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Quantifying the Level of Exposure of Uganda's 132kV Network to Transient Faults

Kajumba Sandra Matty[1], Jane Namaganda Kiyimba[2], Milton Edimu[3]

[1]Makerere University, College of Engineering, Design, Art and Technology, 7062 University Rd, Kampala, Uganda
Email: *mattykajumba[at]gmail.com*

[2]Makerere University, College of Engineering, Design, Art and Technology, 7062 University Rd, Kampala, Uganda
Email: *jnamaganda[at]gmail.com*

[3]Makerere University, College of Engineering, Design, Art and Technology, 7062 University Rd, Kampala, Uganda
Email: *teedimu[at]gmail.com*

Abstract: ***Uganda's power system has grown over the years with an increase in the transmission line network and generation capacity. Conversely, over time, the transmission grid has experienced a number of transient faults with some resulting in cascading failures and total system collapse, thus the need to quantify the level of exposure of the transmission network to transient faults. This paper presents a study done to quantify the level of exposure of Uganda's 132kV transmission network to transient faults. The 132kV network is modelled in DIgSILENT software and the quantification is done based on resilience metrics that have a high maturity index. These include: generation capacity lost, the value of the lost generation, the quantity of the load lost and the value of the load lost. The study then proposes strategies that will reduce the level of exposure and a quantification of the new level of exposure of the transmission network is undertaken. The results of this study will aid in the planning, operation, control and optimization of Uganda's 132kV transmission network to reduce the level of exposure of the network to transient faults and prevent the negative cascading impacts of transient faults.***

Keywords: Exposure, Fault, Metrics, Transient

1. Introduction

A transient fault refers to a fault that remains for a short duration of time while a permanent fault persists in the power system. A number of notable disturbances on the Ugandan power system originating from transient faults have resulted in cascading failures and eventual total system collapse. This is because transient faults propagate faster, resulting in a very high fault current and generator acceleration and the source of transient faults is difficult to locate [1]. Estimates show that transient fault-related power outages in Uganda result in a total lost load of approximately 1275MW per month [2]. In extreme events, transient faults on the 132kV network have resulted in partial blackouts of the electrical supply industry and the decoupling of the regional interconnection tie lines [3].

In this paper, quantitative RMs are used to quantify the transmission system exposure to transient faults. The paper determines the Uganda 132kV transmission lines that are highly exposed to transient faults and consequently conducts a quantification ofthe current exposure level. The next sections of this paper give a detailed discussion of the simulation of transient faults on those transmission lines, the results obtained in terms of the exposure and proposed strategies to enhance the resilience of the 132kV system. In addition, the study determines the new exposure level after the implementation of the proposed strategy.

2. Case Study- Uganda's 132kv Transmission Network

Uganda's electricity industry is divided into three fragments including generation, transmission, and distribution. The generation section is a combination of Government owned power plants and independent power producers in what is known as a Public-Private Partnership (PPP). The transmission section is wholly owned by government of Uganda while the distribution section comprises of assets owned as well as operated by both public and private and players.

The country's generation sources are diversified into four categories including hydro (1,072.9 MW), thermal (101.1 MW), Bagasse (111.7 MW) and grid-connected Solar (60.9 MW) [4]. The country's total installed generation capacity has grown from 1237.49 MW in October 2020 to 1408 MW as of April 2023. UEGCL operates the generation section together with some private power producers.

The Transmission section is wholly operated by UETCL. UETCL owns, operates, develops, and maintains a high-voltage transmission grid [5]. This grid connects power generation plants to load centers throughout the country as well as interconnections with neighboring countries including Kenya and Tanzania [4]. UETCL also owns a National control center that coordinates and monitors all the grid operations including maintenance activities [5]. Currently, the transmission grid comprises of 150km of 220kV, 1443km of 132kV, 300m of 132kV underground cable, 35.2km of 66kV high voltage transmission lines and 20 substations [2].

Uganda's 132kV system has experienced a number of transient faults that have resulted in long outage hours and cascading system interruptions [3]. From the study, it was noted that 64% of the transient faults that were experienced in the years 2018 to 2021 were attributed to electromagnetic transients resulting fromlightning (47%) and switching events (17%) [2]. **Error! Reference source not found.** provides a summary of the sources of transient faults on the transmission network.

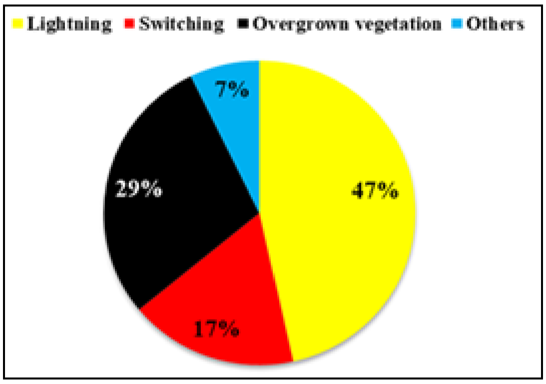

Figure 1: Sources of Transient Faults

The study also noted that most of the transient faults are experienced on the 132kV system as opposed to other system voltages. Figure 2and Figure 3indicate the load and generation lost on the respective system voltages in the year 2021 and 2020 respectively.

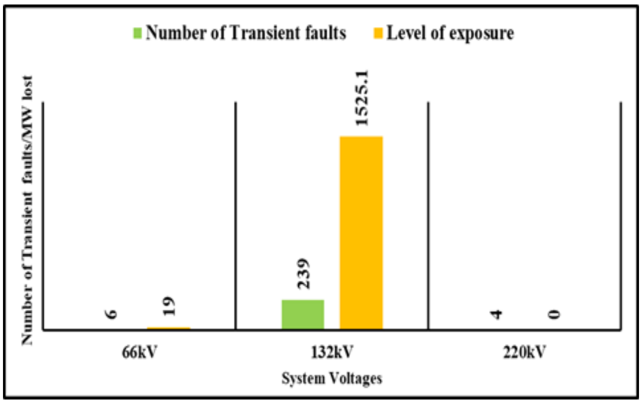

Figure 2:Transient fault exposure based on system voltages in 2021

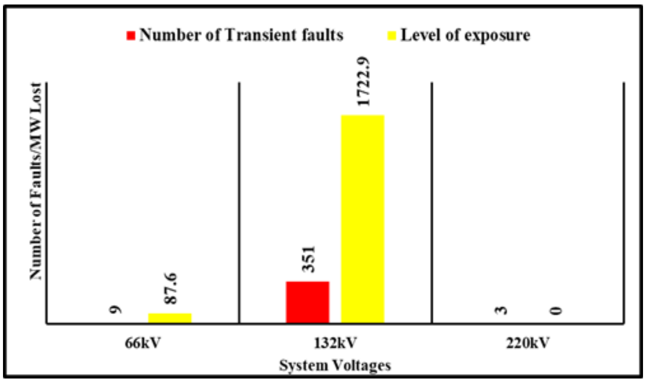

Figure 3: Transient fault exposure based on system voltages in 2020

3. Methodology and Simulations

3.1 Determination of Resilience Metrics

The study determined the metrics that would be used for the quantification of the exposure level. From the studies, it was noted that, there are generally no standardized metrics to measure exposure level [7]. Raoufi et al., (2020) proposes a conceptual framework that enables the classification of RMs in power systems is proposed. As indicated in Figure 4, the performance-based metrics depend on the system level quantities such as system generation, system load etc. while the non-performance-based metrics are independent of the system performance.

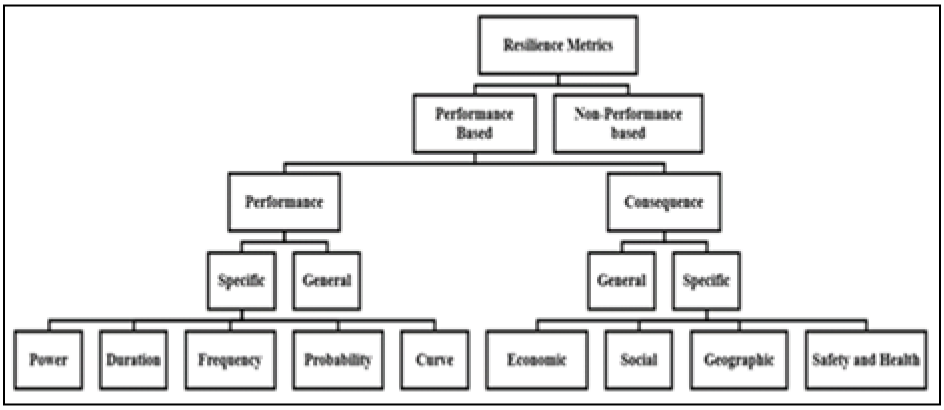

Figure 4: RM Conceptual framework

Performance metrics are the direct output of the power system performance while the consequence metrics are the effect of the power system on the diverse features of the society [8]. From the defined metrics framework, both performance and consequence metrics are divided into two groups: specific metrics and general metrics. The maturity level for general metrics is low and thus are not considered for this study.

Consequently, specific and quantitative measures of resilience were considered for this study because they had a high maturity level. Accordingly, other metrics were not considered for this study because they could not be accurately defined and would thus result in ambiguity during quantification. The study used a combination of power metrics along with cost/economic metrics that are related to load and generation. The metrics considered for this study include the Generation capacity lost on the generators (MW), Cost of the generation lost (UGX based on the generation tariff), Quantity of the Load lost (MW) and Cost of the load lost.

3.2 Data collection

In order to obtain a better insight into the current level of exposure, primary operational and historical data was collected. The historical data included fault data (transient and non-transient), causes of the fault, duration of the respective outages as a result of the faults, load lost as a result of the faults and any generation that could have been affected as a result of the faults.

The operational data collected includes generator data (active power, reactive power (MVAR), mode of operation, damping factor, inertia (prime mover and generator), speed, power factor, rpm), bus data (voltages), transformer data (voltage rating, power rating, impedance, reactance), transmission line data(conductor type, configuration, voltage rating) and Load data (voltage rating, MVA, pf, MW).

3.3 Transmission Line Selection

Transmission line selection was based on three aspects: transient fault count, the impact of the transient fault and the criticality of the lines.

Table 1 provides a summary of the transmission lines considered for the study.

Table 1: Transmission Lines considered

Parameter	Transmission Line Considered
Load Curtailed	Bujagali-Iganga 1
	Masaka West-Mbarara North
Major power plant evacuation lines	Isimba-Bujagali 1
	Nalubaale Lugogo 1
Likelihood	Lugogo clock tower
	Nkenda-Fortportal 2
interconnection lines	Masaka West-Tanzania
	Tororo -Lessos

3.4 Network Modelling and Load flow study

The study modelled the single-line diagram of Uganda's 132kV transmission network using the DIgSILENT power factory software. The model largely focused on high-voltage transmission lines at and above 66kV. Medium voltage lines at 33kV were however included as well to incorporate several distribution generators.

Model validation was used to confirm the fixed characteristics of the modeled grid to be representative of the actual grid. A load flow analysis was performed to validate the model. For fixed topology, the simulated bus voltages and actual bus voltages should be close and comparable for the same level of loading. As indicated in

Table 2, the voltage results from the load flow were comparewith the voltage reading values obtained at different locations along the modelled grid at the same time to ensure consistency.

Table 2: Validation Results of the Model

Substation	Actual Voltage (kV)	Model Voltage (kV)	Percentage error (%)
Masaka West	127.253029	127.333	0.0628
Mutundwe	134.284485	133.759	0.3929
Kampala North	133.959473	133.4	0.4194
Namanve	132.906464	131.7	0.9161
UETCL Mukono	133.745926	132.592	0.8703
Nalubaale	133.745926	132	1.3227
Bujagali	135.131378	132	2.3723
Isimba	134.710464	136.4	1.2387
Tororo main	133.6208	131.632	1.5109
Opuyo	134.543289	132.4845	1.5540
Lira	[redacted]	136.5	[redacted]
Hoima		133.71	
Mbarara North	136.506775	136.147	0.2643
Mbarara South	138.234207	135.4047	2.0897
Lugogo	132.097366	131.17	0.7070
Clock tower	132.14209	126.5	4.4602
Kawanda	132.655045	131.8	0.6487

During the time of data collection, the voltages on Lira Substation and Hoima substation could not be ascertained due to the failure of the voltage transformers. The parameters used to model the grid were then adjusted accordingly to improve the accuracy of results. It is seen that the errors range from 0.06% to 4.4% with an average percentage error of 1.2553%, which is well within the permissible 5% margin.

As indicated in Figure 5, the study then conducted a load flow simulation to determine the operating state of the equipment in the network prior to the Electromagnetic Transient (EMT) simulation and to ensure their operation within the specified limits.

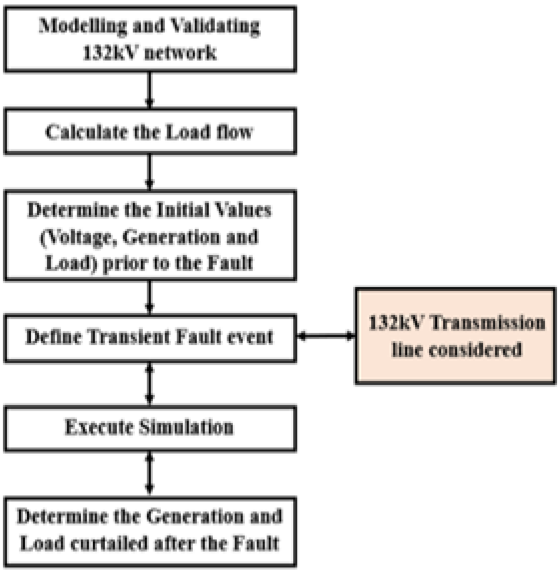

Figure 5: Simulation procedure

3.5 Baseline Level of Exposure

Taking into the number of transient faults that occurred on the respective in the year 2021, total exposure of the 132kV transmission system is 6,679,243,613.08 UGX. **Figure *6*** indicates the exposure on the respective transmission lines Masaka West Tanzania having the highest exposure amounting to 1,067,680,095 UGX.

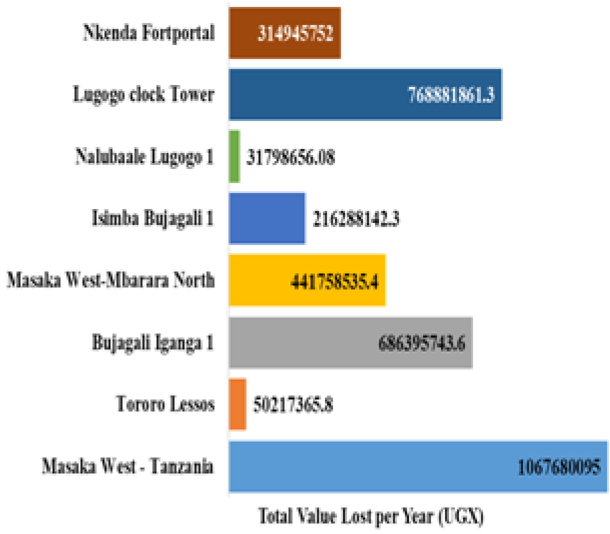

Figure 6: Exposure level on the respective transmission lines

4. Solutions to Reduce Transmission Line Exposure

Utility solutions for reducing the level of transmission line exposure include use of underground transmission lines, enhanced vegetation management, installation of bird guard, uses of series compensation among others. Other solutions include solutions aimed at reducing the system reactance like adding parallel transmission lines and/or using a transformer with low leakage reactance [2]. However, these two techniques for reducing system reactance are quite expensive and where thus not considered for the study. Other techniques based on FACTS are considered as cost-effective alternatives.

a) Enhanced Vegetation Management

The system exposure to the impact of transient faults can be reduced by enhancing the management of vegetation along the 132kV transmission lines [3]. Enhanced vegetation management involves the constant pruning of plants, trees and related grass types away from the transmission lines. This is key to the reduction of transient faults since most of them occur during heavy rains and storms when the branches touch the lines. Vegetation management can be enhanced by increasing the trim cycle and budget for such activities [4]. Prudent utility practice recommends pruning of plants and trees on the transmission corridor three times a year to reduce transients caused by winds and rainfall [1][11].

b) Series Capacitor

The inclusion of series capacitors on the key transmission lines was one of the proposed strategies for reducing the exposure level to transient faults. The microfarad rating of the series capacitors was determined, and the modelling of the system with the inclusion of a series capacitor on Masaka West Tanzania transmission line was undertaken. Series capacitors increase the power transfer capability and thus increase the transient stability of the system, thereby reducing the level of exposure. The power transferred, P, through a transmission line is as indicated in Equation (1).

$$P = \frac{EV}{X_L} \sin \sigma \qquad (1)$$

Where E is the sending end voltage, V is the receiving end voltage, σ is the angle between E and V and X_L is the series line inductance

If a reactance of opposite sign (a capacitive reactance) is introduced in the denominator, the corresponding increase in power transmission is enabled. This increase in power transmission increases the resilience of the transmission network to transient faults and consequently reduces the system exposure. With a series capacitor, the expression for power transfer is represented in Equation 2, Where X_C is the series capacitance.

$$P = \frac{EV}{X_L - X_C} \sin \sigma \qquad (2)$$

5. Determination of Enhanced Resilience

Consequently, the study modelled the132kV Ugandan network with the inclusion of a series capacitors on Masaka West Tanzania transmission line, as indicated in Figure 7.

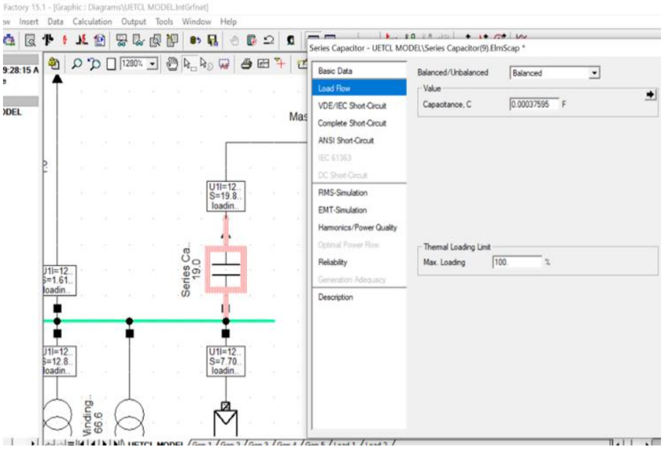

Figure 7: Inclusion of a series capacitor on Masaka West Tanzania

Masaka West Tanzania was considered for the implementation of the proposed study because this feeder is an interconnection line, has experienced the highest number of transient faults and was the most exposed in terms of MW lost. The specifications of this line are indicated in **Table 1.**

Table 1: Specifications of Masaka West-Tanzania

Specification	Quantity
Rated current	470A
Rated Voltage	132kV
Nominal frequency	50Hz
Type	Overhead line
Inductance (L) per km	1.063155mH
Line length	84.5km

When rating the series capacitor, the degree of compensation was an important factor. This degree of compensation is defined as the ratio of capacitive reactance to the total inductive reactance of the transmission line. In power transmission applications, the degree of compensation is chosen within the range $0.3 \leq k \leq 0.7$ which is less than unity and therefore, power is increased when series capacitor on the line is inserted [12] [13] [14]. The total inductive reactance of the line X_L was computed as indicated in Equation 3 where L is the total line inductance.

$$X_L = 2\pi f L \qquad (3)$$

Consequently, the study conducted the sizing of the series capacitor for the 132kV Masaka West Tanzania transmission line for the different degrees of compensation of k=0.3, k=0.5 and k=0.7. The different values of capacitive reactance at the respective degrees of compensation were computed as indicated in
Table **2**.

Table 2: Capacitor ratings at the different degrees of compensation

	k=0.3	k=0.5	k=0.7
Capacitive Reactance (Xc)	8.4669	14.111	19.756
Capacitance (μF)	375.946	225.568	161.120
Bank Sizing (MVAR)	5.61	9.35	13.09

Consequently, the level of exposure because of transient faults on Masaka West Tanzania at k=0.3, k=0.5 and k=0.7 was determined as indicated in Figure 8. This was done by determining the load curtailed and generation lost because of transient faults on Masaka West Tanzania at the different series capacitor ratings. The degree of compensation that provided the lowest level of exposure was considered for this study.

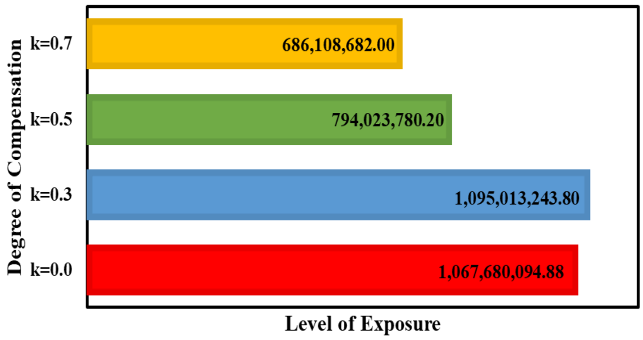

Figure 8: Level of exposure at different degrees of compensation

The study noted that the series capacitor with a compensation degree of 70%, and sizing of 13MVAR provided the least exposure of the network to transient faults. For a transient fault on Masaka West Tanzania, the generation lost reduced from 475MW to 260MW per year. Additionally, the annual load lost was reduced from 1219MW to 806MW. As indicated in Figure 8, the exposure level reduced from 1,067,680,094UGX to 686,108,682 UGX.

The annual savings resulting from the installation of a series capacitor on the Masaka West Tanzania line were estimated at 381,571,412.88 UGX while the cost associated with the installation of the series capacitor were 228,055,603.62 UGX. Consequently, the resultant cost-benefit ratio was 1.67, an indicator of a viable investment [15][16].

6. Conclusion

The current level of exposure of the 132kV system to the impact of transient faults is UGX 3,577,966,151. This significant exposure level was mainly attributed to the reactive vegetation management strategies, the type of transmission corridor and transient overreach of distance relay protection schemes. The study found that enhanced vegetation management, inclusion of series capacitors on highly exposed transmission lines and the installation of bird guards in areas that are prone to transient faults resulting from contact with birds provide a cost-effective solution to reduce the level of exposure as opposed to other industry strategies like undergrounding the transmission lines. The inclusion of a 13MVAR series capacitor on Masaka Tanzania line resulted in a 35.7% reduction in the level of exposure with a cost-to-benefit ratio of 1.67, indicating a viable investment.

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Author Profile

Kajumba Sandra Matty, graduate Student, Department of Electrical and Computer Engineering. College of Engineering, Design, Art and Technology, Makerere University, Uganda.

Dr. Jane Namaganda Kiyimba, Senior Lecturer, Department of Electrical and Computer Engineering. College of Engineering, Design, Art and Technology, Makerere University, Uganda.

Dr. Milton Edimu, Senior Lecturer, Department of Electrical and Computer Engineering College of Engineering, Design, Art and Technology, Makerere University,Uganda.