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Power Transformer Fault Caused by Human Error and Inadequate In the Design

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SUMMARY

This paper presents a case study of earth fault on the Generator Step-Up power Transformer 150 MVA, 15KV/400 KV. The earth fault happened due to human error, which is caused by closing the earth switch at the transformer side when the transformer was energized. Typically, the Generator Step-Up Transformer is one of the essential components of the electrical generating units. Therefore, the earth switches of the transformers are designed to release the remaining magnetic energy from the transformer side during necessary electrical grid condition or the required maintenance activities, such as routine check, oil treatment, and transformer's bushings washing. Meanwhile, these activities are normally carried out in a periodic and planned basis.

A deep investigation was preformed to search behind the causes of the problem. The troubleshooting was conducting through different phases, began with data collection to stand on the strong evidence, then visual inspection which was carried out after dismantling the generator circuit breaker to discover the physical evidence. The investigation results affirmed that two main factors were participating in creating the Transformer earth fault. First one was the human error, and the second cause was the interlocking system between the energized system and earth switch.

This paper reviews the applicable solutions with the relative implementations to prevent this kind of accident from occurring in the future. One of these solutions is to modify the control circuit of the earth switch based on the best international standards and practices. The recommended actions, which include the standards and the advised filed practices, can directly contribute to prevent the reoccurrence of these incidents in the future. Other proposed solutions relate to the technical treatment for such kind of asset, equipment selection, staff training, and operation procedure with supervisory instructions. These solutions are given and discussed herein within this paper.

KEYWORDS
Earth Switch, Interlock systems, Ground fault, Generator step-up transformer, Operator's error, Generator circuit breaker, Lock Out/Tag Out.

1. Introduction

The Samra Electric Power Company (SEPCO) is considered the backbone of the energy generating sector, with the largest share of Jordan's electricity needs. The company has an effective contribution to the total generated power in the national system. SEPCO constitutes 33% of the total generated electrical energy in Jordan. It has a nominal capacity of 1482 MWe. Its facility generation is composed of four electrical power generating phases, all of which are in combined cycle operation mode. Each phase consists of two gas turbines (104 MWe) combined with two heat recovery steam generators, which are blended into one steam turbine (114 MWe). [1]

Figure 1.1 shows the single-line diagram of the electrical system in the Samra power plant. Basically, the diagram consists of the electrical generator, which is connected to the generator step-up transformer via a generator circuit breaker and other auxiliary systems. The generator step-up transformer, 150 MVA, 15 kV/400 kV, performs a vital function in boosting the high voltage produced by the generator and transmitting it to the grid. Likewise, the generator circuit breaker, 15 kV, controls and protects the power system equipment. Both are the most important and costly devices in electrical power systems.

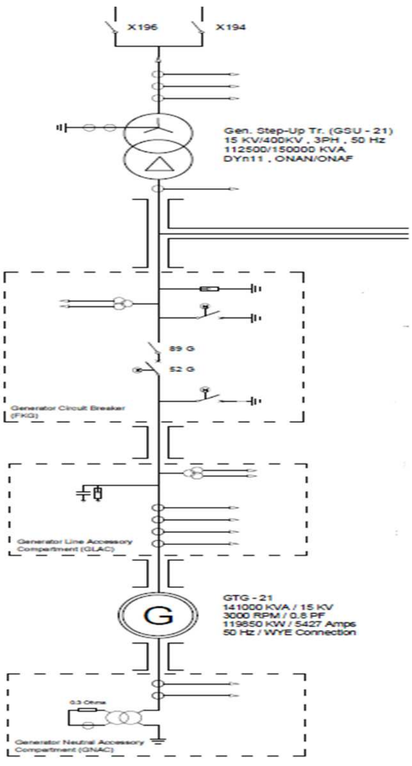

Figure 1.1: Single line diagram of the electrical system

In power-generating facilities where hazardous operations are conducted, the engineering design for the related process is performed by considering in parallel the critical sequence of the facility's operation and the standard safety procedures in parallel. Standard safety precautions play a major role in the power generation facility's operation. Therefore, the plant’s operators are restrictedly instructed to follow all safety procedures. It’s probable in that case that some human errors occur due to various misunderstandings in carrying out the safety instructions or procedures. This might happen in reelection to different factors, including but not limited to human fatigue, work distraction, environmental stress, or any other unforeseen circumstances.

Power plant operations are normally safe and reliable when performed correctly as per the related instructions and procedures. However, things can have undesired consequences when the operation is performed incorrectly. Generally, plant operators have a tendency to take shortcuts to minimize their workload, which leads to a high mistaken probability. To minimize human errors in the power plant, the interlock system should be implemented.

Interlocking systems are designed to mainly allow two mechanisms or functions that are mutually dependent. Furthermore, the interlocking systems are used to prevent the plant operators from accidentally activating the power system switch without authorization. In the field of power plants, most of the interlock systems utilize internal (mechanical and/or electrical) mechanisms to manage the movement of the maintenance earth switch of the generator circuit breaker and prevent its closing when the generator step-up transformer is energized.

The proper design of the generator circuit breaker, the wiring, the control circuit, and the above all interlock systems are usually known as the effective sources to reducing human error. In such circumstances humans play a pivotal role in implementing the electrical system isolation. It should be certain, error-free, and to be performed by qualified personnel who ensures avoiding any failures. Several statistics and studies state that the frequency of the failure occurrence caused by human factors is the highest for most of the accident’s investigation. This happens due to the influence of many other factors that affect human’s performance, where they all are interrelated. Other factors include materials, maintenance programs, management actions, environment, as well as the crew who are involved directly or indirectly in the work implementation.

In 2016, a generator step-up transformer, 150 MVA, 15 kV/400 kV in Jordan, experienced a sudden failure, resulting in collateral damage to the generator circuit breaker, 15 kV connected to the transformer, causing a shutdown of an important part of the power plant facility. Field data evaluation and related data collection were conducted to investigate the possible causes of the failure and evaluate the damage.

2. Failure Investigations

2.1. Field data collection

A planned maintenance was carried out for the generator step-up transformer, 150 MVA, 15 kV/400 kV, to execute the washing of high voltage bushings. Normally, this kind of periodic maintenance is done every 6 months to maintain the cleanliness of the insulator surfaces and reduce the probability of earth leakage currents that may arise from the dust accumulation. The generator step-up transformer must go through a shutdown procedure that is required to comply with the Lock Out/Tag Out (LOTO) system. A permit to work must be issued to initiate the shutdown process and should be coordinated between the operating engineer and the electrical maintenance engineer. Usually, all the electrical isolation needed is carried out by the operating engineer in this type of planned maintenance.

The following series of isolations should be applied sequentially: (i) The generator circuit breaker 15 kV, transformer LV side, is opened first, and the disconnector switch15 kV, transformer LV side, is opened. (ii) Then, disconnect a generator step-up transformer from the grid by opening the line circuit breaker 400 kV transformer HV side, and the relevant disconnector switch 400 kV should be opened. Finally, the earth switch of the 400 kV transformer HV side is closed, so the earth switch of the 15 kV transformer LV side can be closed. In this way, the generator step-up transformer is disconnected from the grid and equipped for maintenance.

A sudden fault occurred after implementing the above-mentioned isolation steps. A loud sound and traces of smoke were emanating from the generator circuit breaker. The overall differential protection was activated and tripped the generator step-up transformer, which stopped the fault and limited the damage. Investigations were conducted to identify the causes of the failure. The generator step-up transformer and the generator circuit breaker 15 kV were assumed to operate in normal conditions. Meanwhile, the fault occurrence was found to have occurred during applied the isolation steps by the plant operators.

Based on the troubleshooting and events collected from the site, the maintenance earth switch on the generator circuit breaker was closed by the operator mistakenly when the generator step-up transformer was energized. Therefore, the terminal side of the LV winding was directly connected to the earth, causing a high current with the ground through the generator step-up transformer. This accident, which in turn indicates a hidden failure in the interlocking system of the generator circuit breaker, should be prevented by manually closing the earth switch when the transformer energizes, which is not implemented in this circuit breaker.

2.2. Visual inspection of accident and assessment the result

The case is grounded to the generator step-up transformer, 150 MVA, 15 kV/400 kV directly with a solid earth switch (Figure 1.2). The transformer is tripped by the overall differential relay of phases V, W, and U. The Buchholz relay and pressure relief valve do not activate.

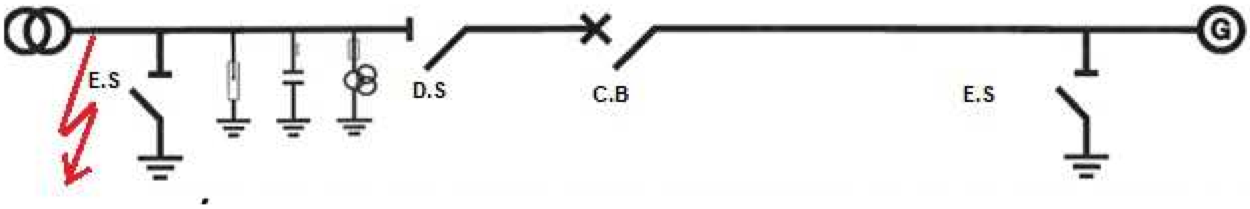

Figure 1.2. Ground fault on generator step-up transformer

As the first step in the diagnostic procedure, the dielectric resistances of the windings to the ground and to each other are measured. The dielectric resistance after 10 minutes is as follows: H−L = 3.12 GΩ, H−G = 2.1 GΩ, and L − G = 3.2 GΩ, where H, L, and G correspond to the HV winding, low-voltage winding, and the ground, respectively. The polarization index (PI) for three cases is determined from the dielectric resistance at 10, and 1 min. The value of the H–L, H−G, and L–G is in the range of GΩ denoting a good condition [2].

The winding resistances of the HV winding were measured as follows: R-N = 1.4Ω, Y-N = 1.43Ω, and B-N =1.45. The low-voltage winding was R-Y = 3.3mΩ, Y-B = 3.4mΩ, and B-R = 3.4m. The result was compared with the factory acceptance test and found satisfactory. moreover, it was decided to take an oil sample and perform the DGA [3]. The results of the DGA show that all values are normal and within the allowable range.

Simultaneously, the generator circuit breaker enclosure is opened to allow an internal view of all components, allowing repair and evaluation of the amount of damage. After inspecting the generator circuit breaker, it is noted that the high voltage fuse has burned down, and the earth switch connections have melted.
It is clear that the problem is in the earth switch arms. It is noted that the internal flashover has occurred on the surface of the earth switch (figure 3.a). In other words, a surface discharge has developed between the earth switch and the ground. Figure 3.b shows the carbon trace on the earth switch due to the flashover, no doubt that a flashover has occurred inside the generator circuit breaker, confirming the operation of the overall differential relay.

Fig.3.a flashover on earth switch

Fig.3.b carbon trace on the earth switch

After repairing the defective part, the electrical tests such as operating times (open and close), the conductivity of the grounding system, gas pressure SF6, and insulation resistance were conducted, and all the results were satisfactory and accepted. Since the tests indicate that the generator step-up transformer 150 MVA, 15 kV/400 kV is passing the fault without any effect in the short term, it was decided to bring the transformer back into service again.

3. Failure causes analysis

One of the ABCs of solving problems is to follow one of the techniques used for troubleshooting, which is to find the root cause for two issues: to prevent the recurrence of this kind of accident and for legal matters, therefore after defining the problem of closing the earth circuit breaker, then collecting much evidence, observations, and data which it is necessary to know the problem further. Here comes the role of identifying the problem causal factors.

Determining the causal factors is one of the most important steps in finding the root cause. Of course, there are four main causal factors for any problem: physical, environmental, administrative, and human errors as well. Therefore, after doing many methods used to find the root cause like 5Whys, Fishbone, the point was reached that the cause of the problem is administrative and human, rather the cause was an administrative factor that led to a human error.[4]

Human factors and equipment design play major roles in preserving productivity and improving the maintainability of power plant facilities. which leads to an increase in the plant's availability and an increase in its safety level. Today, human factors, errors, risk, and performance are addressed with Defense in Depth strategies and are included in integrated safety management, probabilistic risk analyses, and reliability engineering [5]. The previously discussed fault happened due to human acting error and inadequacy in the design of the generator circuit breaker interlock mechanism.

3.1. Human error

Operation activities generally include operating the generation units, controlling the distribution system, isolating and/or switching the electric feeder breaker, responding to system problems, and monitoring all other power plant auxiliary systems. Many people in the power plant commit errors. The operator is, however, the most visible. According to the investigation into the transformer failure, the operator's error was recognized as one of the main contributing factors to the fault occurrence. In this context, some of the reasons for the failure must be considered:

- Incomplete workmanship due to widely performed activity required from the operator at the same time and the lack of qualified operators' staff
- lack of adequate training and experience,
- Decision centralization and lack of communications
- Insufficient work procedures and instructions

the fault happens to materialize during the use or foreseeable misuse, Foreseeable characteristics of human behavior that may impact the likelihood of an occurrence are due to time constraints, work tasks, and lack of awareness of information relevant to the hazard [6]. the above incident, it was found that the most important reasons were the operator's lack of knowledge of the nature of work on the transformer, the lack of communication with the in-charge engineer who responsible for the isolations, as well as the recent transfer of this operator to Joining this team, which formed a fertile environment to work alone without referring to the charge shift engineer, moreover not follow the standard and site-specific safety procedures and the required lock-out/tag-out (LOTO) procedures when performing this type of work.

3.2. Inadequacy in the interlock design

Interlock systems are an integral part of keeping personal safe and protecting equipment from catastrophic damage. Since there are several configurations and applications of the interlocking system monitors that can vary from site to site, in the power plant the interlocking system should be electrical and mechanical, electrically to monitor the position of the maintenance earth switch of the generator circuit breaker and prevent its closing when the generator step-up transformer is energized. Mechanically, it is interlocking a circuit breaker with the maintenance earth switch. The principle is based on the possibility of freeing or trapping the lock keys according to the required conditions of operation.

The manuals and as-built drawings were reviewed to ensure that interlocks are functioning as the recommended design. Figure 4 shows the mechanical interlock which was implemented in the circuit breaker in the proper way.

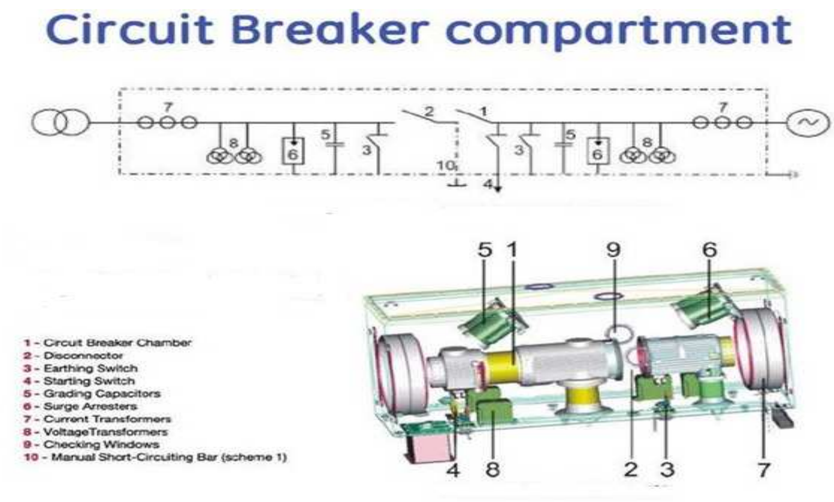

Fig. 4 Circuit Breaker Compartment

The electrical scheme of the generator circuit breaker as shown in Figure 5 shows the wiring of the interlock signal exists but does not connect to the control circuit. This brings us back to the commissioning stages, which may not have installed this signal or carried out some testing that was needed to bypass the interlocks. As a result, it has not been reconnected again.

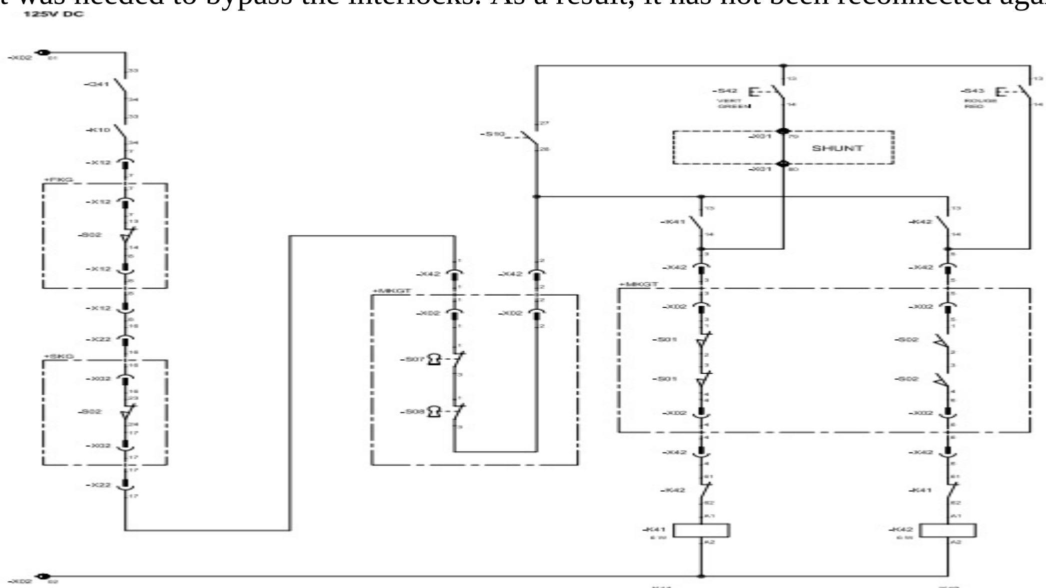

Fig.5 electrical scheme of the generator circuit breaker

Consequently, to enhance the interlocking system and prevent human errors in the future, it was decided to redesign the control circuit and implement it immediately. The modification is adding the voltage control relays to the existing control circuit of the generator circuit breaker to sense the voltage on the generator step-up transformer. In other words, the maintenance earthing switch will not inadvertently be closed when the generator step-up transformer is energized. As a precautionary principle, a comparison was made between sister generating units that were installed by the same main contractor at that time. It was found that the interlocking signals were not set up on the breakers. As a result, the modification was implemented for all other breakers.

4. Improving Human Performance by Using integrated Design

In the folds of the company's journey in continuous improvement to raise the reliability and the availability of the power plant and sustaining the quality standards and occupational safety, there were many lessons learned from the incidents adopted in the long run to preserve the asset lifecycle.

The life cycle of the assets passes through several stages, the most important stages is the design stage then installation, and commissioning. In order to avoid such design and installation deficiencies, the company has taken several steps to prevent their recurrence in future projects. The main actions were to initiate new bids with clear technical specifications, which require the presence of interlock systems and to set corrective measures for the technical specifications of the design to avoid or reduce human errors.

Despite the difficulty of completely getting rid of the human errors, Company has continued to consider the human factor as one of the most important assets and pillars in the electric power generation system, and among the reinforcement measures to eliminate or reduce the occurring possibility of human errors. The company began to automate maintenance implementation and reduce dependence on the human factor through implementing the enterprise resource planning system with an interest in setting Standard Operating procedures and work instructions that obligate maintenance and operation personnel to stick to it and also urging the Quality Department to follow up on the extent of employees' commitment to them. And to enhance this aspect of the personnel, they gave courses in risk management, and one of its outputs was the risk matrix. Among the components of the risk matrix in the stage of risk analysis is to determine the probability of occurrence with the severity of the consequences, where employees work in groups to propose recommendations to reduce the possibility of occurrence, apply them on the site, and monitor their effectiveness.

5. Results and Discussion

Based on the fault that happened on the generator step-up transformer connected to the grid, it was clear that the causes of human errors in the operating activities due to individual and contextual factors, including the poor experience and training of the operator, insufficient written procedures, and unclear, with the major contributor being the operator who had recently transferred to this team, along with the multitask required from the operator and miscommunication between the operator and the in-charge shift engineer.

To reduce human errors, training programs should be developed to assist in bringing awareness of the impact of human errors to the organization, reducing adoption on human factors, establishing clear policies and procedures, and bolstering cognitive factors and environmental factors over and above to review and replace unreliable instrumentation [7]. In parallel, modification of the control circuit of the earth switch to have an interlocking system to prevent human error along with operational activities.

When a large industrial plant suffered a major failure, it became clear that it was time to reevaluate its maintenance practices, to verify that the generator circuit breaker earthing switches have interlocks or other mechanisms to prevent the closure of the earthing switch when the generator step-up transformer is energized and meet the demands of the maintenance activities. The implementation of the following steps is necessary:

- Verify that no jumpers may have been installed during commissioning or another testing to bypass the interlocks.
- If there is no interlock (mechanical and/or electrical), or if it cannot verify that the interlocks exist, first remove the source of energy from the generator step-up transformer, then apply the isolations sequentially.
- During maintenance cycles, The LOTO should be applied by locking/tagging out to avoid any operator mistakes.

The importance of this implant lies in the role of minimizing the impact of errors that may occur during maintenance and operation activity. Therefore, the interlock system should be verified and re-applied prior to operating the system to avoid any accidents in the future.

6. Conclusion

This paper introduces the interlock system that should be present to reduce operator errors in the plant's operations activities. This does not necessarily reduce human error since the operation process always involves control steps and procedures that must be managed and maintained by the operators[8]. The interlock system reduces the possibility of errors that cause personal injury and/or equipment damage.

Operators of the generator step-up transformers are exposed to potential safety concerns, and they are recommended to follow additional safety steps to mitigate the risk of operating without safety interlocks between the earthing switch in the generator circuit breaker and the generator step-up transformer. Due to this, it is recommended that implementation of the previously mentioned steps be done.

In addition, the frequent review of the manuals and site drawings is essential to ensure that the interlocks are employed and functioning as designed, and when performing any work on the critical asset, follow the standard and site-specific safety instructions and any required lock-out/tag-out (LOTO) procedures.

The results of this case study are applicable to failure investigations, improvement of operational activities, and verification of the interlock system.

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