Protection of Terminal Distribution Transformers: A Case Study of Kenya Power

James Muriuki
Department of Electrical and Electronic Engineering
JKUAT
Nairobi, Kenya
jmsmuriuki@yahoo.

Christopher M. Muriithi
Department of Electrical and Electronic Engineering
MUT
Muranga, Kenya
cmmuriithi@mut.ac.ke

Living Ngoo
Department of Electrical and Electronic Engineering
Multimedia University
Nairobi, Kenya
livingngoo@gmail.com

George N. Nyakoe
Department of Electrical and Electronic Engineering
JKUAT
Nairobi, Kenya
nyakoe@eng.jkuat.ac.ke

***Abstract*— The paper presents and analyses the main causes of high failure rate of Terminal Distribution Transformers (TDTs) in Kenya. These transformers are the most susceptible to faults emanating from lightning strikes and associated overvoltage. Over a period of time and more recently, the failure rate of the TDTs have been on an upward trend despite the standard earthing and protection systems being provided. Failed TDTs are quickly replaced without due diligence for innovative ideas to prevent future failures leading to huge revenue loss for Kenya power and electricity consumers. This research therefore provides an innovative solution for TDTs by extending the Medium Voltage (MV) power line one span away from the TDT where installation of Terminal Surge Diverters Earth (TSDE) and Terminal Medium Voltage Earth (TMVE) are done. The results show that with the adoption of this innovative arrangement, the failure rate of TDTs have reduced significantly.**

***Index Terms*--Earthing system, Failure rate, Lighting strikes, Terminal Distribution Transformers (TDTs), Voltage surges**

I. Introduction

The modern society is highly cognizant of their human rights among them the right to have uninterrupted and quality power supply. The uses of semiconductor electronics gadgets that are sensitive to voltage variations have awakened power utilities globally to ensure that power system stability and reliability is upheld. Lightning surges have largely been the source of faults for TDTs where earthing and protection do not meet the acceptable international standards and where it does, the earthing values deteriorate yearly due to poor quality of soil and substandard earthing materials. This leads to poor protection of the TDTs and distribution power lines, hence exposing power electronics devices to risks of damage. Many studies have been carried out to address the effects of overvoltage on TDTs. The studies have focused on installation of surge diverters on medium voltage side and low voltage side but the intervention has not yielded significant reduction for TDTs failure thus requiring further research. Many countries have come up with some policy measures to ensure reliability and quality of power supply to the electricity consumers but some utilities are resistant to these policy changes that safeguard the electricity consumer's interests. The fact that most of the power distribution networks for developing countries are unreliable and becomes unstable with the slightest disturbance, the issue of customer compensation for power outages still remain a vision. For instance, the Kenyan legislative arm of government have severally attempted to amend the energy Act, 2011 to ensure that the consumers are compensated for losses incurred in the event of power outage for more than three hours within a day. However, some countries have stringent rules regarding power outages and customers get monetary compensation for power supply unreliability [1].

To protect the electricity consumers against the frequent power outages largely from lightning strikes, power utility companies need to invest vastly in protection of distribution transformers and power distribution lines. Use of modern protection methods in addition to conditional based preventive maintenance substantially improves the quality of power supplied to consumers. The standard procedures for installation of distribution transformers and TDTs should also be reviewed periodically based on the need and failure rate. It is for this reason that this work intends to provide an innovative solution for protection of TDTs. The failure rate of distribution transformers (TDTs) in Kenya has been on upward trend and consequently putting off many customers from the grid. Many of these transformers have been failing within short duration after commissioning due to vandalism of earth protection and lightning strikes. The life span of distribution transformers is about 60 years [2], [3] however, due to consistent lightning strikes and other disturbances; the useful life span has been reduced to less than 2 years while some TDTs fail shortly after replacement. The replacement of failed TDTs is done without due diligence to provide innovative mitigation measures to prevent future failures. In the report compiled by [4], the highest failure rate of distribution transformers in Kenya has been linked to lightning strikes. For instance, the failure rate of distribution transformers in Kenya is about 10-12% which is much higher than the adopted standard failure rate of 1-2%. In other countries such as Brazil, the failure rate of distribution transformers is 6% [5] and the majority of these failures are related to lightning surges [6]. In the same work, the authors explore the best location for surge diverters to prevent lightning strikes. Lack of universally agreed distance for placement of surge arrestors from the medium voltage bushings further exposes the TDTs to lightning strikes. The lightning can strike between the medium voltage bushings and installed surge diverters. This requires installation of the surge diverters as close as possible to the MV bushings and adequate earthing carried out. In countries like India, the distribution transformer failure rate is at 12-15% [7] with the majority of the failed transformers being TDTs.

In the year 2015, Kenya power came up with various solutions to deter vandalism of distribution transformers such as installation of vacuum distribution transformers that do not use oil as an insulation media. Distribution transformers suppliers are required to supply equipment that deter vandalism and hence improve power supply. Despite suppliers' requirement to supply equipment with a warranty of six years from the date of delivery and commissioning, many installed TDTs and distribution transformers fail within the warranty period. The ongoing research based on increased TDTs failure seeks to find a better and lasting solution between the manufacturers and the users. The utility company has also taken safety measures of installing the distribution transformers in safe location and also welding the transformer bottom to the channels with a view deterring the vandals. Installations of alarms on some vandal prone distribution transformers have been tried with little success. Further methods to deter vandals include the use of steel and aluminium conductors as opposed to copper conductor for earthing. The above approach escalates the failure rate of TDTs and hence calls for innovative ideas for TDTs protection as proposed in this research.

Distribution transformers are also an important link between power supply and the consumers. They are critical and expensive units in power system that needs adequate protection to avoid continued increased failure rate [8], [9]. Globally, transformer failures continue to affect the bottom line for many power utility companies and it has become a global issue that if not addressed, it will be catastrophic because the damages are irreversible [10]. It is therefore important that adequate protection of distribution transformers and TDTs are provided [11]. Recently, researchers have proposed various mitigation measures towards protection of distribution transformers. These methods include those based on Artificial Neural Network (ANN) that detects incipient transformer faults [12], K-nearest neighbors [13] and those based on sweep frequency response analysis [14]. In Brazil, the distribution transformer failure trend did not come down despite connecting surge arrestors adjacent to the MV bushings of distribution transformers and providing appropriate earthing. This made the power company to change the overvoltage design for transformer protection by installing surge arresters on the low voltage side which did not change the failure rate significantly resulting in the utility company to dropping the project [15]–[24]. This shows that the current practice of installing surge arresters on both the Medium Voltage and LV side does not deter the voltage surges from reaching and severely damaging the transformer windings.

Distribution transformers are normally designed with Basic Impulse Insulation Level (BIL) [8]. The BIL rating determines the level of lightning and switching surge voltages that the transformer can withstand without damage [8]. Other recent method for protecting of distribution transformers against voltage surges are based on the Strikesorb surge protection module as shown in Fig.1, Strikesorb surge protection module is designed to comply with specific operational requirements as presented in [25], [26] which use Metal Oxide Varistor (MOV). The strikesorb technology uses large diameter MOVs that allows Strikesorb modules to provide premium performance under extreme conditions. Independent test data confirm that a Strikesorb 40 module can withstand 140 kA strikes without degradation in performance characteristics [26].

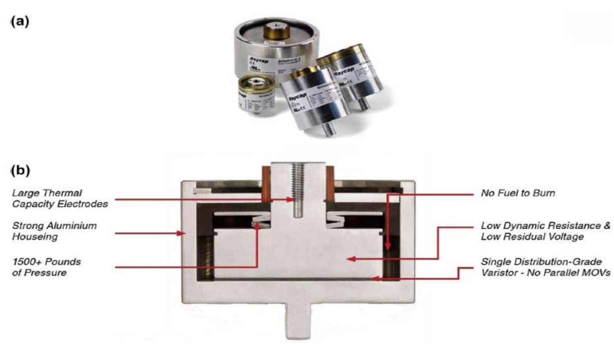

Fig. 1. (a) Four Strikesorb protection modules (b) Cut of a Strikesorb surge protection module designed to operate without fuses [25].

The Strikesorb 80 module can withstand strikes up to 200 kA thus, safeguarding critical electrical and electronic infrastructure against any potential threat [25]. Over voltages in distribution transformers may also be caused by capacitors when switched in and out of the circuit or possibility of a restrike when interrupting the capacitor circuit current. A steep-front voltage excursion may be created from such restrike. These voltage excursions may be high enough to damage rotating machines when applied at the same voltage. A surge capacitor applied at the motor terminals can change the steepness of the wave front enough to protect the motor. A short circuit can cause a voltage surge in excess of 3 times the normal line to neutral crest value. The magnitude and steepness of the wave front is not as severe as that of a

lightning strike, but can cause damage or weaken windings that have the lower BIL ratings than other equipment [8].
When lightning discharges through an arrester, surge currents are discharged to the ground. If the TDTs earths are not precise, TDTs are the first to be hit by the surge currents leading to their failure. It is very important that substations and overhead lines are protected with well-grounded shield wires. It is also equally important that the ground system between pieces of equipment is bonded together with interconnected ground wires that are dedicated to the grounding system [8]. It is important to note that when a surge is released on a line by direct strikes or induced strikes, the strike travels in both directions from the point where it originated. Since wave velocity is an inverse function of the surge impedance, the waves usually travel on an overhead line at approximately 300metres per microsecond, at about (90–180) meters per microsecond in cables and in a buried conductor at about 90metres per microsecond [22], [23]. This demonstrates that despite installation of surge diverters on the medium voltage side of TDTs, the increased failure rate needs improved mitigation measures that are proposed in this work.

This paper presents a practical and innovative solution to protect TDTs through improved earthing system that is only one span away from the terminal distribution transformer. The one span away earthing is described as TSDE and TMVE for the terminal surge diverters and terminal medium voltage respectively. The overhead power lines are further protected against overvoltage using Aerial Earth wire (AEW). The AEW is also connected to TMVE to the earth electrodes providing a solid earthing and protection mechanism against voltage surges.

II. PROBLEM DEFINITION

This work was necessitated by the need to deal with the endemic problem of failing of terminal distribution transformers in Kenya Power and Lighting Company (KPLC). The Utility power company has the highest frequency of TDTs failure where TDT is replaced two or three times in a year. This is made worse because each time the faulty TDT is replaced with new distribution transformer, no scientifically analysis of either the cause or prevention of the failure is done. The failure rates of TDTs are causing severe losses to power consumers and power utilities. As previously mentioned, the distribution transformer failure rate is beyond the acceptable international standard of 1-2%. In Kenya and other developing countries, most of the causes for these failures have been associated with lightning strikes on the medium voltage side of the TDTs in addition to other disturbances linked to overvoltage. Most of TDTs have surge diverters installed slightly above the transformers on MV side while possessing a spark gap in close proximity to the medium voltage bushings. The common practice of connecting together the distribution transformers earthing installations at MVE and surge diverter earth are not recommended in this work. The process of separating the two earths reduces the chances of TDTs being hit by the voltage surges significantly. The surge diverter earth is independently connected to the ground while the medium voltage earth is linked to the metal tank of the transformer and other metal works supporting or enclosing the associated medium voltage conductor connected to the ground with a measured resistance to earth of less than 20 ohms. Also, low voltage earth is installed one span away or at least 9m from the MV earth and connected to the ground with a measured resistance of less than 10 ohms.

The authors of this paper have practically installed and tested the proposed protection arrangement and none of the TDTs installed have failed for the last one year. The TDTs installed with TMVE and TSDE have survived severe lightning strikes and heavy downpour over a period of one year. Therefore, this kind of arrangement is envisioned to reduce the TDTs failure rate. As previously mentioned, research on protection of distribution transformers have been widely carried out and various recommendations given though practical and comprehensive studies on TDTs have not been done. In reality, research on TDTs protection has been ongoing and current and future research need to aggressively address the high failure rate of TDTs. Kenya power being the sole distributor of electrical power from the national grid to consumers in Kenya has a customer base of around 5million with around 45 thousand distribution transformers. These units are expensive thus requiring adequate protection. Table 1 shows the failure rate of distribution transformers within one year against different fault causes.

Voltage surges that cause transformer failure may be due to lightning, single phasing, overload or internal defects. The overloading of the distribution transformer normally weakens its internal windings resulting in short-circuit of some winding of the same phase that ultimately causes insulation failure. The degraded insulation of the windings results in overheating of the transformer and acceleration of failure rate under voltage surges. From Table 1, it can therefore be concluded that 14% of all distribution transformers in one year failed due to lightning strikes. In this paper, the very high failure rate of TDTs due to lightning strikes is addressed through the extension of MV power line one span away where earthing is done and tested. Fig. 2, shows the TDTs failure over a period of one year while Fig. 3, shows the failure trend of distribution transformers in the last two years as a result of lightning strikes. The lightning strike generates a wave that travels at almost the speed of light. When this wave runs into a weaken impedance transformer, the wave continues in the same direction. The wave also reflects back in the opposite direction from which it comes at double the magnitude and unless it is discharged to ground, it will severely damage TDT because it is the first target due nature of their terminal location in the power system network.

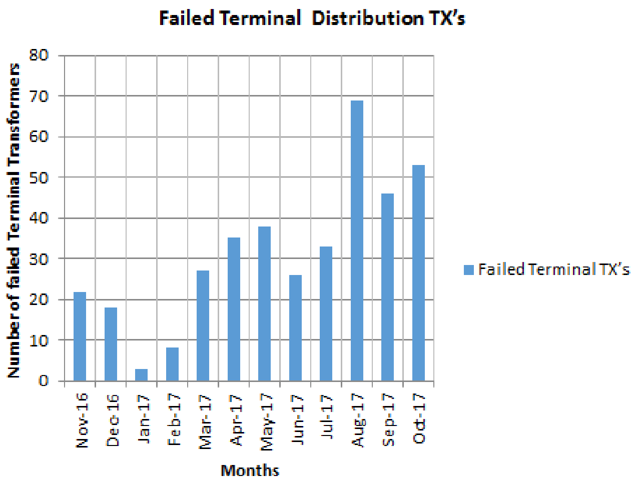

Fig. 2. Trend of failed terminal transformers in Kenya

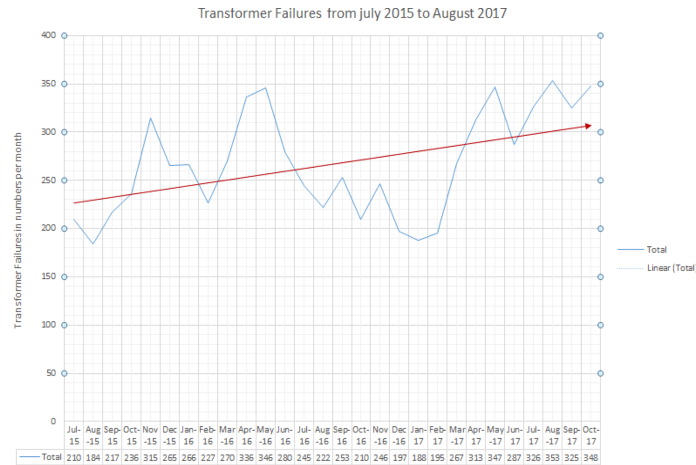

Fig. 3. Trend of transformer failure in Kenya per month

Source: Utility IMS, Network Management Division

TABLE I

Distribution transformer failure against their causes

Causes of fault	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Grand Total
Lightning Strikes	28	23	4	10	34	44	47	33	41	86	58	66	474
Vandalism	15	22	10	16	19	26	30	33	47	40	27	26	311
Fault on LV System	73	31	68	51	74	79	76	67	51	65	76	45	756
Broken Bushings	8	6	3	12	6	10	4	11	7	9	9	16	101
Burnt/Broken Rods	49	54	37	48		16	8	0	15	25	12	81	345
Oil Leakage	41	34	41	27	47	33	37	35	37	29	41	35	437
Accidental Damage	2	1	0	0	0	0	0	0	0	2	4	2	11
Overload	8	12	14	11	13	14	15	12	11	21	17	23	171
Failed on Commissioning	5	8	11	3	9	10	6	7	14	8	8	10	99
Internal Defects	17	6	0	17	65	81	124	89	103	68	73	44	687
Total failed Txs in a month	246	197	188	195	267	313	347	287	326	353	325	348	3392

Source: Utility IMS, Network Management Division

III. INNOVATIVE PROTECTION FOR TERMINAL DISTRIBUTION TRANSFORMERS

Despite having medium voltage earth, surge diverter earth and LV one span way earth, the failure rate for TDTs is still high. In this work, the extension of the medium voltage power line by one span away from the TDT so that the installation of the medium voltage earth and surge diverter earth are separated is proposed. The earthing is done to ensure that TMVE and TSDE are less than that of the TDT earths thereby creating a low resistance path for surges to flow in the event of lightning surges. The low resistance path for the surges to flow will be the TMVE and TSDE to the ground thus safeguarding the TDTs. The above proposal is also enhanced by running an aerial earth wire above the MV power line for a distance of 100m from the power source and 50m to the terminal point thereby ensuring the TDT is fully protected against voltage surges. The TMVE is connected to the aerial earth wire then well grounded. Fig. 4, Shows the proposed and implemented electrical circuit arrangement for enhanced protection of TDTs where the symbols SDE stands for Surge diverter earth, MVE stands for Medium voltage earth and LVE stands for Low voltage earth respectively.

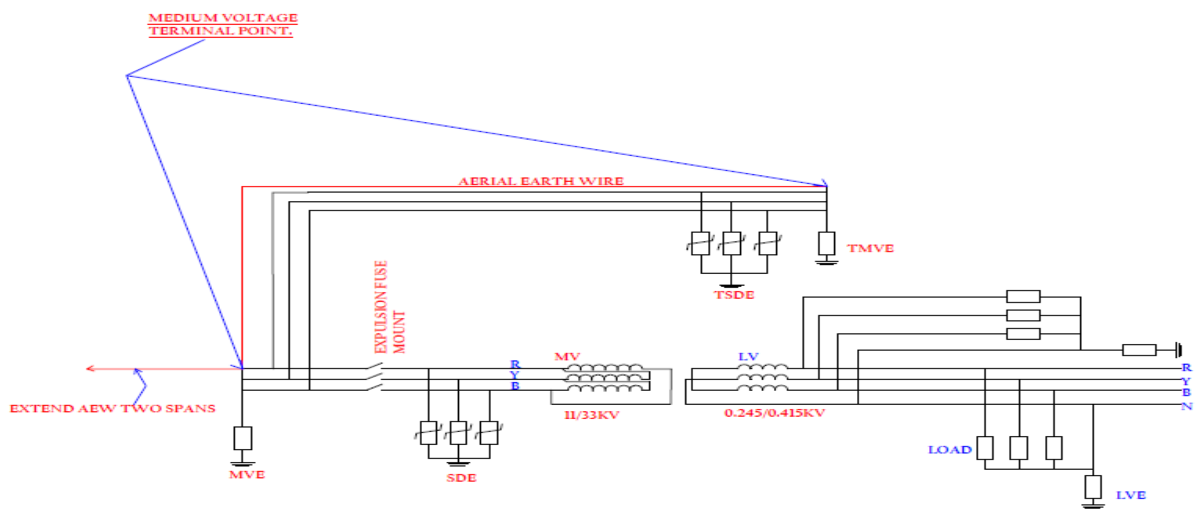

Fig. 4. Innovative protective arrangement for Terminal distribution transformer

IV. CONCLUSIONS

This paper analyzed the failure rate of TDTs in KPLC. It has been shown that, despite the company adopting the standard earthing procedures, the failure rate for TDTs has persistently been on upward trend. It has been established that despite some failures being associated to manufacturers, most failures of distribution transformers are related to users and manifest themselves in many ways as previously discussed. The research study has demonstrated practically that the protection arrangement proposed can be implemented in the field and has therefore reduced the failure rate for TDTs to manageable levels during the period of one year.

V. RECOMMENDATIONS

The failure of Terminal Distribution Transformers is a global occurrence thus; the authors of this work summarized the following key recommendations:

I. All TDTs should have the normal earthing that includes the MV earth (measured resistance to earth <20 ohms), surge diverter earth (measured resistance to earth <20 ohms) and LV one span away (measured resistance to earth <10 ohms). The earth values should be checked every year to ensure that any deviation from the normal resistance values is corrected.

II. All TDTs should have the MV power line extended by one span and additional earthing provided for TMVE and TSDE. The earthing for TMVE and TSDE should be less than that of the TDTs (<20 ohms). This will ensure that in the event of voltage surges, the easier path will be through TMVE and TSDE while the TDTs earthing will act as a backup.

III. All TDTs should have AEW run above the TDTs to the terminal MV power line and two spans to the source.

IV. The earthing for the transformer tank and other enclosures should be connected to AEW wire and the MV earthing facing downward so that in the event of lightning strikes, the surges will flow through the MV earth to the ground thus protecting the TDTs.

V. To avoid seasonal earth variations and protect the earthing conductor and the electrodes, it is proposed that the earthing rods are 50cm below the earth surface.

VI. If the height of the electrode is x cm, the next electrode should be horizontally separated by at least 2x cm to ensure effectiveness and reap maximum benefit otherwise, placing many electrodes in the same point have little benefit for resistance improvement.

VII. All distribution transformers and TDTs should have expulsion fuse mounts with the right MV fuse elements.

VIII. Power utility companies should invest substantially in vegetation management along the power line trace.

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