A Study of the Impact of Broken Neutral in a Distribution System

M. Xivambu AA Jimoh DV Nicolae
Tshwane University of Technology, Department of Electrical Engineering
Private Bag X 017, 0116, Pretoria North
South Africa
Mashangu.xivambu@eskom.co.za jimohaa@tut.ac.za danaurel@yebo.co.za

Abstract: **In this paper a study of the impact of the neutral conductor in a distribution system is presented. The causes which determine faults of the neutral conductor together with its effects are presented. The paper proposes a solution which will minimize the impact of the neutral failure.**

I. INTRODUCTION

Between 30 and 40% of the total investments in the electrical sector goes to distribution systems, but nevertheless, they have not received the technological impact in the same manner as the generation and the transmission systems.

Many of the distribution networks experience operational problems. A large number of public liability claims are submitted to Eskom due to loss of neutral conductors on the network. Different principles were applied by different area claims committees to approve or decline public claims due to loss of neutrals in the network [1].

Ordinarily, the consumption of consumers connected to a feeder fluctuates, thus leading to the fluctuation of the total load connected to each phase of the feeder. This in turn implies that the degree of unbalance of the feeder also keeps varying. The worse the degree of unbalance the poorer is the efficiency and voltage drop on the feeder [2]. It has been well established [2] that load balancing alone can lead to tremendous saving in investment costs while giving good performance to the feeder.

In the case of a distribution system with some overloaded and some lightly loaded branches, there is the need to reconfigure the system such that loads are transferred from heavily loaded to less loaded feeders. Here the maximum load current the feeder conductor can take may be taken as the reference. Nonetheless, the transfer of load must be such that a certain predefined objective is satisfied. In this case, the objective is for the ensuing network to have minimum real power loss. Consequently, phase balancing may be redefined as the rearrangement of the network such as to minimize the total real power losses arising from line branches. Mathematically, the total power loss may be expressed as follows [2], [3]:

$$\sum_{i=1}^{n} r_i \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{1}$$

This paper clarifies some technical aspects related to the loss of neutral in order to have uniformity and consistency when dealing with public claims due to loss of neutral conductors. Loose neutral or loss of neutral conductor in the network will have different impacts depending on the type of supply and installation as well as load balancing at that particular installation. The worse case scenario would include both damage to connected loads or creation of hazardous touch voltages on exposed conductive parts.

Load balancing has been studied in [4], [5], [6]. In this paper the algorithm of automatic reconfiguration [6] is applied with the specific purpose to minimize the neutral current and therefore to minimize the hazardous situation created by the loss of neutral conductor.

II. SYSTEMS AFFECTED BY NEUTRAL FAULTS

The loss of neutral must be dealt with according to the type of supply: from a single-phase transformer, from a dual-phase transformer and from a three-phase transformer.

A. *Supply from a single-phase transformer*

If the neutral loss occurs on a single-phase supply, then the customer(s) connected to that specific transformer will not have supply. Single phase transformers have only one phase and a neutral, as a result, loss of neutral will not damage the loads connected to that transformer. However the earth may become live and dangerous.

B. *Supply from a dual-phase transformer*

A broken or loose neutral will cause the voltage to float up to the line voltage, depending on the load balancing. Some customers will experience over voltage and other customers will experience under voltage. This type of fault condition may damage some of the loads connected to the supply. The earth may become live and dangerous.

C. Supply from a three-phase transformer

A broken or loose neutral will cause the voltage to float up to the line voltage depending on the load balancing. This type of fault condition may damage some of the loads connected to the supply. The earth may become live and dangerous.

III. Type Of Neutral Faults

During this study, few types of faults have been found. These faults are presented.

A. Neutral broken at transformer bushing

One frequent fault is the broken of the neutral at the transformer bushing, see Figs. 1 and 2.

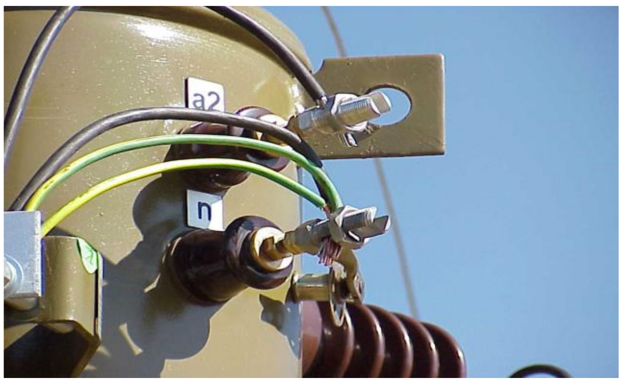

Fig. 1 Plug-in and tight neutral connection

Fig. 2 Lug and tight neutral connection

The main reasons were found to be:

- Neutral conductor not “cleaned properly (Fig.1).
- An improper size of the lug (Fig.2).
- The lug not properly crimped (Fig.2).

B. Broken or loose neutral at pole top box

One other fault found during this study was the broken or loose neutral at pole tope box (PTB), see Fig. 3.

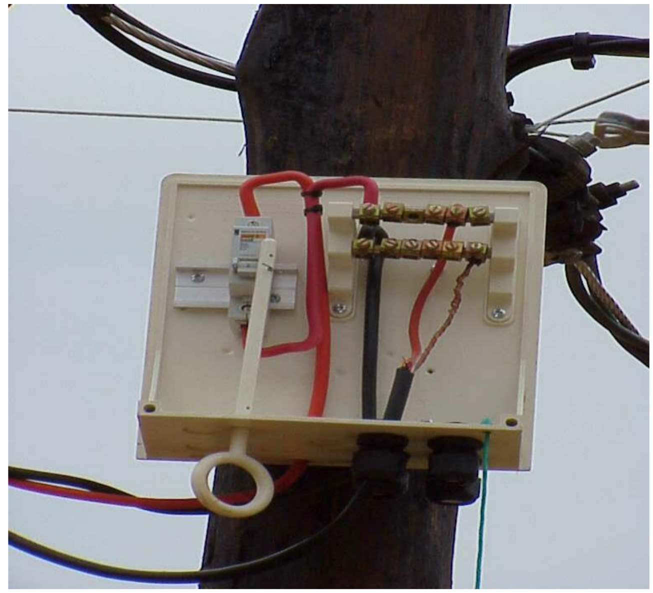

Fig. 3 Pole top box connection

A broken or loose neutral on a PTB is like opening a switch on the circuit, hence there will not be any damage to the loads connected. The earth may however become live and dangerous.

C. Neutral broken at service cable

The neutral can be broken or loose at the service cable entering a house-hold, see Fig. 4.

Fig. 4 Service cable entering the house-hold

A broken or loose neutral on the service cable is like opening a switch on the circuit. There will be no current flow to the customer’s meter box because the return path is broken.

The fault will not result in over-voltage; hence will not damage the customer's equipment. The earth may however become live and dangerous.

D. Neutral floating at high potential

In many situations the reasons for the customers' claims have been found as due to neutral floating. At thorough analysis the neutral floating were found to be due to the following reasons:

- Theft.
- Transformer overloading (Fig. 5).
- Low Voltage fuse by-pass (Fig. 6).
- Improper connection techniques (Fig. 7).
- Less attention given to Low Voltage networks (Fig. 8).
- Broken neutral in a three-phase feeder (Fig. 9).

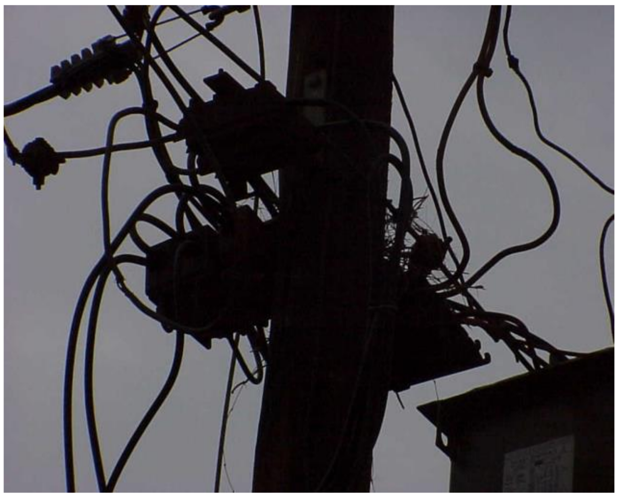

Fig. 5: Transformer overloading

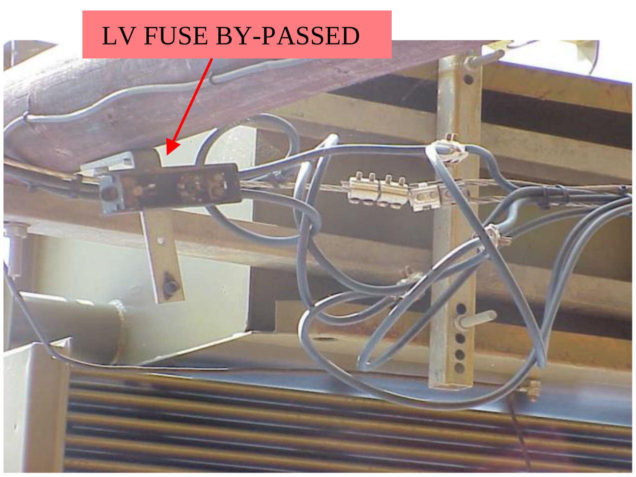

Fig. 6: LV fuse by-pass

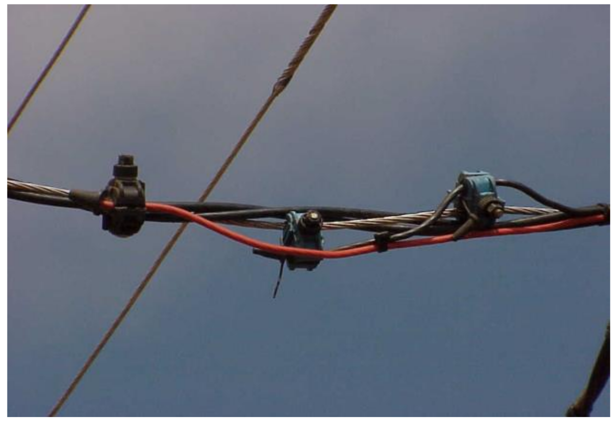

Fig. 7 Improper connections

Fig. 8: Less attention given to LV network

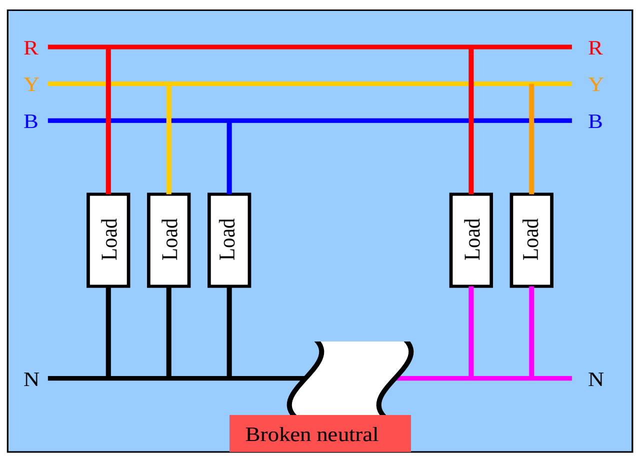

Fig. 9: Broken neutral conductor

Due to the effect of the broken neutral conductor, the equipment in the house hold can experience voltages up to 400V, hence the appliances will be damaged.

IV. Mitigation Solution For Neutral Faults

As presented above, the effect of neutral failure in three-phase system depends on the current balancing of the system. In this regard a reconfiguration algorithm of the loads on a feeder is proposed. Generally, on a feeder can have ***n*** single-phase loads connected between neutral and the phases of the feeder (I_1, I_2… I_k… I_n). In the method proposed in this paper, each load is connected to the feeder via a switch selector, see Fig. 10. The structure of each switch selector is shown in Fig. 11.

Once the reconfiguration algorithm is activated, then, as a result, the neutral current will be minimized.

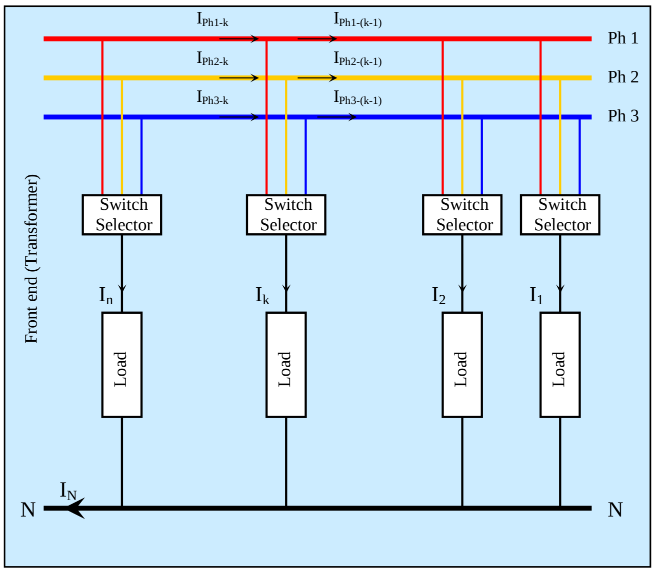

Fig. 10 Three-phase feeder with reconfiguration

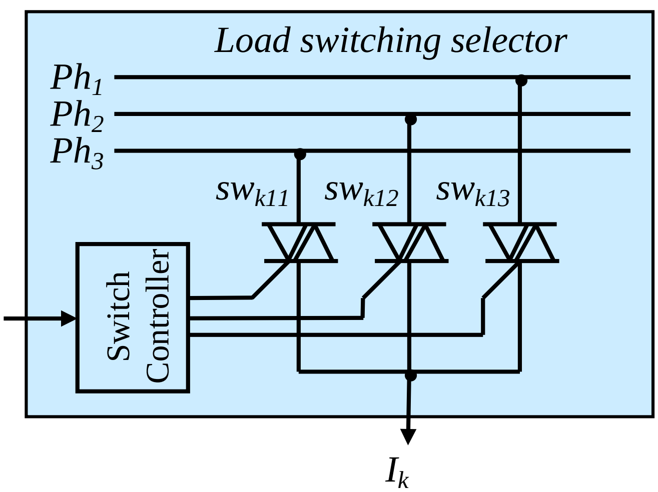

Fig. 11 Switch selector

A. Reconfiguration mathematic model

Given a distribution system as shown in Fig. 10, a network with 3 phases with a known structure, the problem consists of finding a condition of balancing. The mathematical model can be expressed as:

$$\boldsymbol{I}_{ph1k} = \sum_{i=1}^{3} sw_{k1i} \boldsymbol{I}_k + \boldsymbol{I}_{ph1(k-1)} \tag{1}$$

$$\boldsymbol{I}_{ph2k} = \sum_{i=1}^{3} sw_{k2i} \boldsymbol{I}_k + \boldsymbol{I}_{ph2(k-1)} \tag{2}$$

$$\boldsymbol{I}_{ph3k} = \sum_{i=1}^{3} sw_{k3i} \boldsymbol{I}_k + \boldsymbol{I}_{ph3(k-1)} \tag{3}$$

The constraints of only allowing one breaker in each of equations (1) to (3) to be closed can be written as following:

$$\sum_{i=1}^{3} sw_{k1i} - 1 = 0 \tag{4}$$

$$\sum_{i=1}^{3} sw_{k2i} - 1 = 0 \tag{5}$$

$$\sum_{i=1}^{3} sw_{k3i} - 1 = 0 \tag{6}$$

To minimize the neutral current, the objective of this new algorithm is to minimize the difference of the rms value of the phase currents ($I_{phik(i=1,2,3)}$):

$$\text{Minimize } \left[I_{ph1k} - I_{ph2k} \;\; I_{ph1k} - I_{ph3k} \;\; I_{ph2k} - I_{ph3k} \right] \tag{7}$$

B. Study case: unbalanced feeder

In order to validate the reconfiguration, a small feeder with 30 house-holds has been chosen; the feeder is supplied from a 50 kVA three-phase transformer. It is generally accepted that the power factor of a house-hold is close to unity.

Table I shows the rms currents drawn by the loads at a certain moment in time.

TABLE I
STUDY CASE: UNBALANCED FEEDER

I_k (A)	Connected Phase	I_{ph1} (A) ($\angle 0^0$)	I_{ph2} (A) ($\angle -120^0$)	I_{ph2} (A) ($\angle 120^0$)	I_N (A)
9.6	1	9.6	0	0	$9.6\angle 0^0$
17.2	2	9.6	17.2	0	$14.9\angle -86.2^0$
20.4	3	9.6	17.2	20.4	$9.6\angle 163.2^0$
33.5	1	43.1	17.2	20.4	$24.5\angle 6.5^0$
44.1	2	43.1	61.3	20.4	$35.5\angle -86.4^0$
27.4	3	43.1	61.3	47.8	$16.37\angle -134.4^0$
8.9	1	52.0	61.3	47.8	$11.97\angle -102.3^0$
18.3	2	52.0	79.6	47.8	$29.9\angle -113^0$
11.5	3	52.0	79.6	59.3	$24.8\angle -134.8^0$
22.6	1	74.6	79.6	59.3	$18.3\angle -73.7^0$
34.1	2	74.6	113.7	59.3	$48.6\angle -104.2^0$
10.2	3	74.6	113.7	69.5	$41.9\angle -114^0$
20.3	1	94.9	113.7	69.5	$38.4\angle -85.1^0$
15.6	2	94.9	129.3	69.5	$52\angle -95^0$
18.2	3	94.9	129.3	87.7	$38.5\angle -110.7^0$
2.3	1	97.2	129.3	87.7	$37.7\angle -107.4^0$
42.1	2	97.2	171.4	87.7	$79.3\angle -114^0$
5.7	3	97.2	171.4	93.4	$76.1\angle -117.5^0$
51.7	1	148.9	171.4	93.4	$69.5\angle -76.3^0$
35.1	2	148.9	206.5	93.4	$97.9\angle -90.6^0$
24.9	3	148.9	206.5	118.3	$77.5\angle -100^0$
49.1	1	198.0	206.5	118.3	$84.2\angle -65^0$
3.7	2	198.0	210.2	118.3	$86.4\angle -67$
19.2	3	198.0	210.2	137.5	$67.5\angle -69^0$
33.6	1	231.6	210.2	137.5	$85.5\angle -47.5^0$
40.4	2	231.6	250.6	137.5	$104.9\angle -69^0$
41.3	3	231.6	250.6	178.8	$64.5\angle -74.8^0$
9.3	1	240.9	250.6	178.8	$67.9\angle -67.1^0$
52.3	2	240.9	302.9	178.8	$107.5\angle -90^0$
23.7	3	240.9	302.9	202.5	$87.7\angle -97.7^0$

As one can notice, the neutral current to the transformer bushing is quite high which, in the case of loose or broken connection at the bushing, will definitely create a high floating potential.

C. Reconfiguration results

After applying the reconfiguration of the load to different phases, the new situation is presented in Table II.

TABLE I
STUDY CASE: BALANCED FEEDER

I_k (A)	Connected Phase	I_{ph1} (A) ($\angle 0^0$)	I_{ph2} (A) ($\angle -120^0$)	I_{ph2} (A) ($\angle 120^0$)	I_N (A)
9.6	1	9.6	0	0	$9.6\angle 0^0$
17.2	2	9.6	17.2	0	$14.9\angle -86.2^0$
20.4	3	9.6	17.2	20.4	$9.6\angle 163.2^0$
33.5	2	9.6	50.7	20.4	$39.8\angle -138.8^0$
44.1	1	53.7	50.7	20.4	$31.9\angle -55.3^0$
27.4	3	53.7	50.7	47.8	$5.1\angle -29.3^0$
8.9	1	62.6	50.7	47.8	$13.6\angle -10.6^0$
18.3	3	62.6	50.7	66.1	$13.9\angle 72.5^0$
11.5	2	62.6	62.2	66.1	$3.7\angle 115^0$
22.6	1	85.2	62.2	66.1	$21.3\angle 9^0$
34.1	2	85.2	96.1	66.1	$26.3\angle -81^0$
10.2	3	85.2	96.1	76.3	$17.1\angle -93.3^0$
20.3	3	85.2	96.1	96.6	$11.2\angle 177.6^0$
15.6	2	85.2	111.7	96.6	$23.1\angle -145.4^0$
18.2	1	103.4	111.7	96.6	$13.1\angle -93.3^0$
2.3	2	103.4	114.0	96.6	$15.8\angle -98.2^0$
42.1	3	103.4	114.0	138.7	$31.2\angle 138.2^0$
5.7	1	109.1	114.0	138.7	$27.2\angle 130.2^0$
51.7	1	160.8	114.0	138.7	$39.9\angle 31.4^0$
35.1	2	160.8	149.1	138.7	$19.1\angle -28^0$
24.9	3	160.8	149.1	163.7	$13.4\angle 70.9^0$
49.1	2	160.8	198.2	163.7	$35.9\angle -124.1^0$
3.7	3	160.8	198.2	167.4	$34.5\angle -129.6^0$
19.2	1	180.0	198.2	167.4	$26.7\angle -96^0$
33.6	2	180.0	231.8	167.4	$58.7\angle -108.6^0$
40.4	1	220.4	231.8	167.4	$59.4\angle -69.5^0$
41.3	3	220.4	231.8	209.2	$19.7\angle -90^0$
9.3	2	220.4	241.1	209.2	$28.2\angle -100.3^0$
52.3	3	220.4	241.1	261.5	$35.6\angle 150.2^0$
23.7	1	244.1	241.1	261.5	$19.1\angle 112.1^0$

Table II shows that at the transformer bushing the neutral current is 21.8% from the unbalanced situation which will produce a much lower floating potential in the case of broken or loose neutral conductor.

V. CONCLUSIONS

In this paper, causes that produce neutral conductor to broken or be loose and effects of these on the loads connected to a distribution system are presented.

The reconfiguration algorithm applied for a three-phase four wire distribution feeder shows a substantial reduction in neutral current.

VI. ACKNOWLEDGMENTS

The authors will like to acknowledge the support of Eskom-Distribution, Limpopo Province.

VII. REFERENCES

[1] M.H Xivambu, FJC Wahl, A. Kotze and J.A. Engelbrecht, *Public Liability Claims Due to Loss of Neutral*, Eskom Technical Instructions, November 2004.

[2]. A.A. Jimoh, M.W. Siti and I.E Davidson. "Analysis of Domestic feeder technical loss reduction option using both engineering and economic models", *Ninth UIE conference*, Durban, January 2000.

[3]. M.W. Siti, A.A. Jimoh and I.E. Davidson. "Distribution circuit loss minimization through feeder reconfiguration", SAUPEC 2004, Stellnbosch, South Africa

[4]. S. Civanlar, J.J. Grainger. "Distribution Feeder reconfiguration for loss reduction", IEEE Trans. PWRD-3, pp 1217-1223, 1998.

[5]. K. Aoki, H. Kuwabara, T. Satoh and Kanezashi. "An efficient algorithm for load balancing of transformers and feeders by switching operation in large scale distribution system" IEEE Trans. on Power Delivery, vol. 3 no 4 pp 1865-1872 October 1988.

[6] W.M. Siti, AA Jimoh and DV Nicolae, Load balancing in Distribution feeder through reconfiguration, IECON 2005 The 31st Annual Conference of the Industrial Electronics Society, Raleigh, North Carolina, USA, 6-10 November, 2005