Improved Transformer Condition Monitoring with Practical through-fault Detection Algorithm

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Agenda

Transformer protection

Impact of through faults

Improved through-fault algorithm

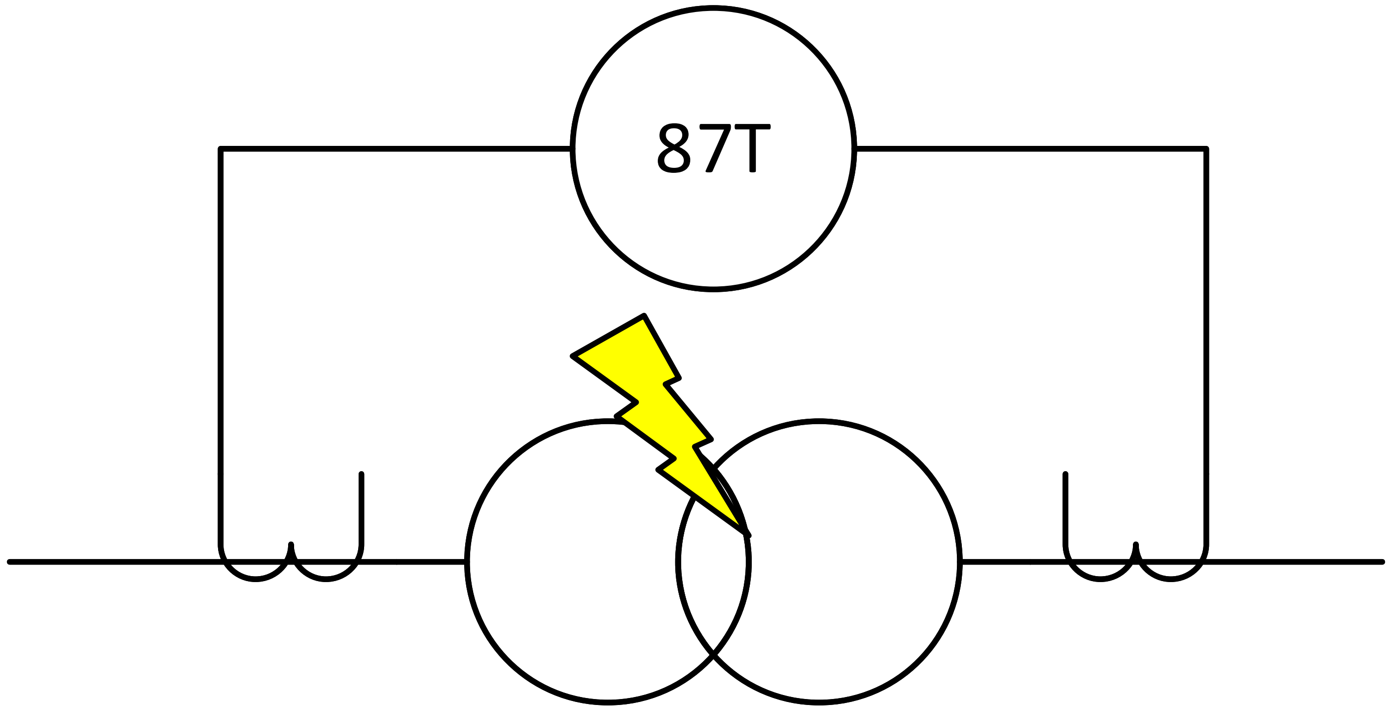
Testing

Transformer zone of protection

Transformers are critical assets

Differential protection guards against internal faults

Zone of protection is around transformer

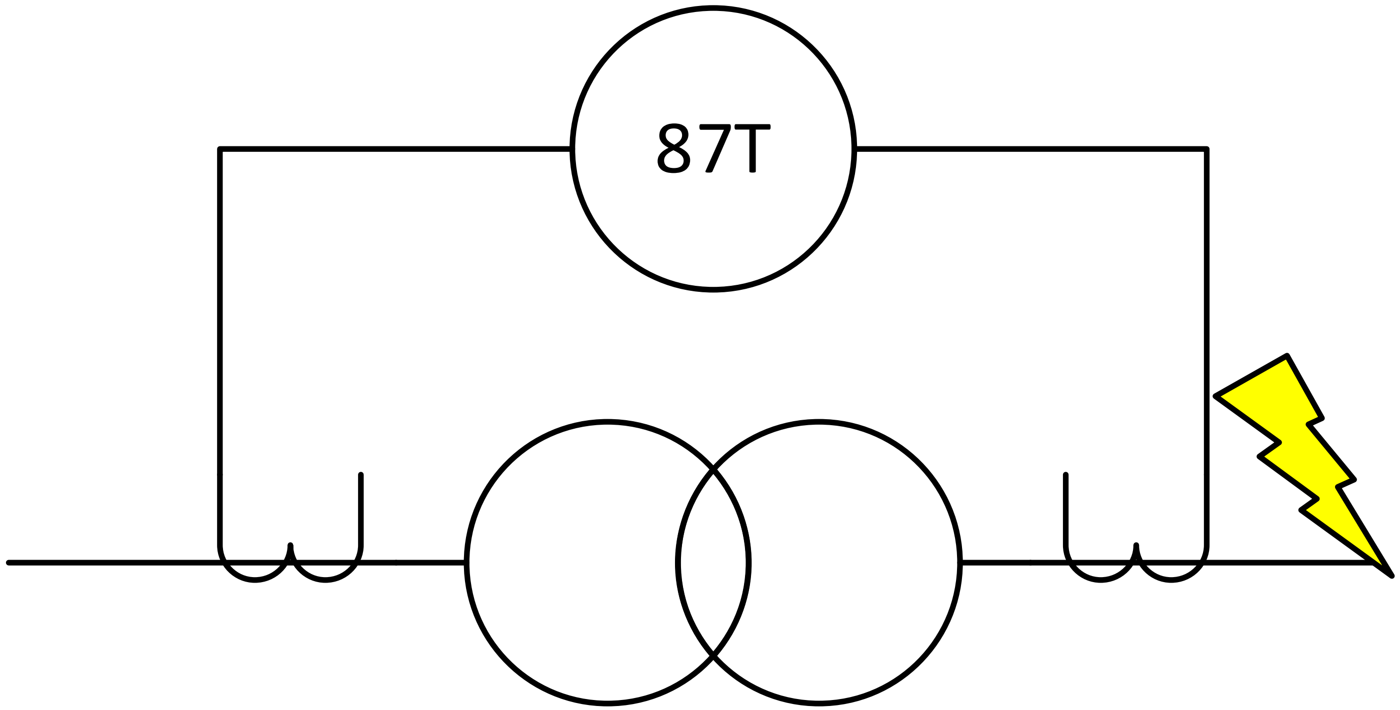


Transformer through-faults cause excessive current

Faults outside differential zone of protection

Excessive currents not detected by differential protection

Transformer life is reduced



Transformer category ratings

Class I, II, and some III are mostly distribution transformers

Class III and IV are transmission transformers

Transmission transformers protected with digital relays

Category	Single phase (kVA)	Three phase (kVA)
I	1–500	15–500
II	501–1667	501–5000
III	1668–10,000	5001–30,000
IV	> 10,000	> 30,000

Transformer short-time thermal load capability

Transformer can withstand excess current for limited time

IEEE differentiates between faults and possible overloads by using two slope characteristics

For Category III and IV withstand based on transformer short-circuit impedance

Time (s)	Times rated current
2	25
10	11
30	6.3
60	4.5
300	3
1800	2

Transformer withstand capability curves

IEEE Std. C57.109-2018 and IEEE Std. C57.12.59-2015 provide maximum through-fault current duration limit curves

Curves based on:

p X ? ñ, ç Eq. 1

Where k is constant determined at maximum current at time t = 2 seconds

Consequently

ç , p X Ñ ? ñ, X[X ? X, WX[U Eq. 2

Where I_b = 25 A is base current per IEEE standards

Smaller current increases maximum tolerable time

Maximum tolerable time for smaller magnitude faults is longer and can be estimated

ñ] US , WX[U / NU:] • X[N² , Z:U^ ï ,   ñ[US , WX[U / NU:[• X[N² , ^ ï   Eq. 3

Different transformer impedances reduce maximum short-circuit magnitudes

p' CWU / WUUS , WUUS / WUS , WUí ó=   p' C\ / WUUS , WUUS / \ S , W :\ ] í ó   Eq. 4

Short-circuit magnitude for 70% at 4.08 s

p' CWU /] US ,] US / WUS ,] í ó=   p' C\ /] US ,] US / \ S , WW:\ ] í ó   Eq. 5

Impact on transformer monitoring

Larger current: less time

Smaller current: more time

IEEE standards mute on accumulating faults above and below 50% of maximum possible current

Accumulation left to algorithm implementation

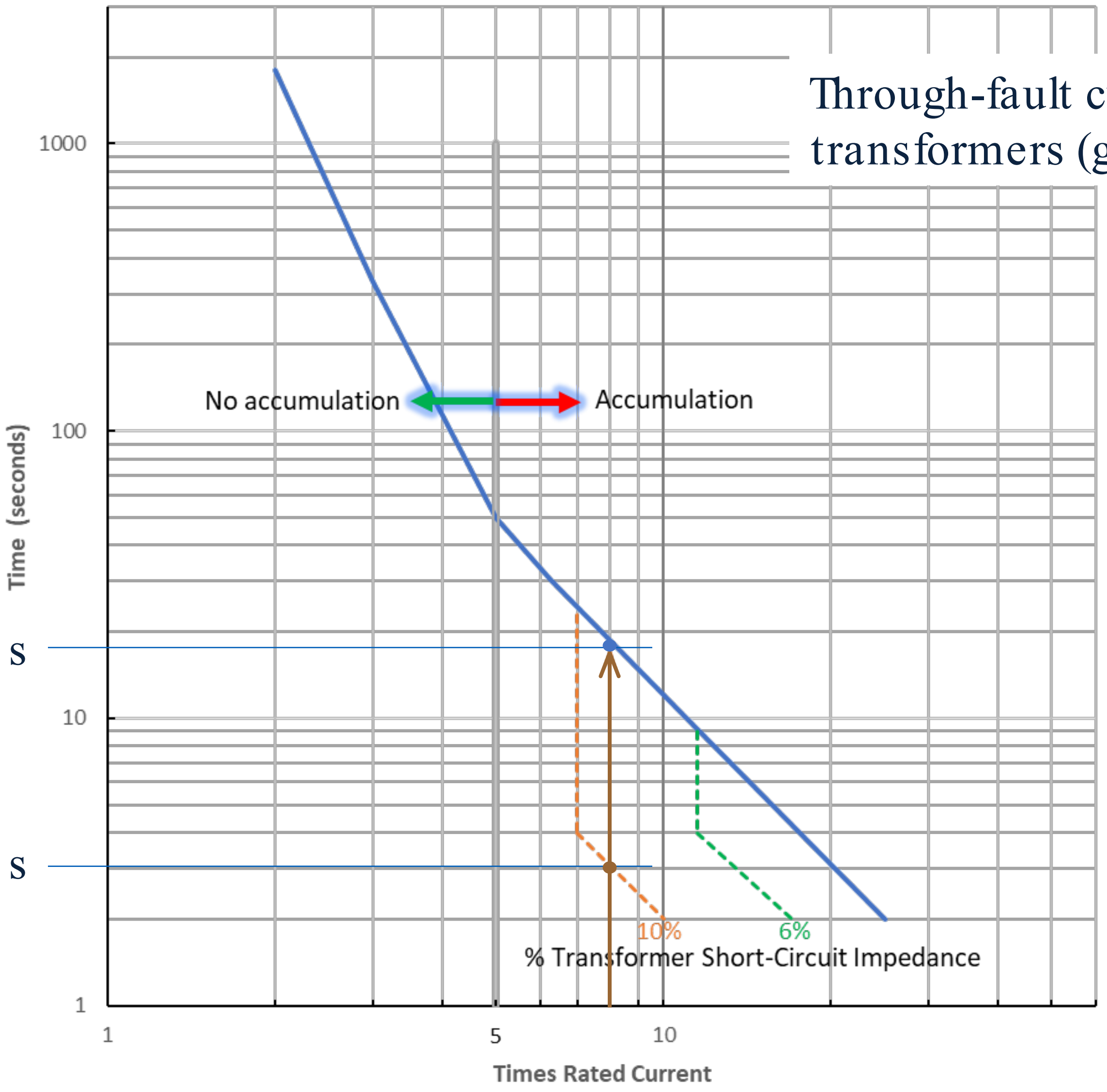
Transformer impedance (%)	Symmetrical short -circuit current (pu of winding rated)		
	100% • I_M, t = 2 s	70% • I_M, t = 4.08 s	50% • I_M, t = 8 s
4 (base)	25	17.5	12.5
6	16.67	11.67	8.33
8	12.5	8.75	6.25
10	10	7	5

Through-fault curves

Through-fault curves for Category IV transformers (greater than 10 MVA)

Thermal damage, 10.8 s

Mechanical damage, 3 s



Improved transformer-monitoring algorithm

Use single accumulator per phase and per winding to obtain accumulation quantity

Category IV example:

{o y| &m s{ hÖÖöè , Σ$_{U}^{ê}$ $\frac{p_{ê}^{X} \bullet Ωñ_{ê}}{sãè}$ 1 záñMíóN   Eq. 8

Where p$_{ê}$ is n fault current magnitude; Ωñ$_{ê}$ is n fault duration; Lim is defined as

If p$_{ê}$ 0 U:[• p$_{t}$ (large magnitude): sãè , X • p$_{t}^{X}$ Eq. 9

Otherwise (small magnitude): sãè , WX[U

For larger magnitude faults, accumulation is faster, based on 2-s requirement

For smaller magnitude faults, accumulation is slower, based on 1250 limit

Improved algorithm example

Category IV transformer, Z% = 8, I_M = 12.5 pu, through-fault duration = 0.1 s

Accumulation and faults tolerated for same-magnitude fault per IEEE standards

I_n (pu)	I_M (pu)	Δt_n (s)	$THRU\_FLT\_Accum$ (pu)	# of faults ((1pu/$THRU\_FLT\_Accu$
12.5	12.5	0.1	0.05	20
10	12.5	0.1	0.032	31
8	12.5	0.1	0.0205	48
6	12.5	0.1	0.0029	347

Required settings

Setting	Purpose
CT SOURCE	Single CT or dual CT (2 circuit breakers)
GROUP COMPENSATION	For CTs outside delta winding; divides current by √3 to obtain winding current
RATED MVA: 100.000	MVA of monitored winding; derive base current
RATED PHS-PHS KV	Rated voltage of monitored winding
WINDING CATEGORY	Transformer Category I, II, III, or IV; to apply proper curve, per standard
MAX FAULT CURRENT	Maximum through-fault current derived from transformer Z% impedance
FREQUENT FLT LEVEL	Threshold for Category II and III for different curves for frequent and infrequent faults
TOTAL ACCUMULATION MAX	Threshold for element output when accumulation exceeds max tolerable
FAULT COUNTER MAX	Through-fault count threshold to alarm
RESET/PRESET ACCUMULATION	Set known value from old relay

Monitored values

Count of through faults, per phase, per winding

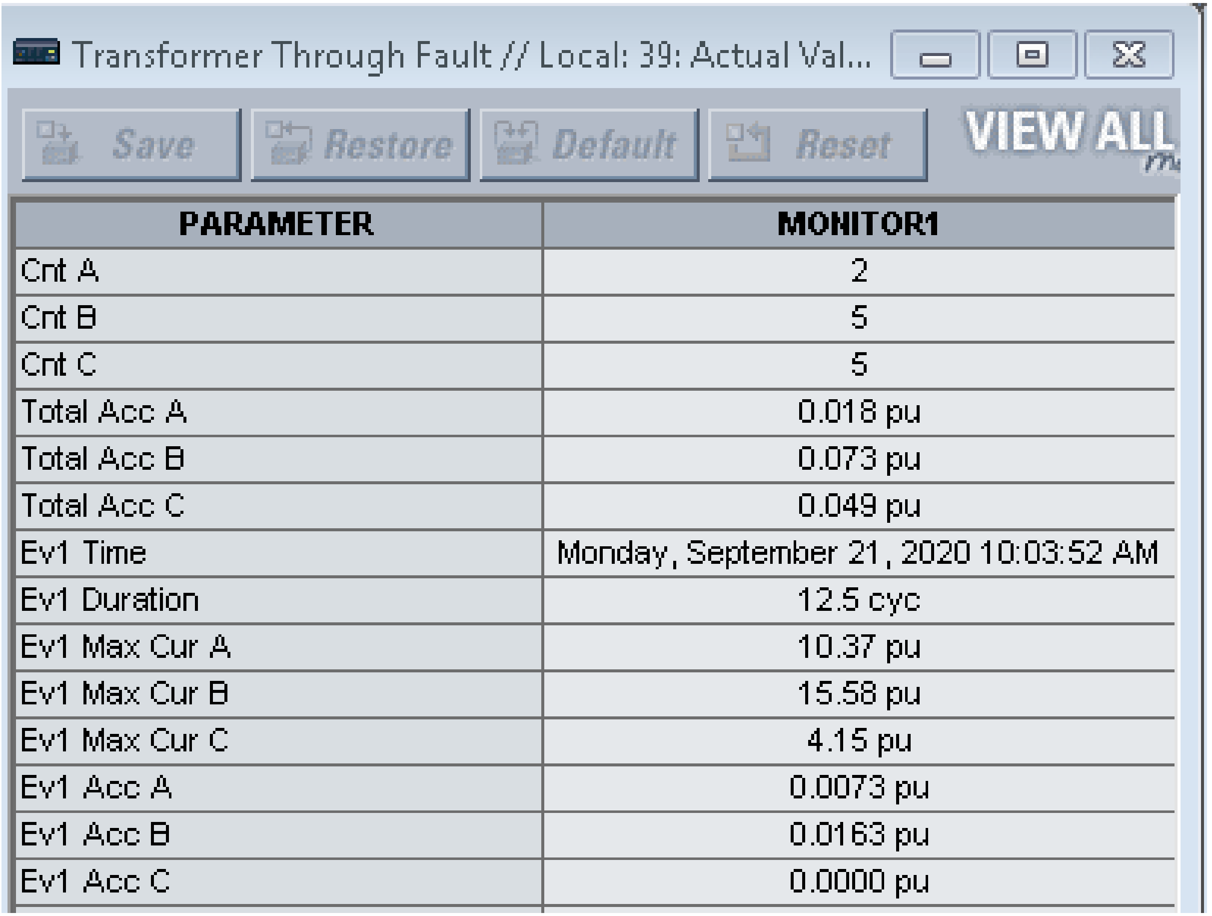
Total accumulation, per phase, per winding

Through-fault time per each event

Through-fault accumulation per each event

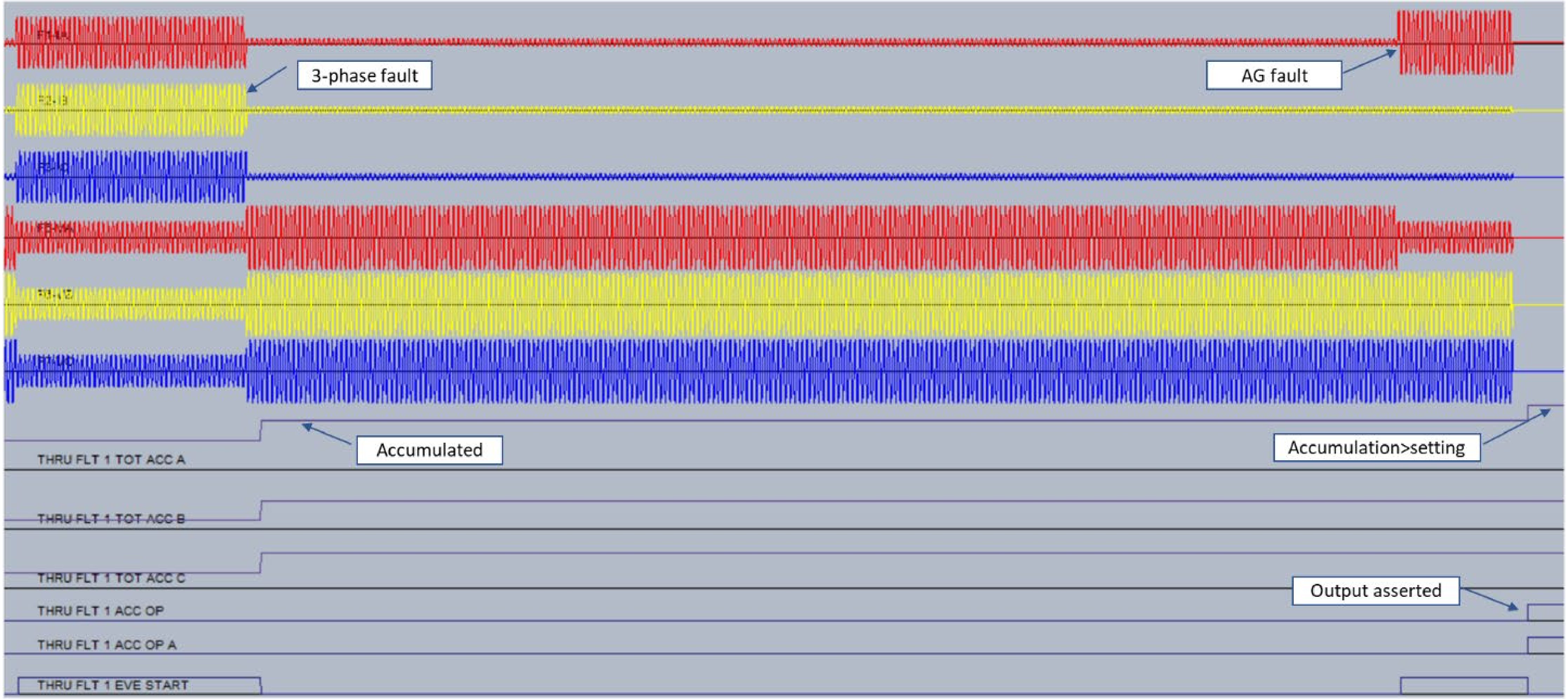
Through-fault duration per each event

Through-fault maximum current,
per each event, per each phase

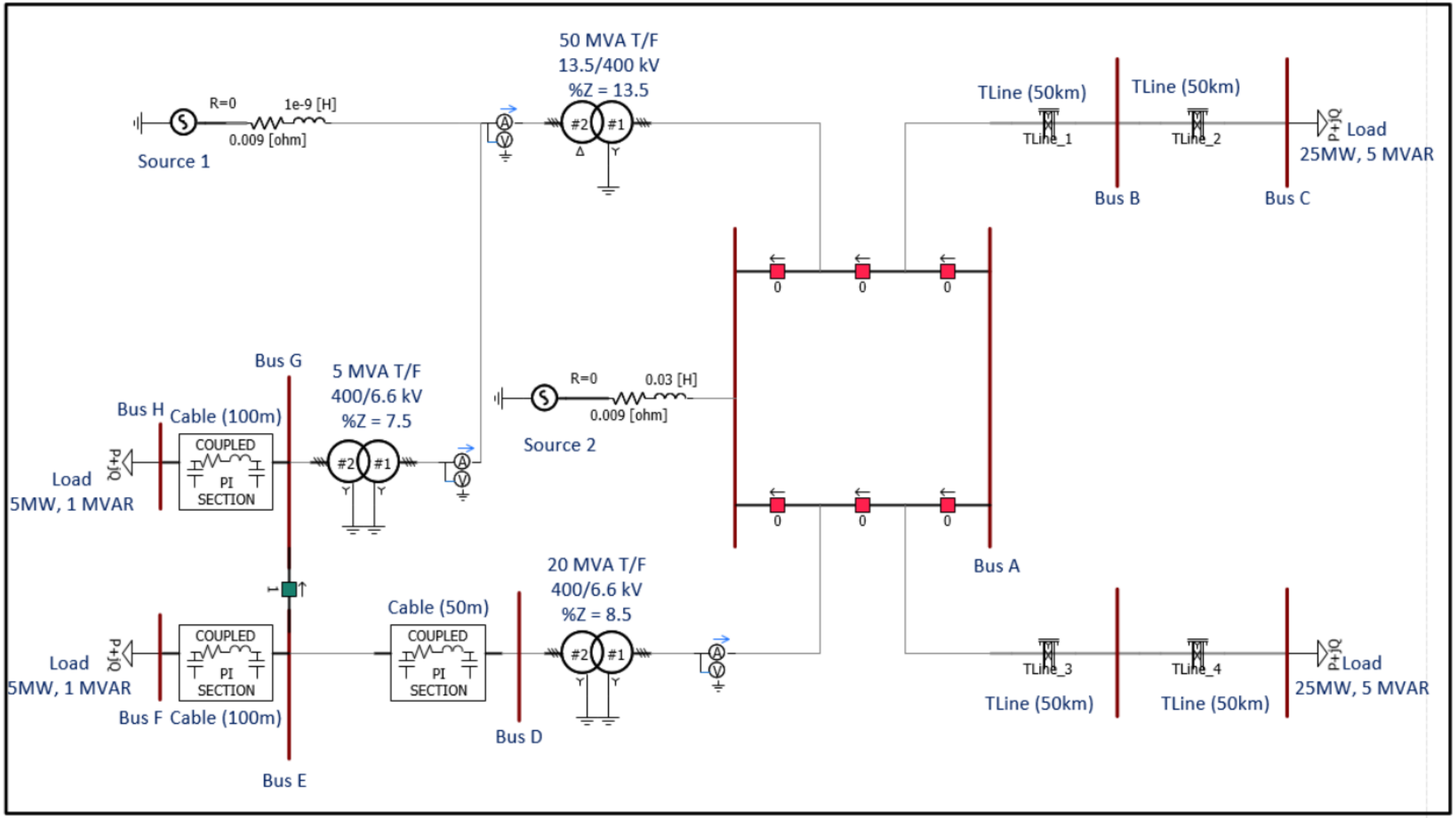


PARAMETER	MONITOR1
Cnt A	2
Cnt B	5
Cnt C	5
Total Acc A	0.018 pu
Total Acc B	0.073 pu
Total Acc C	0.049 pu
Ev1 Time	Monday, September 21, 2020 10:03:52 AM
Ev1 Duration	12.5 cyc
Ev1 Max Cur A	10.37 pu
Ev1 Max Cur B	15.58 pu
Ev1 Max Cur C	4.15 pu
Ev1 Acc A	0.0073 pu
Ev1 Acc B	0.0163 pu
Ev1 Acc C	0.0000 pu

Visualize and analyze through-fault events accumulation; plan predictive maintenance in advance



Test system (EMTP / PSCAD)



Study Category IV transformer (50 MVA, 13.5 / 400 kV, %Z = 13.5)

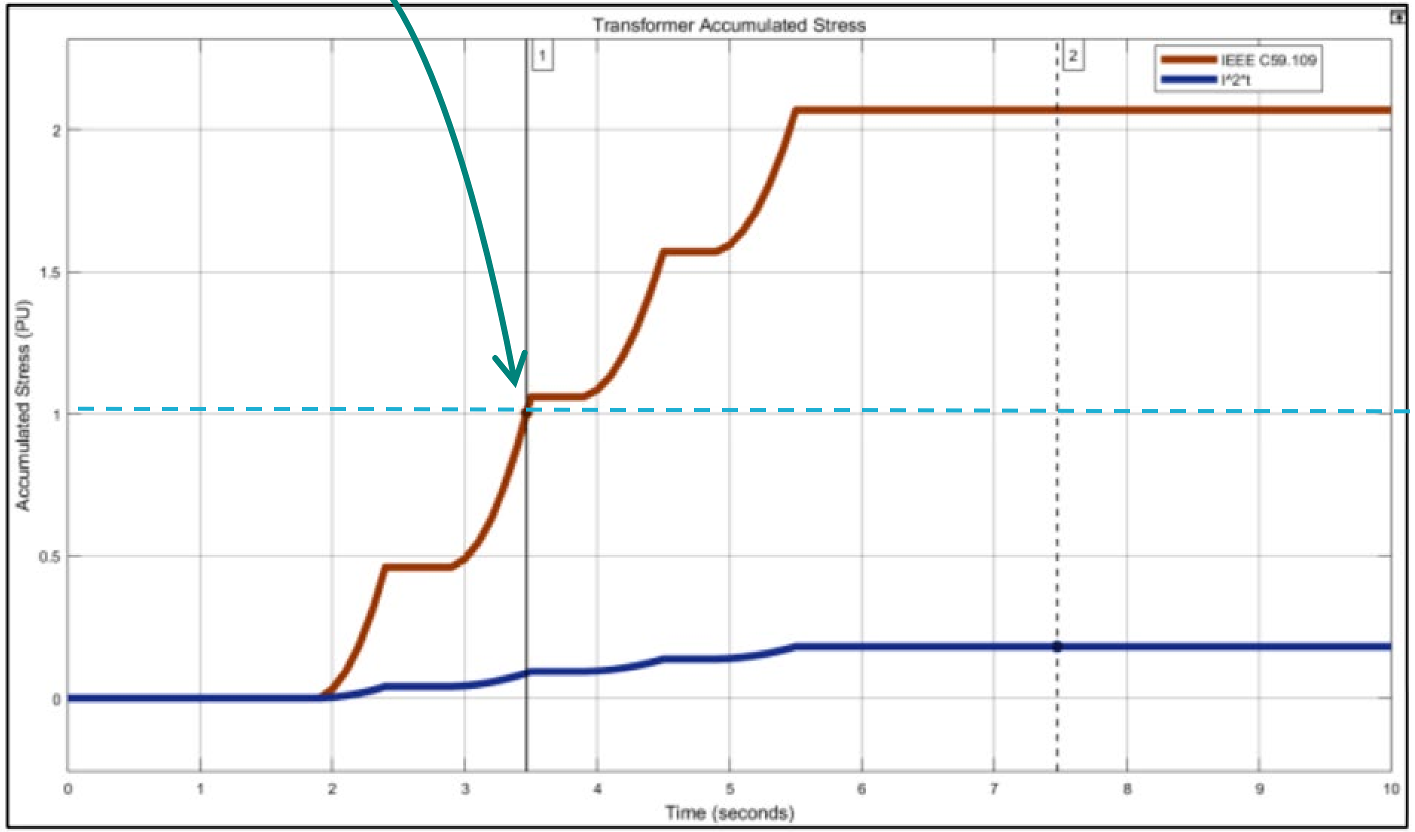
Fault label	R_F (Ω)	Location	Fault type	I_F (pu)	t_F (s)
F1	0	Bus A	LLG	7.07	0.45
F2	10	Bus A	LG	5.6	0.55
F3	0	Bus B	LG	5.3	0.58
F4	10	Bus B	LG	5.12	0.59
F5	10	Bus C	LG	3.6	0.65
F6	15	Bus C	LG	3.4	0.68

Test results compare IEEE and I^2t methods

IEEE method reached at fault F2

I^2t method did not reach threshold

Cumulative thermal and mechanical damage threshold is 1 pu



Conclusions

It is important to monitor through faults to schedule maintenance

Large-magnitude faults cause more mechanical damage than thermal damage

Greater mechanical stress shortens transformer life

IEEE Std C57.109- 2018 and IEEE Std C57.12.59- 2015 provide maximum through-fault, current-duration limit curves

IEEE method provides better performance compared to conventional I^2t method

Questions?