Analysis of Lightning-Caused Distribution Transformer Failures in Ghana*

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Abstract

The Electricity Company of Ghana (ECG) experiences several distribution transformer failures every year. Among the several factors that lead to this is the issue of lightning. This paper presents an analysis of lightning-caused distribution transformer failure in Ghana and proposes remedial measures to tackle the menace. This will help the ECG to protect their distribution transformers and other equipment from lightning transients. Data collected indicate that ECG Global experienced 477 lightning-caused distribution transformer failures between 2011 and 2015. The results show that Western Region experiences the highest number of lightning-caused distribution transformer failures in ECG Global. To address this problem, this paper proposes a design that uses lightning protection system at both terminals of the distribution transformers. Simulation results show improved performance by the proposed method.

Keywords: Distribution Transformers, Transformer Failures, Lightning Protection

1 Introduction

In 2006, a severe lightning strike hit the residence of the Vice Chancellor of the University of Mines and Technology (UMaT), Tarkwa. Two years later, the administration block of African Mining Services Company Limited, also located in Tarkwa and near the University campus, was as well struck by a powerful lightning. In both cases, sensitive electrical equipment, such as computers, printers, telecommunication systems, etc., were damaged even though lightning protection systems were provided on these facilities. Preliminary studies suggested that the protection systems were either not adequate for the facilities or they were improperly installed. Thus, the protection system of the distribution transformer supplying power to these customers could not arrest the lightning surges.

The incidence of a dangerous lightning strike at Fosu in the Central Region in 2015 is evidence to the lightning-caused distribution transformer failures in Ghana. Two people lost their lives at a spot followed by the death of three others the next day and left two people deformed. These people were passing by the transformer during a rainfall when the incident occurred. Studies revealed that the transformer was not protected from lightning. The distribution transformer, which happens to be a Pole Mounted Transformer (PMT), exploded with the bushings, oil tank and windings all scattered.
Another incident of lightning-caused distribution transformer failure occurred at Enchi in the Western Region. Similar to the Fosu incident, a lot of fused systems connecting the secondary circuit of the distribution transformers to customer loads were bypassed using copper wires of less resistance. Four people lost their lives instantly with one person deformed for life. These people were also passing by the transformer during a rainfall. Again, an investigation revealed that there were no proper lightning and grounding protections on the transformer. The distribution transformer exploded and in the process, the bushings, oil tank and windings scattered. This happened in 2013.

A lightning protection system is designed to meet two objectives: firstly, to shield equipment and provide a direct path to ground for the lightning current to flow and lastly, to prevent damage to the equipment as the current flows through the system. Lightning protection systems keep homeowners and their property safe from lightning destruction.
Lightning is one of the most serious causes of overvoltage. If power equipment, especially at an outdoor substation, is not protected, lightning overvoltage will burn down the power equipment. Lightning also causes damage to properties such as buildings, farms and factories. In order to curtail the impact of rampant power failure and lightning effect on distribution transformers, there is need to identify the lightning related failures in distribution transformers and find solutions to mitigate them.

Ghana is located in an area of high isokeraunic level as shown in Fig. 1, with lightning strikes in excess of 140 days per annum. As such, an effective lightning protection system is always required.

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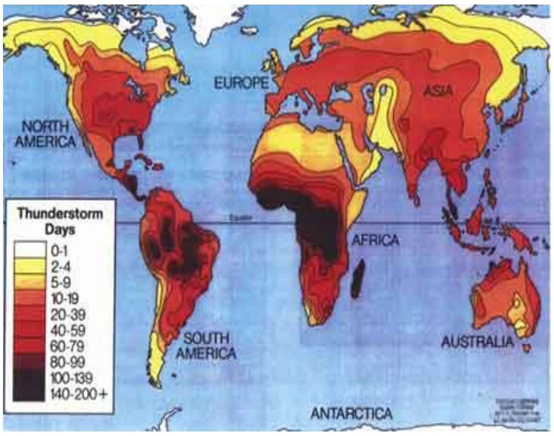

Fig. 1 World Lightning Map

According to the Electricity Company of Ghana (ECG), Western Region is leading in terms of lightning-caused distribution transformer failures in its distribution system. The claim is consistent with a study conducted by William Bartley in 1998 at Siemens (Germany) that classified mode of distribution transformer failures and found that lightning contributed 17.32% of the distribution transformer failures (Taylor and Alehosseini, 2015). The results of that study are shown in Fig. 2, which shows the percentage distribution to the distribution transformer failures to the cause of the failure.

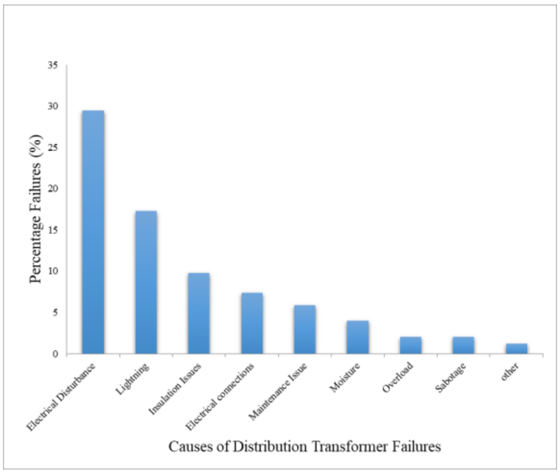

Fig. 2 Distribution Transformer Failure Modes

Equipment mostly used for the distribution of electrical power in Ghana are lightning arresters, lightning connecting strips, connectors and grounding wires. Oftentimes, these protective devices on the distribution transformer are not enough to safeguard them from indiscriminately failing. Distribution transformer failures in Ghana are mainly caused by lightning-related surges, insulation failures; short-circuit in the low voltage system, and overloading. The accepted standard is to use arresters, either on the primary or secondary terminal for the distribution transformer protection.

This paper therefore seeks to investigate lightning-caused distribution transformer failures and find a reliable and cost-effective method of controlling such damages.

2 Resources and Methods Used

2.1 Data Collection and Survey Description

Data on transformer burnouts were obtained from the Maintenance Division of the Operations Directorate, ECG. The 2011-2012 data was separately compiled and 2013-2015 data were lumped together. Hence, it is impossible to separately analyse the trend for each year from 2011 to 2015. However, the analysis is performed on the combined data 2011-2012 and 2013-2015 data.

Unfortunately, ECG does not follow a scientific procedure in determining the causes of burnouts, making our confidence level in the data to be about 85%. However, the overall trend of the damages in the respective Regions and sample site visits provide a clue regarding the actual cause of some of the burnouts. Prevailing practice of distribution transformer protection in ECG is also considered. This is compared with the ECG design guidelines.

2.2 Instrumental Test Analysis of Distribution Transformer Failures

Distribution transformers in Ghana are accessed thoroughly immediately after its breakdown using the right procedure to know the actual cause of the failure. This is done in order to quickly save the working distribution transformers from failing as well. It is then very important to go down into the instrumentation of distribution transformer failures in Ghana. They are, tear down analysis, insulation resistance test, breakdown voltage, and bushing test.

2.2.1 Tear Down Analysis

Two groups of damaged transformers are de-tanked and analysed. The first group is the analysis of the three transformers that failed in 2012 and 2013. The second group got damaged between 2013 and 2015.

The analysis of all the failed transformers followed the guidelines recommended by IEEE task force (IEEE Standard C57.94-1982). Lightning-related transformer failures due to low-side current surges are also investigated.

The easiest method used to locate a secondary surge-induced failure of the transformer was examination of the area surrounding the low voltage bushing. Often, there are spots on the inside surface of the tank. These spots are caused by the ringing transient voltage response of the secondary circuit to the lightning impulse.

As previously documented, secondary-side surge-damaged transformers do not always fail immediately. They often supply 50 Hz overvoltage to the users due to multiple layer-to-layer shorting of the primary windings. This may continue until a customer complains of an overvoltage. If the overvoltage is not detected, internal arcing continues until there are sufficient primary turns short-circuit to cause the primary fuse to operate. Sometimes, subsequent surges accelerate the failure process. The failure of transformers due to low side surge currents is dependent on the load and the load protection. This was verified in the ECG laboratory.

2.2.2 Insulation Resistance Test

This test is performed to determine the insulation strength of the transformer oils. The insulation resistance test is of value for future comparison and also for determining if the transformer is to be subjected to the applied voltage test. The winding insulation resistance test is a DC high voltage test used to determine the dryness of winding insulation system. The test measures the insulation resistance from individual windings to ground and/or between individual windings.

The measurement values are subjected to wide variation in design, temperature, dryness and cleanliness of the parts. This makes it difficult to set minimum acceptable insulation resistance values that are realistic for wide variety of insulation systems that are in use and performing satisfactorily. If a transformer is known to be wet or if it has been subjected to unusually damp conditions, it should be dried before the application of the applied voltage test.

Low readings can sometimes be brought up by cleaning or drying the apparatus. The insulation resistance test should be performed at a transformer temperature as close as possible or at 20 °C. Tests conducted at other temperatures should be corrected a 20 °C with the use of temperature correcting factors. The test equipment is calibrated to read in MΩ and commonly known as a High Voltage (HV) Megger. Typical maximum test set voltage values may be 1 kV, 5 kV or 15 kV. The 30 kV HV Megger is also available.

2.2.3 Breakdown Voltage

Oil degradation can be easily appreciated with this parameter tested and the equipment used is called the Oil Test Set (OTS). The test is based on the insertion of electrodes immersed in oil of an increasing voltage up to when discharge happens. Test is repeated six times to get a repeatable measurement. This is done to know the level of moisture and impurity content in the oil. These contaminants cause the distribution transformer to overheat. The copper losses I^2R increases because the impedance keeps rising (Silva *et al*., 2012).

2.2.4 Bushing Test

The test is done by applying the high voltage lead to the disconnected bushing centre conductor and measuring the tank ground or bushing flange. The purpose of the test is to measure the leakage of the insulation both internally and externally.

2.3 Data Collection and Analysis

The collected data indicate that from 2011 to 2012, ECG recorded 145 transformer failures, of which 98 and 47 are PMTs and Ground Mounted Transformers (GMTs), respectively. From 2013 to 2015, ECG lost a total of 332 transformers through burnouts, made up of 254 PMTs and 78 GMTs. A breakdown of transformer failures per region is given in Table 1. A cursory look at the figures gives an impression of some marginal increase. This is a serious negative trend that requires urgent attention. Most of these reasons are attributed to the inadequate and wrong method of lightning protection system used by ECG.

Table 1 Transformer Failures in ECG

Region	Number of Transformer Failures				Total
	2011 – 2012		*2013 – 2015*		
	PMT	*GMT*	*PMT*	*GMT*	
Accra East	8	11	16	14	48
Accra West	2	9	12	13	36
Ashanti East	9	6	26	10	51
Ashanti West	15	7	30	11	63
Central	16	2	42	4	64
Eastern	11	-	36	5	52
Tema	8	5	17	9	39
Volta	10	3	28	5	46
Western	19	4	48	7	78
Total	**98**	**47**	**254**	**78**	**477**

It was observed that five regions contributed significantly to the burnouts with Central and Western Regions standing tall among them in relation to PMTs. The incidence of GMT failures, although relatively low as compared with the PMTs, was common among Accra East and Accra West Regions.

2.3.1 Causes of Distribution Transformer Burnouts

In the survey, five causes of transformer failures were identified. These are, lightning-related surges, insulation failure, short circuit in the Low Voltage

(LV) system, overloading, and others. These causes of transformer failures are quantified in relation with PMTs and GMTs and depicted in the Table 2.

Table 2 Causes of Transformer Failures in ECG

Causes	Number of Transformer Failures				Total
	2011 – 2012		*2013 – 2015*		
	PMT	*GMT*	*PMT*	*GMT*	
Lightning-related surges	37	18	79	23	157
Insulation Failure	22	14	79	24	139
Short circuit	13	4	33	10	60
Over loading	9	6	30	11	56
Others	17	5	33	10	65
Total	**98**	**47**	**254**	**78**	**477**

Lightning surges and insulation failures are identified as the major causes of transformer burnouts. For 2013-2015, failure due to lightning surges and insulation failure are equal in magnitude; each contributed 29% to PMT failures. Similarly, overloading and short-circuit failure occurrences also contributed about 13% and 15%, respectively, over the same period. Here, the term "others" are used to classify uncommon causes, such as moisture ingress, sea effects (especially transformers mounted in coastal areas), transformer explosion, etc. This also contributed 12% of failure over the same period.

For 2013-2015, GMT failure was mostly as a result of insulation failure, followed by lightning surges, i.e., 32% and 28%, respectively. Overloading also contributed 14% of the total GMT failures, whereas short-circuit is attributed for 13% of the failures over the same period with others resulting in 13% of the GMT failures.

For 2011-2012, lightning surges was the leading cause of PMT failures, followed by insulation failures, contributing 39% sand 23%, respectively. Others contributed 16% of the PMT failures, short-circuit destroying 13% and overloading also destroying 9% of the transformers over the same period. Similarly, in the case of GMTs, lightning surges is the major cause of failure, followed by insulation failures, contributing 38% and 29%, respectively. Overloading also destroyed 13% of the GMTs, others recorded 11% of the burnouts, with short-circuit destroying 9%.

2.3.2 Analysis of Lightning-Caused Failures

When a lightning surge enters the primary side of a distribution transformer, line and phase voltage distribution remains unbalanced across the windings. At the primary windings, large voltage occurs at the layer nearest the primary bushing, and the possibility of breakdown at this point is high. Surge voltage distribution in the transformer windings can be estimated from the following relation:

$$E_{1-2} = E_{surge} \frac{2\sinh\left(\frac{1}{2}\sqrt{k}\right)\cosh\left(n-\frac{1}{2}\right)\sqrt{k}}{\sinh\left(n\sqrt{k}\right)} \qquad (1)$$

where,

$kCT = CG$,
CT = capacitance across transformer turns,
CG = capacitance between turns and grounding (tank),
n = number of turns,
k =fraction of CT.

When lightning surge enters the secondary side of a transformer, large line and phase voltage occurs at the layer closer to the neutral terminal; nearly 62% of the incident surge voltage is taken up on the first turns. Possibility of breakdown at this point is high. Surges entering the transformer from the LV side may, on occasions, allow damage to occur on the HV winding or the LV winding or on both.

At the laboratory, 3 kV surge was injected into a transformer from the LV side. With HV/LV windings of 11 kV/240 V, the turns ratio was 45.8 to 1. The 3 kV is "stepped-up" to a prospective 137.4 kV in the HV winding and this exceeds the standard of 95 kV of the basic insulation level. This transformer failed instantly, as shown in Fig. 3.

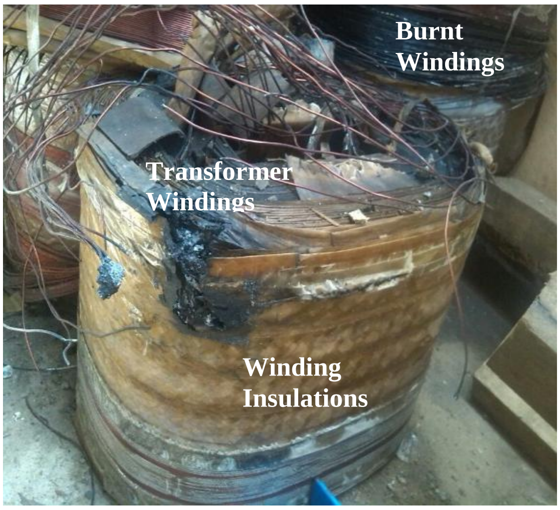

Fig. 3 Transformers Windings due to Lightning

2.3.3 Lightning Signature Failures

It is found that lightning-related failures have the following symptoms:
Primary windings:

(i) Damage at layer nearest the primary bushing;
(ii) Discharge spots occur around primary bushing;
(iii) Dielectric strength of oil is often good; and
(iv) Pittings on the arcing horns.

Presence of water was found in almost all the transformers that were opened. The water gained entry through cracked low voltage bushings and poorly installed tap-changer switch on top of the transformer tank. In some cases, the water got into the tank through the pressure relief valve.
Secondary windings:

(i) Damage at layer closer to the neutral terminal;
(ii) Discharge spots occur around secondary bushing; and
(iii) Dielectric strength of oil is often good.

A suitable application of a surge diverter can minimise the overvoltage effect caused by lightning surges.

3 Results and Discussion

This section proposes an improved protection method and analysis of lightning-caused distribution transformer failures in Ghana. It ends with the modelling results of the proposed method and a discussion of the simulation results.

3.1 Proposed Protection System

Fig. 4 shows the existing protection system and Fig. 5 shows the proposed transformer protection system, where improved capacitors have been installed at both ends of the distribution transformer. The proposed protection system is installed parallel to both the HV and LV terminals of the distribution transformer. Moreover, Medium Voltage (MV) surge arresters are installed at the HV terminals of the distribution transformer. Field experience has shown that if only MV surge arresters are installed, without a surge protection device at the LV side, then the peak of the overvoltage arising at or transferred to the LV side of the distribution transformer may exceed the corresponding insulation level. The simultaneous installation of MV surge arresters at the HV side and surge protection device at the LV side significantly reduces the LV side overvoltage.

In order to increase the transfer of lightning surge to the general mass of the earth, it is very prudent to connect the proposed filter parallel to the arrestor and the grounding electrode of the distribution transformer. This will decrease the magnitude of the resistive path for the lightning surge current to pass through to be neutralised.

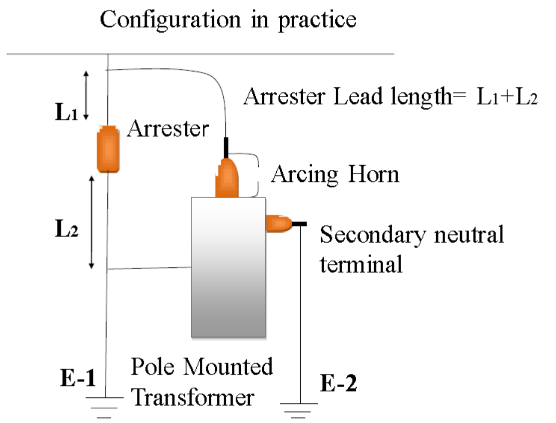

Fig. 4 Existing Protection System for Lightning-Related Surges on Distribution Transformers of ECG

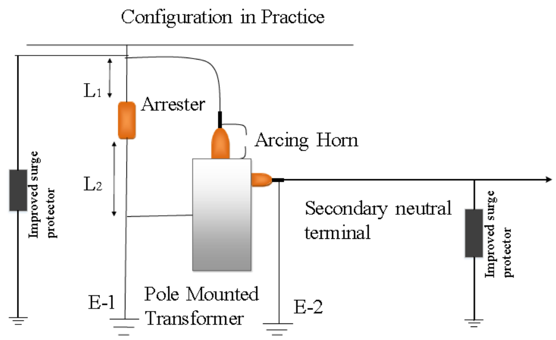

Fig. 5 Proposed Improved Protection System for Lightning-Related Surges on Distribution Transformers of ECG

3.2 Modelling of the Proposed Protection System

Fig. 6 shows a single line lightning-interactive distribution transformer circuit consisting of capacitor, inductor, and resistor components. The circuit is in two terminals, the primary (input terminals) and the secondary (output terminals). It also has lightning terminals and arrester terminals. The following is the legend for Fig. 6:

(i) C = Capacitance of the lightning discharged current
(ii) R = line resistance
(iii) Ra = Ground connection resistance
(iv) L = inductance of the transformer windings
(v) I_1 andl I_6 = line current
(vi) I_2 and I_5 = lightning discharge current
(vii) I_3 and I_4 = Transformer winding current
(viii) Ia = Ground current

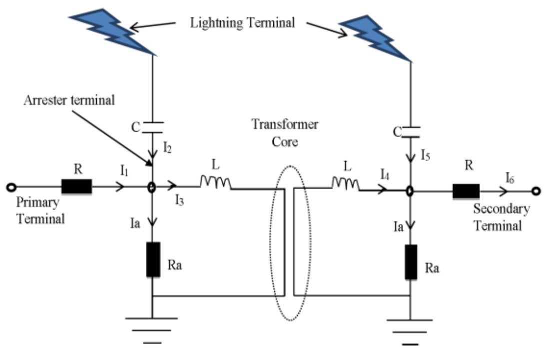

Fig. 6 Protected Lightning-Caused Distribution Transformer Circuit

Both primary and secondary circuits are made up of resistive, inductive and capacitive reactance components. From the primary circuit, Kirchhoff's Current Law, KCL is given by:

$$I_1 + I_2 = I_3 + I_a \quad (2)$$

It can be proved that the transfer function for Fig. 6 is given as:

$$\frac{i_L(s)}{i_N(s)} = \frac{1}{s^2LC + s\dfrac{L}{R_a} + 1} \quad (3)$$

3.3 Simulation Results

The simulation results of electrical network of the distribution transformer give a clear picture as to how the protection system is analysed. The simulation results obtained are presented from Fig. 7-10. Table 3 gives the declared simulation quantities of the step response of the transfer function at no lightning strike and the various step responses of the transfer function of the distribution transformer lightning strike.

Table 3 Simulation Quantity at Normal Operation

Electrical Quantity	Setup 1	Setup 2	Setup 3
Line Resistance (Ω)	20	20	20
Ground Resistance, Ra (Ω)	1	1	1
Transformer Inductance, L (H)	0.047	0.047	0.047
Transformer Voltage (V)	415	415	415
Lightning Surge Voltage, C (MV)	-	15	30

The Fig. 7 shows the step response of the transfer function given in Equation (3) for the three setup scenarios in Table 3 G (Setup 1) represents the transformer performance at normal operating conditions. In this case the charge capacitance between the clouds and the transformer is zero (C = 0), therefore there is a smooth rise of the voltage magnitude in per unit to the steady state operating conditions. The transformer continues to operate in steady state so long as there is a normal operating condition. The scale for the voltage axis is 415 V is to 1 unit. This scale is convenient for MATLAB graph presentation.

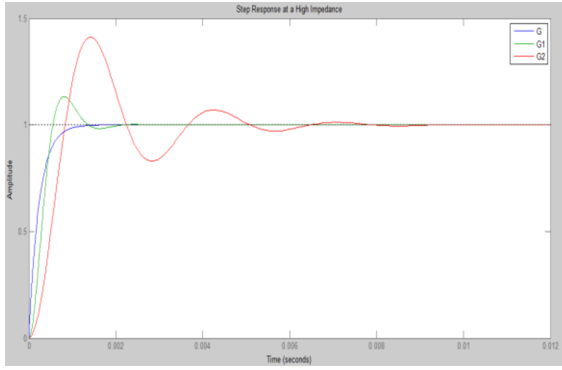

Fig. 7 Comparison of Step Responses at High Ground Resistance

G1 (Setup 2) illustrates the responses for a lightning strike on the DT at a low lightning surge discharge. Due to the low strike, it took about 0.8 ms to rise to the peak at a magnitude of about 1.13 times the normal system operating voltage. It also took less time of about 2 ms to settle hence it did not remain in the system for long. The scale for the voltage axis is 15 MV is to 1 unit. It is required to use this scale on the voltage axis because it makes the MATLAB simulation well presented.

G2 (Setup 3) shows the step response at high lightning strikes on distribution transformer as compared to Fig. 8. At high strike the charge capacitance between the transformer and the cloud is very high. At this condition, peak transient rose to 1.41 times the magnitude of the normal operating voltage at about 0.00141 s. The disturbance also occurred in the system for a long time of about 1sec as compared to that of Figure 8. There is therefore a high probability of destroying the transformer.

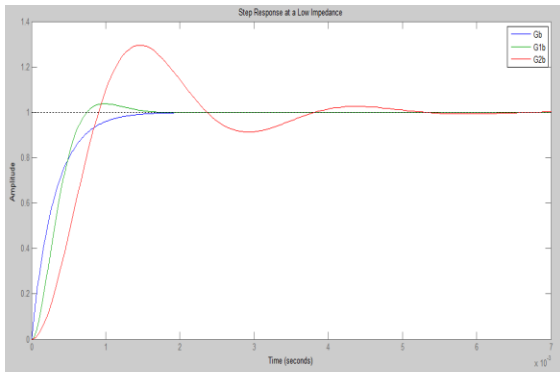

Fig. 8 Step Responses at Low Arrestor Impedance

The protection offered by the arrestor is also crucial as a high impedance of the arrestor due to improper connection or inappropriate earthing can lead to the destruction of the distribution transformer. The scale for the voltage axis is 30 MV is to 1.5 V. It is requested to use this scale on the voltage axis because it makes the MATLAB simulation well presented.

It is realised from the Fig. 7 that there is no effect on the distribution transformer as indicated by the blue coloured G and since at that condition there is also no lightning strike. G1 (Setup 2) represent the step response at low lightning strike while G2 (Setup 3) represent the step response at high lightning strike.

But at G1 the lightning transient surge occurred in the system for long and caused under-damp which leads to a very high probability of causing transformer destruction.

Condition at G2 will definitely destroy the transformer because the arrestor is not able to protect the system. There was a very high peak value at this condition and it occurred for a long time in the system. This means a better protection is required to alleviate this condition.

When additional surge protectors are introduced such that the ground resistance reduces from 1 Ω to 0.8 Ω, then the system in Fig. 8 becomes better as compared to Fig. 7. The arrestor was able to alleviate the under-damp (sag) of the G1b so in this case there will be a transient although but it has no effect on the transformer. Although the nature of the strike is so high in the case of G2b, there may be a reduction in the severity of destruction of the distribution transformer and this is due to the low impedance of the arrestor circuit. The transient condition did not occur for a very long time and also the peak transient voltage has been reduced.

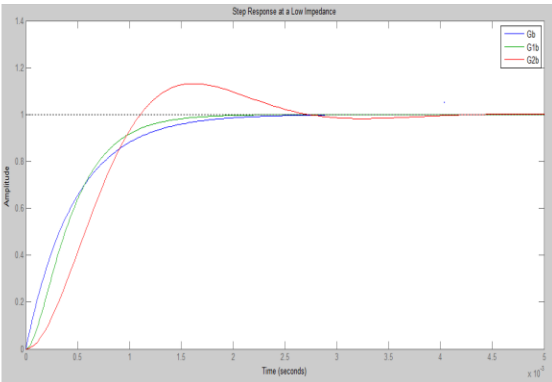

Fig. 9 Step Responses at Adequate Transformer Protection

This means that with further or adequate protection of the distribution transformer, the effects of the lightning strike can further be alleviated, although it cannot be eliminated permanently as shown in Fig. 9, where the ground resistance is further reduced to 0.6 Ω. A further reduction of the ground resistance to 0.4 Ω results in Fig. 10, where a complete filtration occurs. The overshoots and undershoots have now been cleared by the system due to extra protection by the arrestors at either sides of the distribution transformers.

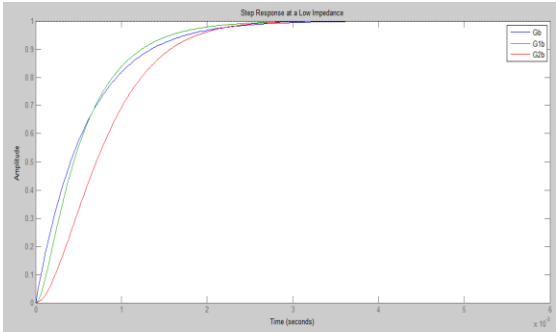

Fig. 10 Step Responses at Adequate Distribution Transformer Protection

4 Conclusions and Recommendations

This paper analysed lightning-caused distribution transformer failures of 477 distribution transformers of ECG in an attempt to find the main causes of the failures in Ghana. An analysis of the data collected show that the protection integrity at distribution substations is riddled with indiscriminate use of copper links to replace blown fuses and high ground resistance. It also presented an improved lightning protection system design for distribution transformers by adding improved surge protection devices at both terminals. Simulation results of the transfer function from the modelling show improved performance by the proposed system. For good performance, we recommend that the earth soil resistance need to be improved for effective grounding system.

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