Gridscale X Advanced Protection Assessment

Transformer Damage Curves – Whitepaper

SIEMENS

Introduction

We have developed a category of curves in Coordination Graphics (CG) to study transformer damage curves. These curves help our users ensuring overcurrent protective devices clear any fault current that flows through the transformer they protect. Two transformer damage curves may be displayed in Gridscale X Advanced Protection Assessment, the so-called thermal and mechanical.

Incorporation of IEEE C57.109-1993[1]

Thermal Damage Curve

Thermal damage curves estimate the time a transformer should withstand the large winding fault currents before thermal damage occurs. This is based on the winding current in terms of multiples of the rated winding current.
For windings with a wye connection, the rated winding current ($I_{wdg\ rated}$) equals the rated terminal current ($I_{term\ rated}$).

Transformer damage curves displayed in Advanced Protection Assessment are developed based on IEEE Standard C57.109-2018, "IEEE Guide for Liquid-Immersed Transformers Through-Fault-Current Duration" [1].

Transformer damage curves represent the transformer's ability to withstand high current during fault conditions. The faults considered in this standard are placed outside the transformer, causing current flowing through transformer windings to rise. Internal faults of transformers are not the concern of the IEEE C57.109 standard.

$I_{wdg\ rated} = I_{term\ rated} = S_{rated}/(1.732*V_{LLrated})$

S_{rated} is the rated power and $V_{LLrated}$ is the rated voltage of the equipment.

For a delta winding, rated winding current is 1/√3 times the rated terminal current

$I_{wdg\ rated} = I_{term\ rated}/\sqrt{3} = S_{rated}/(3*V_{LLrated})$

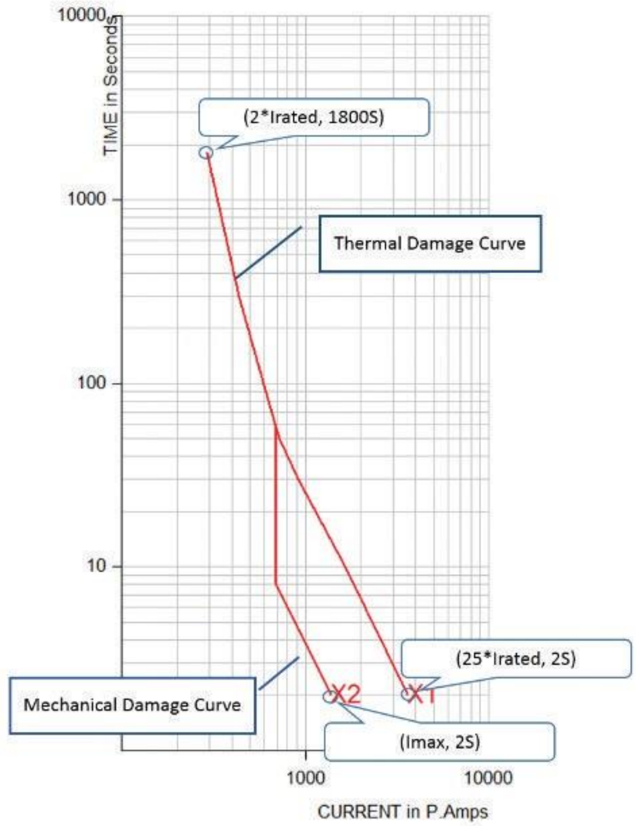


Figure 1: Example of Transformer Thermal and Mechanical Damage Curves displayed in Advanced Protection Assessment

Time to Thermal Damage (seconds)	Winding Current (multiples of rated winding current)
2	25
10	11.3
30	6.3
60	4.75
300	3
1800	2

Table 1: Time to Thermal Damage vs. Winding Current [1]

Mechanical Damage Curve

Mechanical damage is considered only when

- Transformer capability is larger than 0.5 MVA.
- Transformer experiences more than 5 through-faults in life span if transformer capability is less than or equal to 30 MVA.

For transformers with capability lower than or equal to 0.5 MVA, a section of "cumulative mechanical damage" extends from the stopping point on the thermal damage curve and stops at 40 times rated winding current, 0.781 seconds.

The shape of a mechanical damage curve is determined by the maximum through-fault current and the transformer capability.

- Time to mechanical damage is 2 seconds with maximum through-fault current. This is also the stopping point of the mechanical damage curve.
- Maximum through-fault current is calculated assuming three-phase fault occurring at transformer load side terminal.
- For transformer with capability less than or equal to 5 MVA and with a reactance value of XT, the maximum through-fault current is calculated as $I_{max} = 1/X_T$[3] For transformer with capability larger than 5 MVA, system short-circuit impedance at source side terminal X_S has to be added and $I_{max} = 1/(X_S + X_T)$[4]
- Points on a mechanical damage curve follows the equation $I^2 * t = I_{max}^2 * 2S$[5]
- For transformers with capability between (0.5, 5) MVA, mechanical damage curves begin at 70% of maximum through-fault current; for transformers with capability larger than 5 MVA, mechanical damage curves begin at 50% of maximum through-fault current. Time-to-mechanical-damage is calculated using equation[5].

Display Transformer Damage Curves

The transformer damage curves are plotted per transformer. Whenever a new plot is executed, old curves are eliminated.

Damage curves based on each winding are plotted all at once. If the transformer has more than three windings, damage curves are plotted based on the three windings with higher voltage levels. When plotting a fault, the damage point found on one damage curve is based on its own winding current. Time to damage reported in the text area, however, is the smallest value of the time to damage from all windings, on the same type of curves (thermal or mechanical).

If a three-winding transformer has a delta-open tertiary winding, or the impedance of the tertiary winding is greater than 9999 in system per unit, or the tertiary belongs to an autotransformer, damage curves for such tertiary winding are not plotted or reported.

Prepare to Plot

Before plotting the damage curves, make sure the transformer impedances are properly set. Setting the transformer MVA rating in the database is preferred. For transformers modeled as XFMR branches, the program takes transformer rated MVA from the "Self-cooled" tab of the MVA Ratings (see Figure 2). For N-circuit transformers the program takes the largest MVA rating from MVA Rating Group 1, which can be accessed from the Transformer Catalog in the Library menu of the Database Editor (see Figure 3). However, if the MVA rating is not stored in the database, the program will prompt for that information once the plotting is initiated.

Plot Damage Curves for a Transformer

To plot the damage curves, go to the CG module, right-click on the transformer in the Data Tree and select "Damage Curve" (Figure 4). The transformer may be under either "NCKT Transformers" or "Transformers" when you unfold a bus under "Buses."

Based on the information in your database, an initialization form pops up asking for missing information (Figure 5). The initialization form first asks for the rated MVA if it's not stored in the database. If the rated MVA is properly set, the rated MVA tab from the initialization form changes to non-editable.

If the rated MVA is above 5 and "More than 5 times" has been selected for the question of "Through-faults in life span," the form expands to show area for input of system impedance (Figure 6). You can select "User specific" and enter the system impedance in the tab or select one of the three options below and have the system impedance added automatically based on your choice. It should be noted that the system impedance is entered in per unit to transformer's rated MVA.

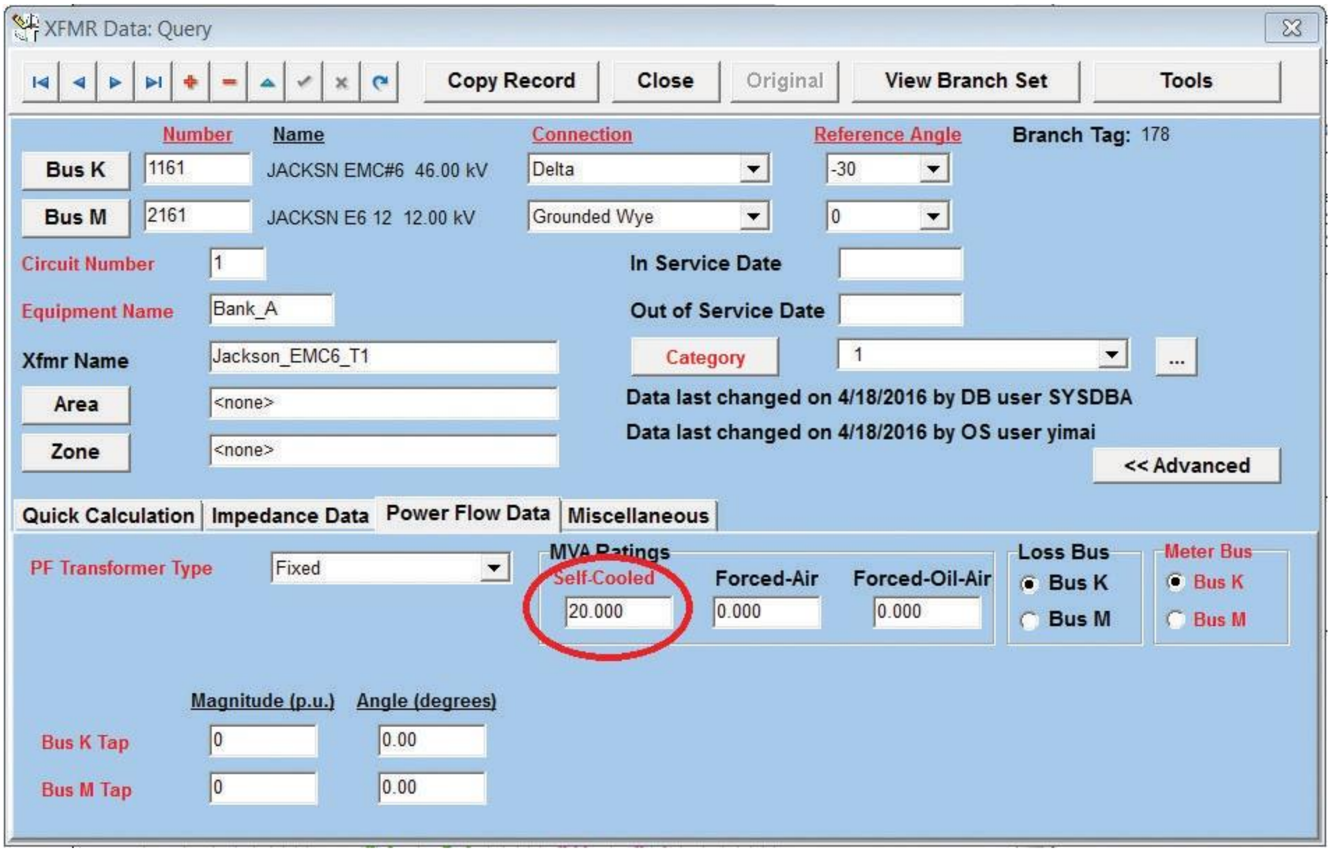


Figure 2: MVA Rating Tab for XFMR Branches

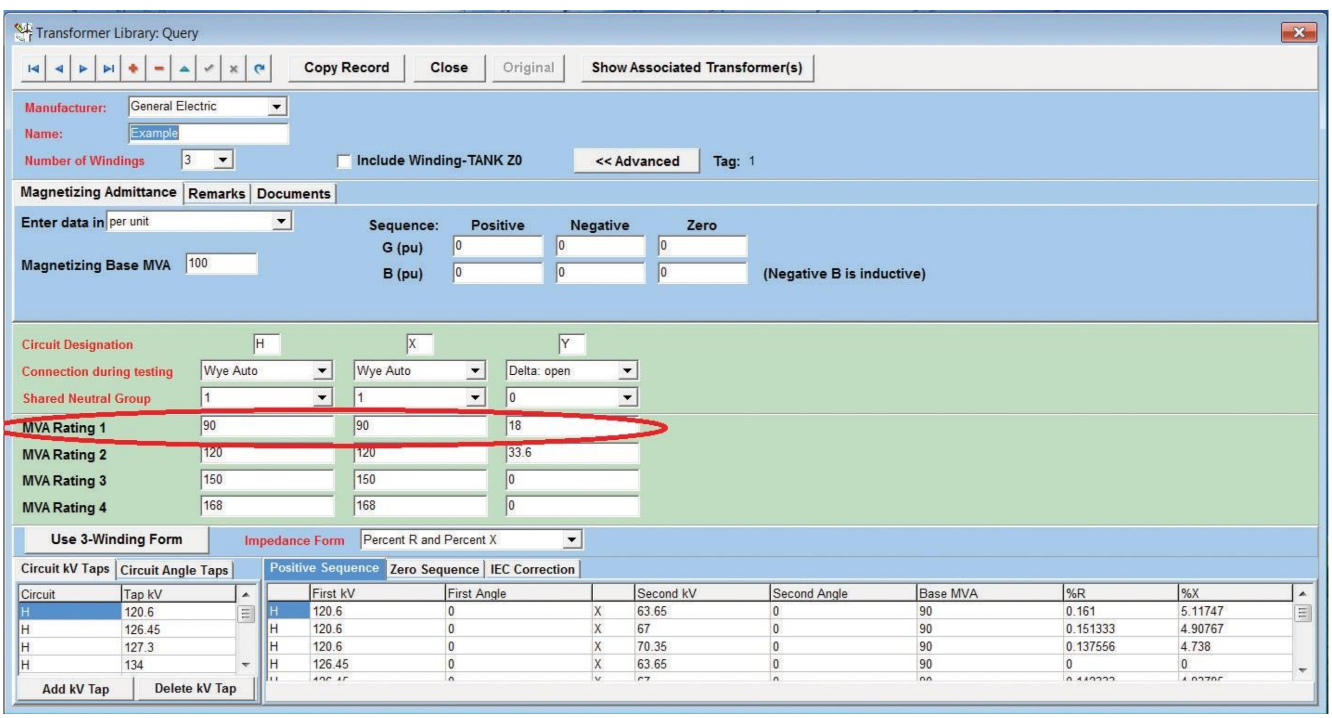


Figure 3: MVA Rating Tab for N-Circuit Transformers

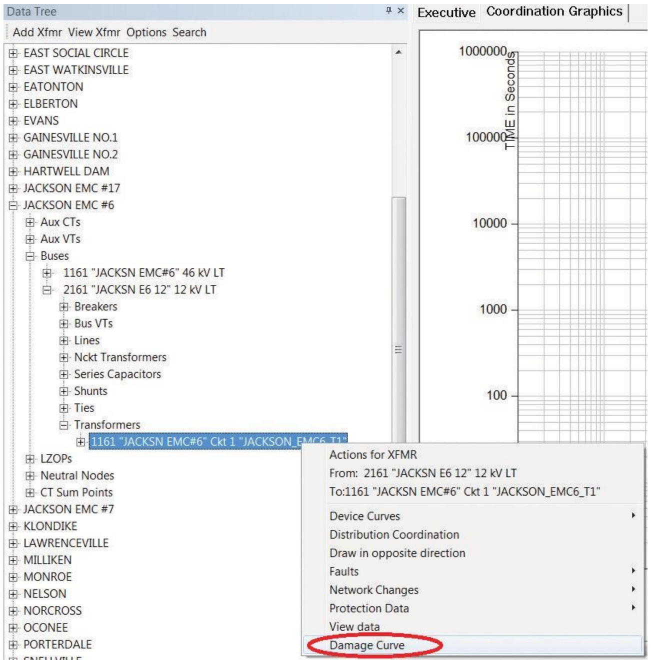


Figure 4: Initiate Display of the Transformer Damage Curves

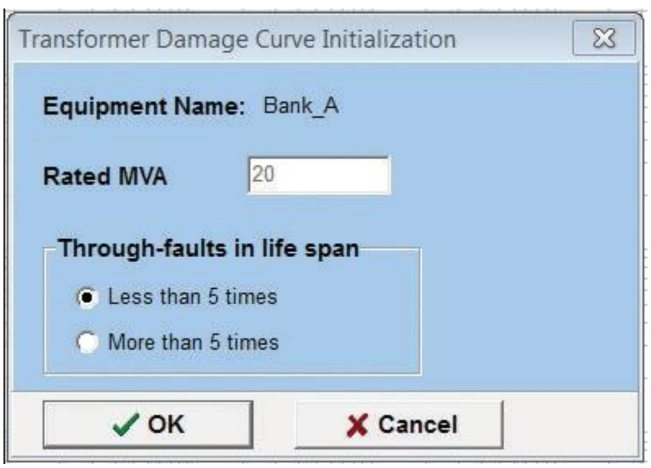


Figure 5: Initialization Form

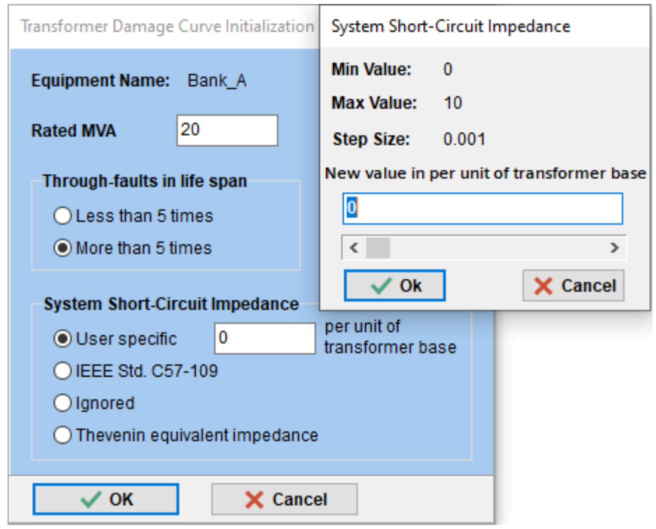
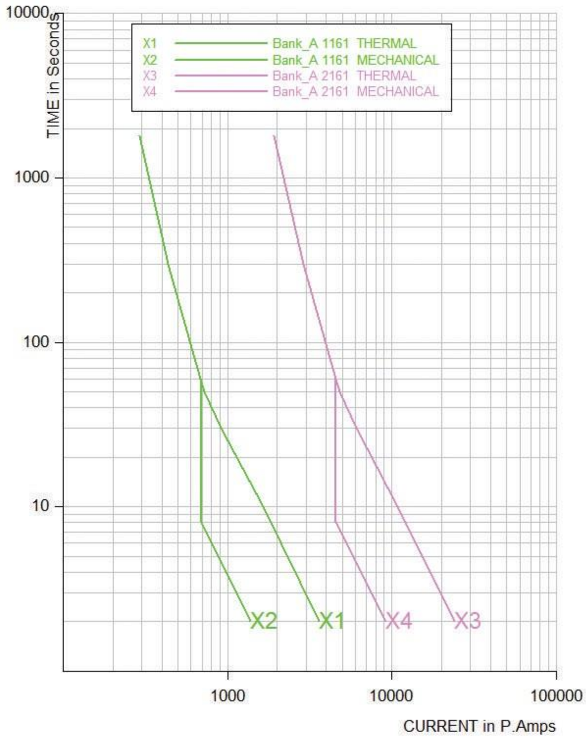


Figure 6: Expanded Initialization Form

Once the initialization is done, the damage curves for the selected transformer are plotted. Figure 7 shows the damage curves plotted for transformer BANK_A in “cape.gdb” (BUS 1161 – 2161, D/YN). Curves X1 and X2 are based on the HV winding, and X3 and X4 are based on the LV winding.

In the text area the following information is reported:

- Transformer name, model type.
- Substation name, LZOP name.
- Transformer category, rated MVA and choice of through-faults in lifespan (for Categories 2 and above.)
- Transformer impedance in p.u. of system base; system short-circuit impedance at source side terminal, in p.u. of system base (for Categories 3 and 4.)
- Winding information: HV/LV, terminal bus number, connection type, and rated winding current in primary Amps.
- Curve points for each of the damage curves.




```
Transformer Damage Curve
Bank_A      Model Type: XFMR
=====================================================
Substation: JACKSON EMC #6;  LZOP: NONE
Category: 3; Rated MVA:   20.00;  Through faults in lifespan: more than 5
System Impedance:  0.000+j 0.300 system p.u. From: user input
Transformer impedance H-L:  0.016+j 0.225 system p.u.

Winding Name      Terminal Bus      Widning Type      Rated Winding Current(A)
H                     1161          DELTA                144.93
L                     2161          WYE-GND              962.28

Bank_A 1161  THERMAL
Winding Current (A)        Time to damage (S)
  289.86                    1800.00
  434.78                     300.00
  688.41                      60.00
  724.64                      50.00
  913.04                      30.00
 1637.68                      10.00
 3623.19                       2.00

Bank_A 1161  MECHANICAL
Winding Current (A)        Time to damage (S)
  689.56                      59.65
  689.56                       8.00
 1379.11                       2.00

Bank_A 2161  THERMAL
Winding Current (A)        Time to damage (S)
 1924.56                    1800.00
 2886.84                     300.00
 4570.82                      60.00
 4811.39                      50.00
 6062.36                      30.00
10873.75                      10.00
24056.96                       2.00

Bank_A 2161  MECHANICAL
Winding Current (A)        Time to damage (S)
 4578.46                      59.65
 4578.46                       8.00
 9156.93                       2.00
=====================================================
```

Figure 7: Damage Curves and Report

Warning Messages

If the inputs indicate that mechanical damage curves should be plotted, but the program found the maximum through-fault current less than 2 times the rated winding current, mechanical damage curves will not be plotted. Warning messages appear after reporting of thermal damage curve points (Figure 8a). This indicates unrealistically large settings of transformer impedance and/or system short-circuit impedance.

If the calculated maximum through-fault current is larger than 25 times the rated winding current, it will be adjusted to 25 times the rated winding current. In such cases, the mechanical damage curves overlap with the lower parts of thermal damage curves. Warning messages appear after reporting of mechanical damage curve points (Figure 8b). It indicates unrealistically small settings of transformer impedance and/or system short-circuit impedance.

If the calculated current of the beginning point of the mechanical damage curve is less than 2 times the rated winding current, the current will be adjusted to 2 times the rated winding current. No warning message is given. However, it is recommended to check the transformer impedances or use a smaller system impedance.

```
Bank_A 2161  THERMAL
Winding Current (A)        Time to damage (S)
 1924.56                    1800.00
 2886.84                     300.00
 4570.82                      60.00
 4811.39                      50.00
 6062.36                      30.00
10873.75                      10.00
24056.96                       2.00
** WARNING: Unable to plot mechanical damage curve. **
** WARNING: Check transformer impedance and system SC impedance. **
=====================================================
```

a. Reporting Failed Plot of a Mechanical Damage Curve

```
Bank D  152  MECHANICAL
Winding Current (A)        Time to damage (S)
 3137.87                    8.15
 3137.87                    8.00
 6275.73                    2.00
** Warning: Maximum through-fault current too large.     **
**          Adjusted to 25 times rated winding current.  **
=====================================================
```

b. Reporting Adjusted Mechanical Damage Curve

Figure 8: Warning Messages

Actions for Transformer Damage Curves

Upon display of transformer damage curves, you can right-click on a curve and choose one of the following actions (Figure 9):

- Change the curve style. Changes color, width, and dash style of the curve.
- Alignment. Align curves based on the selected damage curve or remove alignment, only when an active fault is available in CG.
- Hide XF_DMG curves. You can hide the selected curve, hide curves belonging to the same winding or hide mechanical curves. Hidden curves can be brought back by "Redraw XF_DMG Curves".
- Redraw XF_DMG curves. Redisplay the hidden transformer damage curves. The same action is available when clicking on a blank spot of the graphic area.
- Remove XF_DMG curves. Removes curves from display and resets damage curve buffer. The removed curves cannot be brought back by "Redraw XF_DMG Curves".
- Curve Label Style. Show/hide curve label or bring up info-box. Info-box provides a detailed description of the curve (Figure 10).
- Plot a fault. Plot a fault on all displayed curves.

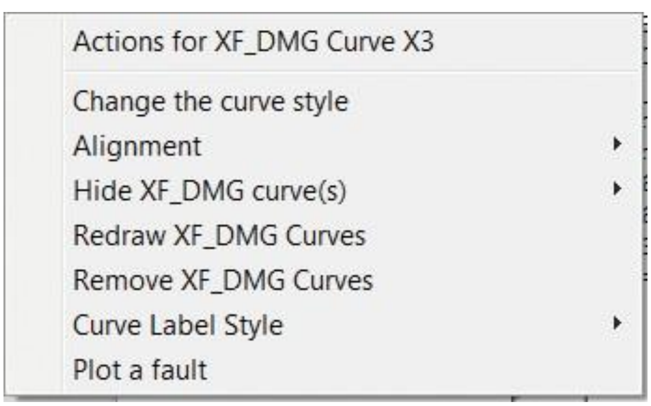


Figure 9: Actions for a Damage Curve

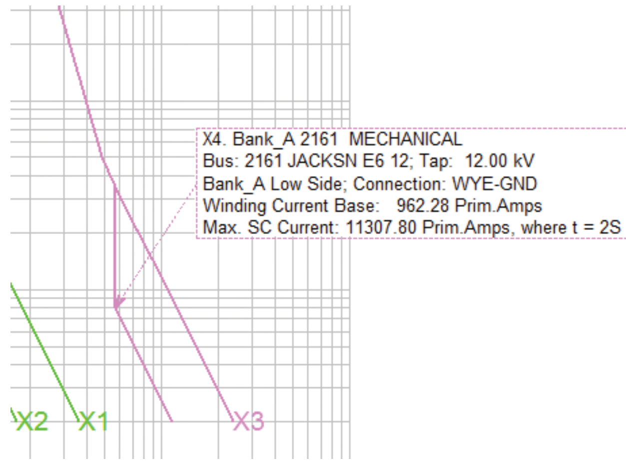


Figure 10: Info-box

Fault Study with Transformer Damage Curves

Display Transformer Damage Curves with Device Curves

The transformer damage curves can be added before or after you add the device curves to display. The titles of damage curves always appear after those of device curves in the key area.

When damage curves are displayed, the unit for current is fixed to Primary Amps.

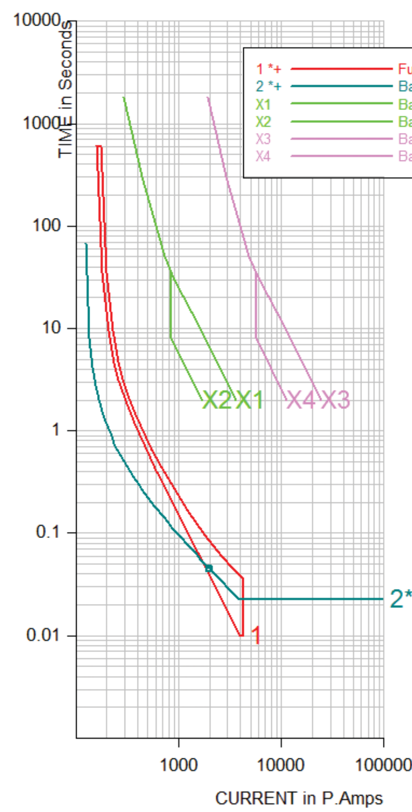


Figure 11: Display Damage Curves and Device Curves in One Graph

Plot Faults and Align Curves

Plotting a fault and alignment with the presence of damage curves is the same as plotting a fault on any device curves. Alignment can be done with either a damage curve or a device curve serving as the base, as long as there is a damage time/operating time associated with that curve (Figure 12).

For two-winding transformers, the damage curves of different windings coincide after alignment. For transformers with three windings and more, the damage curves may not coincide due to the induction with unplotted windings.

If the winding current caused by the fault is within the range of a damage curve, the program plots the fault on that curve. In the text area the time-to-damage is listed following the operating of devices in the fault report. The pickup in the report is the multiples of winding current to the rated winding current for damage curves. Time-to-damage is listed under "Operating Seconds."

The report on transformer damage comes after the fault report (Figure 13). In this report time-to-transformer-thermal-damage is the shortest damage time on all thermal damage curves, hidden or not. Time-to-transformer-mechanical-damage is the shortest damage time on all mechanical damage curves, hidden or not.

If the winding current is larger than the current at the stopping point of a damage curve, the damage time at the stopping point is reported with a note saying "(Rating exceeded)." If the winding current is less than the current at the beginning point, the damage time is "infinite."

If there are any devices, the margin of safety is calculated and reported. Margin_T is the time gap between the operating of an element and Time-to-transformer-thermal-damage. Margin_M is the time gap between the operating of an element and Time-to-transformer-mechanical-damage. If an element does not operate, the margin is reported as "NO MARGIN". If the operating time is larger than the damage time, the margin is a negative value.

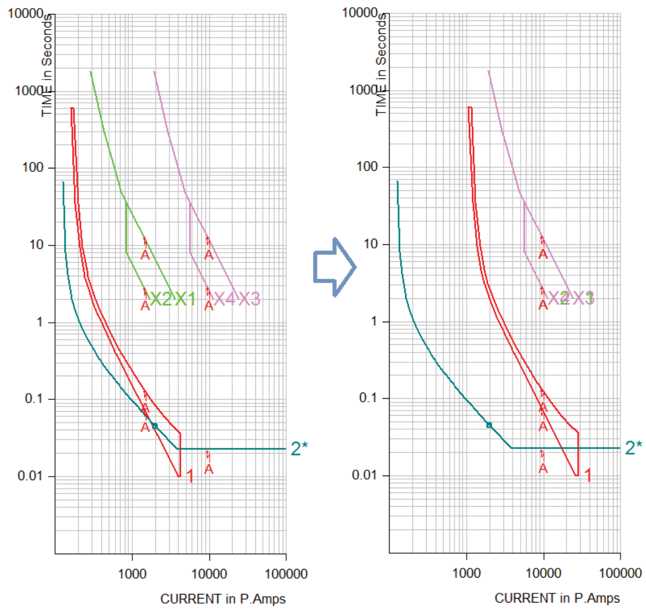


Figure 12: Plot a Fault and Align Curve

```
Fault: A
  SINGLE_LINE_GROUND at bus 2161 JACKSN E6 12

Curve          Current           Operating   Source/Total line (+ seq SIR)
          Primary A  A/Pickup   Seconds
--------------------------------------------------------------------------
  1MM     1429.13      8.97         0.076
  1TC     1429.13      8.16         0.134
  2       9488.73     75.91         0.022     1.94 @-174.1
 X1       1429.13      1.49        12.919
 X2       1429.13      1.49         2.840
 X3       9488.73      9.86        12.920
 X4       9488.73      9.86         2.840

Time to Transformer Thermal Damage:           12.9 Seconds
Time to Transformer Mechanical Damage:            2.8 Seconds
 |
Transformer Protection Safety Margin in Seconds
Margin_T: Safety margin to thermal damage
Margin_M: Safety margin to  mechanical damage
-----------------------------------------------
      Op.Time     Margin_T     Margin_M
  1    0.134        12.8          2.7 Seconds
  2    0.022        12.9          2.8 Seconds
```

Figure 13: Report of Operation and Margin of Safety

References

[1] "IEEE Guide for Liquid-Immersed Transformer Through-Fault-Current Duration," IEEE Std C57.109-2018.

[2] Russ Patterson, Elmo Price, "Transformer Overcurrent Protection Coordination," 69th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, April 29 – May 1, 2015.

[3] Russ Patterson, "A Little about Transformer Damage Curves," PSS®CAPE Users' Group Meeting, Ann Arbor, MI, June 2013.

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