

**Military Technical College
Kobry El-Kobbah,
Cairo, Egypt**



**8th International Conference
on Electrical Engineering
ICEENG 2012**

Reliability and maintainability analysis of medium voltage transformers in Egypt

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Abstract:

In this paper, outage data analysis of 66 kV and 33 kV power transformers is considered. Outage-data is obtained from the Egyptian Electricity Transmission Company. Outage-data analysis over eight years from 2002 to 2009 of 1557 transformers with MVA rating ranging from 10 MVA to 40 MVA is presented. Several indices are determined for evaluating the reliability of power transformers. The knowledge of these indices is essential for proper system planning and operation. Forced outages due to correct and false action of transformer's protection systems are carefully considered. The trend of the determined hazard function indicated that a significant number of the transformers is probably being operated in the wear-out phase; however, detailed ageing analysis is required to determine the reliability state of each transformer. The determined values for the maintainability and availability shows significant variations with time. The results are compared with the IEEE 1979 survey.

Keywords:

Power transformers; transformer failure; outage data; forced outage; customer interruption.

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1. Introduction:

Based on ANSI/IEEE C57.117-1986 [1], a transformer is a static electric device consisting of a winding or two or more coupled windings, with or without a magnetic core for introducing mutual coupling between electric circuits. The study in this paper considers power transformers for utility applications. For abbreviation, the term “transformers” will refer to “power transformers” in this paper. Transformers are an integral part of power systems, and their reliability directly affects the reliability of the whole network. Outage of transformers is a failure, since a failure is the termination of the ability of a transformer to perform its specified function [1]. Transformer outages are either forced or scheduled. Both types are caused by switching operations. Forced outages of transformers are mainly due to automatic switching operations performed by protection systems [1-3]. They are caused by either external causes (such as transmission line faults) or internal causes (such as core failure and winding failure). More details about failure statistics of transformer subassemblies are available at references [2, 3]. For an abbreviation in this paper, the term ‘outage’ refers to ‘forced outage’.

In general, there are three distinct phases that a complex product goes through in its life cycle [1, 4, 5]. These phases are infant mortality (or debugging) phase, useful life phase, and wear-out phase. These three characteristics periods are represented by what is called the bathtub curve [4, 5].

In this paper, outage data analysis of 66 kV and 33 kV power transformers is considered. Outage-data is obtained from the Egyptian Electricity Transmission Company (EETC), over eight years from 2002 to 2009 of 1557 (average number) transformers with MVA rating ranging from 10 MVA to 40 MVA is presented.

2. Preparation of Outage Data:

Outage reports of transformers from 2002 to 2009 are obtained from the EETC. These reports are available only in hardcopy forms and their size is very large (about 4000 pages). The collected data per outage includes the transformer location, date and time, transformer outage duration, protection devices action, transformer restoration (or repair) time, interrupted MW and duration. Data required for conducting detailed ageing analysis could not be obtained.

The installed capacity of the 33 kV transformers in comparison with the 66 kV transformers is very small. In addition, the 33 kV transformers are available only at Middle and Upper Egypt. Therefore, the 33 kV and 66 kV transformers are combined into a single voltage subpopulation, a situation that is accepted and recommended by EETC because both the 66 kV and 33 kV transformers belong to the same dispatching authority.

The total number of transformers in service was 1379 and 1721 in 2002 and 2009 respectively. Table 1 shows the actual and average numbers of transformers in various geographical zones for years 2002 to 2009.

In Egypt, the 66-33 kV network in the EETC system plays a key role in transferring the bulk power generated to the distribution level. Therefore, reliable performance of the 66-33 kV network guarantees delivery of energy generated to the customers.

There are numerous outage causes for transformers. This is mainly due to operating conditions, aging factor, maintenance strategy, and environmental conditions. According to their type and nature, outage causes are categorized into five outage categories as shown in Table 2. These outage categories are transformer related outages, power system related outages, environmental related outages, human factor (or human mistakes) related outages, and unclassified/other outages [6].

Outage-data analysis is conducted according to two basic phases. Failure and repair analysis of transformers is conducted in the first phase while the impact of transformer outages on customers is assessed in the second phase.

Table (1): Total and average numbers of transformers in various geographical zones for years 2002-2009

Year Zone	2002	2003	2004	2005	2006	2007	2008	2009	Average
Cairo	389	405	450	467	486	506	515	528	468
Alexandria	146	151	155	158	161	163	167	168	159
Canal	201	209	218	230	240	244	251	256	231
Delta	299	306	318	327	335	344	349	360	330
Middle Egypt	157	160	160	162	163	170	170	179	165
Upper Egypt	187	191	191	197	209	206	220	230	204
Total	1379	1422	1492	1541	1594	1633	1672	1721	1557

3. Outage-Data Analysis:

3.1 Failure and repair analysis:

The distribution of failure numbers per outage cause for the transformers is shown in Fig. 1. For a given outage cause, the percentage number of failures is calculated by

$$\%AANF = 100 NF / TNF \quad (1)$$

where %AANF is the percentage average number of failures per an outage cause; NF is the average number of failures in the study period per outage cause and TNF is the total number of failures in the study period.

It is depicted from Fig. 1 that the major cause of outages is the outage of incomers (about 40 %) followed by over current protection (about 29%) and differential protection (about 5%).

Table (2): Outage categories and corresponding outage causes for the transformers

Outage categories	Outage causes
Transformer related outage category	<ul style="list-style-type: none"> • Buchholz and Pressure relief (B&P) • Over current Protection (OC) • Earth Fault Protection (EFP) • Differential Protection (DP) • Breakdown and Damage (B&D) • Fire Fighting Systems (FFS)
Power System related outage category	<ul style="list-style-type: none"> • Outage of Incomers (OI) • Bus Bar Protection (BBP)
Power System related outage category	<ul style="list-style-type: none"> • Bad Weather (BW) • Animal and Birds (A&B)
Human factor related outage category	<ul style="list-style-type: none"> • Human Factor or Mistakes (HM)
Unclassified and other outage categories	<ul style="list-style-type: none"> • No Flags or unclassified (NF) • Others

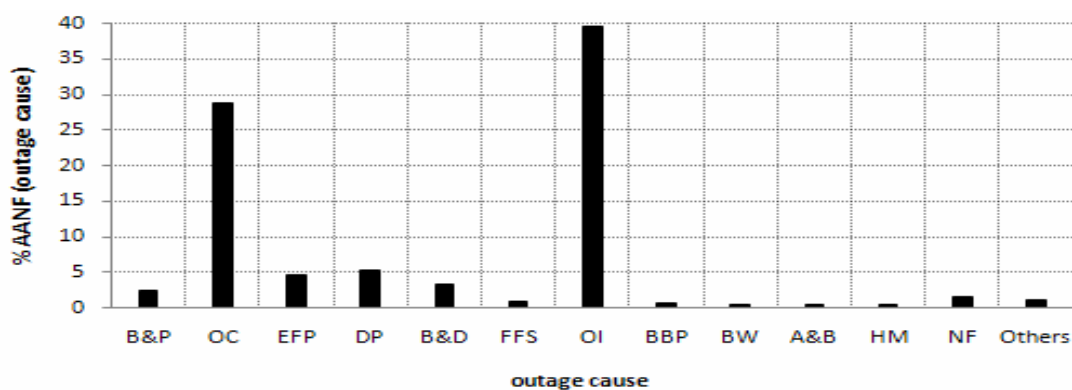


Figure (1): Distribution of failure numbers per outage cause

The distribution of failure numbers per outage category is shown in Fig. 2. The calculations are done using a modified version of equation (1) such that %AANF represents the percentage average number of failures per an outage category and NF is the average number of failures in the study period per outage category. It is depicted from Fig. 2 that transformer related outages are responsible for major number of outages followed by the power system related outages and unclassified-other outages. Minor number of outages is associated with environmental related outages and human factor (mistakes).

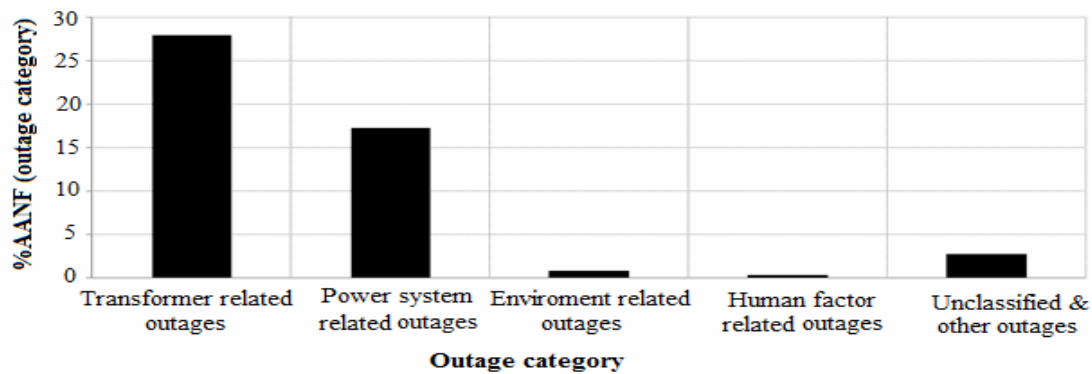


Figure (2): Distribution of failure numbers per outage category

The distribution of failure numbers per outage category per geographical zone is shown in Fig. 3. The calculations are done using a modified version of equation (1) such that %AANF represents the percentage average number of failures per outage category in a given geographical zone and NF represent the average number of failures in the study period per geographical zone.

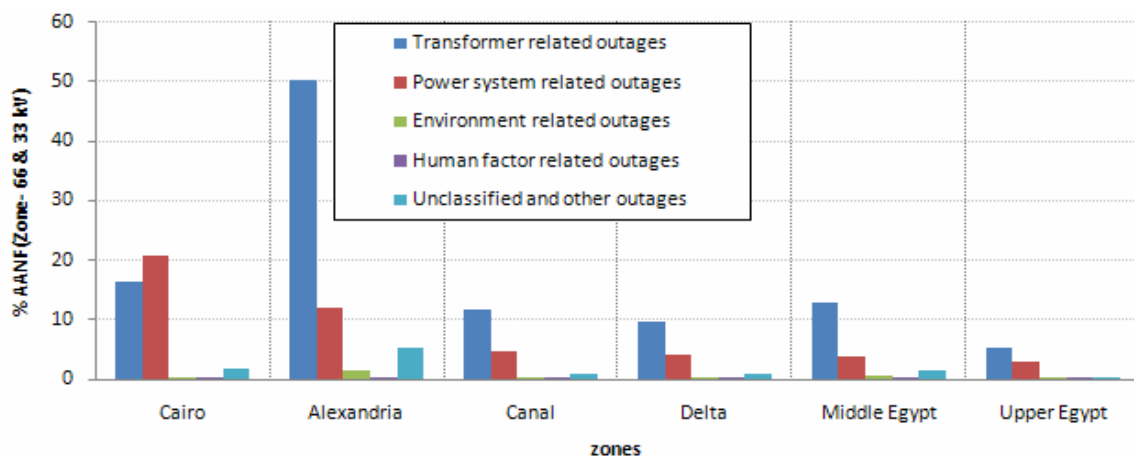


Figure (3): Distribution of failure numbers per outage category for various geographical zones

It is depicted from Fig. 3 that transformer related outages are the major contributors to the total number of transformer failures in all zones except Cairo zone as a result of power system related outages. However, their major impact is in Alexandria zone where the percentage number of outages due to the transformer related reasons is about 50% of the overall number of outages. Power system related outages are the main cause of outages in Cairo zone giving about 21% of the overall number of outages. In addition, their impact is the second for all other zones.

Unplanned outages of power transformers can cost the electric utilities millions of dollars. Consequently, it is important to minimize the frequency and duration of their occurrence. Accordingly, high demands are imposed on the power transformer protective relays that should assure dependability (no missing operations), security (no false trip), and speed of operation (short fault clearing time).

Fig. 4 shows the percentages of false trips of protection devices. The percentage of false trips is calculated as the number of false trips divided by the total number of trips. It is depicted from Fig. 4 that fire fighting systems are the dominant cause of false trips followed by bus bar protection systems. Improper maintenance and monitoring the compressed air line of fire fighting are the main reasons of performance failure of fire fighting protection systems. Lack of maintenance and testing of relays and improper setting of protection devices are the main reasons of poor performance of these systems. Differential protection, Buchholz and pressure relief cause significant number of false outages. Generally, false trips of protection systems can be significantly reduced by improving maintenance procedures, system monitoring, and operation strategies as well as revising the design and settings of protection systems.

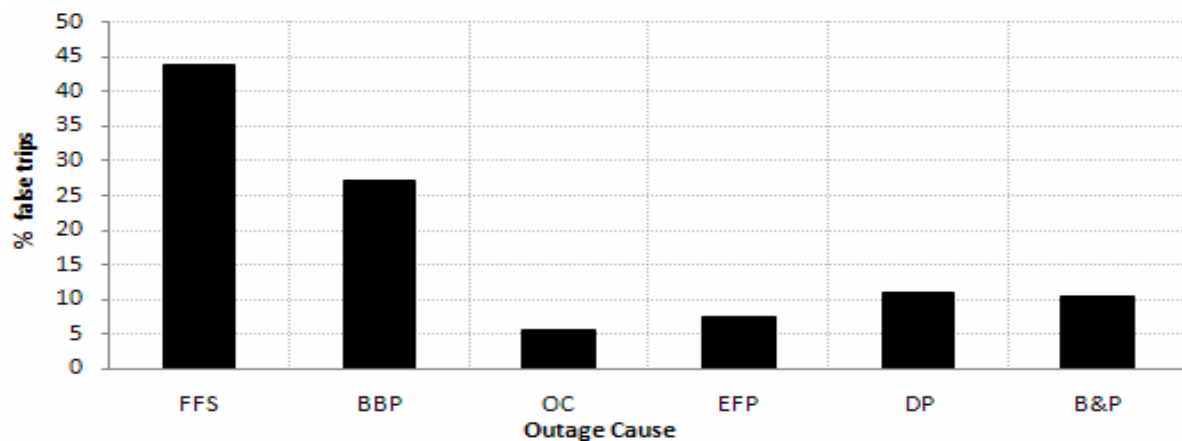


Figure (4): Percentages of false trips of protection devices

The average annual distribution of repair (restoration) time per outage cause is shown in Fig. 5. For a given outage cause, the annual average repair time (AART) per transformer in hours is calculated by

$$AART = TRT / (N.T) \quad (2)$$

where *AART* is the annual average repair time per transformer per outage cause in hours; *TRT* is the total repair time in the study period per an outage cause in hours; *N* is the average number of transformers in the study period; *T* is the study period in years.

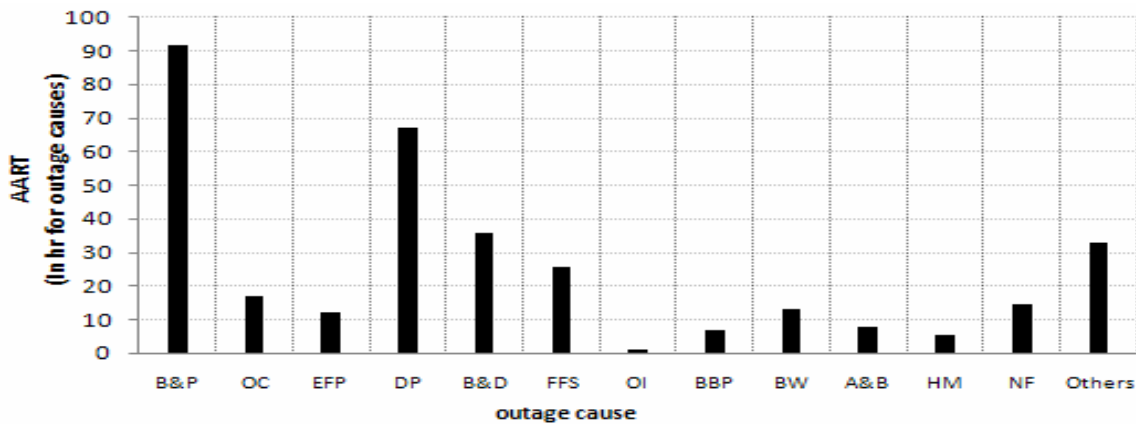


Figure (5): Average annual distribution of repair time per outage cause per transformer

It is depicted from Fig. 5 that among all outage causes, transformer failures that include actions of Buchholz and pressure relief relays take the longest repair time due to severe transformer faults associated with these outages. Differential protection caused the second lengthy repair time because it's associated with an overall routine (site) tests on the transformer and the differential relay. Breakdowns and damages are responsible for the third cause of lengthy repair time to fix or replace the damaged equipment.

The annual average distribution of repair time per outage category per transformer is shown in Fig. 6. The calculations are done using a modified version of equation (2) such that *AART* is the annual average repair time per transformer per outage category in hours, and *TRT* is the total repair time in the study period per an outage category in hours. It is depicted from Fig. 6 that the longest annual average repair times are associated with transformer related outages followed by unclassified and other outages.

The average annual distribution of repair time per outage category per geographical zone per transformer is shown in Fig. 7. The calculations are done using a modified version of equation (2) such that *AART* is the annual average repair time per transformer per outage category per geographical zone in hours. *TRT* is the total repair time in the study period per an outage category per geographical zone in hours, and *N* is the average number of transformers in the study period per geographical zone. It is clear from Fig. 7 that transformer related outages are responsible for long average annual repair time per transformer in all zones. The highest value of average annual repair time occurs in Middle Egypt. Average annual repair times associated with other outage

categories are insignificant in comparison with that associated with transformer related outages.

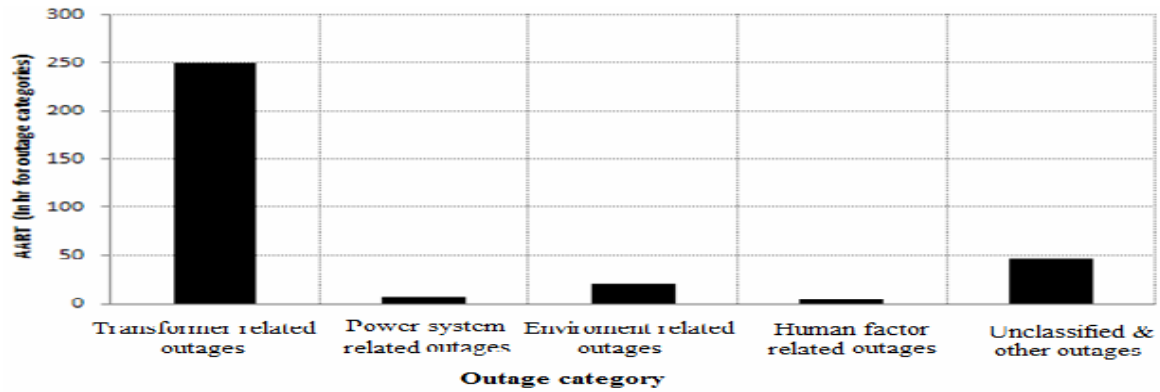


Figure (6): Annual average distribution of repair time per outage category

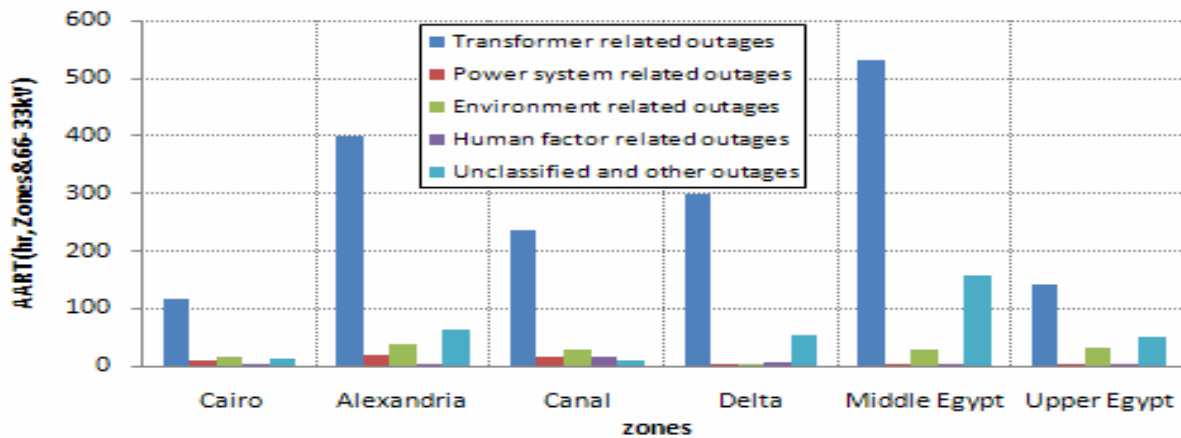


Figure (7): Average annual distribution of repair (restoration) time per outage category per geographical zone

3.2 Customer interruption analysis:

Two indicators are used to represent the impact of transformer outages on customer interruptions. These indicators are the annual average interrupted MW (AAIMW) and the annual average customer-interruption duration (AACID). Customer interruption costs can be assessed using these indicators; however, calculation of these costs is retained for future work.

The annual average distribution of customer interrupted MW per outage cause per transformer is shown in Fig. 8. For a given outage cause, the annual average interrupted MW per transformer (AAIMW) is calculated by

$$AAIMW = TIMW / (N.T) \quad (3)$$

where $AAIMW$ represents the annual average interrupted MW per transformer per outage cause; $TIMW$ is the total interrupted MW in the study period and N is the average number of transformers in the study period.

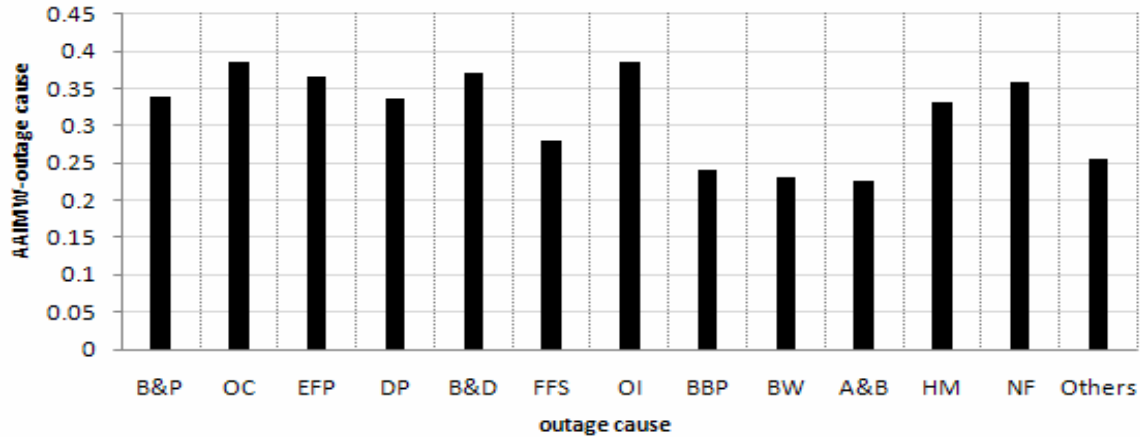


Figure (8): Annual average distribution of customer interrupted MW per outage cause

It is depicted from Fig.8 that the largest values of $AAIMW$ are associated with both outage of incomers and over current protection. Most of these outages occur due to heavy loads and insufficient capacities to face these loads. Furthermore, outages that include breakdown and damage, earth fault protection and no flags caused high values of $AAIMW$.

The $AAIMW$ per outage category is shown in Fig. 9. The calculations are done using a modified version of equation (3) such that $AAIMW$ represents the annual average interrupted MW per transformer per outage category, and $TIMW$ represents the total interrupted MW in the study period per an outage category.

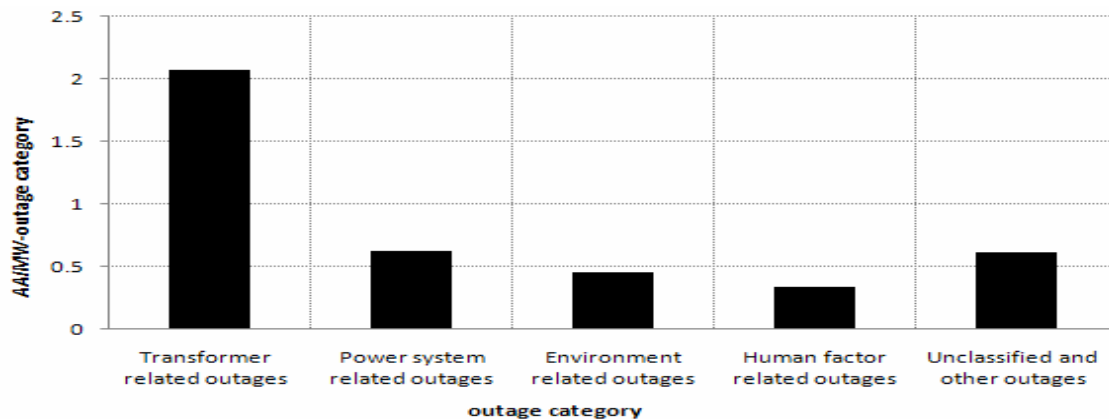


Figure (9): Annual average distribution of customer interrupted MW per outage category

It is depicted from Fig. 9 that the highest AAIMW is caused by transformer-related outages. Significant values of AAIMW are associated to both unclassified and power system related outages.

The annual average distribution of customer interrupted MW per outage category per geographical zone is shown in Fig. 10. The calculations are done using a modified version of equation (3) such that AAIMW is the annual average interrupted MW per transformer per outage category in a given geographical zone and TIMW is the total interrupted MW in the study period per an outage category in a given geographical zone.

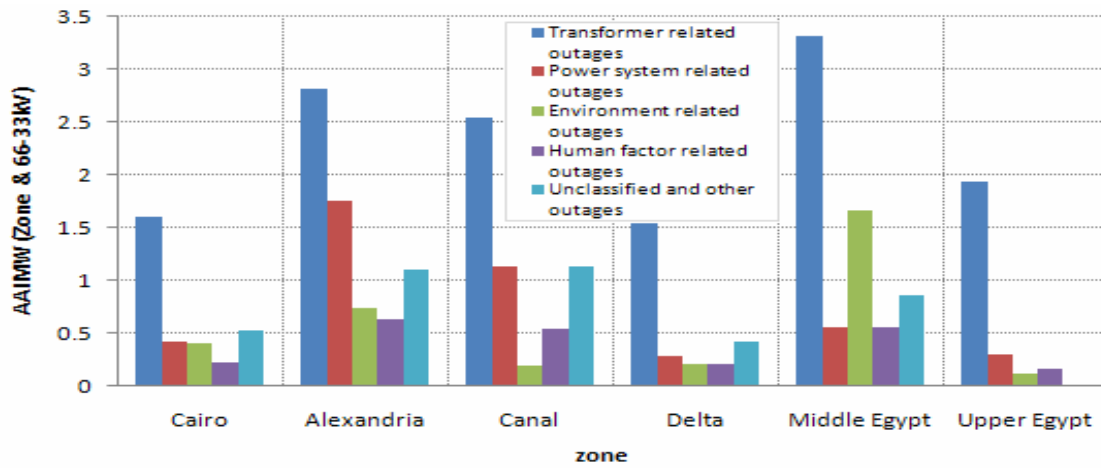


Figure (10): Annual average distribution of customer interrupted MW per outage category for various geographical zones

It is depicted from Fig. 10 that transformer, power system, unclassified and other related outages are the main contributors to the AAIMW. Transformer-related outages cause the highest values of AAIMW in all zones. Unclassified and other related outages are the second cause of AAIMW in Cairo and Delta. Power system related outages are associated with a high contribution of AAIMW in Alexandria and Canal.

The annual average distribution of customer interruption duration per outage cause per transformer is shown in Fig. 11. For a given outage cause, the average annual customer interruption duration per transformer (AACID) in hours is calculated by

$$AACID = TCID / (N.T) \quad (4)$$

where AACID is the annual average customer-interruption duration per transformer per outage cause; TCID is the total customer-interruption duration in the study period per an outage cause and N is the average number of transformers in the study period.

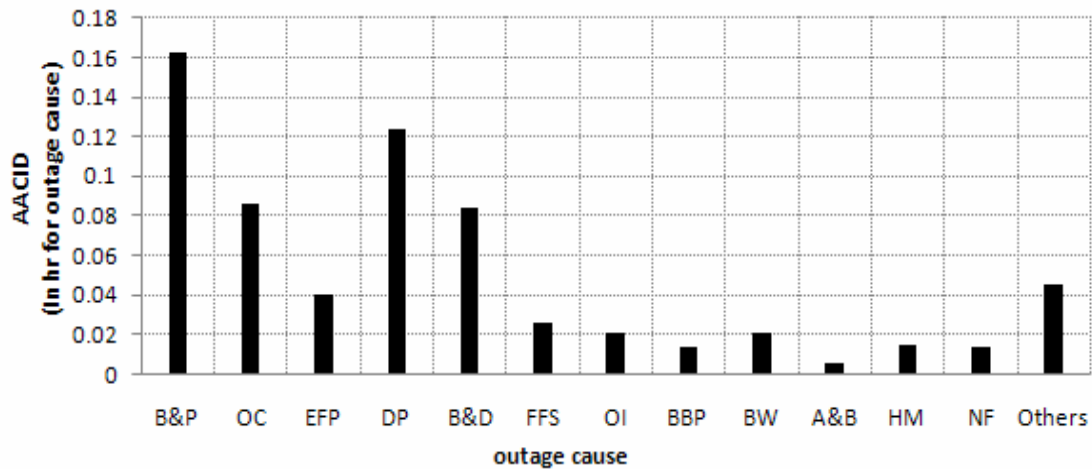


Figure (11): Annual average customer-interruption duration per transformer per outage cause

It can be shown from Fig. 11 that longest AACID occurs due to outages that include Buchholz and pressure relief and differential protection.

The annual average distribution of customer interruption duration per outage category per transformer is shown in Fig.12. The calculations are done using a modified version of equation (4) such that *AACID* is the annual average customer-interruption duration per transformer per outage category, and *TCID* is the total customer-interruption duration in the study period per an outage category.

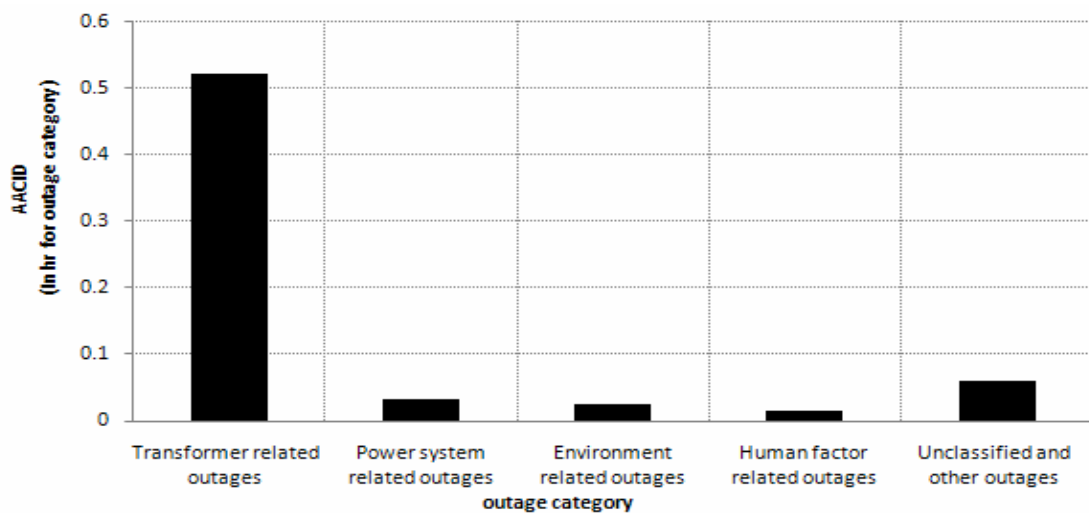


Figure (12): Annual average customer-interruption duration per transformer per outage category

Fig. 12 clarifies that the longest annual average customer interruption duration is associated with the transformer related outages followed by unclassified and other outages.

The annual average distribution of customer interruption duration per outage category per geographical zone per transformer is shown in Fig. 13. The calculations are done using a modified version of equation (4) such that AACID is the annual average customer-interruption duration per transformer per outage category per geographical zone TCID is the total customer-interruption duration in the study period per an outage category per geographical zone and N is the average number of transformers in the study period per geographical zone.

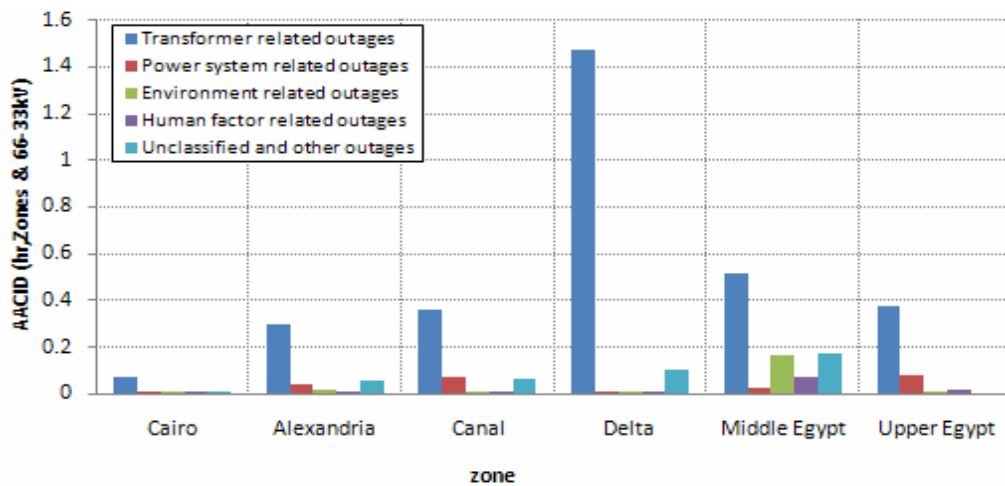


Figure (13): Annual average customer-interruption duration per transformer per outage category per geographical zone

Fig. 13 shows that longest AACID occurs in Delta. Transformer-related outages cause the highest values of AACID in all zones. Large impact of power system, unclassified and other related outages on the AACID is shown in most zones.

4. Failure rate, Availability, and Maintainability Evaluation:

Based on reliability theory, the following definitions apply [1,4,7]. The failure rate is a measure of the basic design of the transformer as well as the operating and maintenance practices employed. Maintainability is the measure of the ability of an item to be restored or retained in a specified condition. The significant difference between maintainability and maintenance is clarified in [6, 8]. Availability is the percentage of time the item is available to perform its required functions. Availability is a function of both MTBF and MTTR.

4.1 Failure rate:

During the useful-life phase of a product, the failure rate (λ) can be defined as the number of random (unscheduled) occurrences of failure of the product to perform its intended function divided by the length of time the product was functioning [1, 4, 7]. More details of failure rate are mentioned in [6]. In this case, the failure rate (or the hazard function) for this group would be estimated by dividing the total number of failures experienced by the total service years of all transformers in the group as shown in equation (5).

$$\lambda(t) = TNF(t)/(N(t).T(t)) \quad (5)$$

In calculating the failure rate, the actual number of transformers for each year in the study period shown in Table 1 is used. Failure rates (or the hazard function) of transformers are shown in Fig. 14.

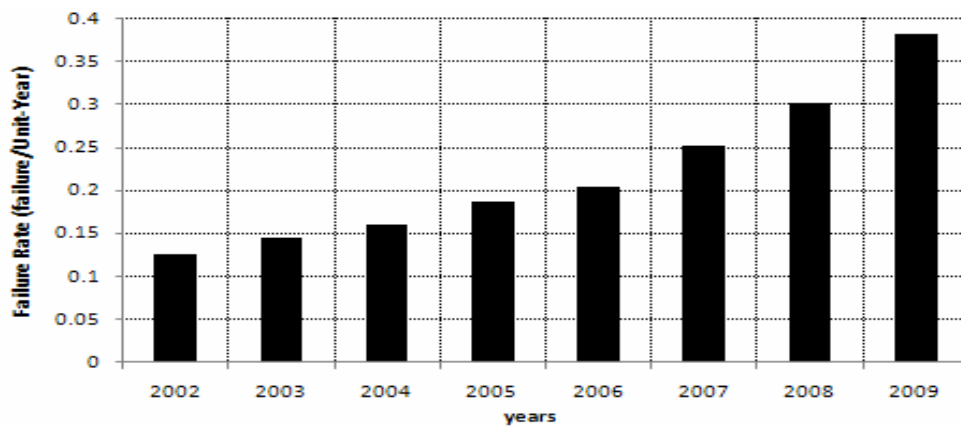


Figure (14): Transformers hazard function

The trend of the determined hazard function shown in Fig. 14 indicated that a significant number of the transformers is probably being operated in the wear-out phase; however, detailed ageing analysis is required to determine the reliability state of each transformer. Therefore, it is recommended to carefully inspect the past failures for each transformer in the considered group in order to define its reliability state. The failure rates values shown in Fig. 14 are compared with the previous IEEE 1979 survey [9]. For convenience, Table 3 shows the results of the IEEE 1979 survey. Based on Fig. 14 and Table 3, it is depicted that the failure rate is very high in comparison with the calculated failure rates in IEEE power transformers survey in 1979.

Table (3): IEEE power transformers – 1979 survey

Equipment subclass	Failure Rate (Failures per Unit-Year)	Average Repair Time (Hours per Failure)	Average Replacement Time (Hours per failures)
All Liquid Filled	0.0062	356.1	85.1
Liquid Filled 300- 10 000 KVA	0.0059	297.4	79.3
Liquid Filled > 10 000 KVA	0.0153	1178.5*	192.0*

*Small sample size; less than eight failures

4.2 Maintainability Evaluation:

Maintainability of transformers is shown in Fig. 15. It is depicted from Fig. 15 that the annual values of maintainability are time dependent. Management, human skills, and environmental conditions have their impact on the variation of time required for repairing failures.

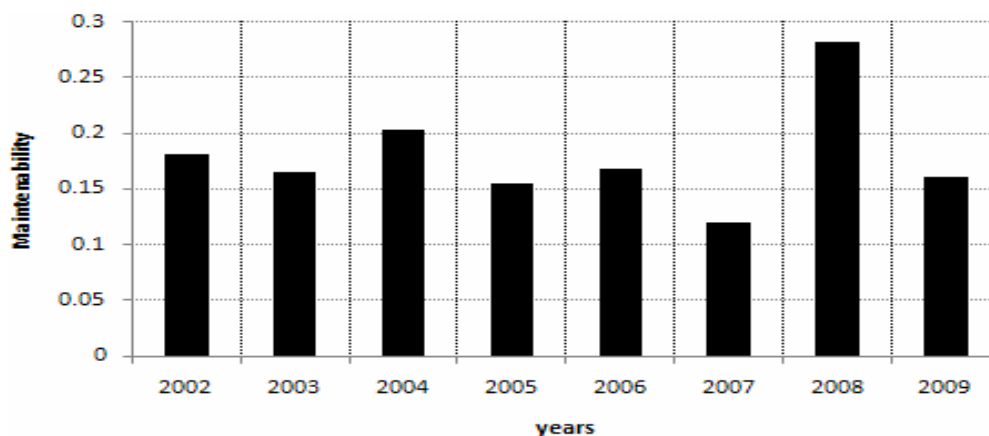


Figure (15): Maintainability trend of transformers (in hours)

The estimated MTTR in comparison with the 1979 IEEE survey Table 3 [9] shows that MTTR of the transformers of the EETC is less than time required for repairing transformers in 1979 IEEE survey.

4.3 Availability Evaluation:

The availability is calculated by equation (6) and annual values of transformer availability are shown in Fig. 16.

$$A(t) = MTBF(t)/(MTBF(t) + MTTR(t)) \quad (6)$$

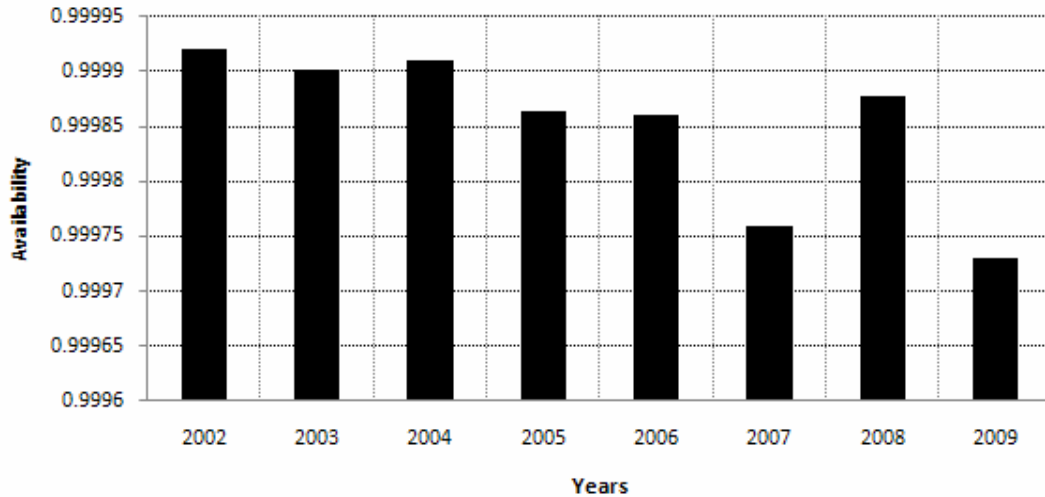


Figure (16): Availability trend of transformers

It is clear from Fig. 16 that the annual values of transformer availability are time dependent. Based on equation (6) and the data shown in Table 3, the average availability is 0.9992 for liquid filled transformers. Therefore, the availabilities of EETC transformers are higher than average availability of the 1979 IEEE survey. Although EETC transformers are having a very high failure rate, their availability is high. This is due to the very small MTTR. Accordingly, the MTTR is considered the most significant factor that can quickly and dramatically have a positive or negative impact on availability.

5. Conclusion:

In the 66-33 kV transformers, the largest AANF and AAIMW were caused by outage of incomers and over current protection due to heavy loads. This indicates that the number of 66-33kV transformers is insufficient to supply the present loads. The longest AACID and AART occurred due to outages that include Buchholz and pressure relief and differential protection as a result of a possible internal failure inside the transformer.

Among all outage categories, transformer related outages recorded the largest AANF and AAIMW in all regions. Furthermore, it caused the longest AART and AACID in all regions

The trend of the determined hazard function indicated that a significant number of the transformers is probably being operated in the wear-out phase. The considered transformers show higher maintainability and availability in comparison with the 1979 IEEE survey. The maintainability and availability vary with respect to time, and its behavior is random. The differences between the estimated values and the IEEE 1979

survey are caused by many reasons. These reasons are mostly related to local climatic/electrical conditions, logistics management, human skills, and the age of transformers.

It is found by investigation that the poor performance of fire-fighting systems is mainly due to improper maintenance of the compressed air line of these systems. In addition, it is found that lack of maintenance and testing of relays, and improper settings of protection devices are the main reasons of poor performance of bus bar protection systems. Generally, false trips of protection systems can be significantly reduced by improving maintenance procedures, system monitoring, and operation strategies as well as revising the design of protection systems. Therefore, it is recommended to improve the maintenance and design of protection systems especially the fire fighting systems in order to limit the false trips of power transformers.

Acknowledgment:

The authors would like to express their gratitude to the Egyptian Electricity Transmission Company (EETC) for their valuable discussions, data, and support.

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Biographies



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