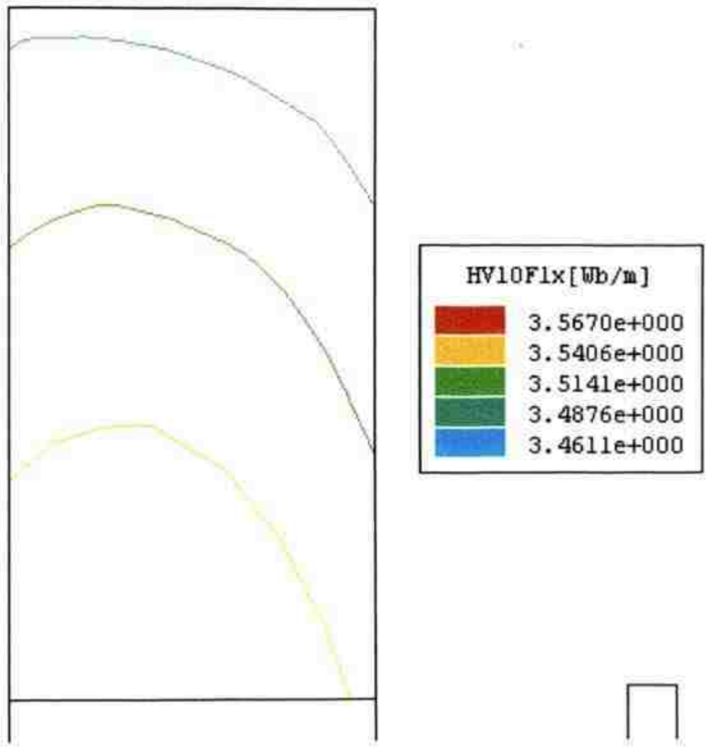



Figure C.14. Transformer $Tx_{A(Subtractive)}$: High voltage (compartment HV10) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

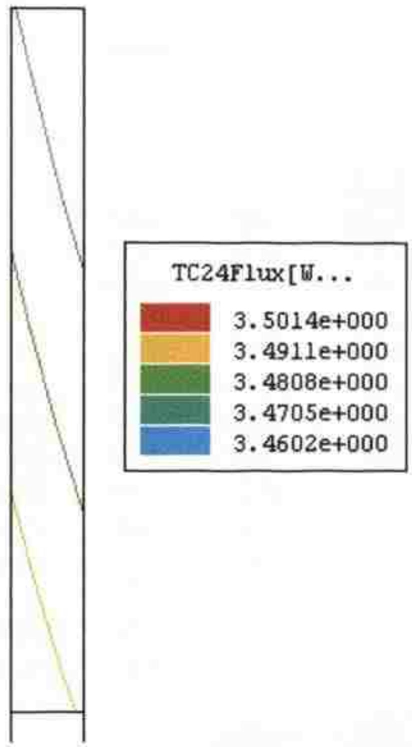



Figure C.15. Transformer $Tx_{A(Subtractive)}$: Upper tap (compartment TC24) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

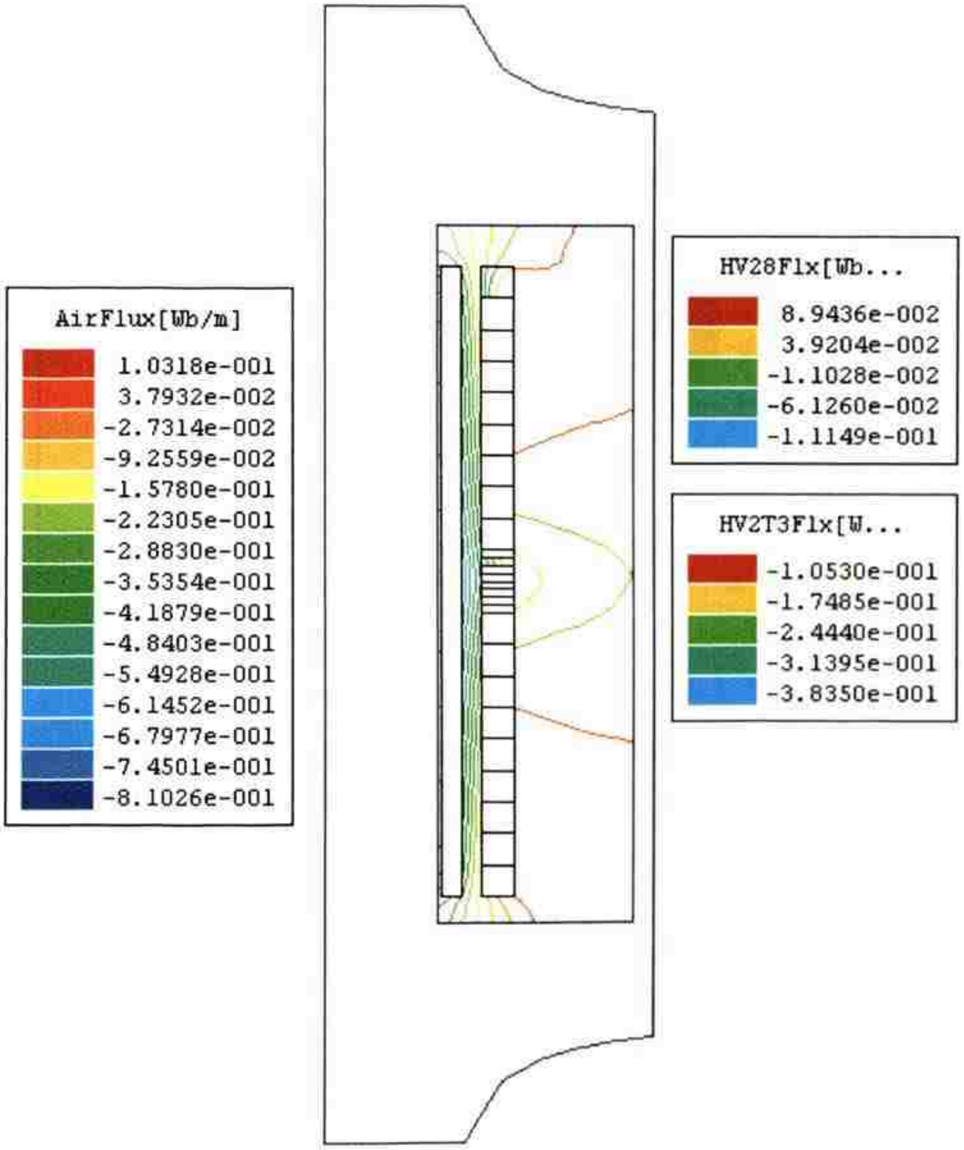



Figure C.17. Transformer $Tx_B$ (Center Entry): Air gap, high voltage (compartment HV28) winding, and tap (compartment 2T3) winding flux line plots during short circuit conditions.

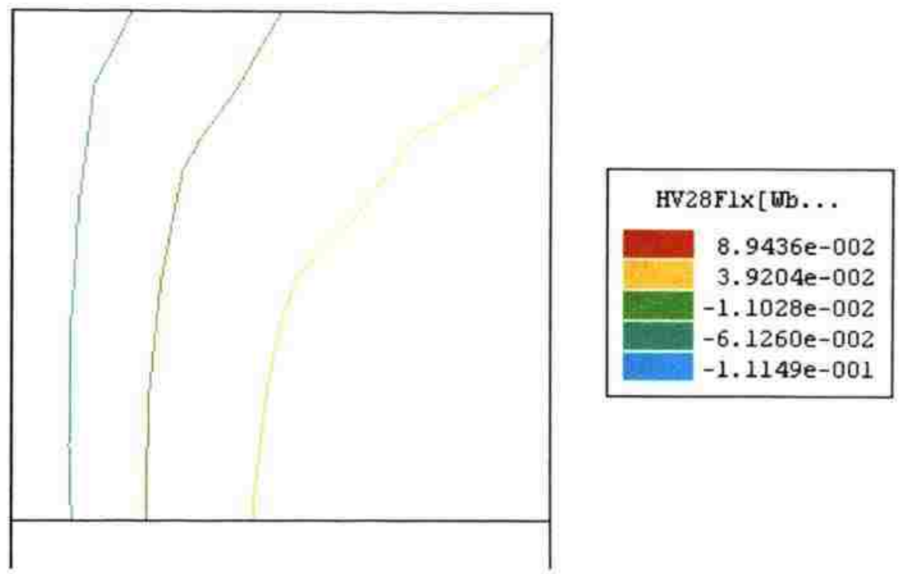



Figure C.18. Transformer $Tx_B$ (Center Entry): High voltage (compartment HV28) winding flux line plots during short circuit conditions.

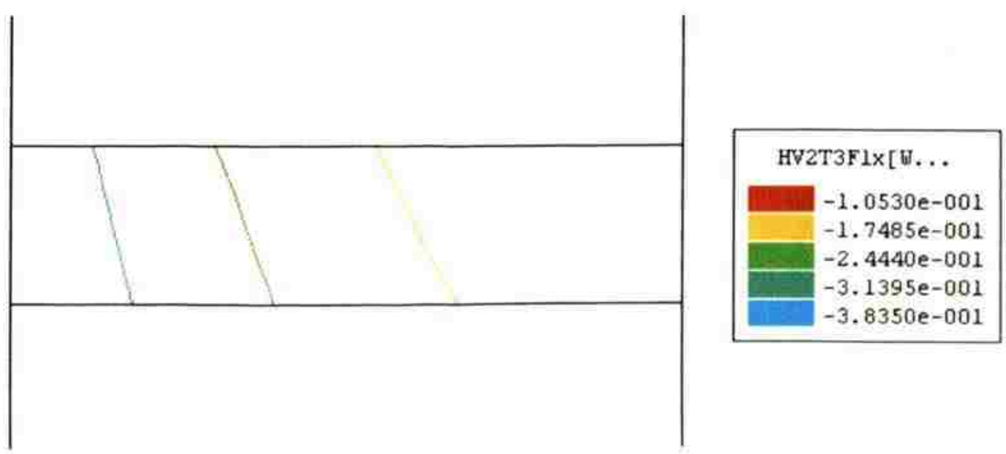



Figure C.19. Transformer $Tx_B$ (Center Entry): High voltage tap (compartment 2T3) winding flux line plots during short circuit conditions.

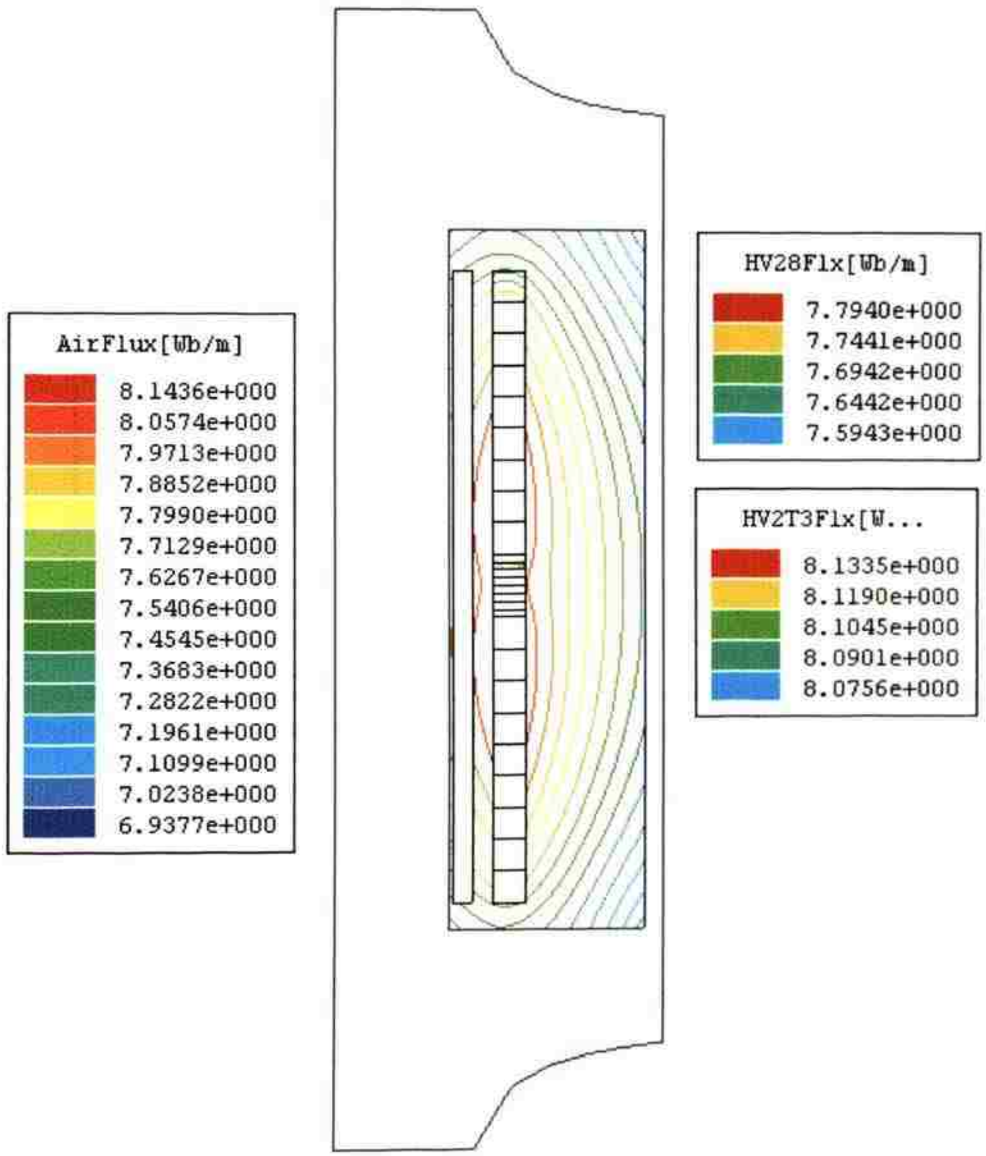



Figure C.20. Transformer $Tx_B$ (Center Entry): Air gap, high voltage (compartment HV28) winding, and tap (compartment 2T3) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

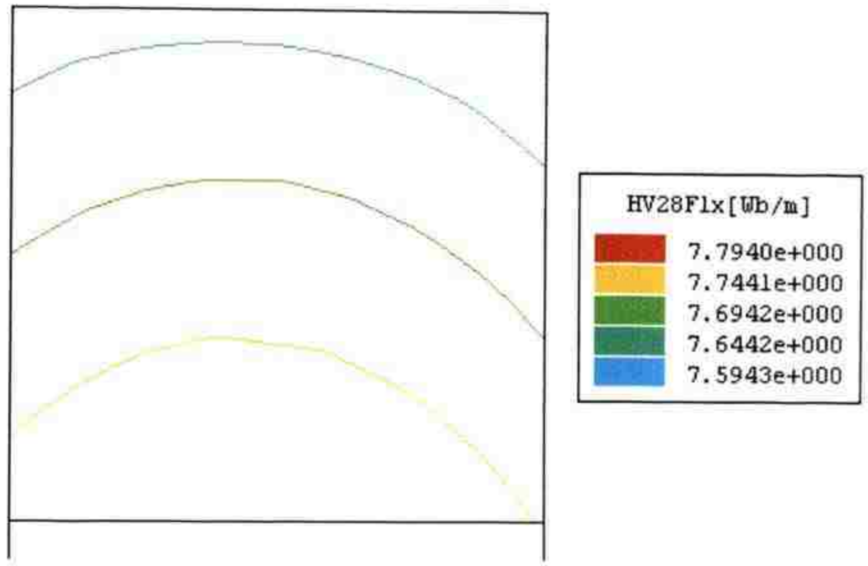



Figure C.21. Transformer $Tx_B$ (Center Entry): High voltage (compartment HV28) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

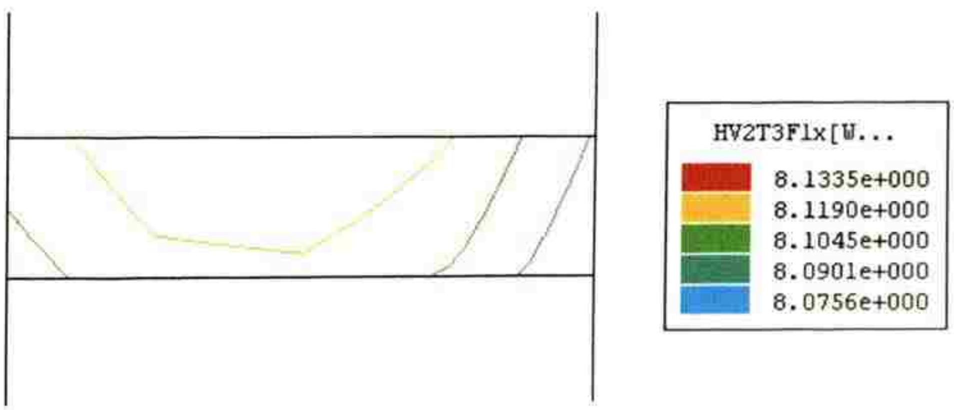



Figure C.22. Transformer $Tx_B$ (Center Entry): High voltage tap (compartment 2T3) winding flux line plots during short circuit conditions.

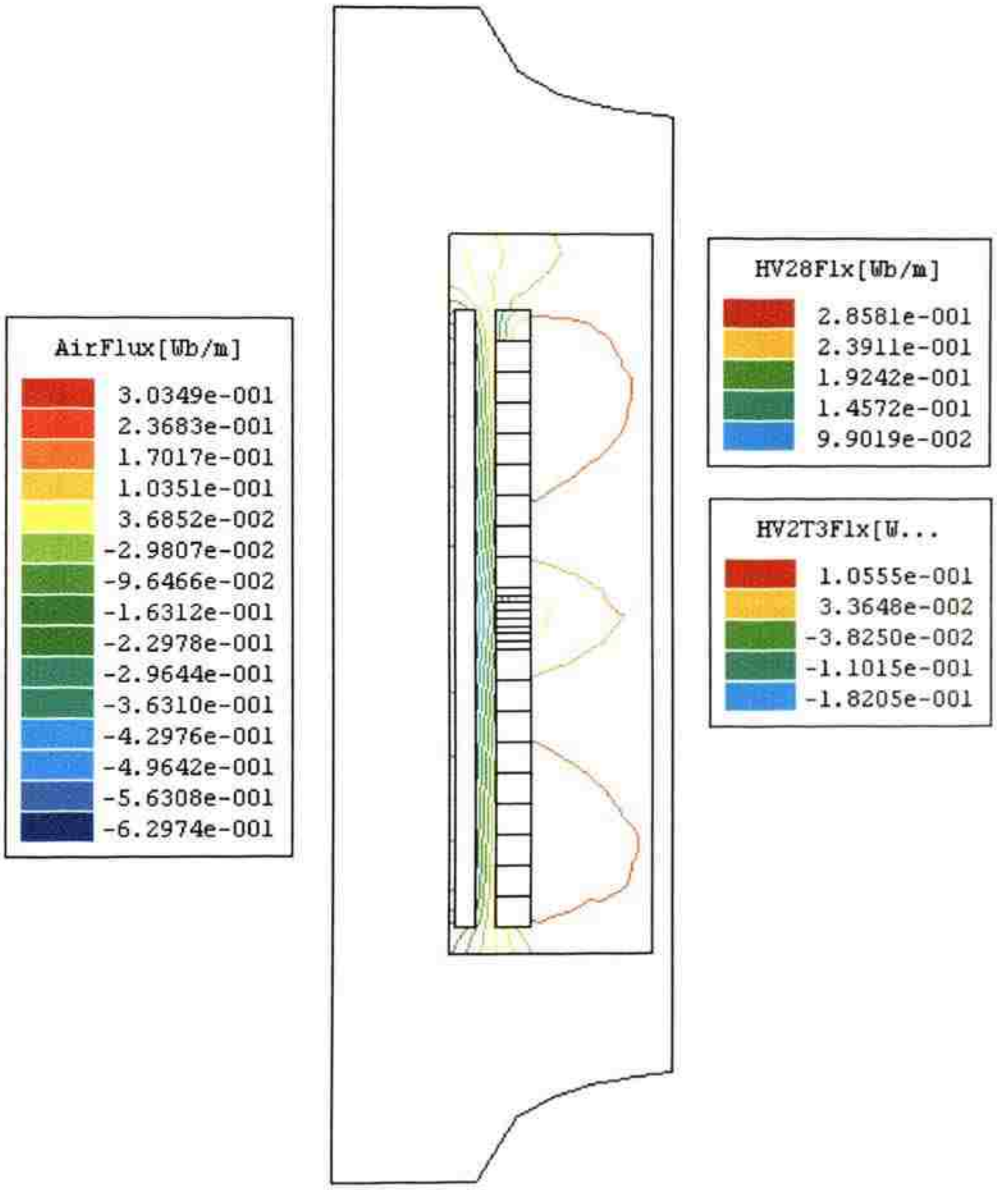



Figure C.23. Transformer $Tx_B$ (Yoke Entry): Air gap, high voltage (compartment HV28) winding, and tap (compartment 2T3) winding flux line plots during short circuit conditions.

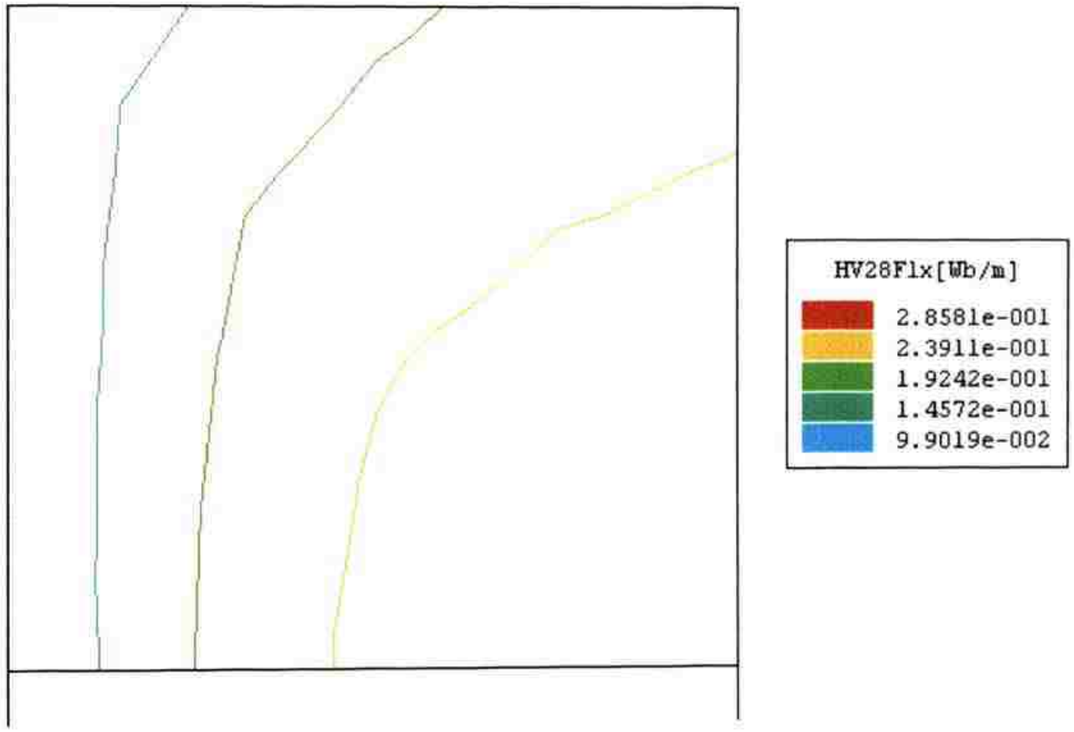



Figure C.24. Transformer $Tx_B$ (Yoke Entry): High voltage (compartment HV28) winding flux line plots during short circuit conditions.

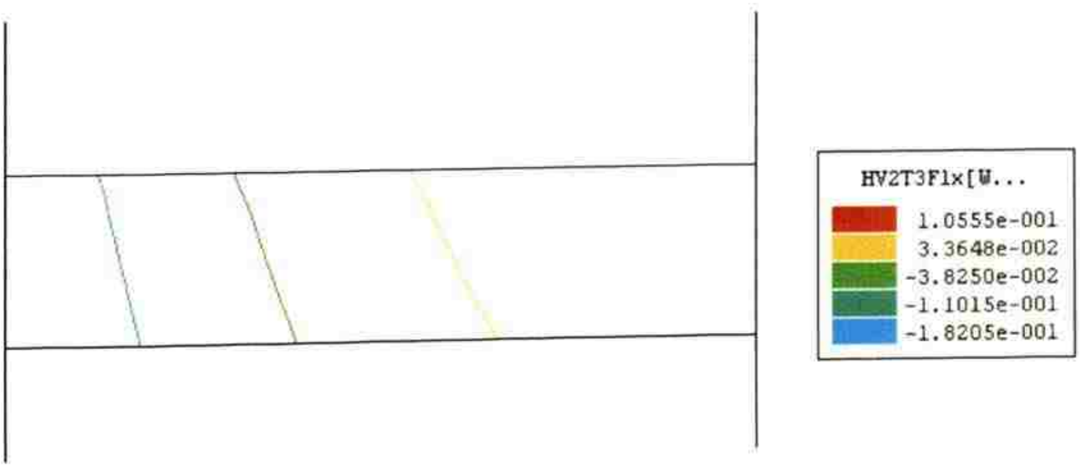



Figure C.25. Transformer $Tx_B$ (Yoke Entry): High voltage tap (compartment 2T3) winding flux line plots during short circuit conditions.

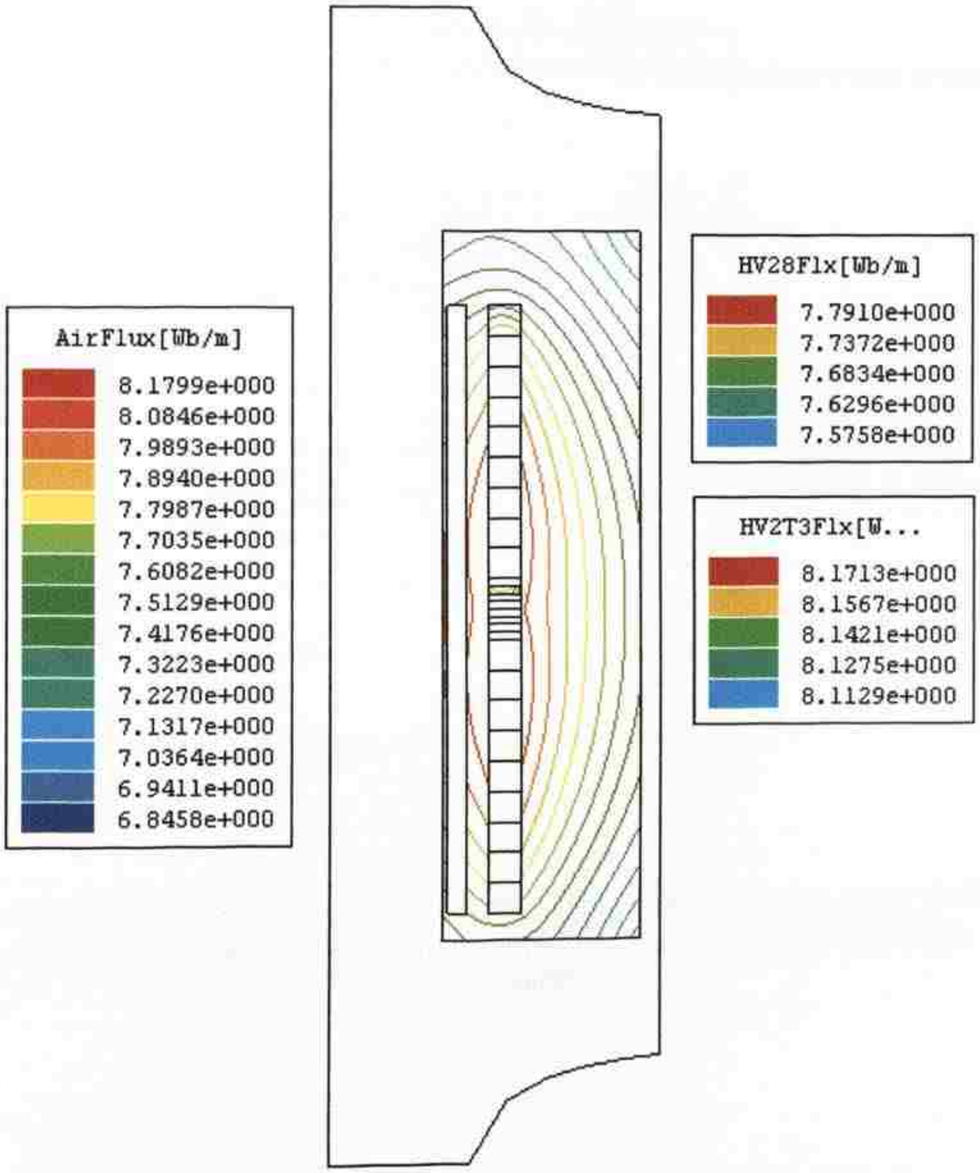



Figure C.26. Transformer $Tx_B$ (Yoke Entry): Air gap, high voltage (compartment HV28) winding, and tap (compartment 2T3) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

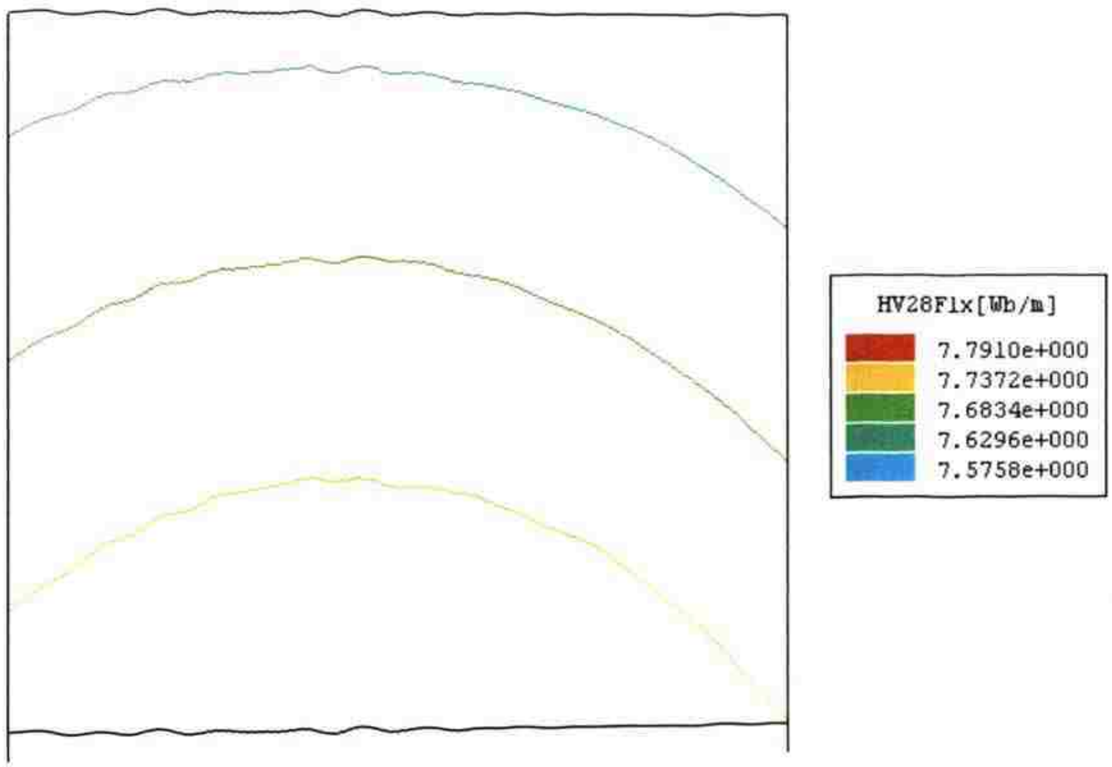



Figure C.27. Transformer $Tx_B$ (Yoke Entry): High voltage (compartment HV28) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

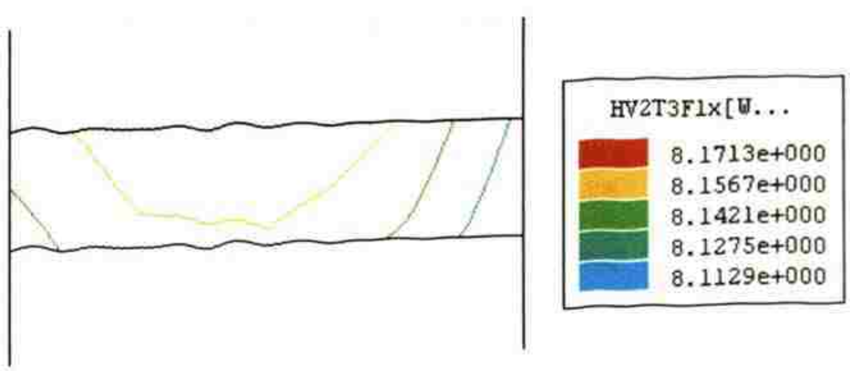
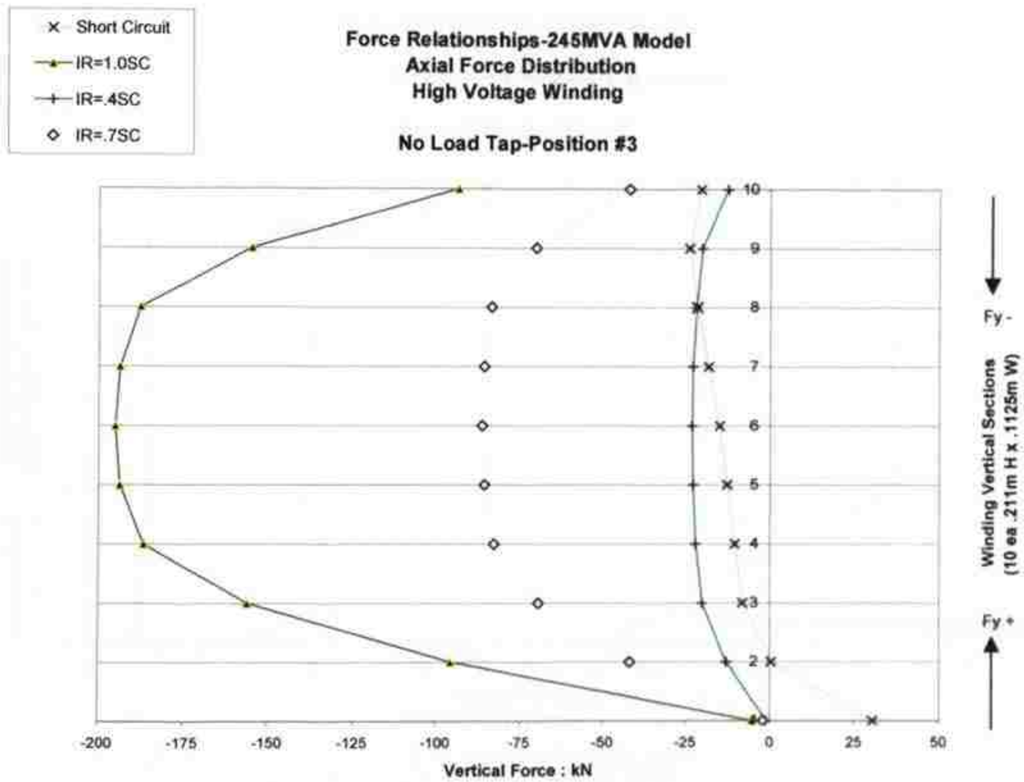
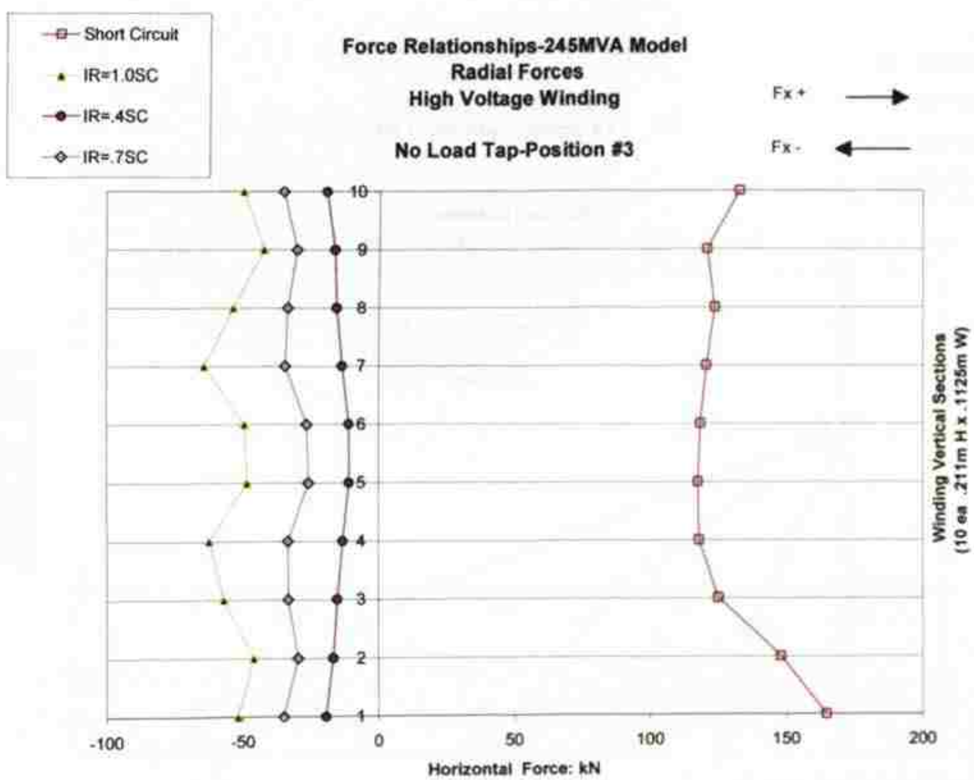
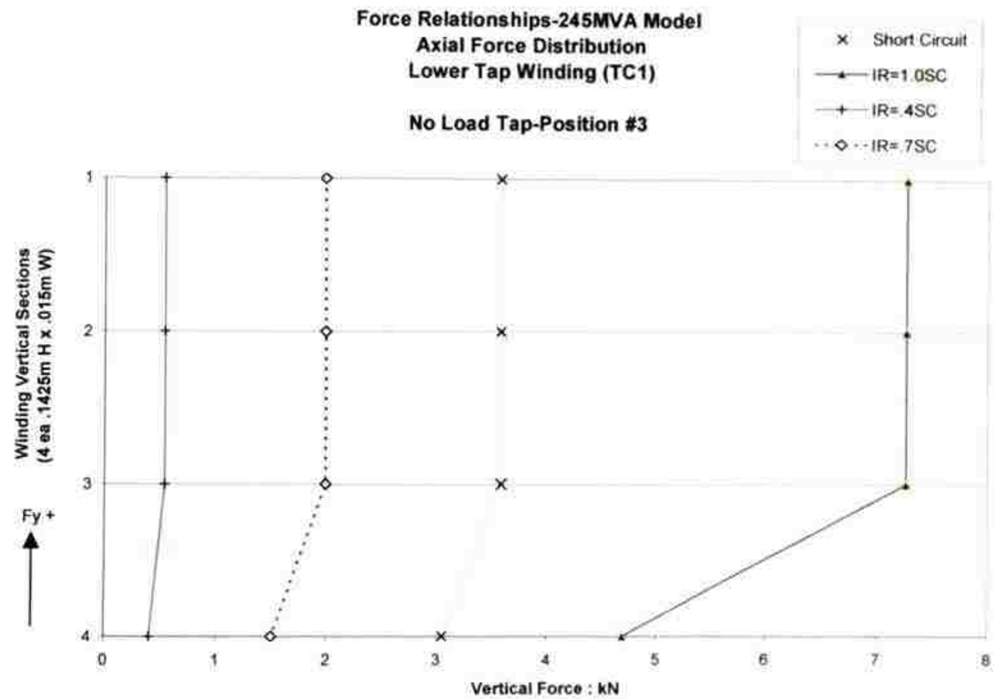
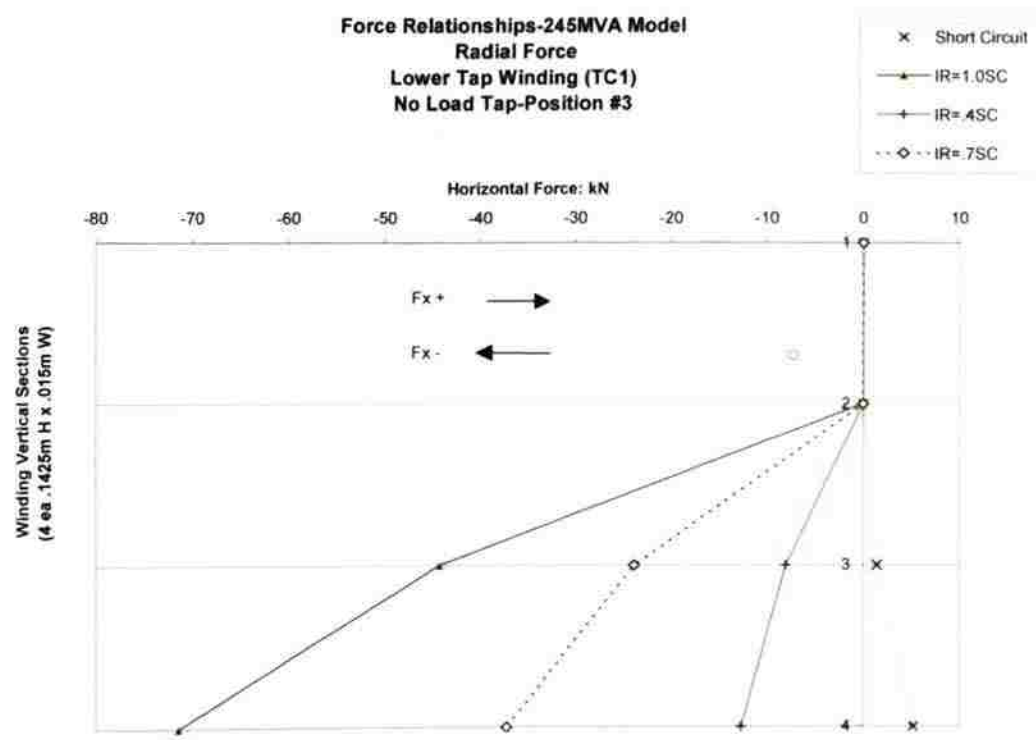


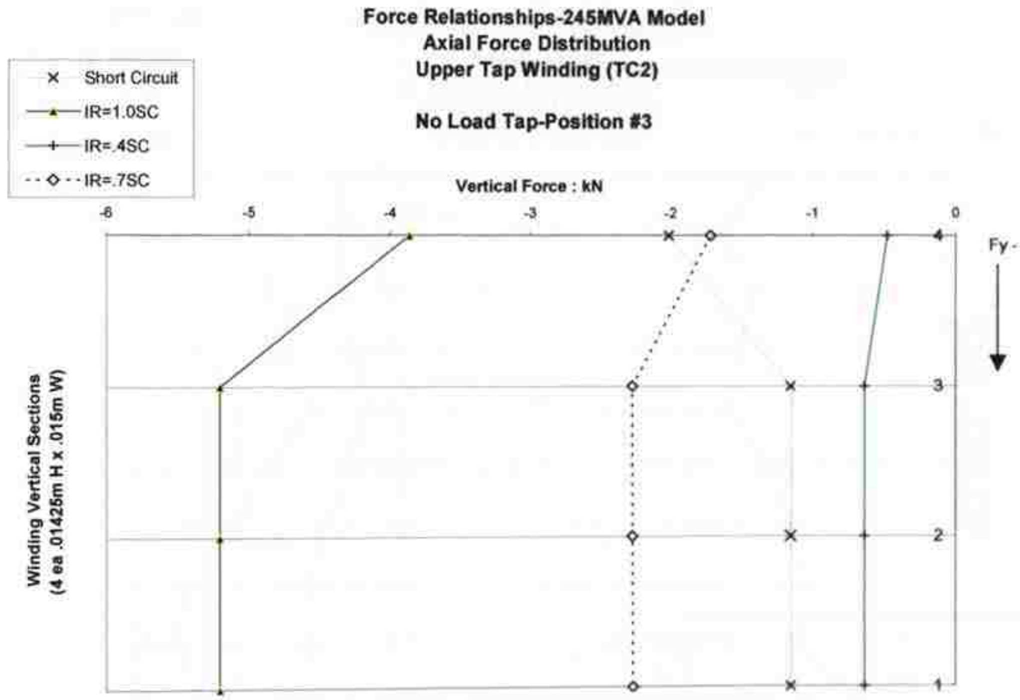

Figure C.28. Transformer $Tx_B$ (Yoke Entry): High voltage tap (compartment 2T3) winding flux line plots during inrush current conditions (Inrush current equals 70% of short circuit).

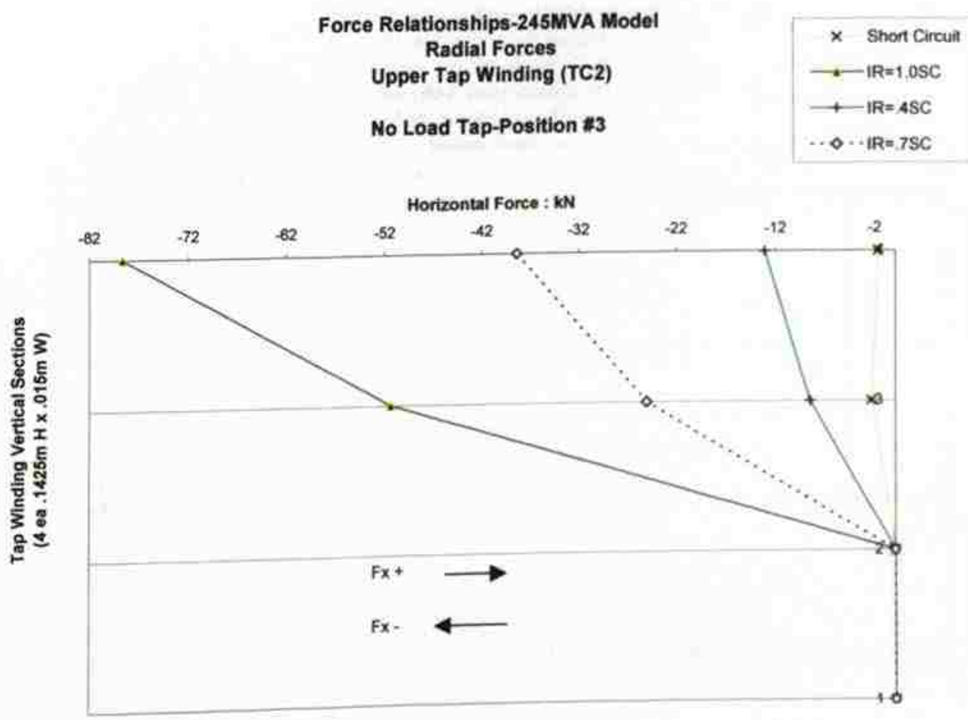

Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Force Relationships-245MVA Model
Axial Force Distribution
High Voltage Winding
No Load Tap-Position #3
Fy -
Fy +
Winding Vertical Sections
(10 ea .211m H x .1125m W)
Vertical Force : kN

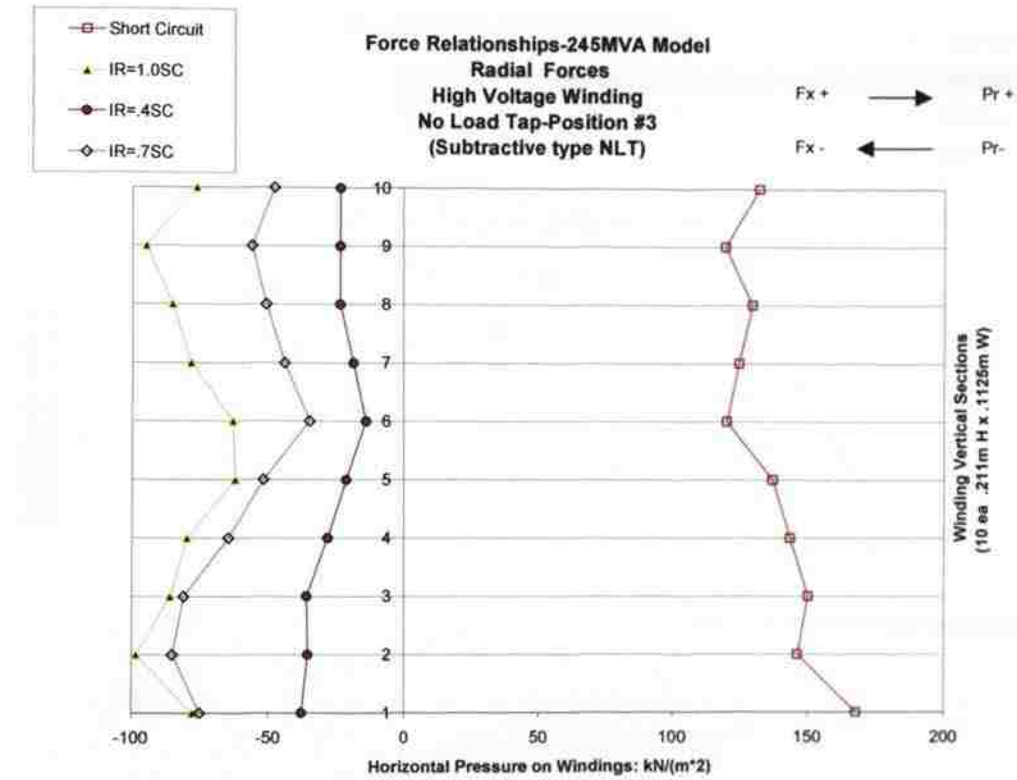

Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Force Relationships-245MVA Model
Radial Forces
High Voltage Winding
No Load Tap-Position #3
Fx +
Fx -
Winding Vertical Sections
(10 ea .211m H x .1125m W)
Horizontal Force: kN

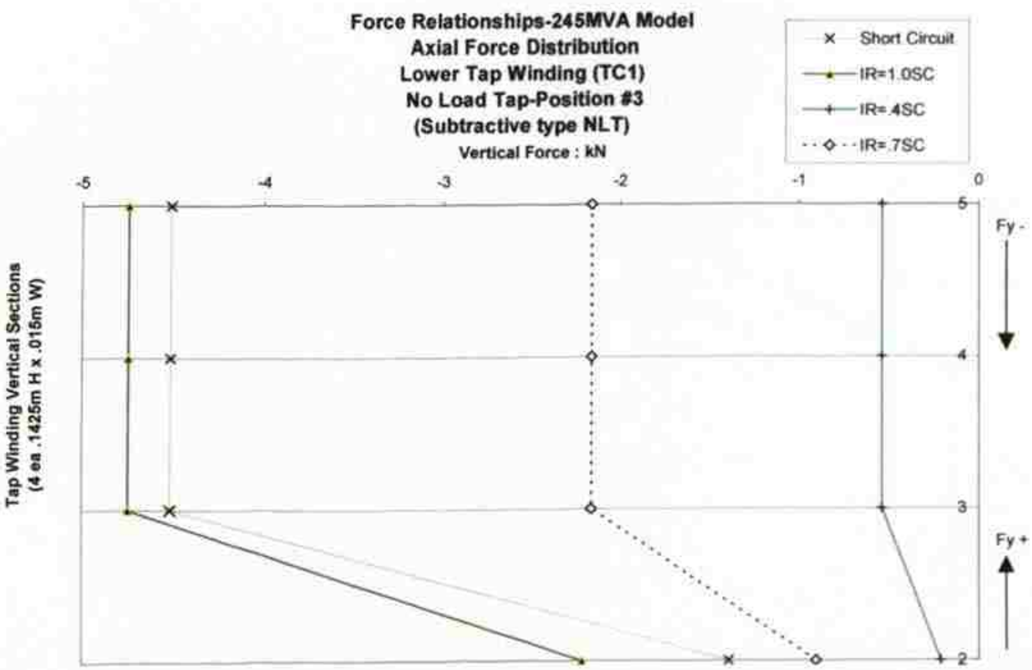

Force Relationships-245MVA Model
Axial Force Distribution
Lower Tap Winding (TC1)
No Load Tap-Position #3
Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Winding Vertical Sections
(4 ea .1425m H x .015m W)
Fy +
Vertical Force : kN
0
1
2
3
4
5
6
7
8

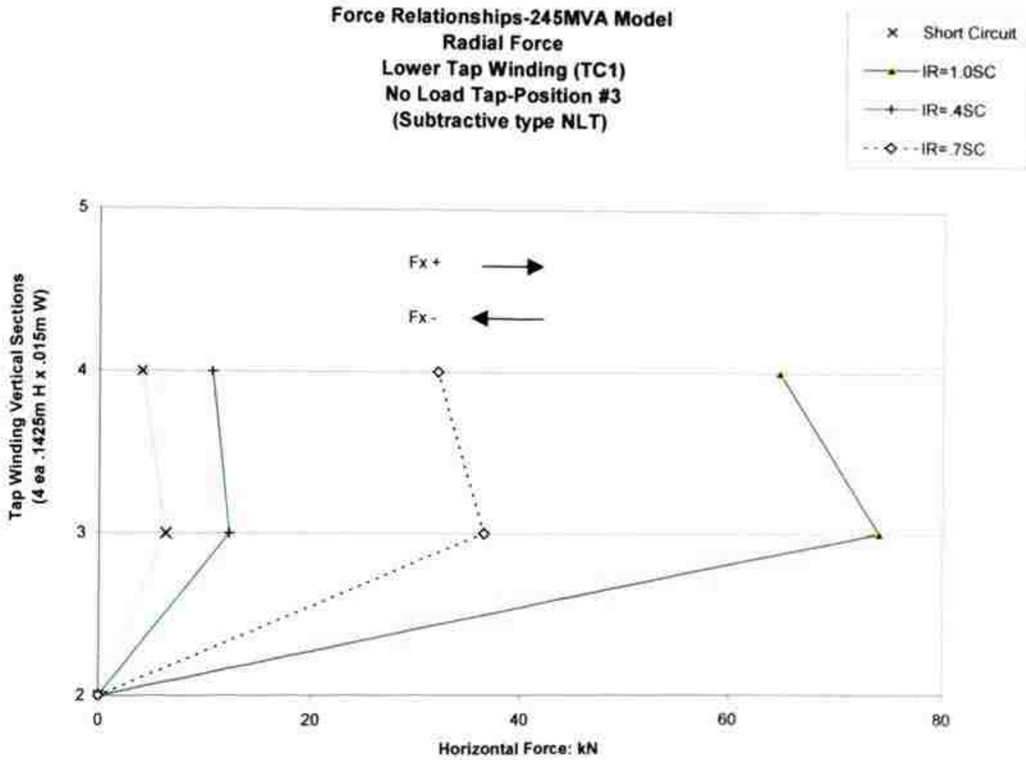

Force Relationships-245MVA Model
Radial Force
Lower Tap Winding (TC1)
No Load Tap-Position #3
Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Horizontal Force: kN
-80
-70
-60
-50
-40
-30
-20
-10
0
10
Fx +
Fx -
Winding Vertical Sections
(4 ea .1425m H x .015m W)
1
2
3
4

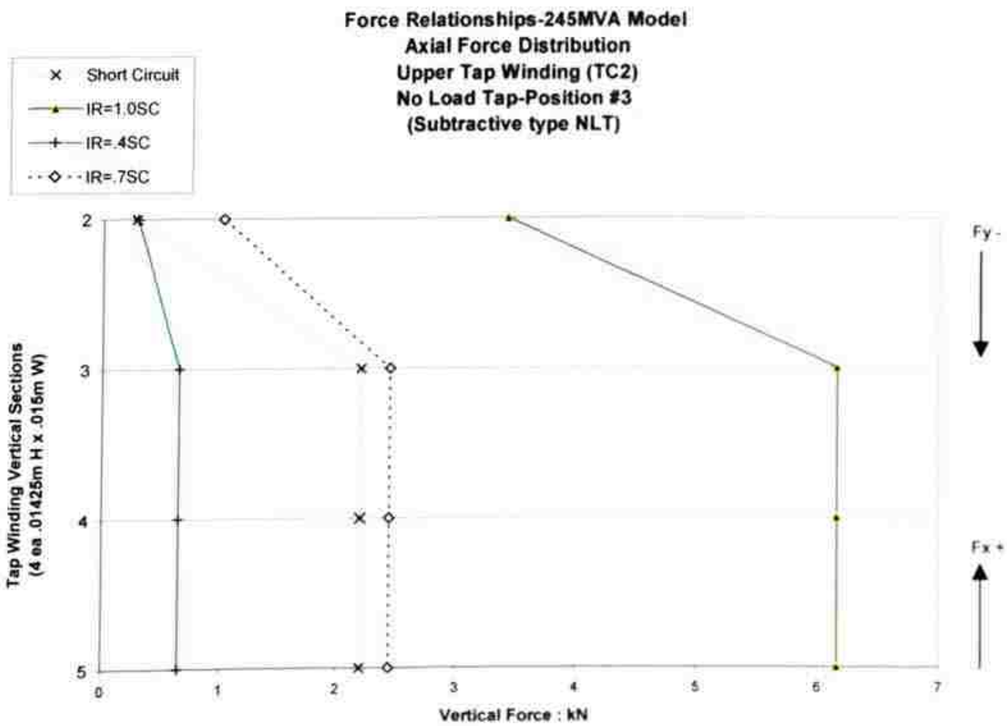

Force Relationships-245MVA Model
Axial Force Distribution
Upper Tap Winding (TC2)
No Load Tap-Position #3
Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Vertical Force : kN
-6
-5
-4
-3
-2
-1
0
4
3
2
1
Fy -
Winding Vertical Sections
(4 ea .01425m H x .015m W)

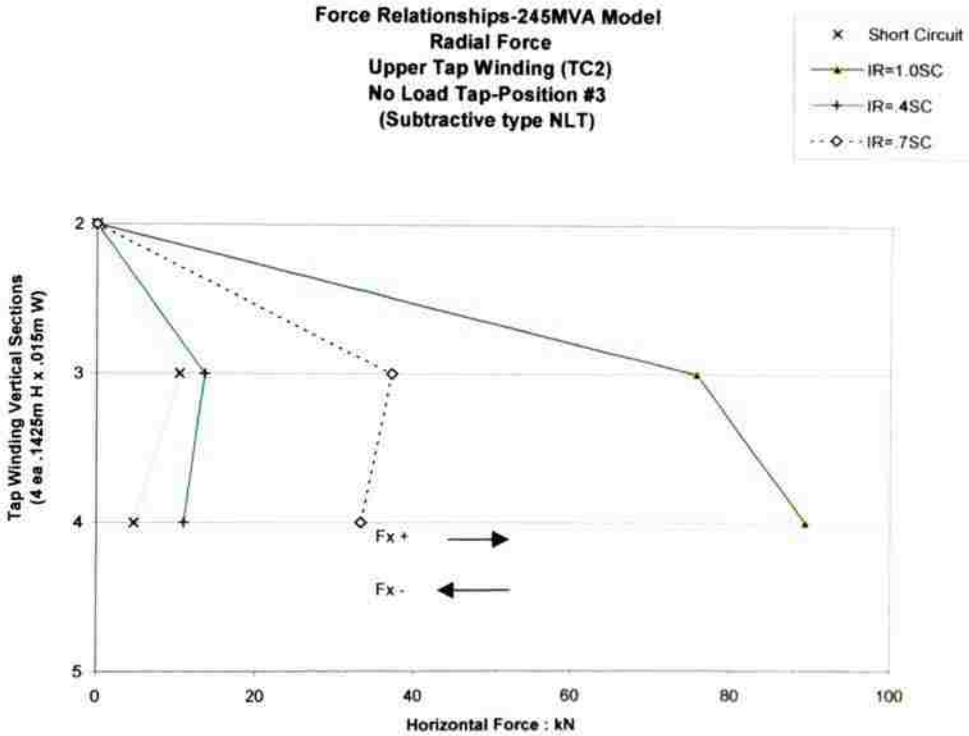

Force Relationships-245MVA Model
Radial Forces
Upper Tap Winding (TC2)
No Load Tap-Position #3
Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Horizontal Force : kN
-82
-72
-62
-52
-42
-32
-22
-12
-2
2
1
Fx +
Fx -
Tap Winding Vertical Sections
(4 ea .1425m H x .015m W)


Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Force Relationships-245MVA Model
Radial Forces
High Voltage Winding
No Load Tap-Position #3
(Subtractive type NLT)
Fx +
Pr +
Fx -
Pr-
Winding Vertical Sections
(10 ea .211m H x .1125m W)
-100
-50
0
50
100
150
200
Horizontal Pressure on Windings: kN/(m^2)

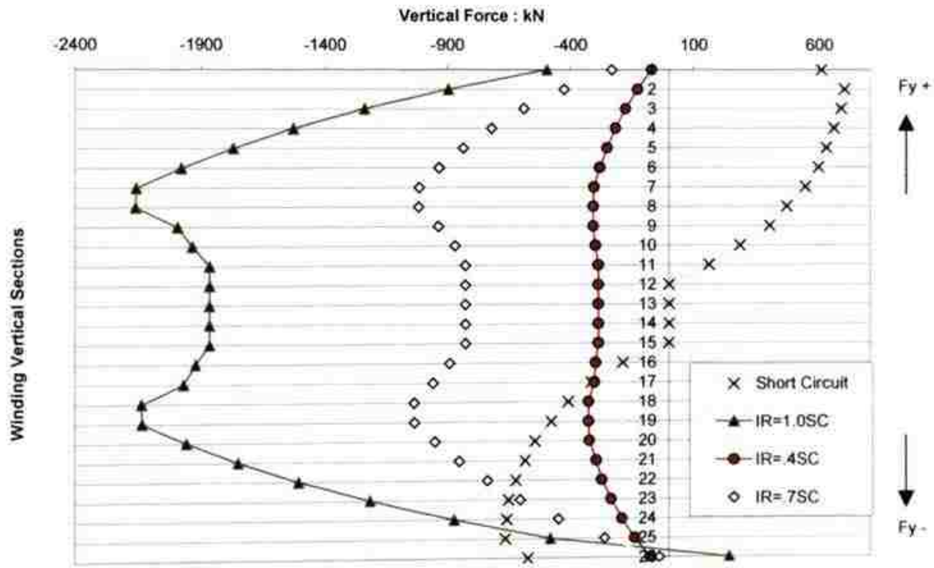

Force Relationships-245MVA Model
Axial Force Distribution
Lower Tap Winding (TC1)
No Load Tap-Position #3
(Subtractive type NLT)
Vertical Force : kN
Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
-5
-4
-3
-2
-1
0
Tap Winding Vertical Sections
(4 ea .1425m H x .015m W)
Fy -
Fy +


Force Relationships-245MVA Model
Radial Force
Lower Tap Winding (TC1)
No Load Tap-Position #3
(Subtractive type NLT)
Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Fx +
Fx -
Tap Winding Vertical Sections
(4 ea .1425m H x .015m W)
Horizontal Force: kN

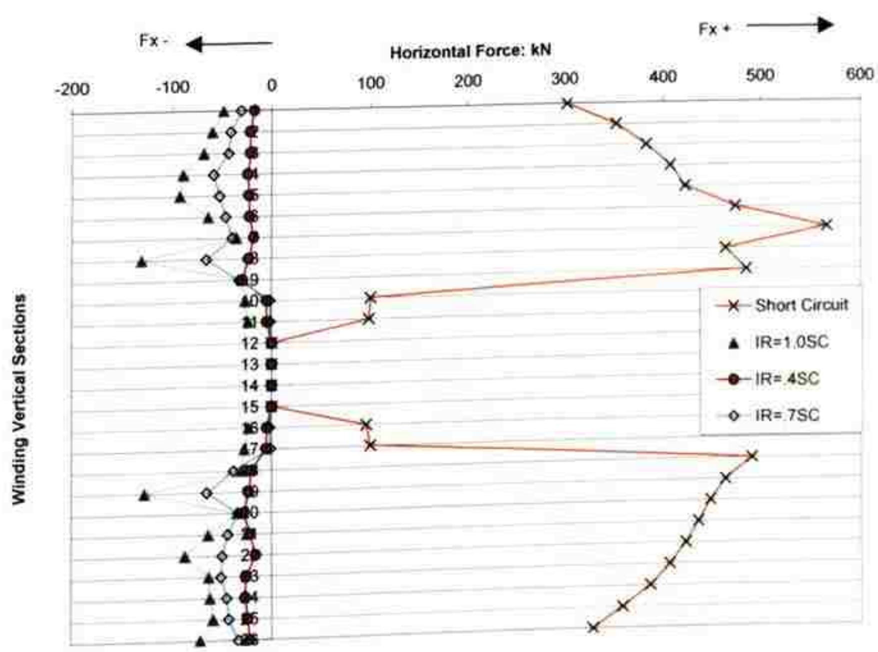

Force Relationships-245MVA Model
Axial Force Distribution
Upper Tap Winding (TC2)
No Load Tap-Position #3
(Subtractive type NLT)
Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Fy -
Fx +
Tap Winding Vertical Sections
(4 ea .01425m H x .015m W)
Vertical Force : kN


Force Relationships-245MVA Model
Radial Force
Upper Tap Winding (TC2)
No Load Tap-Position #3
(Subtractive type NLT)
Short Circuit
IR=1.0SC
IR=.4SC
IR=.7SC
Tap Winding Vertical Sections
(4 ea .1425m H x .015m W)
Fx +
Fx -
Horizontal Force : kN
2
3
4
5
0
20
40
60
80
100

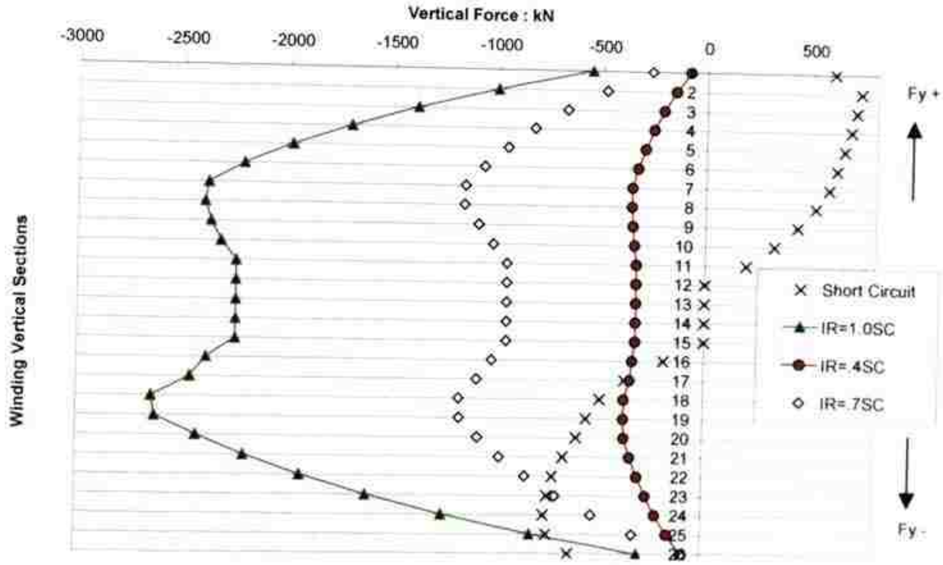
**Force Relationships-230MVA**
**Axial Force Distribution**
**High Voltage Coil**
**No Load Tap-Position #3**




**Force Relationships- 230MVA**
**Radial Force**
**No Load Tap-Position #3**



**Force Relationships-230MVA**
**Axial Force Distribution**
**High Voltage Coil (Yoke Entry Connection)**
**No Load Tap-Position #3**




**Force Relationships- 230MVA**
**Radial Force (Yoke Entry Connection)**
**No Load Tap-Position #3**