Practical Case Study of Electrical Safety Issues within an Imbalanced Three-Phase Power System

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Abstract: ***Electrical safety is generally referred to when it comes to implementing policies, procedures and the use of Personal Protection Equipment in the execution of any work activity in relation to electrical power and equipment. The above assumes a fully functional protection system and an acceptable quality of supply within the working environment in such a way that in case all the relevant measures are adhered to, personnel would remain in a safe condition. Surprisingly, we have been involved in a specific context - in Southern Africa where, all the above measures were existent but the power supply system from the utility suddenly became imbalanced thus causing some unthought issues such as a considerable difference of potential between transformers' secondary star point, known as neutral point, and the earth bars. As a result, maintenance personnel became subject to potential electrical shock despite the established safety policies such as the isolation and lockout procedure which mostly consists of isolating live phase conductors only. In addition, switchgears and cables earthing not being a common practice for Low Voltage unlike Medium and High Voltage Systems, the hazard was maintained and correspond risk unchanged. Therefore, using a practical case, this paper aims to highlight the identification of an imbalanced high voltage power system, its probable consequences to the low voltage level and how best they could possibly be mitigated in case users are not in position to fully address the root cause.***

Keywords: Electrical Safety, Power System, Three-phase, imbalanced system, neutral

1. Introduction

In the mining industry worldwide Lockout, Tag-out and Try-out also known as LOTOTO is a very common practice. It consists of isolating every source of energy, placing a lock with a tag on the switch handle, in case of an electrical energy source, and testing that the equipment is not supplied with voltage by pushing the start button and/or testing the presence of voltage. Most of the time, the isolated switches are single or three-phase and therefore, the neutral conductor is not isolated. Nevertheless, it still becomes safe due to the power system being balanced, thus a neutral point to a potential close enough to OV, but also due to the earthing of the neutral point specifically while using IT and TT earthing systems (IEC, 2001; Lacroix & Calvas, 1995, pp.7-10).

We have experienced in a mine site in Southern Africa where the high voltage power supply three-phase system was found imbalanced with balanced phase-to-phase voltages but very imbalanced phase voltages, up to 10 %; measured from the 33 kV distribution substation meters.

This resulted in the neutral to earth voltage going over 100V at the 400V Low Voltage system and much higher at 550V system leading to variable speed drive trips, damage of few sensitive instrumentation devices and worse, employees feeling uncomfortable when performing some cable termination; by being subject to touch or step voltage (IEEE, 2000, pp.17-19). Such a disturbance is generally not considered while studying the quality of supply for a power system (Bollen, 2003).

The lesson learned here was that, only the few Low Voltage transformers with neutral point not properly earthed for several reasons were subject to the above nuisance. Ultimately, once earth terminations were addressed, the issue got fixed. However, in such a case, it is paramount to determine what is the problem's origin, between site load and the power supply utility grid in order to performance further studies and identify the exact root cause.

2. Goal

The objective of the present study is to create or even revive the awareness to the described issues among professionals potentially subject to similar problems that are seemingly frequent in the African region. Furthermore, the following will show how major issues could be identified and pointed out using daily tools, with no requirement for special equipment and software. Also, it appears to be important to remind about the necessity of some basic safety precautions provided by standards and regulations. And lastly, this would ultimately raise the requirement for further research and improvements in the domain, specifically for the African continent.

3. Material and Method

Our analysis will consist of the monitoring both the supply voltage, phase angles, power factor, line currents as well as active, reactive and apparent power mainly at the incoming substation level (33 kV) and part of them at the low voltage level (550V and 400V).

Considering that the system imbalance could be caused by the mine network (load) or could come from the supply network itself, the monitoring of the above variables will be made at different loads, from full load to no load. Different site feeders, distributing power to specific types of load, will be sequentially load-shed. In addition, the two available power factor correction units shall be sequentially switched ON and OFF while observing the system performance.

Common tools will be mainly used during this exercise. Firstly, a software called Cewe Config 3.4.0, used for power monitoring, will help visualize the network parameters at 33kV. This software imports its data in real time from the incoming substation main meter on the secondary side of the 220 kV to 33 kV transformers. Secondly, a FLUKE 1664 FC digital earth resistance tester will test and confirm that the earth resistance is below 5 ohms and therefore acceptable (IEEE, 2000, pp.64). Lastly, a FLUKE 376 digital multimeter will be used to measure phase to phase, phase to neutral and neutral to earth voltage at Low Voltage level.

Following the system monitoring, we will be interpreting the readings and hopefully getting to an informed conclusion prior to making any recommendation.

4. Results and Discussion

4.1. Affected transformers characteristics

As mentioned previously, disturbances were recorded on few site equipment from the time the supply became imbalanced. These were trips, damage to few equipment and uncomfortable feeling for people. The common point between all the above items is that they were fed by transformers which had their neutral point unearthed at the time.

Earthing of the secondary start point is part of the standard in the considered mine site, however for different reasons, those specific transformers were not. However, the remaining 67 units, part of a 71-transformer infrastructure, were compliant.

Those reasons a spreading between “unknown reason” as there is no justification for it to a rusted contact surface between the cable lug and the tank or even electricians not connecting the earth cable in the first place while commissioning a pump station which coincided with the problematic period.

Table 1 provides the identified reasons behind which led to having four site transformers unearthed on their secondary star point as well as some specifications, brand and physical location for each of them.

Table 1: Affected transformers

Characteristics	Make	Type	Location	Reason
2500kVA, 33kV/550V	ACTOM	Power	Plant	Unknown
1250kVA, 6.6kV/525V	WEGEZI	Power	Pump station 1	Negligence
1250kVA, 6.6kV/525V	WEGEZI	Power	Pump station 1	Negligence
15kVA, 525V/400V	POWERMITE	Distribution	Pump station 2	Rusted connection

4.2. Initial system performance

Following recorded disturbances, the system figures were monitored using Cewe Config in order to discover any abnormality. Two concerns could be noticed: a 12% phase voltage imbalance between L1 and L2 (17.83 kV & 20.27 kV). In addition, phase angle was found to be much lower between L1 and L3, compared to the others hence a higher phase power factor for L3 as well. Figure 1 displays the phase angles as well as different readings at a particular point in time.

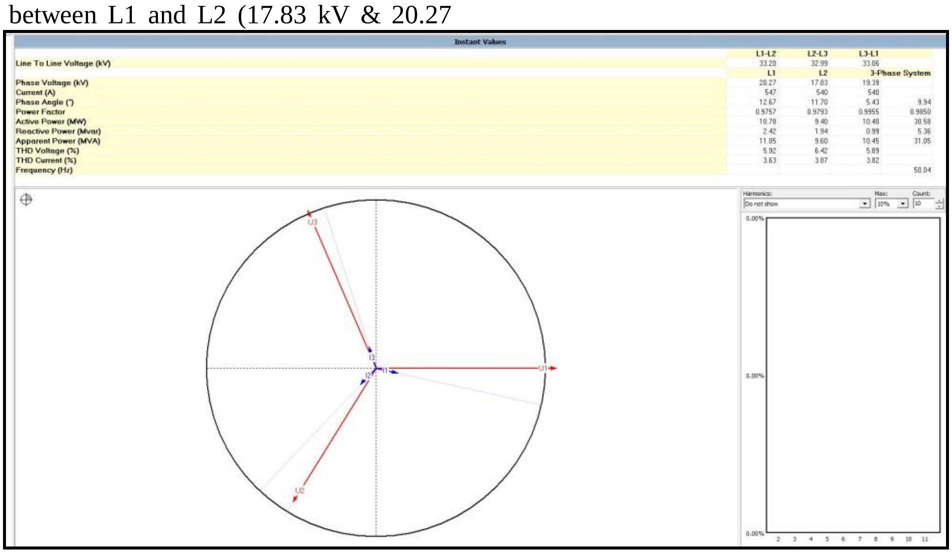

Figure 1: Initial System performance

Thereafter, measurements were taken on the 15kVA distribution transformer, both on the primary and secondary side before and after fixing the neutral point earthing as provided in Table 2. These measurements reveal that while phase-to-phase voltages remain somewhat balanced, with an imbalance lower than 1% at all time, phase-to-neutral readings are a bit different. While there is a just noticeable 1% difference between the first and second phase, we have been able to measure up to a 4% discrepancy with the third one. More importantly, the neutral-to-earth voltage practically equals the third phase-to-neutral voltage in the first time then vanishes right after the earth connection is fixed.

Table 2: Low voltage readings

Terminals	Initial measurements	Measurements after Earthing
A-B	545V	555V
A-C	540V	552V
B-C	540V	555V
a-b	422V	428V
b-c	412V	425V
a-c	418V	428V
a-n	246V	247V
b-n	243V	247V
c-n	236V	245V
E-n	234V	0V

4.3. System monitoring

The previous measurements initially gathered, revealed that the system had lost its balance and it was paramount to investigate further and determine what the source was. Therefore, a series of actions were taken to try and isolate each and every feeder, the power factor correction units and finally shed the whole load in order to assess the system performance in each specific condition. The following figures represent and describe the most salient.

From observations, it was seen that the imbalanced varied with time in an uncontrolled manner. Getting from quite severe, as for Figure 1 to a bit better as per Figure 2 which describes the initial status on the test and monitoring date.

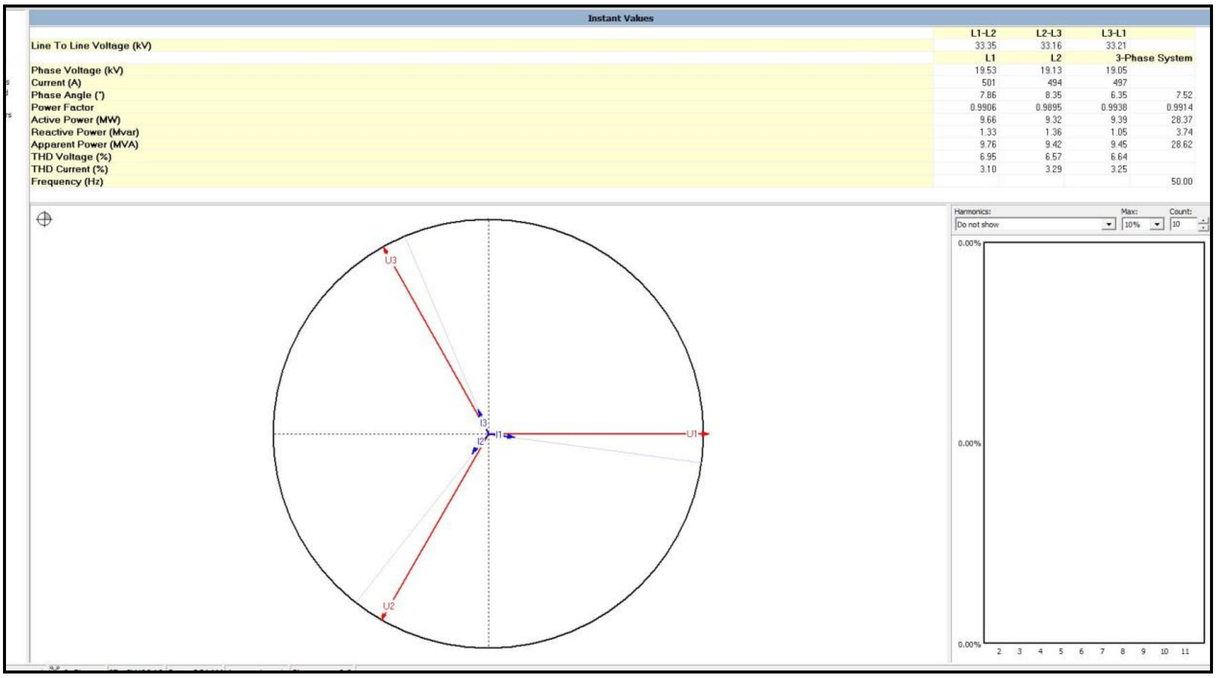

Figure 2: System status prior to sequential monitoring at low voltage and angle difference

At this stage the voltage ratio by considering the extremes (L3 divided by L1) is 97.5% hence a 2.5% imbalance. However, the angles differences taken from the extremes (third divided by second) is 76% which implies a 24% difference.

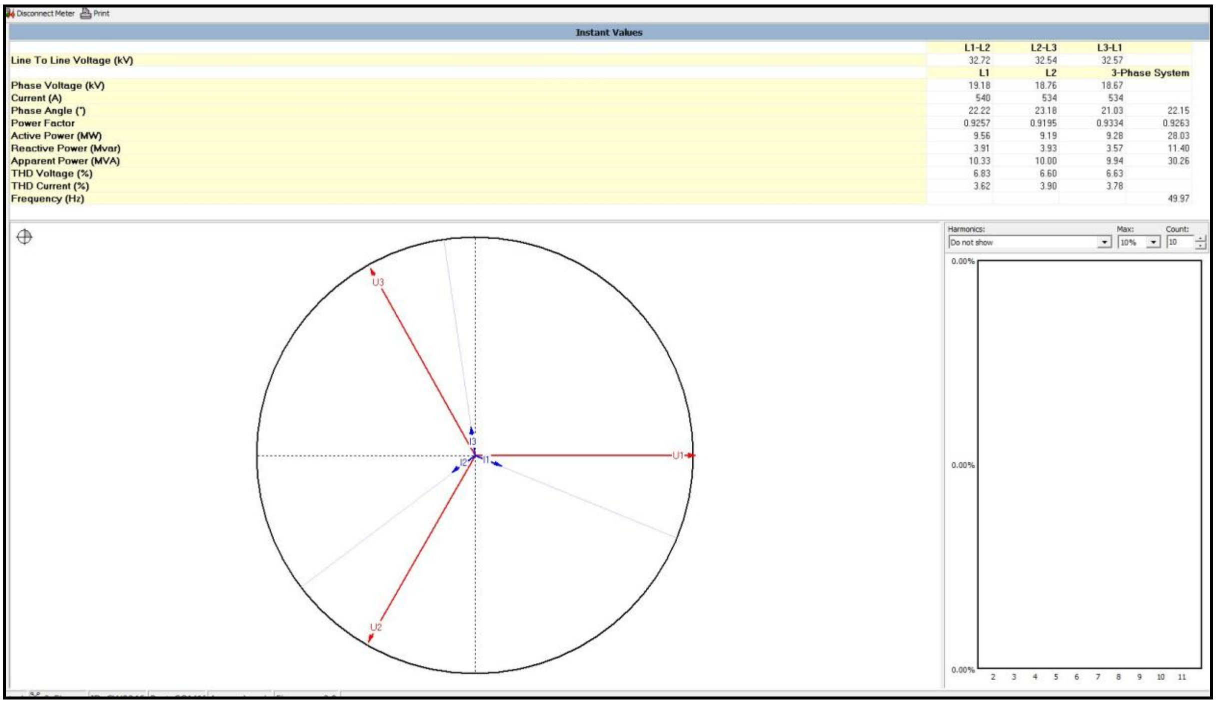

Figure 3: Power factor correction units isolated

This logically resulted in a power factor fall from an average of 0.9914 to 0.9263 with an improvement in voltage angle ratio by comparing the extremes from about 76% to 90%. This could lead to believe that the power factor correction unit have a negative impact on voltage angles.

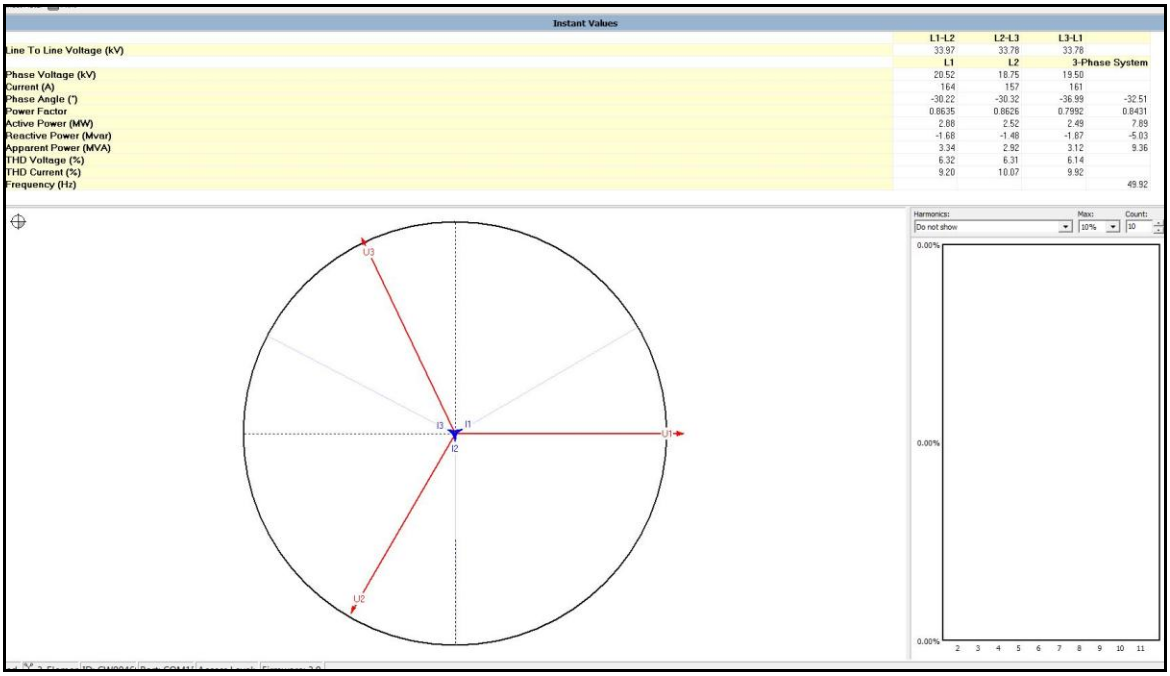

Figure 4: Major plant load shedding (Feeder#2 isolated)

At this stage, the voltage ratio slightly reduced to 95% and angle ratio to 82% with a 72% reduction in load (from 28.03 to 7.89 MW). This reveals that the plant load is a factor of equilibrium.

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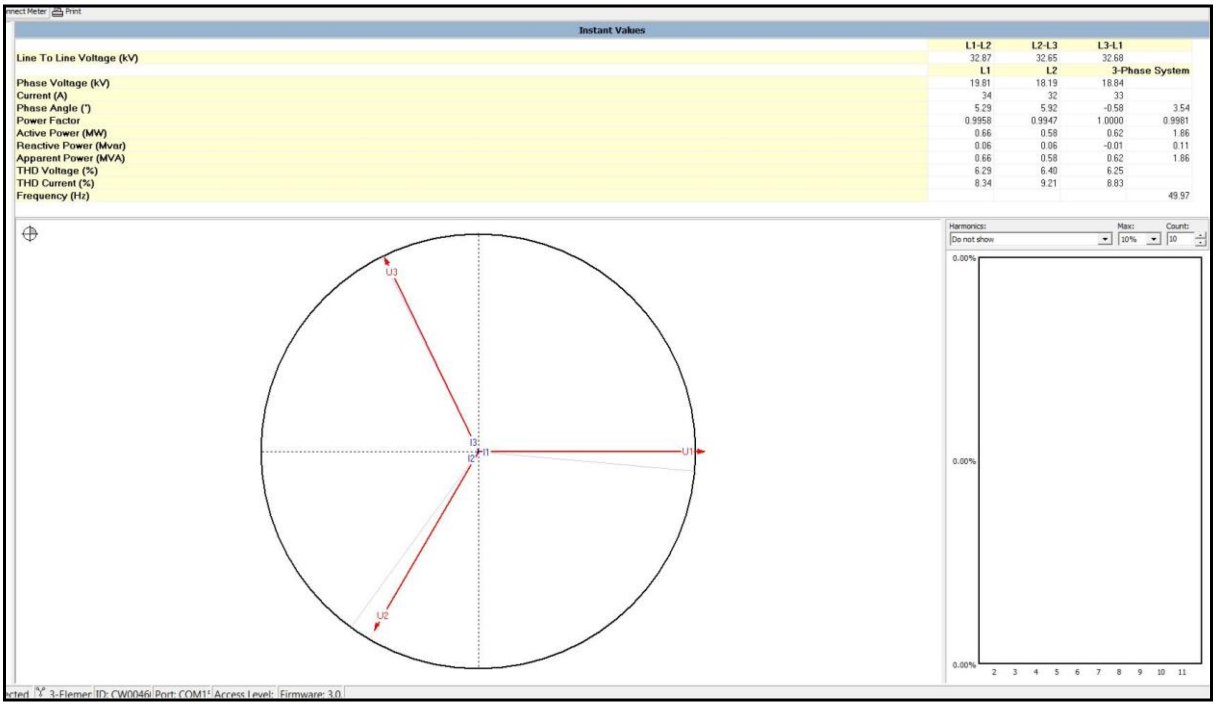

Figure 5: Pit dewatering load shedding (part of Feeder #3 isolated)

A further 21% reduction in load maintained the voltage ratio (now L2/L1) dropped to 92% while the angle ratio gets lower than 10% from the previous 82%.

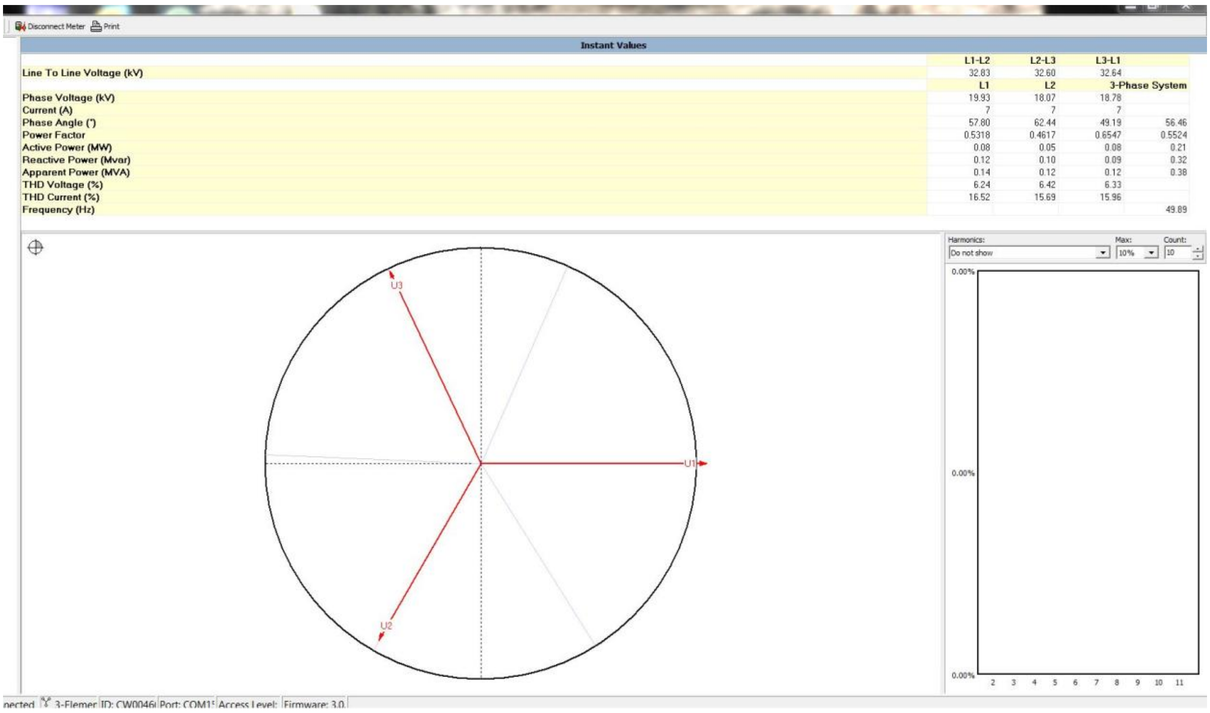

Figure 6: Load shedding of the remaining plant load (Feeder #1)

With only a 0.75% load, the voltage ratio reduced further to 91% while the angle ratio jumped to 79%.

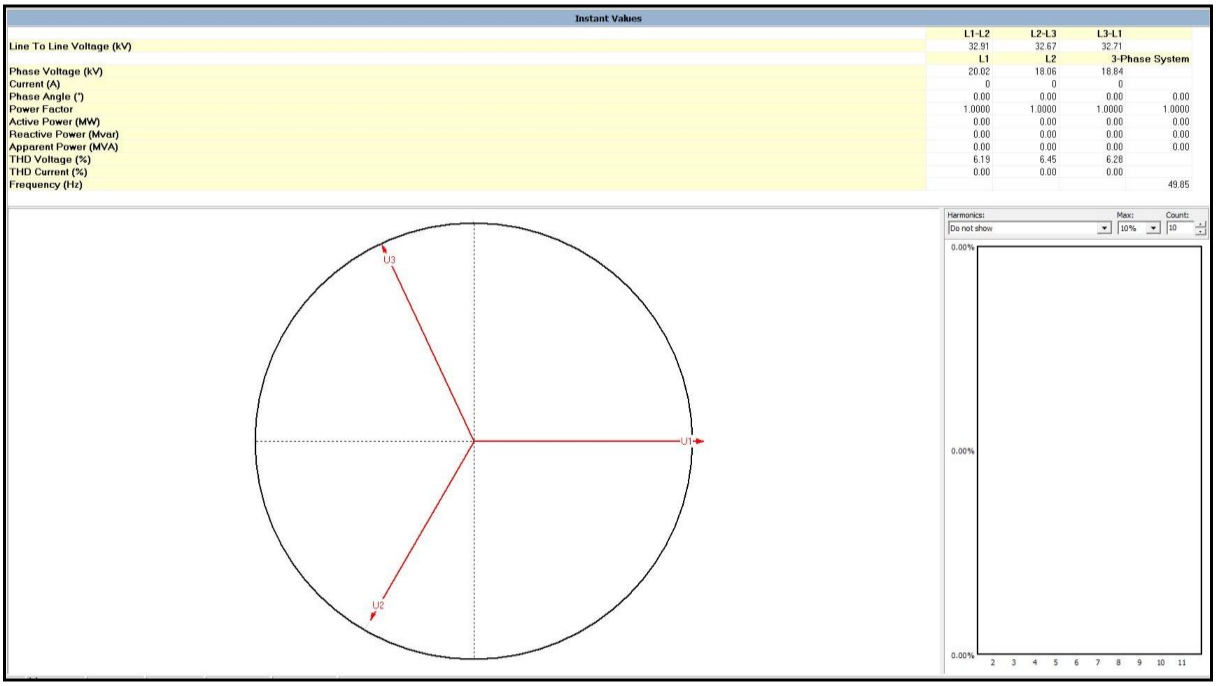

Figure 7: Full site outage

At no load, voltage ratio drops further to 90% hence a 10% imbalance and display the high voltage grid actual performance. All three phases' angles become null due to no load hence no current flowing on the feeder.

4.4. Results interpretation

From the above data, we have pointed out that system performance has been constantly changing at different point in time. Firstly, it appeared that power factor correction units were adding in angle imbalance. However, as the load carried on reducing, the system further lost its equilibrium. This reveals that the local system positively influences the supply performance, unlike our first thought which considered the site network and load as the possible root cause.

An additional finding is that power factor, and voltage angles, kept fluctuating at different load levels, depending on its nature at that specific point in time, between plant and pump station motors and later camps, offices and other buildings, after both pit and plant were isolated.

In summary, the system performance tends to become worse when the load reduces up to reaching a voltage imbalance of 10% at no load. This is specifically for the phase-to-neutral voltage, while phase-to-phase voltage is somewhat balanced. Looking at it, this is similar to what was measured on the low voltage transformers' terminals using a multimeter, means a different measuring tool. Therefore, we should comfortably argue that the presence of a voltage between the transformer secondary star point and the earth is the consequence of an imbalance at the high voltage level. Consequently, the issue lies on the supplier side and is independent from the site equipment.

5. Conclusion

The present paper has been able to link safety hazards to personnel and users in the field at low voltage level to major system issues on the high voltage grid far above in the hierarchy. This serves to reveal how problems could cause consequences to a completely different system and environment. In case these are not carefully monitored and analyzed, they could remain unsuspected and therefore unaddressed.

The learning, however, has been that only transformers which had the secondary star point unearthed suffered from those consequences. This reminds about the importance to maintain some periodic inspections on equipment and those should be performed with a careful attention after full adherence to commissioning good practice. Also, reinforcing the current Lockout procedure, with for instance the earthing of circuits and sub-circuits in Low voltage too, would be an additional measure which would enforce the personnel and users' safety.

However, the root cause being a poor high voltage system performance, it is paramount that the power supply utilities also maintain high standards of maintenance and control practices. Unfortunately, due to the interlinking between national grids of different countries part of the Southern African Power Pool, issues from one country could influence others, with in fact a much better performance. This therefore extrapolates local issues to a vast region and requires an even higher attention (Guo & Yu, 2004).

This study has been made with the tools on hand and therefore shows how important data could be easily gathered and analyzed in order to obtain an informed decision. On the other hand, major issues, like this specific one, could best be analyzed with more sophisticated tools, techniques and resources. We hope that these would be made possible further to this submission. Moreover, due to the several energy limitations and poor quality of supply in sub-Saharan

Africa, more studies should be encouraged in order to generate sustainable solutions. Those however imply important investments into the correspondent fields as well as the research and development domain in general.

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