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Ferroresonance Analysis Due to the Effect of External Faults on a 20 kV Voltage Transformer

Maulana Hidayatullah[1] **Iwa Garniwa** [2]
[1,2] Department of Electrical Engineering
Universitas Indonesia
Email: maulana.hidayatullah@ui.ac.id , iwa@eng.ui.ac.id

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Ferroresonance, Inductive Voltage Transformer, Medium Voltage Switchgear.

Abstract

Medium Voltage (MV) Switchgear is an essential component in the electric power distribution system with a working voltage of 20 kV. MW Switchgear consists of Circuit Breaker (CB) and Voltage Transformer (VT). VT is one component that often fails in MW Switchgear in the power distribution system, where conditions cause the VT iron core to saturate. This saturation zone will make whatever capacitance reactance value (X_C) that generated from the power system network will be the same value as the inductive reactance value of the indsuctance VT (X_L), which causes the impedance value to be zero. A very wide frequency range will be able to trigger a ferroresonance which results in a large current flowing on the primary side of VT and has the potential to cause failure in VT and MV switchgear, characterized by an explosion. This research will focus on the main causes of ferroresonance emergence due to external disturbance, 20kV VT specification and MV Switchgear. Ferroresonance simulation is carried out by ATPDraw Software, external disturbance variations, VT and MV Switchgear specifications are given for simulation to observe the response of VT's voltage and current. The variables studied include disturbances of CB switching operations which have an impact on the emergence of variations in network capacitance values and produce subharmonic mode ferroresonance with voltage value reaches 150% of the nominal voltage for Cg = 0,005 – 0,1 μF and 275,5% of the nominal voltage for Cs = 0,05 – 1 μF, then disturbances of lightning impulse currents which will cause ferroresonance in networks with small capacitance values, this disturbance is very dangerous because it creates ferroresonance with the amplitude of the primary voltage VT can reach 14.391% of the rated voltage, and quasi-periodic mode's ferroresonance resulting from a single phase to ground fault which reaches 201.47 % of the rated voltage value. The choice of a VT design with a voltage factor of 1.9Un/8h and an MV Switchgear design which loads the VT burden with an inductance composition that is greater than its resistance and approaches 80% of the VT burden specification can mitigate the emergence of ferroresonance.

1. Introduction

Medium voltage switchgear is an electrical power system equipment that functions as a divider, connector, controller, and protection. In Indonesia's electric power system, managed by the State Electricity Company, medium voltage switchgear is generally used in Substations. Medium voltage switchgear is one of the essential components in the electric power distribution system with a 20 kV rated voltage. Several types of medium voltage switchgear have main constituent components in the form of circuit breakers (CB). As its functions for protection and metering, medium voltage switchgear is also equipped with instrument transformers in the form of Current Transformers (CT) and Voltage Transformers (VT). There are various kinds of problems in medium voltage switchgear that cause failure of the distribution system, one of the worst of these failures is an explosion which disrupts the distribution of electric power to customers. Most of these failures are caused by explosions generated by the Voltage Transformer (VT). Based on Research and Development Center of State Electricity Company shows that the ferroresonance phenomenon causes the highest VT failure. The explosions of VT due to ferroresonance occur in certain types of VT, and production years. Therefore, designing the right VT and medium voltage switchgear is essential to avoid this ferroresonance phenomenon.

Ferroresonance is a non-linear resonance phenomenon that can affect the voltage and current conditions in the electrical power network. This phenomenon can cause abnormal harmonic values, overvoltage, and overcurrent transient or steady state, which are dangerous for electrical equipment [3]. Ferroresonance is described as a complex resonant oscillation in a series RLC circuit. This phenomenon often occurs in electric power distribution systems due to the saturated non-linear inductance of voltage transformers and capacitive effects from the distribution network [2,4]. The capacitive effect is provided by some reason, such as protection equipment (switches), electric power transmission components (conductor capacitance to earth, coupling between line circuits, capacitor banks), insulation components (bushings capacitance), or measurement components (Capacitive Current Transformers). Ferroresonance occurs when there is a transient fault (transient overvoltage, lightning overvoltage, or transient fault) or switching operation (energize transformer or fault relief) (Hernanda et al., 2020)[5].

This research will discuss more specifically the triggering factors for the ferroresonance occurrence in the form of changes in the magnitude of the VT load from electromechanical to digital meters and relays with small VA power consumption. In addition, VT design errors and its use in medium voltage switchgear trigger a sudden saturation of the VT iron core, which causes ferroresonance and failures and explosions, characterized by an increase in the value of current and voltage on the primary side of VT, so that the primary side becomes burned. This research will be carried out on the main cause of the saturation of the iron core VT which triggers the emergence of ferroresonance in the VT installed in the medium voltage switchgear. Differences in the VT saturation point design will be combined with variations in disturbances in the power distribution system, such as circuit breaker switching operations, single phase to ground faults and the presence of impulse currents or lightning, and VT load value in medium voltage switchgear design. After finding the cause of ferroresonance, an ideal composition of the VT and medium voltage switchgear will be designed to mitigate the occurrence of ferroresonance (Kraszewski et al., 2022).

2. Materials and Methods

A. Inductive Voltage Transformer

Conventional inductive voltage transformers work with the principle of an open secondary winding, as shown in Figure 1 (Minkner & Schmid, 2021).

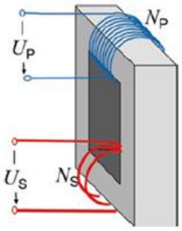


Fig. 1 Inductive Voltage Transformer

The secondary voltage U_S is proportional to the primary voltage U_P and the ratio of the number of turns of the secondary winding N_S and the primary winding N_P. The secondary voltage can be calculated to $U_S = U_P . N_S / N_P$. The accuracy of the voltage transformer depends on the size of the iron core, the resistance of the primary winding, the leakage inductance, and the connected burden.

Figure 2 shows the equivalent circuit diagram of the inductive voltage transformer, reduced to the secondary side. The primary winding is represented by the ohmic resistance *Rp* of the primary winding and the leakage inductance *L*P, and the secondary winding by the ohmic resistance *R*S of the secondary winding and the secondary leakage inductance *L*S. The behaviour of the iron core is represented by the main inductance *L*m and the ohmic losses of the core *R*Fe. The impedance of the external burden is represented by the ohmic part *R*B and the inductive part *L*B. The primary values are converted to the secondary side (Minkner & Schmid, 2021).

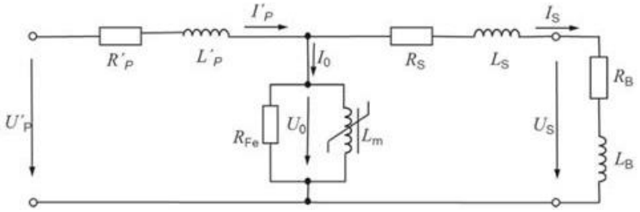


Fig. 2 Inductive Voltage Transformer Equivalent Circuit

There are 3 VT magnetization zones, as shown in Figure 3. The Linear Zone Section 0 – straight line, normal VT operated. The turning point/saturation point is the risk point for VT to experience a saturation zone. In the saturation zone, whatever the value of the capacitance reactance will match the value of the inductance reactance VT and compensate each other so that the impedance becomes 0. The frequency range for the occurrence of ferroresonance becomes very wide. So, it prevented VT not to operate in the saturation zone .

B. Ferroresonance

Ferroresonance is a non-linear resonance phenomenon caused by two main factors: non-linear inductance and a particular capacitance value. Non-linear inductance is caused by the iron core's ferromagnetic nature, which can saturate in Voltage Transformers (Pal & Roy, 2022).

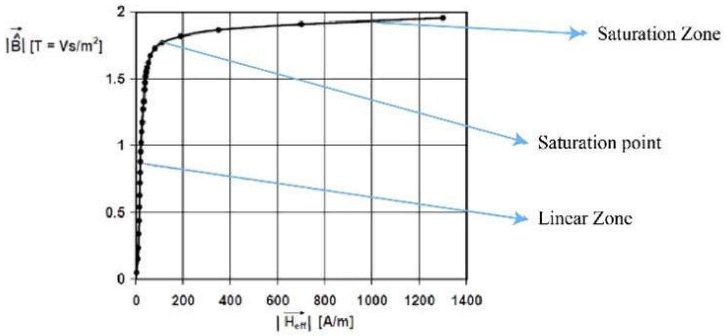


Fig. 3 VT Magnetization Zone

While the value of capacitance is due to the operation of switching circuit breakers in medium voltage networks, substations, the use of CVT (Capacitive Voltage Transformer), and distribution channels at specific lengths, the emergence of ferroresonance is triggered by electrical power breakers operation, such as load shedding, energizing transformers, de-energizing transformers, fault clearing, or disturbances that occur in the power network such as overvoltage transient disturbances due to lightning strikes and short circuits. These triggering factors encourage transformer saturation [5]. A simple circuit of ferroresonance is shown in Figure 4 [3].

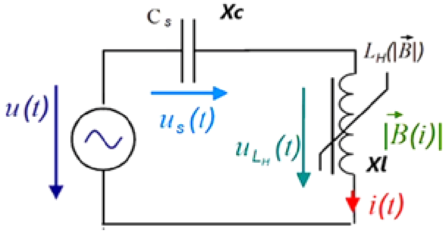


Fig. 4 Simple Circuit of Ferroresonance

Key
$u(t)$ = AC Voltage Source
$u_S(t)$ = Voltage at series capacitance
$u_{LH}(t)$ = Voltage at the main inductance of the voltage transformer (VT)
$i(t)$ = Circuit current
C_S = Series Capacitance
$|\vec{B}|(i(t))$= Flux density as a function of the current i(t)
$L_H(|\vec{B}|)$= Non-linear ain inductance of voltage transformer

The schematic shown in Figure 4 is for series resonance. Resonance occurs when $|X_C| = |X_L|$. If written in complex numbers, then $Z = jX_L - jX_C$. Inductance and capacitance have different polarities, so a short circuit will occur when the voltage applied to the impedance is equal to 0. It seems to result in a short circuit in the primary winding due to ferroresonance. This occurs at a particular frequency of a value X_L and X_C[1,5]. Where X_L is the primary winding inductance VT and X_C equal to capacitance from the network or due to CB switching operations (Heidary et al., 2020).

Based on IEC 61869-102, soft excitation is a ferroresonance oscillation with a slow increase, while hard excitation is an oscillation with a sudden increase rapidly [3]. This hard excitation often occurs in electric power systems, especially distribution systems, as discussed in this study. A sudden iron saturation in the transformer iron core is caused by a switching process in the network or a ground disturbance [3]. Then from these two groupings, there are steady-state and non-steady-state excitations.

EXPERIMENT AND SIMULATION MODEL

In this research, disturbance modeling that can potentially cause ferroresonance will be carried out using ATPDraw software. In addition, variations on the characteristics and burden loading of VT were carried out. To carry out this simulation, initial parameter values are given for VT specification as shown in table I and II.

Table I VT Parameters

Parameters	Value	Unit
Line to line RMS Voltage ($V_{L-L\ RMS}$)	20	kV
Frequency	50	Hz
Primary Resistance (*Rp*)	998.67	Ω
Primary Inductance (*Lp*)	0.0003536	mH
Secondary Resistance (*Rs*)	0.046	Ω
Secondary Inductance (*Ls*)	0.4356	mH
Magnetization Resistance (*Rm*)	95	MΩ
Ideal Transformer Ratio	200	-
Burden Resistance (*Rb*)	100	Ω
Burden Inductance (*Lb*)	5	mH

Table II Non-Linear Inductance Parameters

I(A)	Flux linked (Wb-T)
0.0075	123.79
0.018562	129.59
0.0745246	136.45
0.222739	137.82

A. Ferroresonance due to Circuit Breaker Switching Operations

In this simulation, the disturbance of the Circuit Breaker (CB) switching operation, which causes a value of grading capacitance (Cg), together with the ground capacitance (Cs) that represent channel capacitance to ground, will change the value of capacitance in a distribution network. In this simulation, the variations in capacitance value and its response to ferroresonance phenomenon will be observed. The simulation circuit is shown in Figure 5.

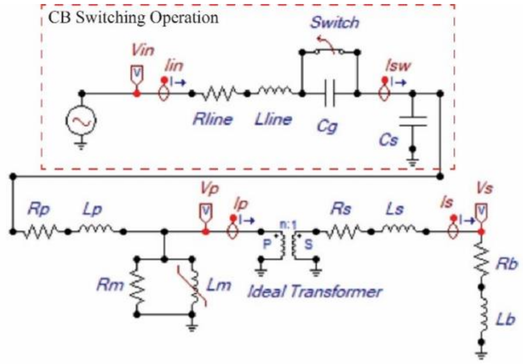


Fig. 5 CB Switching Operation Disturbance Simulation Circuit

Additional and disturbance parameters are varied to carry out the simulation, as shown in Table III.

Table III CB Operation Disturbance Simulation Parameters

Parameters	Value	Unit
Channel Resistance (*Rline*)	0.0020161	Ω/m
Channel Inductance (*Lline*)	0.001285	mH/m
Grading Capacitance (*Cg*)	0.001 - 100	µF
Shunt Capacitance (*Cs*)	0.001 - 100	µF
CB Switching time	0.25	s
Channel Length	1000	m

B. Ferroresonance due to Ground Fault

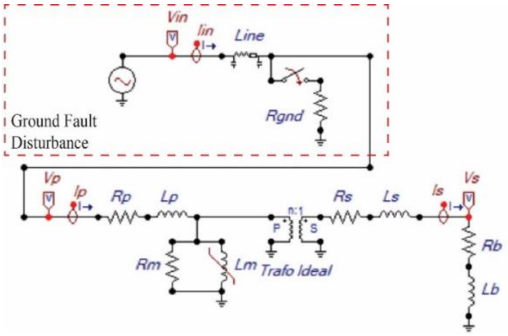


Fig. 6 Ground Fault Disturbance Simulation Circuit

Table IV Ground Fault Disturbance Parameters

Parameters	Value	Unit
Channel Capacitance	0.005 - 5000	pF/m
Channel Length	1000	m
Lightning strike time	0.25	s
Short Circuit Resistance (*Rgnd*)	1	Ω

In this simulation, the disturbance of ground fault will occur after 0.25 seconds from the simulation starting point. The ground fault simulation circuit is shown in Figure 6, and the parameter variations were the capacitance of the distribution line, as shown in Table IV. The primary voltage value will be observed after a ground fault occurs.

C. Ferroresonance due to Lightning Strike

In this simulation, an impulse current with 10 kA amplitudes will be given to the simulation circuit at 0.25 seconds, as shown in Figure 7.

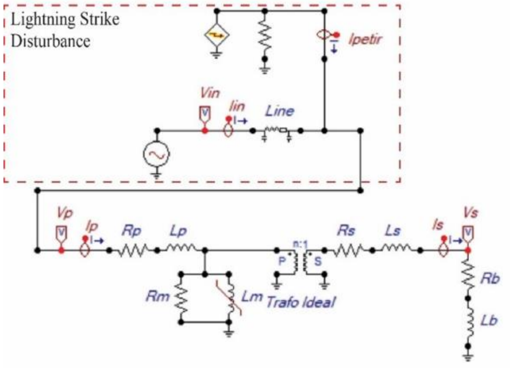


Fig. 7 Lightning Strike Disturbance Simulation Circuit

Distribution line characteristic data is shown in Table V, and the impulse variations characteristic to determine primary voltage response after disturbance is shown in Table VI.

Table V Lightning Strike Disturbance Parameters

Parameters	Value	Unit
Channel Capacitance	0.005	pF/m
Channel Length	1000	m
Lightning strike time	0.25	s
Impuls Current Front Time	0.5 - 2	μs
Impuls Current Tail Time	5 - 200	μs
Impuls Current	10	kA

Table VI Lightning Strike Disturbance Variations

Impuls Variations		Simulation Number	front time (μs)	tail time (μs)
Constant tail time	Decreasing Front time	1	1.2	50
		2	1	50
		3	0.8	50
		4	0.5	50
	Increasing Front Time	5	1.5	50
		6	2	50
Constant Front Time	Increasing Tail Time	7	1.2	75
		8	1.2	100
		9	1.2	150
		10	1.2	200
	Decreasing Tail Time	11	1.2	25
		12	1.2	10
		13	1.2	5

D. Voltage Transformer Non-Linear Inductance

After conducting experiments in the laboratory with the VT Analyzer, it was found that the specification of the Voltage Factor, which is different from each VT, will affect the magnetization curve or saturation point, therefore in this simulation, the response of the primary voltage to changes of non-linear inductance magnetization curve will be observed. The variation of saturation points of VT is shown in Table VII.

Table VII Non-Linear Inductance Saturation Point 1.2x Initial

I(A)	Flux linked (Wb-T) 1.2x Initial	Flux linked (Wb-T) 0.8x Initial
0.0075	148.55	99.03
0.018562	129.59	103.67
0.0745246	136.45	109.16
0.222739	137.82	110.26

E. Voltage Transformer Burden

In addition to the internal VT design factors that influence the emergence of ferroresonance, this simulation will observe the response of the primary voltage value to the variation of the VT burden installed on the medium voltage switchgear. This variation of burden loading is carried out by changing the resistance and inductance values, as shown in Table VIII.

Table VIII VT Burden loading variations

No. Simulasi	*Rb* (Ω)	*Lb* (mH)	X_L(Ω)	Z (Ω)	Burden (VA)	%Burden Load
1	10	0.1	31.4	32.95	8.90	30%
2	10	0.2	62.8	63.59	17.17	57%
3	10	0.3	94.2	94.73	25.58	85%
4	10	0.4	125.6	126.00	34.02	113%
5	10	0.5	157	157.32	42.48	142%
6	25	0.1	31.4	40.14	10.84	36%
7	50	0.1	31.4	59.04	15.94	53%
8	75	0.1	31.4	81.31	21.95	73%
9	100	0.1	31.4	104.81	28.30	94%
10	125	0.1	31.4	128.88	34.80	116%

3. Results and Discussions

A. Normal Condition Simulation

Under normal conditions, the primary side voltage waveform VT can be observed, as shown in figure 8.

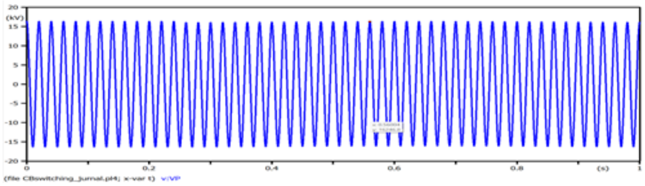


Fig. 8 Primary Voltage under Normal Condition

The rated voltage of the distribution system is alternating (AC) line-to-line RMS ($V_{L-L\,RMS}$) of 20 kV with 50 Hz Frequency.

Therefore, the line to neutral RMS voltage value RMS ($V_{L-N\,RMS}$) is equal to this calculation:

$$V_{L-N\,RMS} = \frac{V_{L-L\,RMS}}{\sqrt{3}} \qquad (1)$$

$$V_{L-N\,RMS} = \frac{20{,}000\ V}{\sqrt{3}} = 11{,}547\ V$$

So, the line to neutral peak voltage ($V_{L-N\,peak}$) can be calculated as follows:

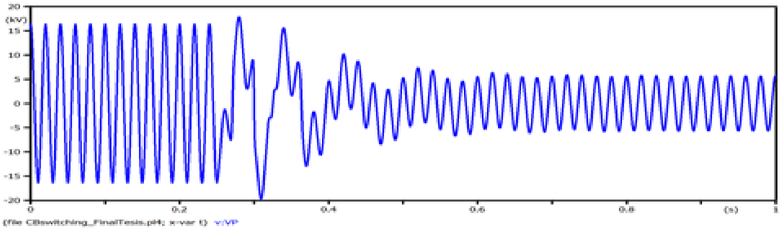
$$V_{L-N\,peak} = V_{L-N\,RMS} \times \sqrt{2} \qquad (2)$$

$$V_{L-N\,peak} = 11{,}547 \times \sqrt{2} = 16{,}329.93\ V$$

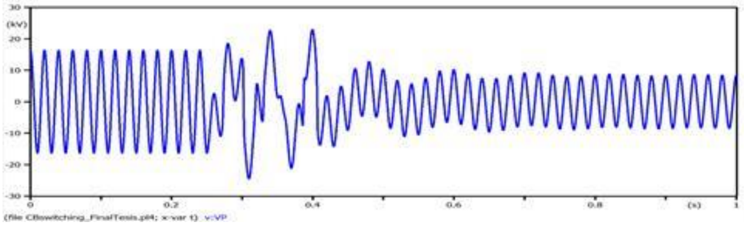
B. Ferroresonance due to Circuit Breaker Switching Operations Simulation, Variation of Cg Value, Cs Constant = 0.01 µF

After simulating the disturbance of CB switching operation on the distribution network, it can be seen in figure 9 that after 0.25 seconds there are different responses to the variations Grading capacitance value, where resonance with the subharmonic mode occurs at Cg = 0.01 µF, where the primary voltage peak increases up to 150% of the nominal voltage and resonates with a long time.

The resonance that occurs with other variations of grading capacitance shows a damped resonance. From the variations of grading capacitance with magnitudes from 0.001 µF to 10 µF as shown in Table IX, the ferroresonance phenomenon only occurs at capacitance quantities of 0.005 µF and 0.01 µF.



(i)



(ii)

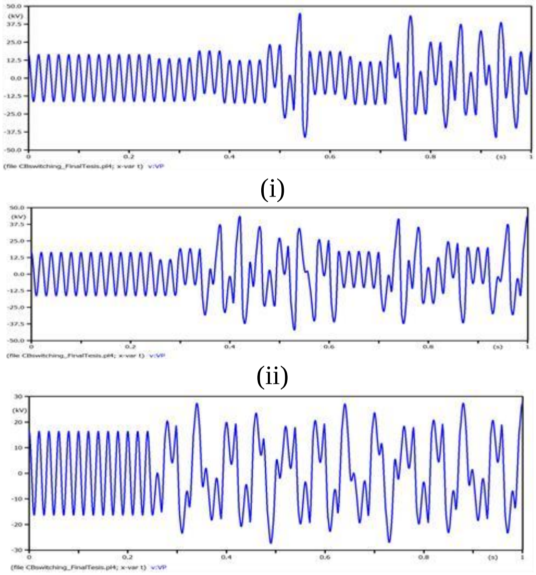
Fig. 9 Primary Voltage under CB switching operation response of Cg variations (i)0.005 µF, (ii)0.01 µF

Table IX Voltage and Current value of VT under CB switching operation simulations response of Cg variations.

Cg (µF)	Peak Value					Ferro-resonance?
	Vp (kV)	% of rated Vp	Ip (mA)	Vs (V)	Is(A)	
0.001	10.264	62.9%	2.66	51.29	0.512	No
0.005	-19.73	120.8%	-5.12	-98.6	-1	Yes
0.01	-24.48	150.0%	-6.36	-122.3	-1.22	Yes
0.05	15.78	96.6%	4.1	78.86	0.788	No
0.1	16.106	98.6%	4.18	80.49	0.804	No
0.5	16.289	99.7%	4.2	81.45	0.813	No
1	16.162	99.0%	4.21	80.997	0.811	No
5	16.27	99.6%	4.22	81.3	0.813	No
10	16.295	99.8%	4.23	81.443	0.814	No

C. Ferroresonance due to Circuit Breaker Switching Operations Simulation, Variation of Cs Value, Cg Constant = 0.01 µF

In the variation of the capacitance of the line to ground, the influence of Cs variation does not significantly impact the magnitude of the VT primary voltage. The resulting ferroresonance mode is also the subharmonic mode, as shown in figure 10.



(i)

(ii)

(iii)

Fig. 10 Primary Voltage under CB switching operation response of Cs variations (i)0.05µF, (ii)0.1µF, (iii)0.5 µF.

Table X Voltage and Current value of VT under CB switching operation response of Cs variations.

Cs (µF)	Peak Value					Ferro-resonance?
	Vp (kV)	% of Nominal VP	Ip (mA)	Vs (V)	Is(A)	
0.001	16.282	99.7%	4.24	81.649	0.816	No
0.005	16.252	99.5%	4.22	81.09	0.812	No
0.01	16.255	99.5%	4.23	81.451	0.814	No
0.05	44.99	275.5%	11.69	224.84	2.24	Yes
0.1	43.4	265.8%	11.28	217.43	2.17	Yes
0.5	27.32	167.3%	7.1	136.57	1.36	Yes
1	16.963	103.9%	4.4	84.77	0.847	Yes
5	7.313	44.8%	1.9	36.55	0.365	No
10	5.033	30.8%	1.3	25.15	0.25	No

Details of the simulation results on the variations of line to ground can be seen in Table X. It can also be observed that the ferroresonance phenomenon occurs at small capacitance values or high impedance values.

D. Ferroresonance due to Ground Fault

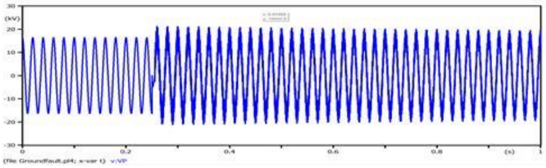


Fig. 11 Primary Voltage under ground fault disturbance with different sampling time.

As can be seen in Figure 11, the voltage waveform generated from the primary voltage VT due to a phase-to-ground fault is a ferroresonance with quasi-periodic mode. However, this ferroresonance in a single-phase-to-ground fault can only occur at very small network capacitance values or very high impedance values. With the fulfillment of this low capacitance value, the magnitude of the voltage waveform soars very high and can even reach 201.47% of the nominal voltage.

In Table XI, it can be seen in detail the response of the primary voltage VT to the variation of the network capacitance value due to phase-to-ground fault. It can be observed that ferroresonance occurs over a wide range of capacitance values.

Table XI Primary Voltage of VT under ground fault disturbance with Line capacitance variations

Line Capacitance (pF/m)	Vp Peak (kV)	% of Nominal Vp	Ferroresonance?
0.005	21.17	129.64%	Yes
0.05	21.26	130.19%	Yes
0.5	21.175	129.67%	Yes
5	19.85	121.56%	Yes
50	16.81	102.94%	Yes
500	-32.9	201.47%	Yes
5000	-29.4	180.04%	Yes

E. Ferroresonance due to Lightning Strike

This simulation gives a disturbance as a lightning impulse current at 0.25 seconds. The magnitude of the given lightning impulse current is 10 kA. Based on the simulation results, It can be observed that the primary voltage increases with a very high voltage magnitude which can cause VT to explode with a voltage order of thousands of kilovolts, as shown in Figure 13. It also can be seen that the generated ferroresonance mode is quasi-periodic with a very high frequency. This resonance fault continues up to 0.14 seconds after the lightning strike disturbance.

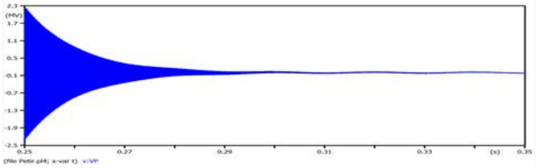


Fig. 12 Primary Voltage under lightning strike disturbance

Table XII shows a more detailed value of the primary voltage response to lightning strike disturbances with front time and tail time variations based on Table VI. It can be observed that the reduction and addition of the front time do not have a significant impact on the resulting impulse waveform and the response of the primary voltage VT. Still, a long tail time will cause a greater magnitude of the primary voltage, whereas vice versa, if the tail time is shorter, the magnitude of the impulse waveform also gets smaller. The disturbance resonance time of the front time and tail time variations of the lightning impulse current show the same number, 0.14 seconds.

Table XII Voltage and Current value of VT under lightning strike disturbance variations.

Simulation Number	Vp (kV)	% of rated Vp	Vs (kV)	Ip (A)	Is (A)	Ferroresonance?
1	2,350	14,391%	11.64	70.2	9.25	Yes
2	2,342	14,342%	11.612	70.05	9.22	Yes
3	2,335	14,299%	11.57	69.8	9.19	Yes
4	2,324	14,232%	11.52	69.5	9.15	Yes
5	2,361	14,458%	11.7	70.5	9.29	Yes
6	2,381	14,581%	11.8	71.1	9.37	Yes
7	2,391	14,642%	11.85	73.4	9.67	Yes
8	2,411	14,764%	11.9	75.03	9.89	Yes
9	2,432	14,893%	12.05	76.6	10.11	Yes
10	2,444	14,966%	12.11	77.48	10.22	Yes
11	2,208	13,521%	10.9	61.2	8.03	Yes
12	1,707	10,453%	8.46	37.8	4.87	Yes
13	758	4,642%	3.75	-13.5	-1.63	Yes

F. Voltage Transformer Non-Linear Inductance Characteristics Variation

In this simulation, variations are made on the characteristics of the non-linear inductance VT, where an initial non-linear inductance magnetization curve has been given and shown in figure 14, from this value a variation is carried out by increasing and decreasing the saturation point of the non-linear inductance. Then a disturbance of the switching CB operation is given with Cg = 0.01 µF and Cs = 0.01 µF, this disturbance chosen because it occurs most often in the distribution system.

1) Normal Saturation Point

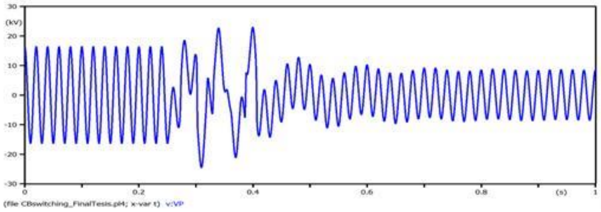


Fig. 13 Initial VT’s Magnetization Curve

Variations are made by multiplying each initial fluxlinked quantity by 1.2 to increase the saturation point of the magnetization curve and decreasing the saturation point of the magnetization curve by multiplying the initial fluxlinked by 0.8.

2) 1.2× Normal Saturation Point

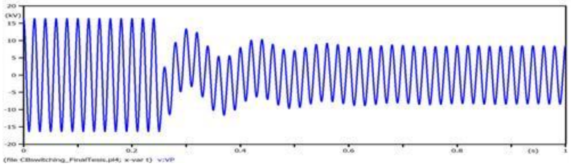


Fig. 14 1.2x initial VT’s Magnetization Curve

3) 0.8× Normal Saturation Point

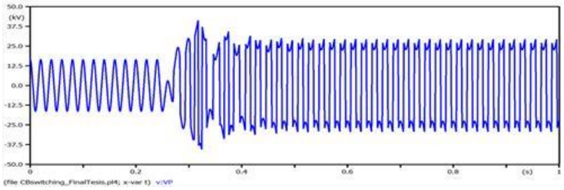


Fig. 15 0.8x initial VT’s Magnetization Curve

Table XIII Primary Voltage Value under CB Switching Operation disturbance with VT's magnetization curve variations.

Saturation Point Variations	Vp (kV)	% of rated Vp	Ferro-resonance?
Normal	18,207	111,5%	Yes
1,2 x	12,365	75,7%	No
0,8 x	16,971	103,9%	Yes

It can be seen in Table XIII that with a higher saturation point, VT will be more resistant to ferroresonance. In contrast, a lower saturation point will make it more susceptible to ferroresonance. It can also be seen in figure 15 that multiplying the saturation point by 1.2x of the initial value will dampen the occurrence of ferroresonance. On the other hand, the lower the saturation curve point of the non-linear inductance, the ferroresonance continues to oscillate and is not damped, as shown in Figures 14 and 16.

G. Voltage Transformer Burden Variations

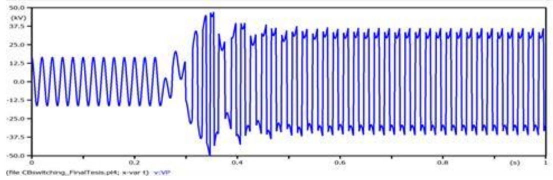


Fig. 16 Primary Voltage Waveform due to burden variations,
R = 125 Ω L = 0.1 mH

This simulation is carried out by varying the value of the burden load, which consists of resistance and inductance. A disturbance of the switching CB operation is also given with Cg = 0.01 µF and Cs = 0.01 µF. With an increasing inductance value with constant resistance, as shown in the data in Table XIV, the voltage value has a lower peak waveform. Still, the ferroresonance disturbance continues to resonate long with the fundamental mode. Meanwhile, increasing the resistance value and keeping the inductance at a lower and constant value will produce a higher and damped primary voltage ferroresonance peak waveform magnitude, as shown in Figure 20.

Table XIV Primary Voltage Value under CB Switching Operation disturbance with VT's burden loading variations.

Simulation Number	Vp (kV)	%rated VP	Ferroresonance ?
1	8,85	54,2%	No
2	8,85	54,2%	No
3	8,86	54,3%	No
4	8,87	54,3%	No
5	8,88	54,4%	No
6	10,86	66,5%	No
7	12,46	76,3%	No
8	15,43	94,5%	No
9	-24,7	151,3%	Yes
10	-49,95	305,9%	Yes

4. Conclusion

From the various disturbance simulations given to the VT installed in the medium voltage switchgear, several conclusions can be drawn as follows: CB switching operation is a disturbance that often occurs in the distribution system, and this impacts the appearance of network capacitance values which results in saturation of the VT iron core and causes ferroresonance. The type of ferroresonance generated is the subharmonic mode, with voltage value reaches 150% of the nominal voltage for Cg = 0,005 – 0,1 μF and 275,5% of the nominal voltage for Cs = 0,05 – 1 μF. Ferroresonance resulting from a single-phase to ground fault occurs at high line impedance values with a high-frequency quasi-periodic mode where the magnitude of the primary voltage can reach 201.47 % of the rated voltage. For lightning impulse current disturbances, the variation of the long tail time will significantly impact the magnitude of the primary voltage. This lightning impulse disturbance is the most dangerous, so it is necessary to have special protection equipment, especially a fuse to protect this VT because the resulting ferroresonance has a huge magnitude which can reach 14.391% of the rated voltage.

Based on the results of the simulations and analyses that have been carried out in this study, it can be concluded that ferroresonation can occur due to various kinds of disturbances in the distribution system, especially in the case of this study, the emergence of voltage and current spikes which make the primary side of the VT explode or burn. It is also necessary to pay attention to the VT loading installed to the medium voltage switchgear because it can trigger ferroresonance. MV Switchgear design which loads the VT burden with an inductance composition that is greater than its resistance and approaches 80% of the VT burden specification can mitigate the emergence of ferroresonance. Besides that, the design factor of the magnetization curve of the non-linear inductance VT is also critical because it can prevent VT from ferroresonance due to capacitance variations that arise in the distribution network, The choice of a VT design with a voltage factor of 1.9Un/8h mitigate the emergence of ferroresonance.

5. References

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