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An Investigation into Protection Integrity of Distribution Transformers - A Case Study

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Abstract—**This paper investigates protection integrity of distribution transformers in Ghana. The purpose of the study was to find the main causes of distribution transformer failures in Ghana. The study was conducted in the Ashanti East Region, one of the operational areas of Electricity Company of Ghana ECG with high incidence of distribution transformer burnouts. Data on status of protection systems on 676 distribution transformer stations were taken and analyzed. It was found that protection integrity at distribution substation is riddled by indiscriminate use of copper links to replace blown HRC fuses and high ground resistance. The study clarifies why distribution transformers with lower power ratings are more vulnerable to abuse of protection systems than distribution transformers with higher rated powers. The paper reports on the investigation and proposes alternative solutions in mitigating the problem. Although the background work of the study is restricted to Ghana, the applicability and importance of the work would be useful to the scientific community.**

Index Terms: **Distribution transformers, transformer burnouts, lightning arrestor circuitry, Ground Mounted Transformer, Pole Mounted Transformers.**

I. INTRODUCTION

"Today, revenue collection from power sold to customers by utility companies, especially in developing countries, is intense. Disconnection of customer supply for non-payment of electricity bills is now aggressive. As a result, customers are gradually becoming aware of their rights and are demanding high quality and safe power supply for their money. There are number of legal cases in court against utility companies in relation to poor service delivery [1]. In some jurisdictions, customers are beginning to receive monetary compensation for poor supply reliability [2]. As power utility companies thinks of maximizing revenue collection from their operations, customer needs will demand that they reinvest in their distribution network in terms of optimizing equipment protection in their distribution networks to guard against needless equipment breakdowns and failures.

Equipment damage, especially distribution transformers, presents one of the greatest challenges to the Electricity Company of Ghana [ECG].

Every year, ECG looses about one hundred and forty distribution transformers through burnouts [3]. This has become a major concern to both ECG and its customers - to the company; equipment damage is a loss of revenue and capital assets and could threaten the financial sustainability of the company. In the case of the customer, this is total nuisance and loss of economic productivity.

In 2004-2006, ECG lost a total of 332 transformers through burnouts, made up of 254 Pole Mounted Transformers PMTs (77%) and 78 Ground Mounted Transformers GMTs (23%) [3]. The trend is found identical to 2007 data which indicates 68% and 32% failures for PMTs and GMTs respectively but with total burnouts of 145. On the average, the incidence of burnouts recorded in 2004-2006 is lower (111) as compared with 2007 figure of 145. In monetary terms, it was noted that from 2004-2007 ECG spent a total of about four million Ghana cedis [GH¢4.1million or US$2.76million] in replacement of burnt transformers. This means ECG spends about US$690,000 every year on replacement of burnt transformers. The situation is more disturbing, especially, coming at a time ECG is relying heavily on these equipment to breakeven on its business front and are also obliged by the Public Utilities Regulatory Commission (PURC) to meet a standard system performance. In November 2007, the PURC announced an increase of 35% in electricity tariffs. It is believed that even at this tariff regime, ECG is not operating at full cost recovery. In Ghana, electricity consumption has been growing at 10 to 15% per annum for the last two decades [4]. It is projected that the average demand growth over the next decade will be about 6% per year [4].This is an indication of financial stress and strain on the company in the years ahead, and much would be expected from ECG to operate in such a way to reduce its high rate of equipment damages in order to meet its performance demanded by the PURC and also to be able to stay in business.

This paper investigates protection integrity of over 676 distribution transformers in attempt to find the main causes and solutions to distribution transformer failures in Ghana. The study was conducted in the Ashanti East Region, one of the operational areas of ECG with high incidence of distribution transformer burnouts. It is found that protection integrity at distribution substation is riddled by indiscriminate use of copper links to replace blown HRC fuses and high ground resistance. The paper reports on the investigation and proposes alternative solutions in mitigating the problem.

II. DISTRIBUTION TRANSFORMERS AND THEIR APPLICATION IN GHANA

Distribution transformer is a static electrical device which steps down voltage by electromagnetic induction to feed different type of loads. They are designed to operate in different voltage levels and at different capacities. With given secondary voltage, distribution transformer is usually the last in the chain of electrical energy supply to households and industrial enterprises. In Ghana, distribution transformers mostly step down voltages from either 33kV or 11kV (on

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primary sides) to 440 Volts between phases and 230 Volts between phase and neutral (on secondary sides) through delta–star windings.

Unlike power transformers which are rated in MVA and are meant for transmission purposes, distribution transformers are rated in kVA and are meant for distribution and utilization of electric power. Generally, power ratings of distribution transformers range from 50 to 1000kVA depending on the type of mount. Basically, there are two types of mount- Pole Mounted Transformer [PMT] and Ground Mounted [GMT]. By standard, the ECG limits installation of PMT to a maximum capacity of 200kVA. However, within the confines of distribution transformer ratings, there is no specified capacity limit for installation of the GMT. In other jurisdiction, higher rated capacities for GMT are available.

Distribution transformers are expensive and critical equipment in electricity distribution network. They constitute a large portion of a typical utility's power delivery investment and form essential link between power utility and large number of customers. Outages due to distribution transformer failure cause immense inconvenience in network management and involve high expenditure in relation to repair or replacement. Therefore, it becomes important to protect them against faults such that much life as possible could be extracted from them.

III. INVESTIGATION PROCEDURE

Data on status of protection devices/systems on 676 distribution transformer stations were taken and analyzed. These included ground resistance values of lightning arresters, fuse rating on both high and low voltage side of the transformers, dielectric strength of the transformer oil, peak loads on the transformers and state of the associated distribution pillars. Lightning arrestor circuitry was also examined. Lightning arrester lead length of 0.6m was used as standard reference [5]

Earth resistance readings were taken using the earth clip-on tester; DET10C. Earth resistance values greater than 10Ω were considered high [6]. Earth resistance readings given by the DET10C tester were compared with the traditional earth tester, DET3TC, whose operation demands isolating the transformer from service. Error margin of 1% were observed between the two testers. Dielectric strengths of transformer oil were taking using the FOSTER OTS 60AF/2 oil test set. Breakdown voltage of oil below 30kV was regarded as bad oil. About 99% of the oil tested did pass the dielectric strength test. As a result, distribution transformer failure analysis in relation to insulation degradation was disregarded

IV. RESULT AND DISCUSSION

Fig-1 shows population of distribution transformers in the Ashanti East Region represented by its districts. It is observed in Fig-2 that transformer failure rate in the region is assuming an exponential function. From Fig-2, twenty five transformers would be expected to fail in the 6^{th} year if the status quo is maintained. Where 1, 2, 3, 4, 5 and 6 on the x-axis in Fig-2 represent year 2007, 2008, 2009, 2010, 2011 and 2012 respectively. Fig-3 shows the district's contribution to the failure rate. It is observed that Manhyia, Asokwa and Konongo are relatively low in terms transformer failures. However, it was noted from Fig-4, that Manhyia, Ayigya and Asokwa were districts with high population of transformers indiscriminately fused with copper links. The general expectation is that such abuse of protection integrity should rather result in high failure rate. Unfortunately, the situation is on the contrary.

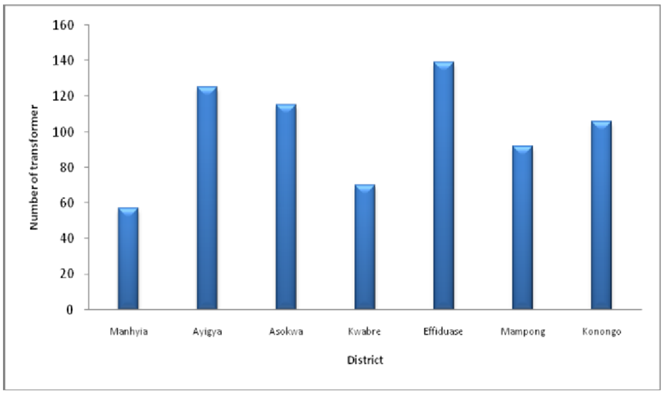

Fig-1: Distribution of transformers in the Ashanti East Region

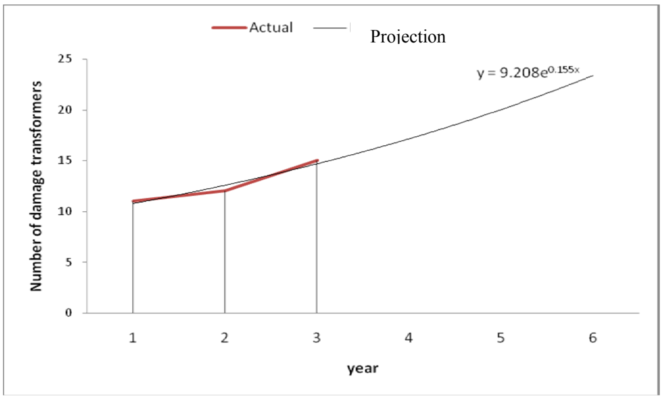

Fig-2:Trend of transformer failures in the Ashanti East Region

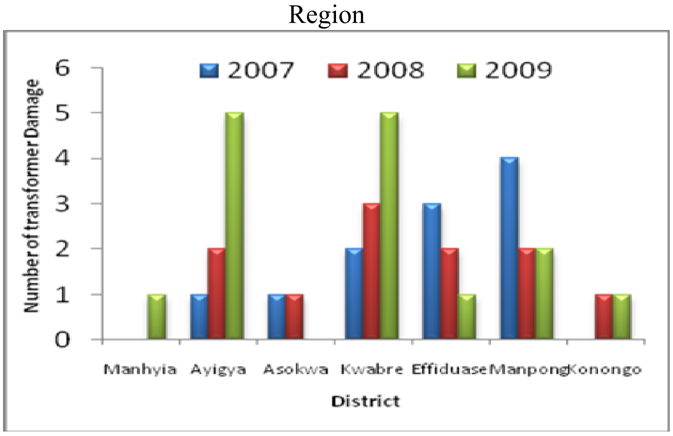

Fig-3: Number transformer failure in the districts

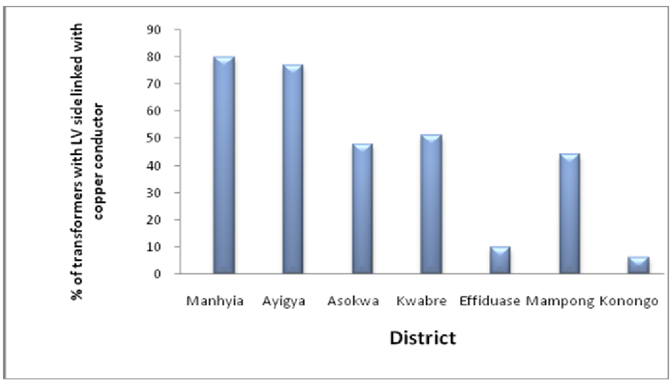

Fig-4: Transformer with LV side fused with copper links

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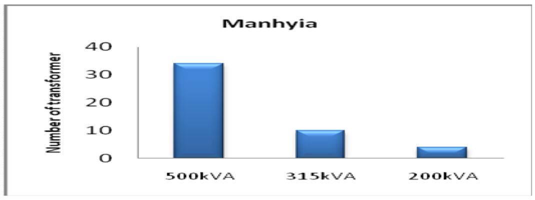
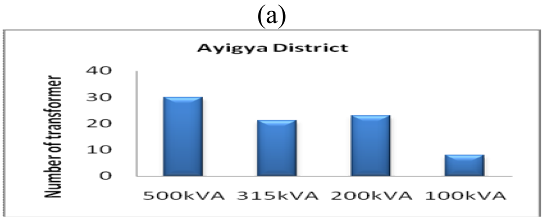
To explain this phenomenon, population of transformers in the respective district in relation to power ratings was examined; this is shown in Fig-5. A profile of damage transformers relative to transformer capacities was also examined, see Fig-6. From Fig-6 it was observed that the failures were common among 50, 100 and 200kVA transformers. From this standpoint, one may be tempted to draw a conclusion that these transformers might have some inherent deficiencies. Our investigation pointed to over fusing resulting from the use of the copper links. The size of copper links used as fuses in all the district were the same: a double of $4mm^2$ ($8mm^2$) copper link were used irrespective of transformer capacities, see Fig-7. Using the relation given below for determining appropriate wire size for fusing [7], it was found that whereas the copper link may be considered safe for a 500kVA transformer (on its low voltage side), it could represents an over fusing for 50, 100, and 200kVA transformers base on the associated distribution board used and number of out-going feeders fused with the copper links.

$$33\left[\frac{I}{A}\right]^2 t = \log\left[\left(\frac{Tm - Ta}{234 + Ta}\right) + 1\right] \quad (1)$$

Where, I=currents in Amps, A= area of wire in circular mills, t= time the current flows in seconds, Tm= melting point in degree Celsius, Ta= ambient temperature in degree Celsius



(a)



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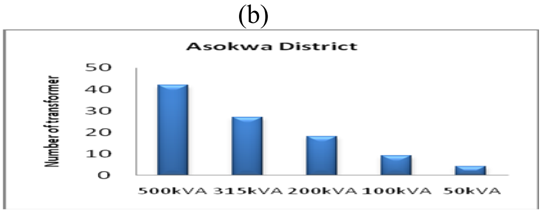

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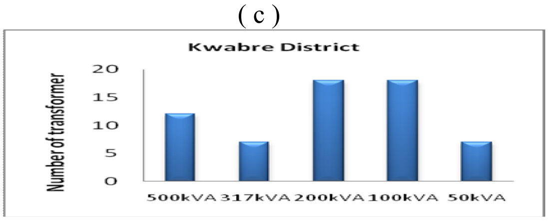

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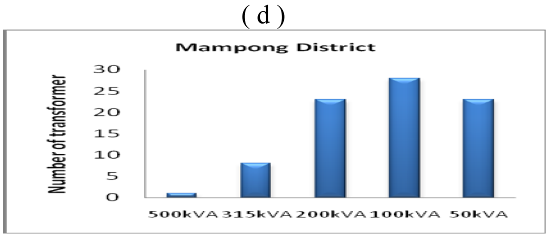

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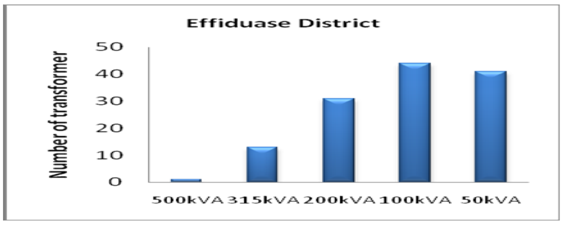

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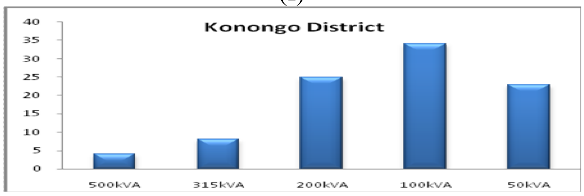

(g)

Fig-5: Population of transformer in relation to power ratings: (a) Manhyia (b) Ayigya (c) Asokwa (d) Kwabre (e)Mampong (f)Effiduase (g) Konongo

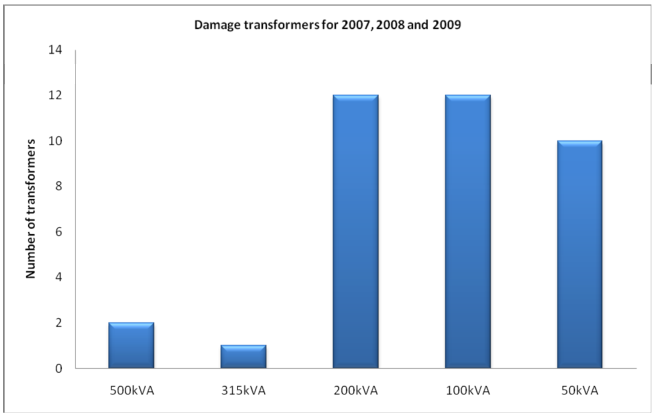

Fig-6: A profile of damage transformers in relation to transformer capacities

Fig-7: Copper links used as Fuses

As an example, consider a 500kVA transformer distributing power through a 6way distribution board (6 out-going feeders). Using a $8mm^2$ copper link as fuse on each out-going feeder, a total of $48mm^2$ ($8mm^2$ x 6-way) copper link would have been used on each phase of the low voltage side of transformer windings. Application of equation (1) based 35 degree Celsius as an ambient temperature and 300 seconds (typically recommended for HRC fuses) as the time the current flows, produced $40mm^2$ copper link as the appropriate fuse link. Thus the $48mm^2$ copper link used on the transformer

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would allow 120% overload on the transformer. Overloads are permitted on distribution transformers at certain conditions; distribution transformer can be overloaded by 150% for only two hours and 130% for 10hrs [8].
A 50kVA transformer, distributing power through one out-going feeder fused with 8mm^2 means overloading the transformer by 100% as the appropriate size of copper link given by (1) is 4mm^2. Similarly, for 100kVA transformer, a 2-way distribution with a total copper link of 16mm^2 (8mm^{2}x2) means overloading the transformer by 100%. In the case of 200kVA transformer, a 4-way distribution using a total of 32mm^2 (8mm^2 x4 out-going feeders) copper links also means subjecting the transformer to 200% overload.

This explains why Manhyia , Ayigya and Asokwa , although were district with high incidence of copper links used as fuses, yet were low in terms of transformers failures. These are district with high population of 500kVA transformers. From afore discussion, it is shown that the 500kVA transformers incidentally are not vulnerable to the size of copper links used.

The effect of the copper links was rather seen on the distribution pillars, see Fig-7. Districts with high incidence of LV copper links as fuses recorded high incidence of DP burnouts- the links were directly hooked to fuse contacts in the DPs. As a result, the DPs and their associated instruments were exposed to naked fire of the copper links during fusing. Mampong was also high on copper links but with no DP burnout because wedge type fuses (aerial fuses) were predominately used in the district.

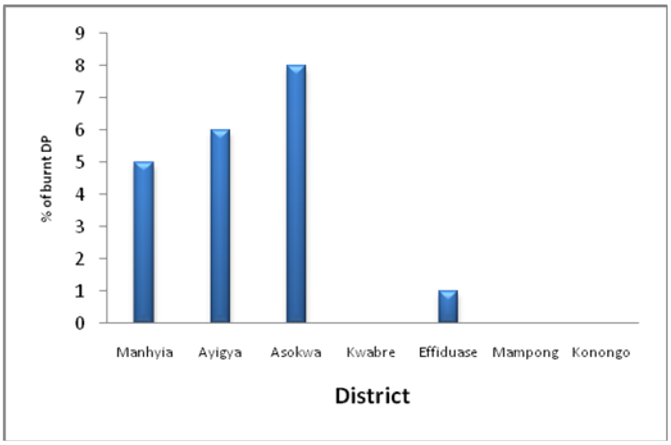

Fig-8: Number of Distribution Pillar Burnout

Fig-9 shows percentage of distribution transformers in the districts with lightning arrester ground resistance greather than 10-ohms. There appears to be a strong relationship between high arrester ground resistance and number of transformer damages in the districts, see Fig-3. This gave an indication that the higher the ground resistance values, the more the failures. It is noted from the preceding discussion that the failures are prevalent among the 50, 100 and 200kVA transformers. These transformers are mostly Pole Mounted Transformers [PMTs]. As high arrester ground resistance impinges on lightning protection integrity, it is our belief that the cause of the failures may also be attributed to lightning surges. Unlike Ground Mounted Transformers [GMTs] which are fed from cable with some degree of surge attenuation properties, PMTs are fed from overhead power lines that are vulnerable to lightning activities.

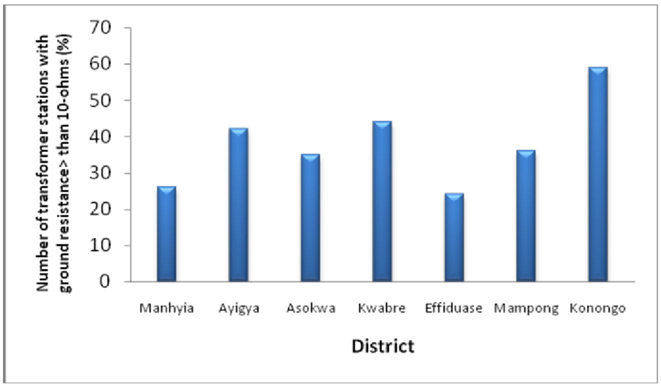

Fig-9: Transformers with lightning arrester ground resistance greater than 10-ohms

LIGHTNING ARRESTOR CIRCUITRY

The lightning arrestor circuitry was found to be standardized for all the 676 distribution substations visited, see Fig-10. Arrestor's lead length was found to be approximately7meters. We considered this too long for effective protection of the transformers. Arrester selected for an equipment protection must have a discharge voltage lower than the BIL of the equipment. For example, surge arrester with a discharge voltage of 43kV is considered adequate for a protection of 75-kV BIL transformers. This arrester provides 74% protective level on transformers.

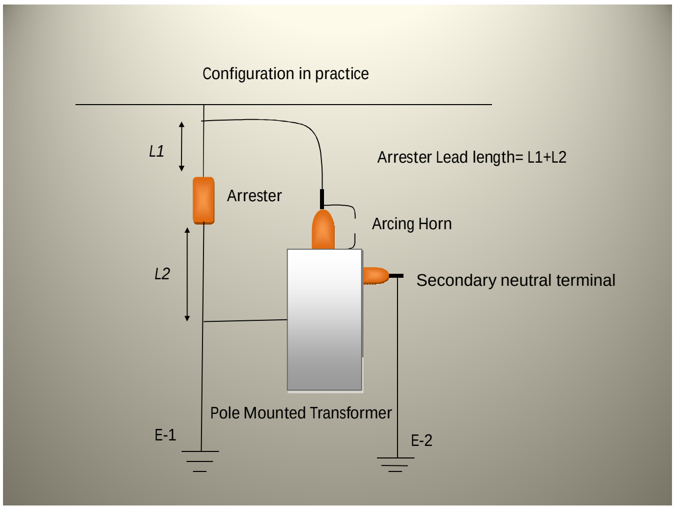

Fig-10: Lightning arrestor lead length

The lead length voltage drop $L = {di}/{di}$ during arrester discharge is critical. *L* can be estimated from the following relation:

$$L = 0.2 \ln {l}/{r} \text{ micro-henry/meter}$$

Where, l is length of conductor and r is radius of the conductor

However, in practice a rule of thumb is assumed. This is a drop of 1.64-kV per meter of lead length [9] and is added to

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the arrester discharge voltage. This is conservative for a standard 10-kA (8/20µs) wave parameter. Using a 7 m. lead wire and 8/20 µs, 10 kA surge parameter, voltage drop across the arrestor lead length would be equal to 11.48 kV, reducing the protective level to 36%. It is known that during arrester discharge, some amount of the surge voltage is let-through the transformer. This voltage, though considered harmless, could be destructive in a repetitive surge environment. A transformer with low arrestor protective level could be expected to fail when subjected to repetitive surge incidence. To optimize protection level of surge arrester, the arrester should be installed directly across the terminals of the equipment to be protected, refer to Fig-11. Arrestor lead length of 0.6m is recommended.

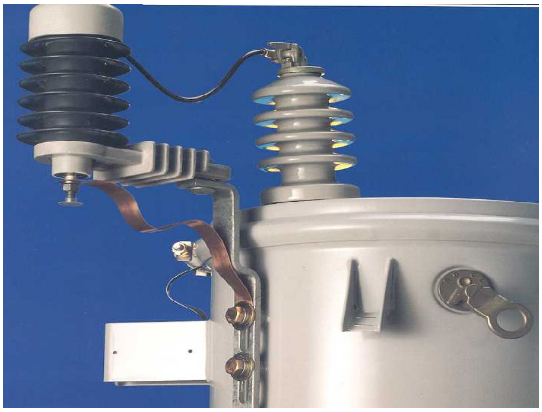

Fig-11: Recommended lightning arrestor circuitry

PROPOSAL

REDUCING HIGH GROUND RESISTANCE

From the data collected and followed by field periodic monitoring, it was observed that ground resistance values varied in order of 200% over a year. In our previous study [10], Palm Kernel Oil Cake [PKOC] was identified as an alternative to ground resistance-reducing agent. The PKOC has shown to offer significant reduction and stabilize ground resistance values over the years. The PKOC is applied using the critical resistance area concept [11]. Although our study of the PKOC on lightning protection performance on distribution transformer is yet to be complete, operational records in high isokeraunic areas so far indicate reduction in transformer failure in areas where PKOC have been applied. It is therefore our proposal that the PKOC is used to improve ground resistance values in areas where lightning arresters' ground resistance is high.

SELECTING APPROPRIATE FUSE SIZES

From our investigation, it was observed that the indiscriminate use of copper links as fuses on the distribution transformers was related to a shortfall that existed between supply of HRC fuses and their utilization by the operations staff. High consumption of the HRC fuse was found to be a function of high level of faults in the low voltage network. In an attempt to maintain continuous supply to customers during HRC fuse shortages, the copper links were resorted to but were wrongly applied. Solving this problem was found to be straight forward:

1. Keep reliable data on frequency of fuse blow-outs and eliminate shortfall in the supply of the HRC fuses.
2. Maintain a healthy network to avoid short circuit and earth faults or
3. Apply appropriate engineering approach in the use of the copper links

Our proposal here is to address the 'appropriate engineering approach' in the application of the copper links. This should, however, not be considered as the best solution to replace HRC fuses but should be regarded an alternative in an event of shortfall in the supply of HRC fuses.

Solution: Protection engineers rely on fusing tables to select fusing ratings for transformers. These fusing tables are developed by manufacturers and are used by the operations personnel to determine the fuse needed for a distribution transformer protection. In the case of copper link, their respective fuse current based on equation (1) can be used. To apply the copper links for transformer protection fusing ratio is necessary.

Fusing Ratio in this respect may be defined as:

$$\frac{\textit{fuse current carrying capacity}}{\textit{transformer full load current}}$$

As an example, consider a three-phase, 500kVA, 11/0.43kV transformer fused with

1. 40mm^2 copper link
2. 49mm^{2}copper link

The transformer full load current on the LV side

$$= \frac{500}{\sqrt{3}(433)}$$

= 667Amps

The current carrying capacity for:

40mm^2 copper link at 30^{0C}= 667Amps

49mm^2 copper link at 30^{0C} =700 Amps

Fusing ratio:

40mm^2 copper link= 667/667=1.0

49mm^2 copper link= 800/667 =1.20

The significance of the fusing ratio is that it provides an indication of how the transformer is protected. The 1.0 fusing ratio means the 40mm^2 fuse link will permit the transformer to be loaded to 100% of its capacity whilst the 1.20 fusing ratio gives an indication that the 49mm^2 fuse link could allow 20% overload on the transformer. Whilst a high fusing ratio implies more transformer failures on overloads, a low fusing ratio means fewer transformer damage by over loads.

V. Conclusion

The paper investigates protection integrity of over 676 distribution transformers in attempt to find the main causes of distribution transformer failures in Ghana. It was found that protection integrity at distribution substation is riddled by

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indiscriminate use of copper links to replace blown HRC fuses and high ground resistance. The study has clarified why distribution transformers with lower power ratings are more vulnerable to abuse of protection integrity than the higher rated ones. In conclusion, the paper has presented:

- Logical approach to selecting appropriate copper links in an event of shortfall in HRC fuses.
- A case for reducing lightning arrester leads length for effective lightning and surge protection system.
- Effective method of reducing high ground resistance values.

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