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Fault Tree-Based Reliability Assessment of a 132-kV Transmission Line Protection Scheme

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***Abstract:* -** The reliability of a power system network depends greatly on the performance of the protection system. Improving the reliability of the protection scheme of the transmission lines will enhance the overall reliability of the power system network. The focus of this paper is the improvement of the reliability of a power system transmission line using fault tree analysis (FTA). The paper considers the development of fault tree diagrams for the protection scheme of the 150km-long 132-kV transmission line in Northern Nigeria. The existing protection scheme is analyzed and compared with a proposed scheme equipped with a redundancy arrangement. And the result shows that the new scheme offers significant improvement (about 51%) in the availability of the line.

***Keywords:* -** *failure rate, fault tree analysis, mean time before failure, power system reliability, component unavailability*

I. INTRODUCTION

The ability of an electric power system to supply electricity constantly and reliability has a direct effect on the social, economic and industrial development of any nation. The power system is vulnerable to system abnormalities such as control failures, protection and / or communication system failure, and disturbances which include lightning, human operational errors, etc. Therefore, maintaining a reliable power system is an important issue for power system design, operation and maintenance. Reliability study helps system operators in making engineering decisions in planning, designing and operating the entire system, and it is the probability that an item or system will perform a required function without failure under stated conditions for a stated period of time [1]. It is always desirable that an electric power system satisfies the system load requirement with a reasonable assurance of continuity and quality. This concept of power system reliability is extremely broad and covers all aspects of the ability of the system to satisfy consumer requirements. The IEEE Power Engineering Task Force on Bulk Power System Reliability describes a proper level of electric utility system reliability as that which meets customer load demands and energy at the lowest possible cost while maintaining acceptable levels of service quality [2]. In addition, power system reliability has to do with system adequacy and system security. Adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer’s load demand, while system security relates to the ability of the system to respond to disturbances arising within the power system [3]. Vitally important to power system reliability are protection systems. And it can be said that a power system is as reliable as its protection systems, which are collections of devices that detect defective power system elements or conditions of an abnormal or dangerous nature, initiate the appropriate control action, and isolate the appropriate power system components [4]. Meanwhile, a fault is any condition that causes abnormal operation of the power system or equipment serving the power system. This fault includes but is not limited to short or low impedance circuits, open circuits, power swings, over voltages, elevated temperatures and off-normal system frequency. Although the function of the protection system (which uses electronics or electromechanical relays) is not to prevent faults, it must be able to take immediate action upon fault recognition, which is to protect equipment and limit injury caused by electrical failure. This function suggests that the system must have an appreciably high level of reliability. Therefore, the aim of this work is to employ a graphical approach to assess the reliability of a protection scheme of the 150km-long 132-kV transmission line in Northern Nigeria with a view to improving it.

II. FAULT TREE ANALYSIS (FTA): A REVIEW AND PROCEDURE

Fault tree analysis (FTA) was developed in 1962 for the US Air Force by A. H. Watson of the Bell Telephone Laboratories for use with the Minuteman control system, was later adopted and extensively applied by the Boeing Company. FTA is one of many symbolic logic analytical techniques found in the operations research discipline [1]. Following the Aerospace Industry, the nuclear power industry discovered the virtues and benefits of deploying it for nuclear power plants. Many key individuals in the nuclear power industry contributed to advancing fault tree theory and fault tree software. This method used and refined over the years is attractive because it is a practical tool any engineer can learn to use while computer programs are available to assist in developing and analyzing complex fault tree [2]. Fault Tree analysis is a model that graphically and logically represents the major faults or critical failures associated with a product or system, the causes for the faults, and potential countermeasures [6]. In this respect, FTA is a systematic deductive technique, which allows the development of the causal relations leading to a given undesired event. It is deductive in the sense that it starts from a defined system failure event and unfolds backward its causes, down to the primary (basic) independent faults. The method focuses on single failure mode and can provide quantitative information on how a particular event can occur, to what consequences it leads, while at the same time allowing the identification of those components, which play a major role in determining the defined system failure. Moreover, it can be solved in quantitative terms to provide the probability of events of interest starting from knowledge of the probability of occurrence of the basic events, which cause them [7]. In fault tree analysis, a desirable event (which generally represents a system failure mode or hazard for which predicted reliability data are required) is called a top event. And the lower events in each branch of a fault tree are called basic events. These basic events are linked via logic gates symbols to one or more undesirable top events [8], and represent hardware, software, and human failures for which the probability of failure is given based on historical data. Most FTA can be carried out using four basic components: 1) the rectangular boxes used for top and intermediate events. The top event is the foreseeable, undesired event towards which all fault tree logic flows, while the intermediate event describes a system state that is generated by antecedent events, 2) the 'OR' gate, which produces an output if any of its inputs exists, 3) the 'AND' gate, which produces an output if all its inputs co-exist, and 4) the circular boxes used to represent the basic events, which are events initiating fault/failure. The basic events mark the limit of resolution of the analysis. Normally, when analyzing a protection scheme using the FTA method, the scheme failure of concern is designated as the top event, and the probability that the scheme fails for the top event is a combination of the failure probabilities of the components in the scheme. Whereas for an OR gate, in which any input can contribute to scheme failure, the total probability is the sum of the input events, for an AND gate, in which all inputs to that gate must fail together to cause scheme failure, the upper level probability for scheme failure is the product of input probabilities.

To quantify the probability of the top event in a fault tree, the probability of each basic event must be provided. These basic event probabilities are then propagated upward to the top event using the Boolean relationships for the fault tree. The input data that must be supplied for a basic event is usually a component failure probability in some time interval, event occurrence probability in some time interval, pure event probability, or component unavailability [4]. The component unavailability is used for the assessment in this paper and is provided for the basic event to be able to generate the overall unavailability of the top event. This information is provided for a component that is repairable or checkable, i.e., a component which is out of service and unavailable if called upon to operate [7]. And this is exactly the situation with protective schemes.

To estimate the failure probability for each device in the scheme, the device failure rate can be used. One industry practice is to provide failure rates as Mean Time Between Failures (MTBF), which could be based on field failure data or on assumptions about complexity and exposure of equipment. To use this information to estimate probability, the fraction of time that a device cannot perform is assumed [10]. Equation (1) gives the unavailability, q, in terms of MTBF [9]

$$q \cong \lambda T = T / MTBF \qquad (1)$$

where λ is the failure rate, and T the average down time per failure. Because each failure causes down time T, then the system is unavailable for time T, and the fraction of time the system is not available is depicted in eqn. (1).

III. THE CASE STUDY: 132-KV KANO – KANKIA POWER TRANSMISSION LINE

The case study, 132-kV Kano – Kankia transmission line is supplied via two parallel 132-kV bus bars. This is to allow for operational flexibility and redundancy of the system. These buses are with their associated isolators and circuit breakers to allow for operational flexibility. The132-kV Kano – Kankia transmission line is a very important line as it supplies the Katsina Steel Rolling Mill and other consumers. More importantly, it is an inter-country transmission line, as it also takes power to Gazaoua at Niger Republic. It is a radial transmission line and its length is about 180km with a load of about 30MVA, including the Gazaoua load in Niger Republic.

The protection scheme used on the 132-kV transmission line is the non-pilot three-zone distance protection scheme. The distance protection zones offer backup protection and take care of phase to phase, phase to phase to ground, and phase to ground faults, operating independently of each other. This scheme uses the Siemens' type electromechanical relay and has a reach setting that is up to 80% of the protected line for instantaneous zone 1 protection (based on the line impedance). Zone 2 setting covers the remaining 20% of the line impedance. The minimum setting of the protected line is 120%. Zone 3 setting is delayed beyond all other protection within its reach and is determined for maximum fault in-feed. Its reach is set to at least 1.2 times the impedance presented to the relay for a fault at the remote end of the second line section. Additionally, breaker failure protection provides backup protection for the primary circuit breaker if it fails to clear a system fault.
The data used in this work are the Kumbotso 330/132/33-kV transmission station single-line diagram and the single-line schematic of the principle of protection and measuring diagram. This information was made available by Power Holding Company Nig. Plc., Kano transmission station, Kano. The data (MTBF) required for the reliability assessment of the protective scheme were obtained from field experience as given in [10]. The protection components on this line are as listed below:

- Distance protection relay 1 piece
- Over Load Relay 2 pieces
- Current transformer 12 pieces
- Voltage transformer 3 pieces
- Circuit Breaker 7 pieces
- Bus differential Relay 2 pieces
- Breaker failure relay 1 piece
- DC battery bank (110V) 1 piece

IV. CONSTRUCTION AND ASSESSMENT OF THE FAULT TREE

FT for the protection scheme used on the 132-kV Kano – Kankia transmission line is now developed from the system schematic diagram. The scope of this assessment is limited to the Kaduna downstream of the line. The resolution is the level or extent to which the failure causes for the top event will be developed. Here the top event is given as general protection failure (Main and Back-up). And the immediate faults and or failures that could lead to the top events are:

- 132-kV protection failure (Main & back up)
- 110-V battery bank failure
- Kumbotso 330-kV backup failure
- Kaduna 330-kV circuit breaker failure.

These four events can lead to the occurrence of the top event. They are linked to the top event via an 'OR' gate showing that any of them that occur can cause the top event. These events are broken down until the basic event is finally reached. In addition, the gates relating one level of events to another were duly selected based on the relationship between the events.
Now the unavailability of the basic event components is calculated for the protective relays, instrument transformers, DC power supply and circuit breakers as highlighted below.

- **Protective relays:**

The distance protection, bus differential, and the overload relays used for this protective scheme are the electromechanical type. Based on field experience, they require routine testing for proper operation, so their reliability is dependent on their regular testing and maintenance. Failure of these relays could go unnoticed until the next maintenance period or until their operation is required. Failure could occur the day following a maintenance test or a day before the next period, which is an average time of six months. T is always large because of lack of automatic supervision. Therefore, from field experience an MTBF of this relay is assumed as 200 years. Hence, unavailability $q = (6 \times 30) / (200 \times 365) = 0.002465. \approx 2465 \times 10^{-6}$.

- **Instrument Transformers:**

These include both Current Transformer (CT) and Capacitor Voltage Transformer (CVT). Based on field experience, an MTBF of 500 years and an average protection down time of 2 days are assumed. Therefore, unavailability q = 2 / (500 x 365) = $1.095890411 \times 10^{-5} \approx 10 \times 10^{-6}$.

- **DC Power Supply:**

The dc power bank is 110V and it consists of battery, charger and distribution circuit. The loss of dc alarm is monitored and responded to promptly in less than a day, say 0.5 day. MTBF is 27 years. Hence, unavailability q = 0.5 / (27 x 365) = $5.073566717 \times 10^{-5} \approx 50 \times 10^{-6}$.

- **Circuit Breaker:**

The circuit breaker used is the oil type circuit breaker. The unavailability of 300×10^{-6} is assumed.

V. PRESENTATION OF RESULTS

The unavailability of the basic events and component unavailability are tabulated as in Table 1 below to allow for quick inspection.

Table 1: Unavailability of the Several Protection Components.

S/no	Component	MTBF	T	Unavailability 10^{-6}
1	Over Load Relay	200	6months	2465
2	Current transformer	500	2days	10
3	Voltage transformer	500	2days	10
4	Circuit Breaker	-	-	300
5	Bus differential Relay	200	6months	2465
6	Distance protection relay	200	6months	2465
7	Breaker failure relay	200	6months	2465
8	Wiring	-	-	1000
9	DC battery bank (110)	27	0.5day	50

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The fault tree (shown in Appendix 2) illustrates the unavailability of the basic events inserted and propagated upward. Using the rare event approximation, the unavailability associated with each event expressed with the OR gates is summed up and the ones associated with AND gates are multiplied. The unavailability of this protection system, i.e., general protection failure on the 132kV Kano-Kankia transmission line is 5085.023×10^{-6}. From the assessment, it could be seen that the relays are the most vulnerable components in this protective scheme because they lack automatic supervision. And this implies that the principal weakness of this scheme is its dependency on several electromechanical relays.

This protection scheme, however, can be improved upon by adding redundant relays to the existing system. The relays could be added as shown in Figure A3 in Appendix 3. The unavailability of the top event (general protection failure) with this redundancy arrangement is 2616×10^{-6} as against the unavailability of 5085×10^{-6} of the protection scheme without redundancy. Therefore, the percentage improvement is 51.45%.

VI. CONCLUSION

The fault tree approach to reliability assessment of the 132-kV Kano-Kankia transmission line protective scheme has been successfully carried out. The reliability index used for this assessment is the unavailability. The unavailability of the existing protection scheme of the 132-kV Kano-Kankia has been found to be 5085×10^{-6}. With a redundancy arrangement of relays, a percentage improvement of 51.45% has been realized. The FTA is a very useful tool for design and operation of complex systems. It helps to identify critical components and enhance system understanding. As a diagnostic tool, it can be used to predict the most likely causes of system failure in the event of break down. As design tool, it helps in eliminating costly design changes and retrofits. In order to improve the reliability of the system, however, electro-mechanical relays should be replaced with modern digital self-test relays and pilot distance protection should be adopted as pilot communications between relays have an added advantage of discrimination and isolation of fault in good and reasonable time.

VII. ACKNOWLEDGEMENTS

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APPENDIX 1

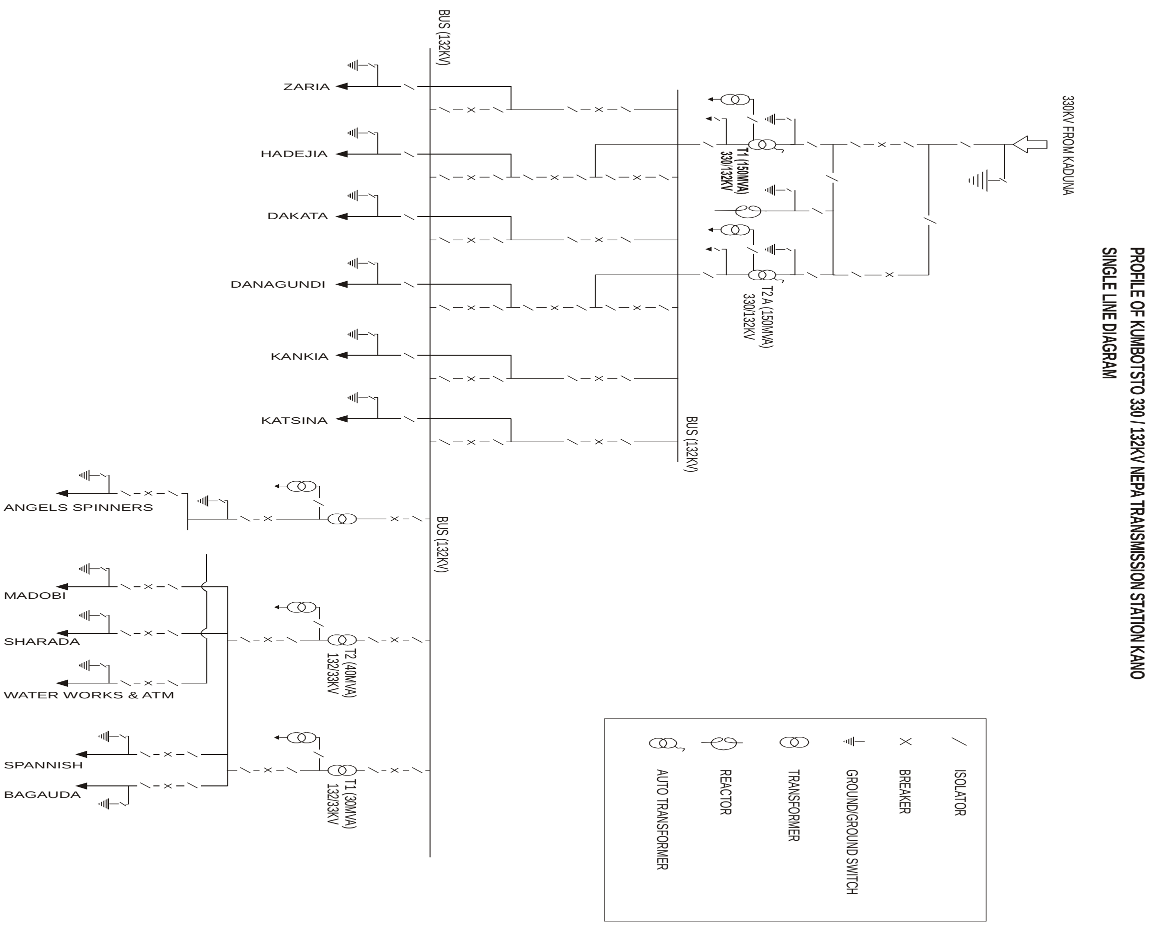

Fig. A1. Single Line Diagram of the132-kV Kano – Kankia transmission

APPENDIX 2

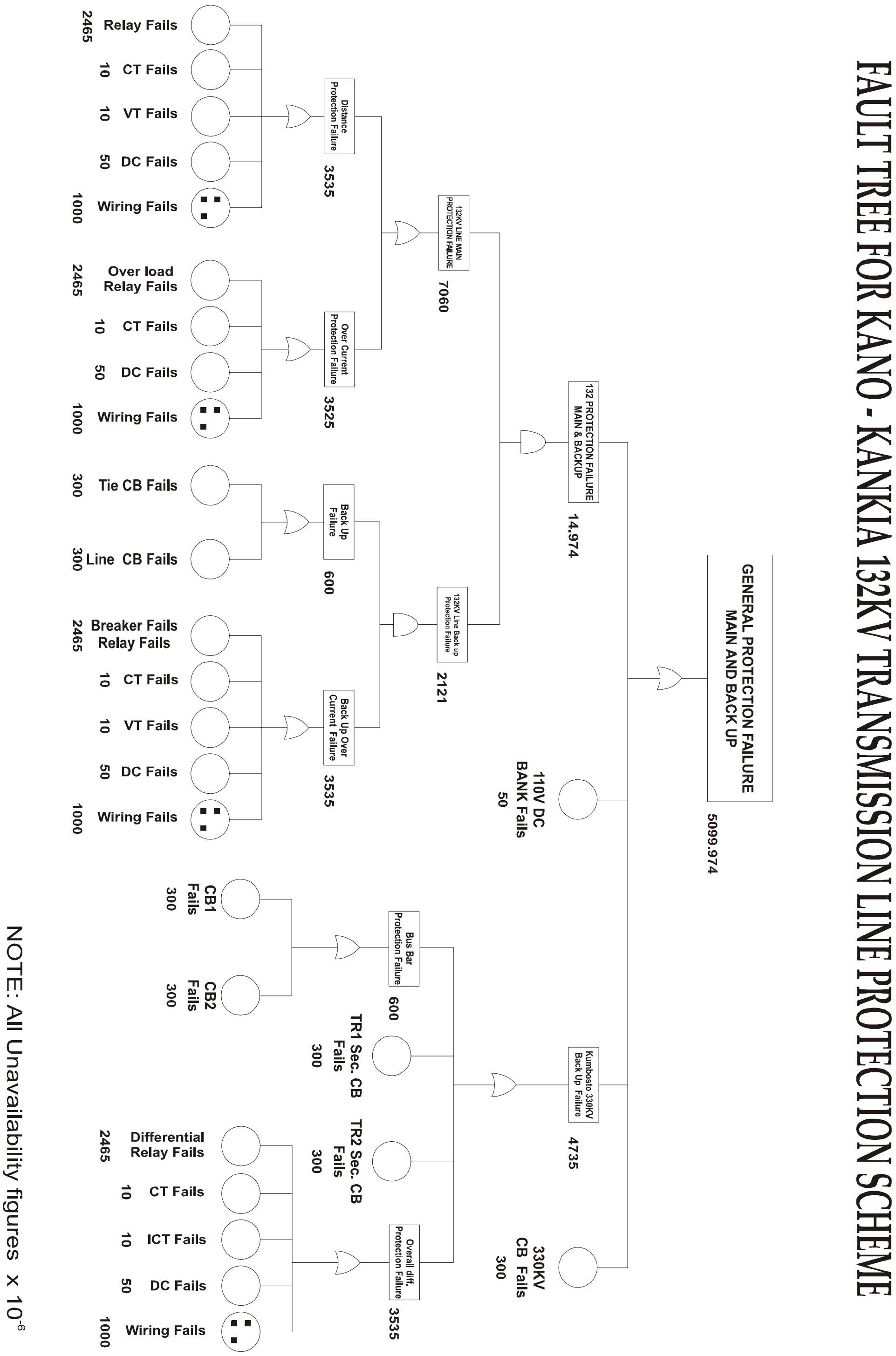

Fig. A2. Fault Tree with unavailability values inserted

APPENDIX 3

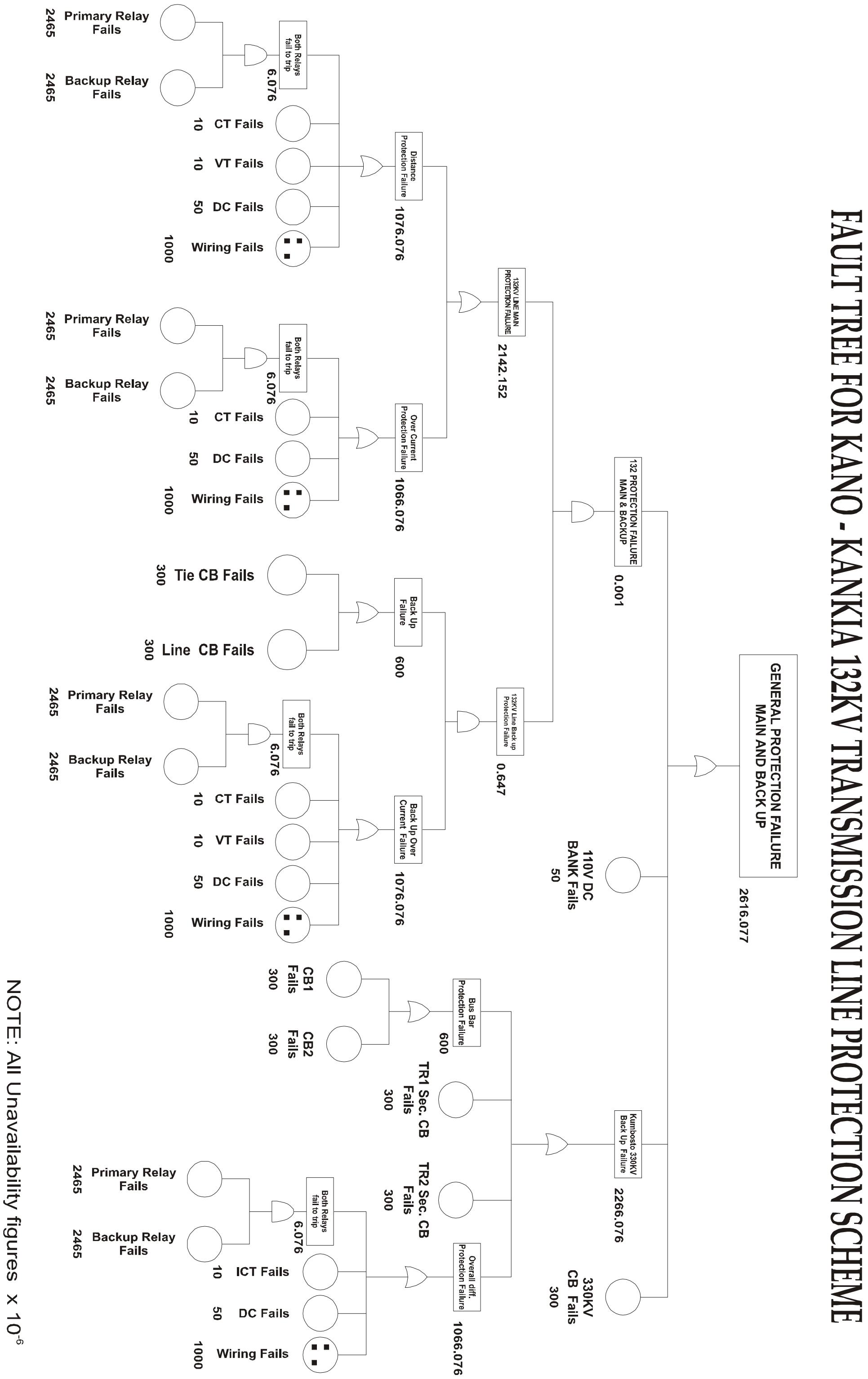

Fig. A3. Fault Tree of the Protection scheme with Redundant Relays