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An Advanced Protection Scheme to Avert Blackouts due to Transmission Network Overload

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Abstract

The Uganda power network has suffered various transformer overloads which have reduced power availability and utility income generation. Although frequency monitoring ensures system stability and calls for the Under Frequency Load Shedding scheme, other conditions that threaten power system stability like the loss of a tie line, overload trip of a power transformer, and overload trip of a transmission line need to be automated as well. This will not only improve reliability and continuity of service but also fast decision making, reduce the blackout zone, unnecessary load shedding, and minimal downtime. This paper presents a load management scheme that performs automatic load monitoring and feeder restoration by strictly following the set threshold values using PCM600, an ABB tool. The 11KV feeder load shedding hierarchy was strictly selected according to utility income-priority, strategic supply and safety. The logic configuration from PCM600 was validated and the Generic Object Oriented Substation Events (GOOSE) report was published. The Configured IED Description (CID) file from each IED (in PCM600) was saved in Substation Configuration Language (SCL) format and imported into IEDScout to simulate the IEC61850 communication. The simulation using IEDScout achieved a 500ms GOOSE messaging sequence and the traffic on the Ethernet cable was captured and analyzed using WireShark, a graphic user interface network protocol. A cost benefit ratio of 1.647 (greater than 1) was obtained to declared economically acceptable. This design caters for emergencies, i.e. very rare, non-continuous but possible and very catastrophic occurrences on the power system. Therefore this research provides an efficient solution to transmission line and transformer overload by automating downstream load-shedding and load restoration.

Keywords: Transmission line overload; Load shedding; Transformer overload; Downstream load shedding; Automation load restoration

Introduction

The primary aim of an electric power system is to provide satisfactory uninterrupted electrical power supply to customers within the set limits of frequency and voltage (reliability), however, the power system must also be able to remain secure without serious consequences to any contingencies (stability) [1]. Any violation of the set parameters must be harmonized timely before the power system becomes unstable.

The generation, transmission and distribution sectors of the Uganda power system have installed protection and control schemes to ensure stability and reliability. While the under-frequency load shedding scheme on the transmission network monitors the system frequency and timely sheds-off load to maintain frequency within set limits, the overload condition on the transmission network has only been left to overcurrent relays and operators for monitoring and load shedding decisions [2]. Events that push a power system towards unsafe modus operandi usually develop slowly but when the unsafe status is reached, events occur almost instantly in milliseconds [3].

The current load management action involves reduction of load on the affected substation through the Supervisory Control and Data Acquisition (SCADA) system by remotely opening feeder circuit breakers [2]. This research seeks to automate load shedding which has been left to operators who remotely and manually isolate loads to maintain system stability. The challenge with manual action is the lack of accuracy, isolating too much load or too little load which reduces the time taken to stabilize the power system, further, when the load-violation occurs very fast, the operator cannot make a very fast decision hence brownouts, blackouts or cascaded failures [4]. According to [3], operators should be able to monitor and quickly identify critically loaded components within the power system. This becomes even harder as the network expands into power pools, therefore, there is a need for smart operation of the power system [5]. The manual response to overload events should be automated to increase network reliability and power system stability. This paper presents a design used to increase availability of the power components not only by smart downstream automatic feeder isolation but also ensuring that load shedding sequences are initiated before the transmission line protection relays operate.

This paper avails a load management SAS for Lugogo substation to automate load monitoring, isolation, and re-connection mechanisms of the transmission lines and power transformers. The developed scheme ensures continued availability of critically loaded transmission lines and power transformers by monitoring their loads and initiating load isolation mechanisms based on IEC61850 standard. The system is intelligent enough to ascertain the overload condition as well as initiating a self-healing mechanism. According to [2,6,7], the power system network of Uganda lacks a smart overload monitoring and control scheme [8]. Further points out that Uganda experiences an average load shedding period of about 11 times per month and 46% of the outages are forced as shown below. This indicates a high dependence on the operator's (manual) action that is often characterized by inefficiency and human drawbacks; therefore, there is a severe need for smart schemes that are driven by information and communication technology (Figure 1).

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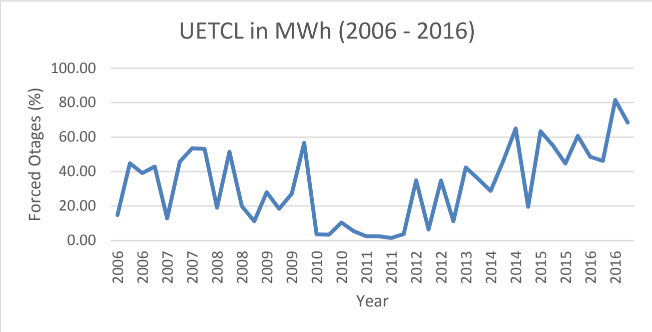

Figure 1: Power outage statistics (Source: ERA ESI database).

Compared to the existing UFLS scheme on the Uganda network, the developed scheme is unique because it involves a smart self-healing mechanism that remembers the status of every circuit breaker before re-energizing the feeders. The scheme also has a very fast reaction time, high efficiency, and accuracy to only isolate the appropriate load.

Methodology

Research design

The research followed an experimental nature through design, simulation, analysis, and discussion of research outcomes. This research is purely applied research as it aims at providing a solution to a problem faced by the power transmission sector of Uganda. The designed scheme can be used in many other networks like the sub-transmission and distribution networks.

A mixed research approach which involves both qualitative and quantitative methods was used. The quantitative approach involved a statistical analysis of the network fault data and the loading statistics of the transmission network to establish a suitable case study, while the qualitative aspect involved subjecting the data obtained from the quantitative selection to qualitative scheme, modeling and explaining simulation outcomes. This explanation borrowed an insight from the discernment and knowledge obtained from the focus groups, interviews, and engineering theory.

Case study and sampling

A non-probabilistic, purposive sampling was used. Due to the nature of research, there are only a limited number of substations that can serve as primary study cases in Uganda. The case study must be able to provide realistic results as well as being diverse enough to cater for all possible loading conditions and consequences.

As the intention of the research is to solve an existing problem, a baseline of UETCL line outages was used to select a substation that allows the different transmission line loading conditions and substation equipment diversity. Such a substation must possess the following characteristics.

- At least a pair of parallel transformers.
- Supplied by parallel transmission lines or in a circuit with possible bipolar power flow.
- Possess more than four load feeders from the station bus.

Secondary data was used because outages are rare, unexpected and some of the parameters to be measured are short lived. An attempt to obtain primary data would be expensive and requires a lot of time to generate adequate data for a study. The secondary data obtained from UETCL achieves was measured using instrument transformers and other accurate energy meters. This equipment is tested for reliability, and accuracy before installation, to the standards of the utility.

The outage data obtained from Uganda Electricity Transmission Company Ltd (UETCL) was analyzed to obtain the most vulnerable substation to act as a case study. The data were grouped, categorized and tallied to obtain the outages of the different substations.

The redundancy of the selected case study was used to determine the safe loading percentage of the transmission equipment (transmission line and power transformer). Below is the process flow during scheme development. Two IEDs: RET670 and REL670 interact with each other and with other power system components like circuit breakers. The Figure 2 below also shows the decision making hierarchy in each of the IEDs. The decision making hierarchy was used in setting the configurations of PCM600.

IEC61850 standard was used to develop the scheme using PCM600, an ABB development tool. The two IEDs, RET670 and REL 670, for transformer differential and line protection were used because the same IEDs are being used by UETCL thus can be easily adopted when implementing the developed scheme. The two IEDs can communicate with each other using Generic Object Oriented Substation Events (GOOSE) for peer-to-peer data exchange [9]. Also, the status of the circuit breakers was monitored and sent as GOOSE to the IED.

IEC61850 was used for this research because of its capability to obtain information from different measurement devices at different locations on the network and share it with devices on station bus levels [10]. PCM600 presents the following advantages over the other development tools:

- The ability to develop the logics of the automation system using IEC61850 standard.
- Simplified accesses and exchange of information, allows for both analog and digital peer-to-peer data exchange, and high performance with more data exchange of up to 12MBps.
- The devices can be directly connection to the communication network, and programming can be done independently of wiring
- Has defined data models mapped to various protocols, for example: to Generic Object Oriented Substation Events (GOOSE).

Data analysis: A three-year (2017, 2016, and 2015) historic outage data of the Uganda transmission network was obtained from UETCL achieves. The data obtained included annual outages, cause of the outages, feeders and transmission lines affected, substations where the feeders and transmission lines belong, outage duration, and MW load lost.

Quantitative raw annual outage data was obtained. Descriptive statistics were used to summarize the data and to identify the substation with the highest number of outages. The data was organized, categorized, grouped, and tallied to obtain the actual substation outage statistics.

i. The raw data were organized according to substations to enable clear visualization of faults per substation. Scatter plots were used to eliminate outliers and the standard deviation of the different categories of data was obtained.

ii. For every substation, the faults were grouped according to the voltage level. The voltage of interest was 132 kV because only the transmission network was under consideration. The faults on the feeders and distribution networks on the transformer secondary are not relevant to this research.

iii. The 132 kV faults were tallied and graphs were developed to compare the number of outages and lost load for different substations as shown below.

This sampling method ensures that the case study substation represents other substations. This is because the listed conditions represent the worst case configuration scenario on any substation (Figure 3).

Although Owen falls dam has the highest number of outages, it has the second highest average load lost, as shown below Figure 4.

The power generation substations: Nalubaale (formerly known as Owen Falls Dam) has the highest number of outages. Similarly, Kiira and Bujagali have high outages. The different factors that contribute to the high outages are qualitatively categorized as shown below Table 1.

Case study selection

Although Nalubaale substation has the highest number of outages, it is a generation substation; therefore it is not possible to perform downstream load shedding at this substation. Naluba ale substation cannot be used as a case study because of the following reasons.

- It only has generation step up transformers which cannot be strained with overload given that they are limited by the generators' maximum capacity. A substation with load transformers can be used as a case study instead.
- The overload condition of the transmission lines can only be combatted by downstream load shedding which is at the load substation.

The lost load at Naluubale substation has a standard deviation of 3.55 and a mean value of 40.17MW. This value indicates a normal distribution of values around the mean with a slight skewness of -0.476. The bar chart below shows the outages on the transmission lines and power transformers (generation) at Nalubaale substation (Figure 5).

The average outages of the two-year data were used to compare the performance of the different transmission lines and power transformers. From the table above, Lugazi substation has the highest number of outages however, Lugogo substation (with the second highest outages) has been considered as a case study because; the 66 kV Nalubaale-Lugazi transmission line is a single line. Any fault on such a line can only lead to protection isolation giving no room for the load management scheme to operate. Lugazi, therefore, does not make a good case study for this particular research. Also, Unlike Lugogo substation, Lugazi substation's power transformers have got no history of overload and have a considerably high redundancy even when one of them is out of service. This is demonstrated in the chart below Figure 6.

Practically, Lugazi substation does not have Relion IEDs. The relays at Lugazi are basic (not IEDs) and so they have limited capabilities [11] as regards compatibility with PCM600 and their ability to perform GOOSE. The relay life has four main stages: active, standard, limited, and obsolete. Support from the factory is maximum during the active phase and almost none at the limited phase. Lugazi relays are in the limited phase and so no support is expected from the manufacturer. Designing a load management scheme for Lugazi substation would not only be tiresome but also technically unsustainable.

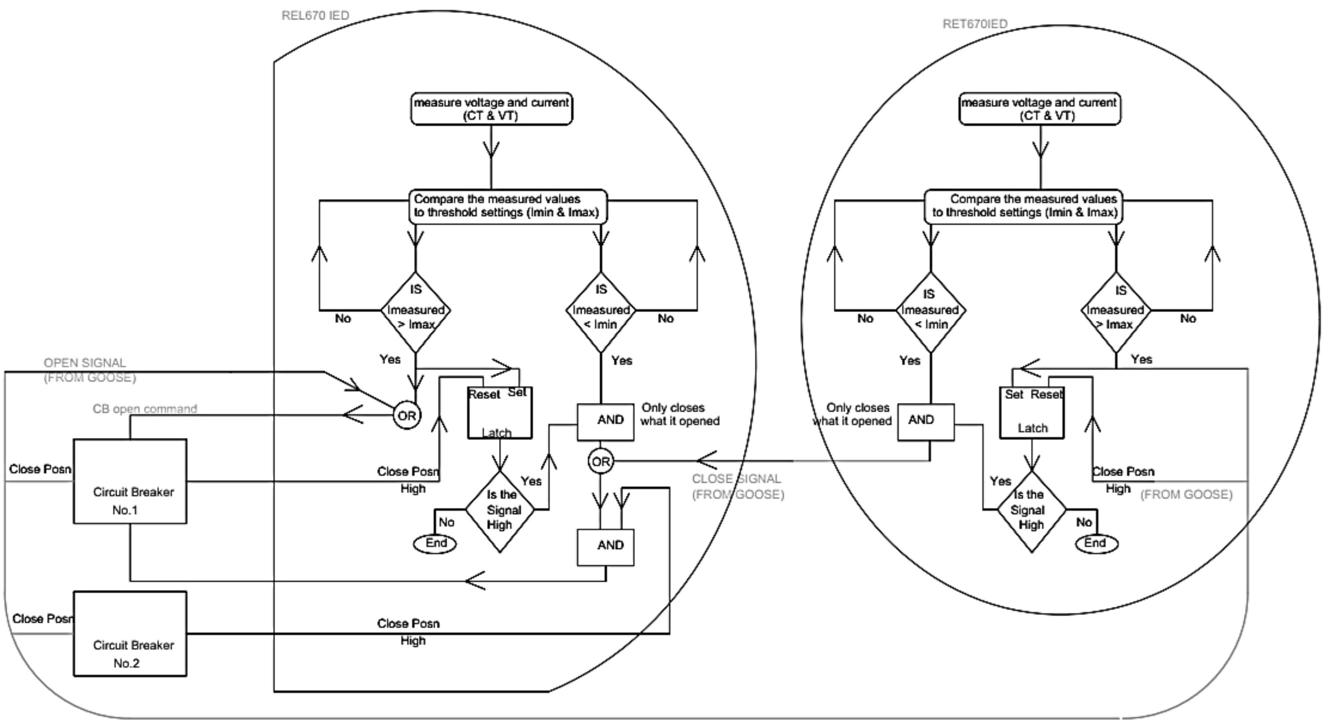

Figure 2: Scheme development process flow.

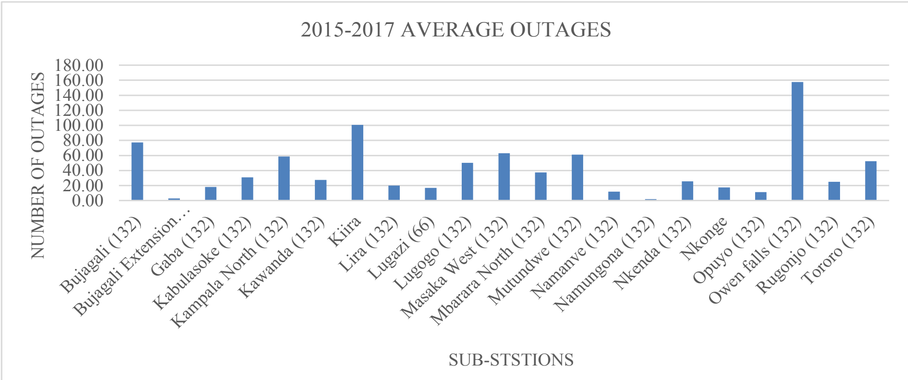

Figure 3: 2015-2017 Nalubaale Substation outages.

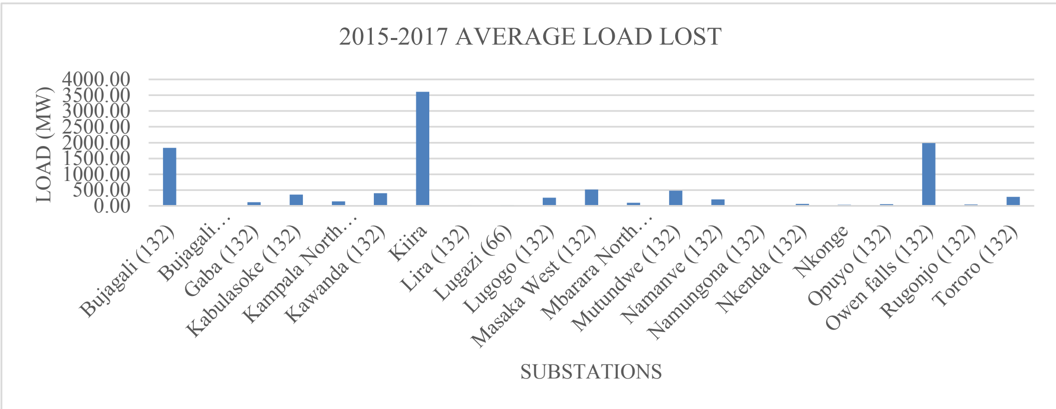

Figure 4: 2015-2017 Average Load Lost at Nalubaale substation.

Cause of Outage	Number of outages (2017)	% outages	Number of outages (2016)	% outages	Average Outages. % (2017 and 2016)
Low Hydrology	6	3.87	11	5.64	4.76
Faults	35	22.58	76	38.97	30.78
Shutdown-Emergency	4	2.58	3	1.54	2.06
Shutdown-Maintenance	110	70.97	103	52.82	61.89
High Freq. Control (Low Demand)			1	0.51	0.26
Under Frequency Load Shedding			1	0.51	0.26

Table 1: Causes of Outages at Nalubaale substation.

Therefore, Lugogo substation will be considered as a case study. The double transmission lines (Lugogo1 and Lugogo 2) supply two pairs of transformers. One pair supplies the 132/11 kV bus and the other supplies the 132/33 kV bus. This substation fulfills all the specified requirements for purposive sampling: at least a set of parallel transformers, supplied by parallel transmission lines or in a circuit with possible bipolar power flow, possess more than four load feeders from the station bus, additionally, the parallel power transformers on the 11 kV and 33 kV buses are unable to handle the entire bus bar load in case of an outage of one of the transformers on that particular bus. When such a condition occurs, the remaining transformer will be lost on overload, or the load management scheme will grade and isolate load feeders automatically. The chart below represents the average values of the annual outages for the different transformers at Nalubaale substation (Figure 7).

The one-line diagram of Naluubale substation is shown below. Any sustained faults on the feeders can have a direct effect on the synchronous generators because the 33 kV bus bar is shared by both the 33 kV feeders and four synchronous generators. If the generators are affected or abruptly shut down, this can lead to a cascading failure.

Lugogo substation is supplied by a double circuit (Lugogo 1 and Lugogo 2) from Nalubaale hydropower plant. The substation has two pairs of 32/40 MVA transformers. Two of them are 132/11 kV step down transformers supplying the 11 kV bus and the other two 132/33 kV step down transformers supply the 33 kV bus. Given that Lugogo (1 and 2) transmission lines have a high number of faults, there is a high likelihood of failure of one circuit. This will subject the entire load of the bus bar (11 kV or 33 kV) onto the healthy circuit. Note that, Lugogo substation supplies Mutundwe, Kampala north and Queens's way substations [12]. Below are the single line diagram of Naluubale substation and the One Line Diagram of Lugogo substation is shown in

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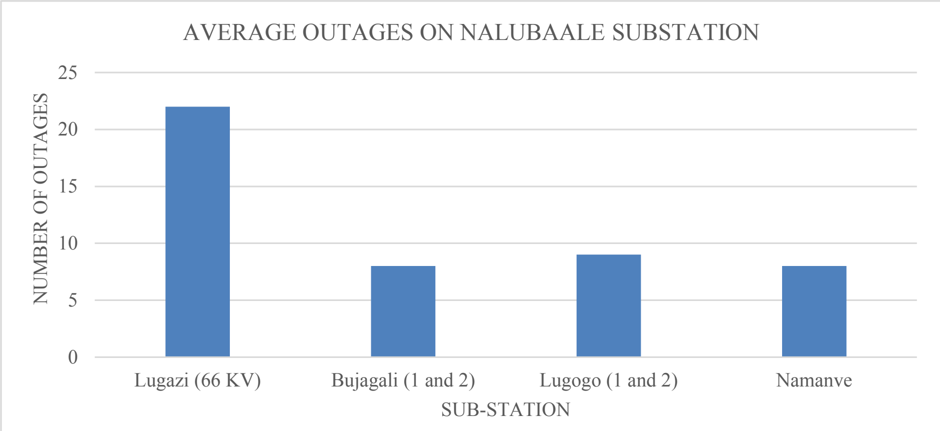

Figure 5: Nalubaale substation transmission line outages.

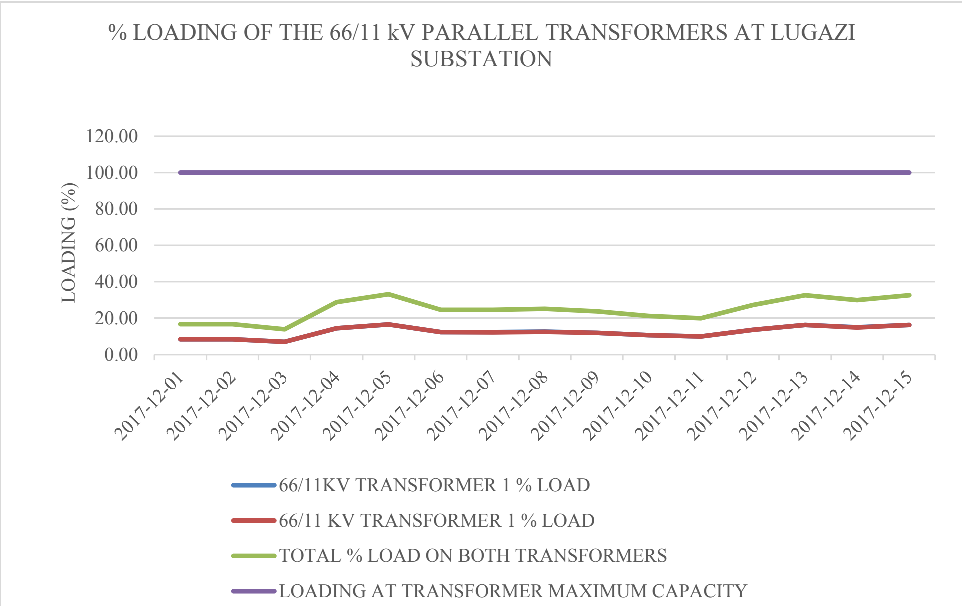

Figure 6: Lugazi Substation 66/11 kV parallel transformer loading.

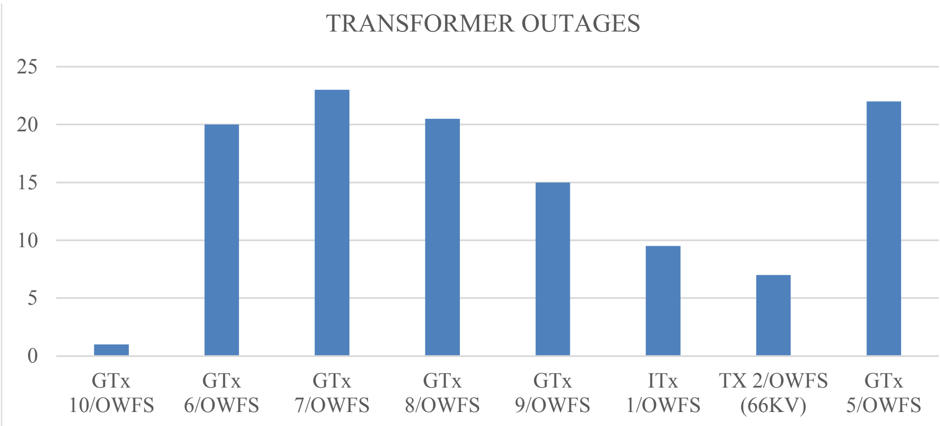

Figure 7: Nalubaale substation transformer outages.

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Figure 8, Lugogo 132 kV/33 kV/11 kV substation single line diagram (Figure 9) [12].

The substation's 11 kV and 33 kV parallel power transformers lack enough redundancy to supply the power demand of the entire bus in case of failure of one of the transformers. The graphs below show the 2017 annual loading of the transformers both for the 11 kV and 33 kV (Figure 10).

The maximum load on the 11 kV bus as contributed to by both

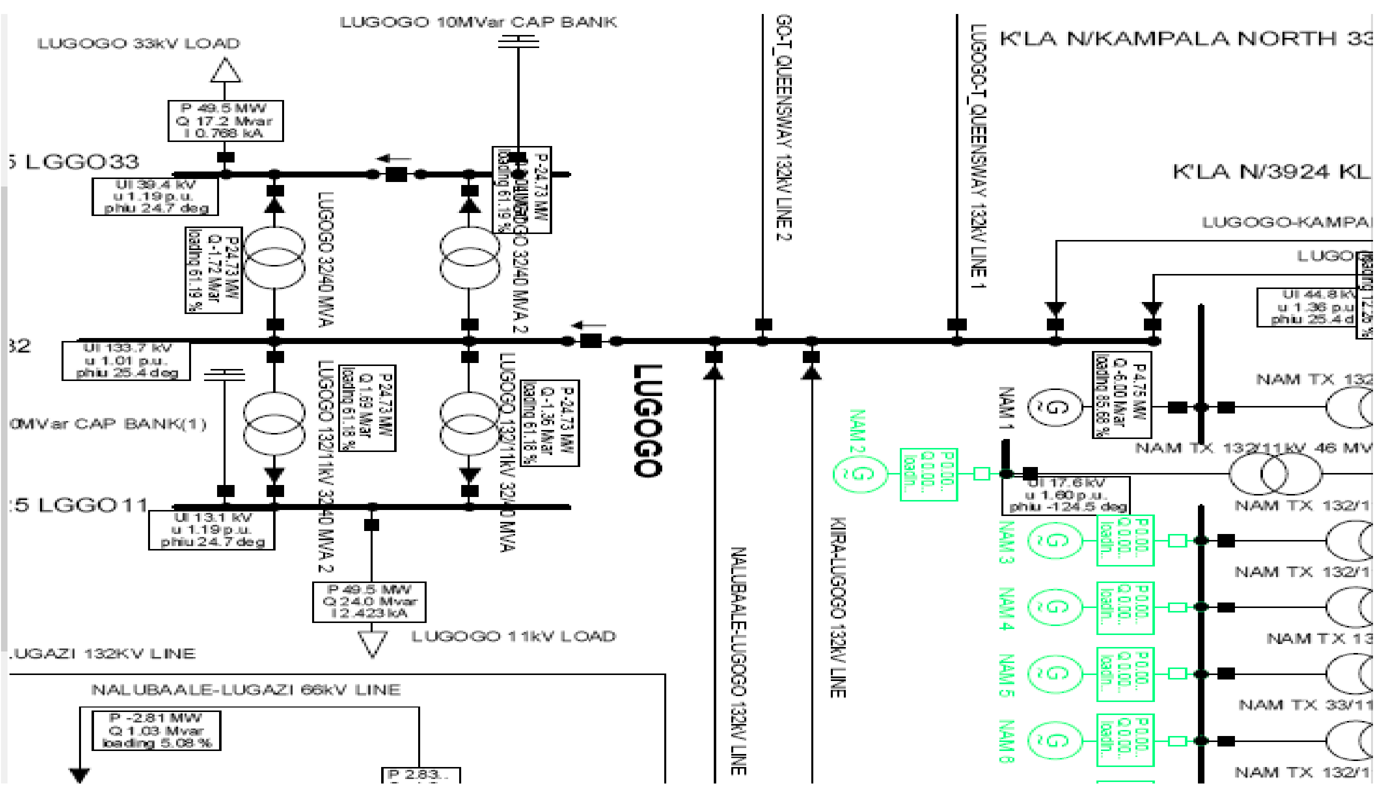

Figure 8: Lugogo 132 kV/33 kV/11 kV substation single line diagram.

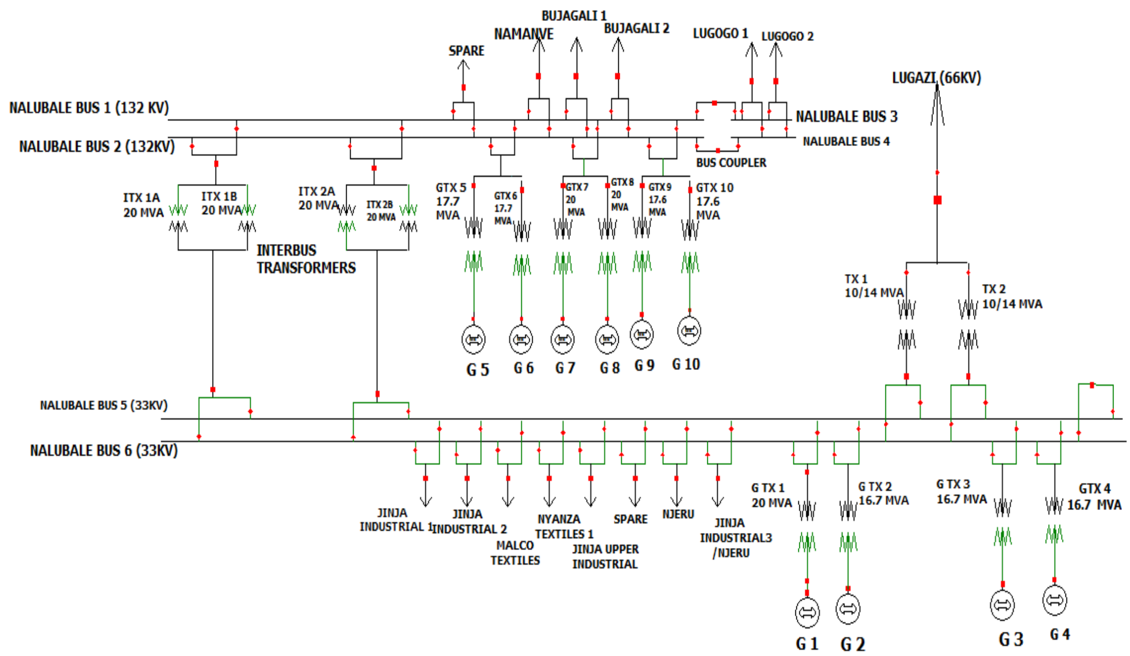

Figure 9: One Line Diagram of Nalubaale Substation.

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transformers is 94.47%. This is only 5.53% below the capacity of each power transformer. On the other hand, the 33 kV bus has a maximum load of 110.55% which is 10.55% greater than the rated capacity of the 132/11 kV 40 MVA transformer. The annual statistics of the power on the 33 kV bus is shown below Figure 11.

The obtained data from UETCL archives indicate a maximum achievable total load of 44.7 MVA and 34.79 MVA for 33 kV and 11 kV buses respectively.

From the above Figure 12, since the transformers are rated 32/40 MVA, this calls for an extra 12.75/4.75 MVA on the 33 kV bus. The 11 kV bus transformer would require extra 5.79 MVA at 32 MVA rating and it would have an extra 2.21 MVA at 40 MVA. It is possible for the transformer's forced cooling to fail especially due to age, therefore, all ratings have been compared to the maximum possible load as shown below Figure 13.

In the above Figure 13, the positive redundancy values indicate the ability of the transformer to supply extra complex power while the negative redundancy values indicate a deficiency of complex power by the transformer to efficiently supply the load. Note that, the maximum power any transformer can handle depends on a number of factors like age, the efficiency of cooling systems, insulation capacity of the transformer oil, etcetera. Similarly, a well maintained power transformer can be momentarily loaded to about 120% of its rated load [13]. Under the condition of MVA deficit, load management must be performed if the transformer is to stay on. This is being manually done by power system operators in the National Control Center (NCC) and is characterized by a number of drawbacks like lack of efficiency, accuracy, and precision. Therefore, Lugogo substation requires a load management system to enable continuity of supply when one of the 132/11 kV or 132/33 kV transformers is out on maintenance or fault conditions. This can be achieved by downstream load shedding so as to maintain an acceptable load on the transformer. The scheme should be able to automatically re-energize the feeders when the load on the transformers has reduced.

Lugogo substation's load bus: Whereas the 11 kV bus directly supplies power to the load, the 33 kV feeders supply power to the substations at different locations, sometimes forming ring interconnections. These ring interconnections are not a good choice for auto-isolation because de-energizing one feeder will take out the other

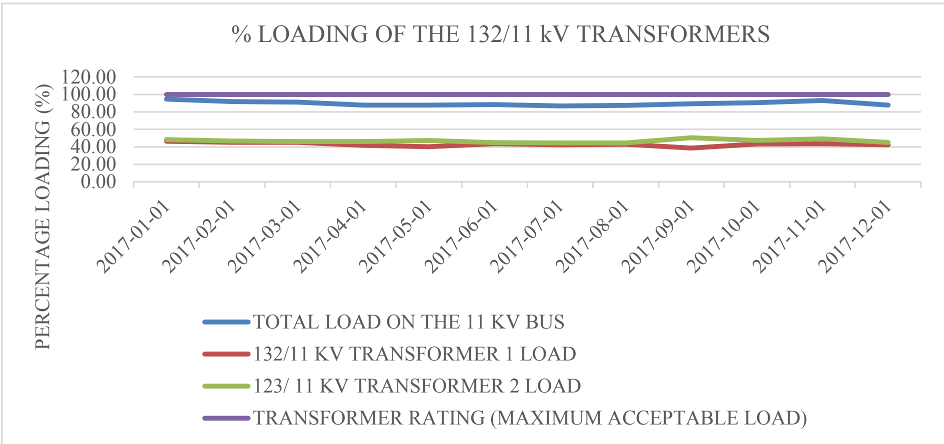

Figure 10: 2017 annual load on the 132/ 11 kV transformers.

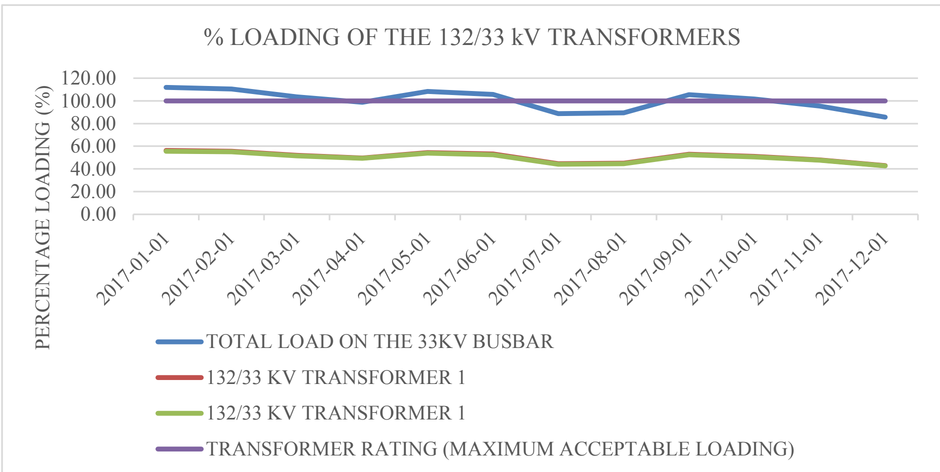

Figure 11: 2017 percentages loading of the 132/ 33 kV transformers.

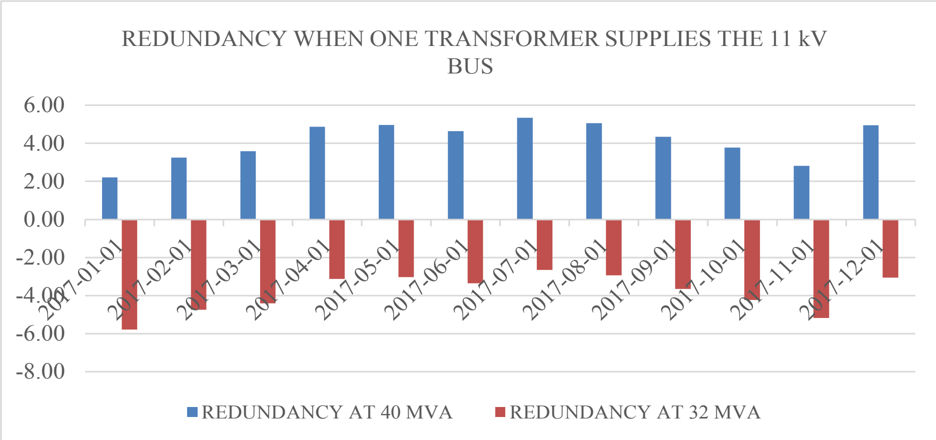

Figure 12: Annual redundancy of the 132/11 kV transformer.

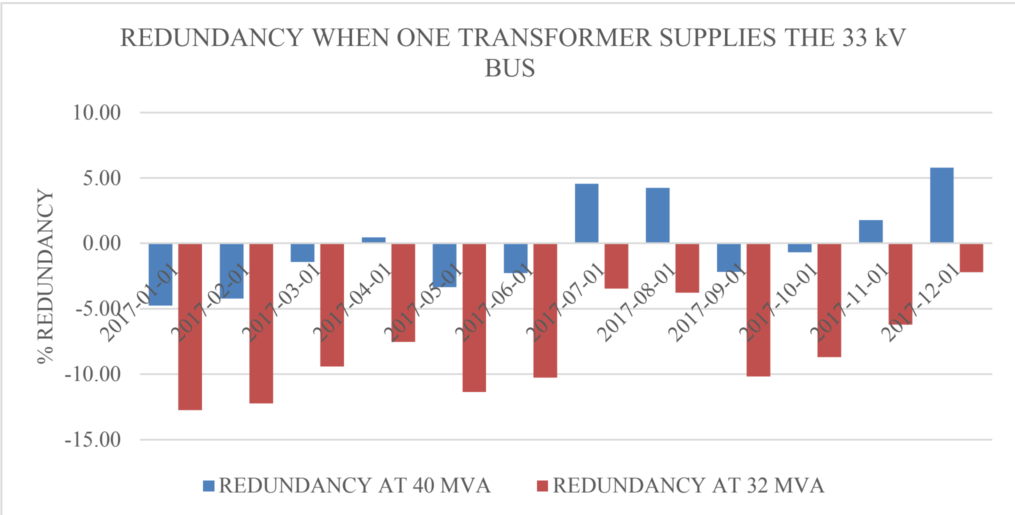

Figure 13: Annual redundancy of the 132/33 kV transformer.

ring feeder on overload. This will be against the scheme's load shedding decision and so knocking off excess load. The 11kV bus shown in the below Figure 14 has 10 feerders that is: Bugolobi, Kololo, Naguru, Kibuli, Kitante road 2, Kitante road 1, Jinja road 1, Kampala industrial, CMB, Britania.

Current and power set limits

The Table 2 below shows the current control limits of the various equipment at Lugogo substation. The factors considered to obtain the appropriate hierarchy for auto load shedding. Include: revenue capacity of the connected loads (Industrial or non-industrial), presence of health facilities especially government hospitals that may not regularly afford fuel, and if the feeder supplies a busy city center.

Factories that consume a lot of power and so generate a lot of income for the utility were given the highest priority. Public hospitals always find it hard to install backup equipment and so power outages would have direct implications on the facility which can lead to loss of lives. Busy city centers should have less power interruptions because an outage can lead to security risks like robberies, rape, theft and commotion. Below is the load shedding hierarchy. Note that load reconnection will follow the 'Last Out First In' order (Table 3).

Transformer load shedding and load reconnection

Given that the high current limit setting of the transformer is 36 MW, and the low current limit is 32MW, the color on the HMI of the SCADA will turn yellow at 32 MW which corresponds to 90% of the load. This corresponds to a current of 1800A. Below is the load shedding schedule (Table 4).

The color on the HMI of the SCADA will turn red when the transformer is loaded at 36MW (100% of the load). According to [14], a well maintained and normally operating transformer will momentarily operate up to 120% of its rated load. Thus, irrespective of the color code warning sign, the relay will trip the circuit breaker at 120% of the transformer's rated load. Therefore, the scheme must load shed before the relay operates (to de-energize the entire 33 kV bus bar). Load shedding starts at 113% up to 120%. Unless there is a sustained fault on

Equipment /Feeder	Power Limit 1 (Mw)	Power Limit 2 (Mw)	High Current Limit (A)	Low Current Limit (A)
Lugogo 1 (LINE)	160MW	155 MW	700	680
Lugogo 2 (LINE)	160 MW	155MW	700	680
TRANSFORMER 1 (40MVA)	36 MW	32 MW	2000	1800
TRANSFORMER 1 (40MVA)	36MW	32 MW	2000	1800
Britania			400	360
CMB			450	420
Kampala Industrial			390	365
Jinja road 1			360	350
Kitante road 1			360	350
Kitante road 2			360	320
Kibuli			360	320
Kololo			400	390
Bugolobi			400	380
Nagulu			360	320

Table 2: Current Control Limits of the various equipment at lugogo substation.

No.	Feeder name	Reason
1	Jinja road 1	The Load is dominantly industrial
2	Kampala Industrial	The Load is dominantly industrial
3	Britania	The Load is dominantly industrial
4	Kololo	Critical load: State house, Hotels, Embassies.
5	Kitante road 1	Critical load: Embassies
6	Nagulu	The Load is dominantly commercial. Supplies police headquarters and residences.
7	Kitante road 2	Relatively critical load: primary school.
8	Kibuli	The Load is dominantly commercial and residential
9	Bugolobi	The Load is dominantly commercial and residential
10	CMB	The Load is dominantly commercial and residential

Table 3: Justification of load shedding hierarchy.

Event/Feeder name	Transformer load (A)	Current Increment (A)	Load setting in PCM600 (%)	Action
Telemetered value turns yellow on SCADA HMI	1800	_	90	Telemetered value turns yellow on SCADA HMI
Telemetered value turns red on SCADA HMI	2000	_	100	Telemetered value turns red on SCADA HMI
CMB	2260	0	113	CMB Opens
Bugolobi	2280	20	114	Bugolobi Opens
Kibuli	2300	20	115	Kibuli Opens
Kitante road 2	2320	20	116	Kitante road 2 Opens
Nagulu	2340	20	117	Nagulu Opens
Kitante road 1	2360	20	118	Kitante road 1 Opens
Kololo	2360	20	118	Kololo Opens
Britania	2380	20	119	Britania Opens
Kampala Industrial	2380	0	119	Kampala Industrial Opens
Jinja road-1	2400	20	120	Jinja road-1 Opens
Entire transformer is de-energized	2400	_	120	Entire transformer is de-energized

Table 4: Load limits for load shedding.

the feeders or HT transformer, the first four loads should be enough to stabilize the transformer load to prevent outage of the priority feeders. The load at which load shedding occurs (2260A) corresponds to 113% of the transformer load. The reconnection will start at 83% to 85% as shown below.

Note that the load re-connection follows a Last Out Fist In (LOFI) arrangement. The priority loads will be reconnected first and the least priority loads last. Given that by nature of current flow, the transformer loading will increase as the feeders are being reconnected (Table 5).

Transmission line over load and load reconnection

The transmission line has a maximum load limit set at 700 A (100%) and the minimum limit set at 680 A (98%). Therefore, at 680 A the telemetered value at the National Control Center's (NCC) SCADA HMI will change color from green (normal) to yellow (warning) (Table 6).

The table above shows the transmission line load shedding hierarchy. Load isolation will start at 791 (113%). The transmission line settings present a very narrow range for load management after the full load warning at 100%.

Load reconnection will start at 644 A (92%) up to 633 A (90%). The current setting in the General Current and Voltage protection function block has a limited resolution thus the current magnitude must be a whole number, and in percentage of the rated load. In order to switch

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the ten feeders, the percentage load of the feeders at reconnection has been split into three groups: the industrial loads (Jinja road 1, Kampala Industrial, Britania), the semi-critical loads (Kololo, Kitante, Nagulu), and the residential and small commercial loads (Kitante road 2, Kibuli, Bugolobi, CMB) and the hierarchy is shown in the below Table 7.

Britania and Jinja road have been given an operational range of 2A because they are industrial loads. All other feeders will be reconnected at an interval of 1 A as shown above.

IED RET670 and REL670 settings

The transformer protection IED RET670, and transmission line protection IED REL670 Version 2.2 that belong to the ABB's Relion family were used in this project. PCM600's function blocks in the Application Configuration Tool (ACT) and Parameter Setting Tool (PST) were used to configure the IEDs to perform the desired load management tasks.

Analogue inputs: These can be used to obtain measurements of current or voltage from the real time measurement devices (current transformers and voltage transformers) of the power system which usually provide the ratio value of the primary measurement for purposes of control and protection. The analog input channels were configured and set properly to get correct measurement results and correct protection operations (Table 8).

Action	Transformer load (A)	Current Increment (A)	lumped % load
Jinja road 1 closes	1660	0	83
Kampala Industrial closes	1660	0	83
Britania closes	1660	0	83
Kololo closes	1680	20	84
Kitante road 1 closes	1680	20	84
Nagulu closes	1680	20	84
Kitante road 2 closes	1680	20	84
Kibuli closes	1700	20	85
Bugolobi closes	1700	20	85
CMB closes	1700	20	85

Table 5: Transformer reconnection schedule.

Event / Feeder name	Transmission line load (A)	Current Increment (A)	Tripping load (%)	Action
Telemetered value turns yellow on SCADA HMI	680.4	–	97.2	Telemetered value turns yellow on SCADA HMI
Telemetered value turns red on SCADA HMI	700	–	100.0	Telemetered value turns red on SCADA HMI
CMB	791	0	113	CMB Opens
Bugolobi	798	7	114	Bugolobi Opens
Kibuli	805	7	115	Kibuli Opens
Kitante road 2	812	7	116	Kitante road 2 Opens
Nagulu	819	7	117	Nagulu Opens
Kitante road 1	826	7	118	Kitante road 1 Opens
Kololo	826	0	118	Kololo Opens
Britania	833	7	119	Britania Opens
Kampala Industrial	833	0	119	Kampala Industrial Opens
Jinja road-1	840	7	120	Jinja road-1 Opens
Entire line is de-energized	840	0	120	Entire line is de-energized

Table 6: Transmission line-based load shedding hierarchy.

Event	Lumped % load	Transformer load (A)	Current Increment (A)
Jinja road 1 closes	85.00	595	0
Kampala Industrial closes	86.00	602	7
Britania closes	86.00	602	0
Kololo closes	87.00	609	7
Kitante road 1 closes	87.00	609	0
Nagulu closes	88.00	616	7
Kitante road 2 closes	88.00	616	0
Kibuli closes	89.00	623	7
Bugolobi closes	89.00	623	0
CMB closes	90.00	630	7

Table 7: Transmission line-based load reconnection hierarchy.

VT settings of the Transformer Input Module (TRM) for both RET and REL were set 'To Object'. The primary voltage for RET, and REL Transformer Input Modules (TRM) were set to 11 kV and 132 kV respectively, while the secondary voltage for RET, and REL Transformer Input Modules (TRM) were both set to 110 kV.

Integrating current and voltage measurements: The current and voltages measured by the CTs and VTs could also be measured physically for every phase and hard wired to the IED, however, inside the IED, these values of current and voltage need to be integrated to form a three-phase single signal. The grouped signal is available at the AI3P (for current measurement) or AU3P (for voltage measurement) output of the SMAI function block. This output was used as input to other function blocks which needed current or voltage measurement values.

The voltage and current modules were pointed to the SMAI function block in the Signal Matrix for Analog Inputs (SMAI) function block. The Analog-Input-Type for SMAI to interfaces with the CTs and VTs was set to 'current' and 'voltage' respectively. The Global BaseSel value was set to 5A which is also the actual setting at the substation today. The Connection Type, in SMAI, was set to 'Phase – Phase (ph-ph)'.

Voltage and current measuring: The current and voltage measurements from the input/output devices are fed to SMAI in software. The three-phase output is at SMAI's I3P and V3P for voltage and current respectively. These measured values must be compared with a threshold current rating to determine if any of the phases is overloaded.

The General current and voltage protection (CVGAPC) function block has a number of very important features settable in PCM600 that enable overload detection. The overcurrent relay operates at 120% of the equipment's full load current [15]. This scheme aims at minimizing outage due to overload by selectively load shedding feeders to maintain the transmission line or transformer operational. The sequence of automatic load shedding and load reconnection will be such that the priority loads are isolated last and are reconnected first. The table showing the transformer and transmission line loading for automatic outage and reconnection is shown in Tables 4-9.

CVGAPC has two overcurrent steps, two overvoltage steps, two undercurrent steps, and two under voltage steps. Only the two overcurrent and the two under current steps will be considered for this design. In order to reduce the number of function blocks, one CVGAPC function block was used to operate two feeder circuit switches. The operation current level was set to 113% and 114% for the feeders one and two respectively. Curve type_OC1 was set to IEC definite time curve for both stages such that tDef_OC1 setting is zero.

Circuit breaker: Circuit breakers are functions used to close and interrupt an AC power circuit under normal conditions or to interrupt the circuit under fault, or emergency conditions. A circuit breaker is represented by function block SXCBR. SXCBR was used to provide the actual status of the positions and to perform the control operations, that is, pass all the commands to the primary apparatus via output boards and to supervise the switching operation and position. Each feeder was allocated its own circuit switch. Below are the settings made to the circuit switch (Table 10).

Signal binary logic: The circuit breaker function block has the following signal outputs. The outputs of the circuit breaker (SXCBR) and the General Current and Voltage Protection block (CVGAPC) are binary. CVGAPC compares the measured current values to the threshold current settings. When the current is above the threshold overcurrent or below the threshold undercurrent, the default value at the TROC1 or TRUC1 output changes to a high to initiate load shedding or load reconnection respectively Table 11.

Parameter	Setting (RET)	Setting (REL)
CT star point	To Object	To Object
VTsec	110 V	110 V
VTprim	33 kV	132 kV
Secondary current	5 A	1 A
Primary current	3500 A	700 A

Table 8: Analog input channels configuration.

Parameter	Setting
GlobalBaseSel	= 5 (for transformer), 1 (for the transmission line)
Current Input	Max phase
Current restraint	Off.
Relay characteristic angle (RCADir)	0° (equipment is part of a high impedance network)
Relay Operating angle (ROADir)	90° (relay operating angle)

Table 9: General current and voltage protection settings.

Parameter	Setting
tStartMove	0.001 s (1ms)
tIntermediate	0.01 s (10ms)
AdaptivePulse	Adaptive
tOpenPulse	1 s
tClosePulse	1 s.
Switch Type	Disconnector.

Table 10: Circuit Switch settings.

The out puts of both function blocks need to be integrated through a logic gate in order to achieve a single output only when certain conditions are met. The circuit breaker should only open if and only if it was closed before the overcurrent condition happened. The open position output of the function block is zero (low), therefore, if the CB is closed, the output value should be one (high). The two signals are ANDED to get a single output. Below is the load shedding truth Table 12.

The close command is to be generated only and only when the load current is above the threshold when the CB was closed. Using an AND gate, a high will be generated when both signals are high. The generated signal was sent to the circuit switch (SXCBR) for opening action. The open signal from the IED will be high for one second (refer to XCBR settings). Once the circuit breaker is open, the CB close command will stop because the status of the CB will update the above truth table such that no signal is generated. Below is the PCM600 arrangement of the function blocks.

The Figure 15 demonstrates the relations between the IEDS RET670 and REL 670. The two IEDs are interconnected physically by an Ethernet cable which conveys GOOSE messages between the two IEDs.

The instrument transformers are represented as Transformer Input Module (TRM), in software, which associates with the other function blocks to initiate a series of sequential logic for decision making.

Reconnection logic

The re-close logic will operate on condition that the circuit breakers' open command must have been given, meaning that the scheme must only close what it opened. The current magnitude must be at/less than the preset threshold value, this means that the load on either the transformer or transmission line must be within the safe range to permit reconnection, basically, the decision made by this algorithm will be nearly the same one made by a human being in the control center. The only difference is that the scheme will be more efficient, accurate and can be fully relied on. The NAND latch below is capable of executing the above conditional logic (Figure 16).

The inverted output of the latch is ANDED with the signal from the current measurement equipment to obtain an output. If this output is from the transformer, it must be combined with the output of the transmission line latch, from REL670, transmitted via GOOSE, to obtain the final close command. The load reconnection truth Table 13 is shown below.

GOOSE

GOOSE communication in every IED is controlled by the GOOSE Control Block (GCB) which has the data attributes that must be

Function block output pin	CB initial Status	Initial value	Status after change of binary value	Invoking action	Note
OpenPos (CB open position)	Opened	0	Closed	1	Reflects the status of the hardware via *PosOpen*
ClosePos (CB close position)	Closed	0	Opened	1	Reflects the status of the hardware via *PosClose*
Open (Signal to immediately open the switch)	No signal to close the CB	0	CB close signal	1	The status from the logics immediately sends an open command to the switch via *Ex-Open*
Close (Signal to immediately open the switch)	No signal to open the CB	0	CB close signal	1	The status from the logics immediately sends an close command to the switch via *Ex-Close*

Table 11: Circuit breaker function block.

Citation: Rwendeire A, Bakkabulindi G, Kizito R (2018) An Advanced Protection Scheme to Avert Blackouts due to Transmission Network Overload. J Electr Electron Syst 7: 283. doi: 10.4172/2332-0796.1000283

Circuit breaker position	Transformer loading status	Output signal	Corresponding action
0 (open)	0 (no overcurrent signal)	0	Nothing
1(Closed)	0 (no overcurrent signal)	0	Nothing
0 (open)	1 (overcurrent signal)	0	Nothing
1 (Closed)	1 (overcurrent signal)	1	CB close command

Table 12: Transformer load shedding truth table.

published. Every IED has a GOOSE control block whose settings must be updated in the IEC61850 configuration option of every IED. Below are the set parameters for the IEDs REL670, and RET670.

The maximum time for GOOSE messages to be published when there is no change in event was set to 500 ms, while the minimum time was set to 2 ms. GOOSE configuration was completed by mapping the data attributes in RET670 to the function block of the REL670 that is supposed to receive the GOOSE message. This was done in the Signal

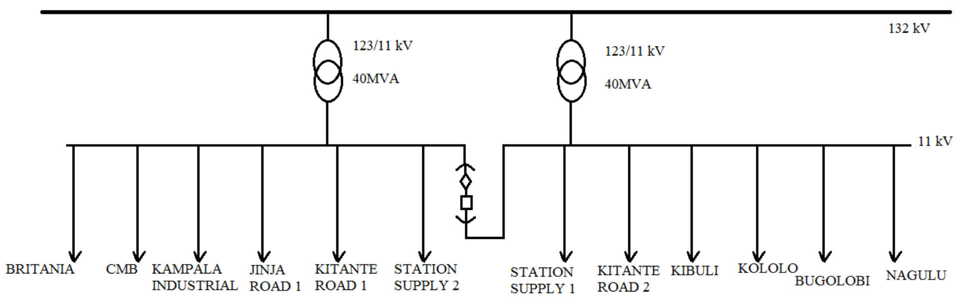


Figure 14: 11 kV bus at Lugogo Substation [11].

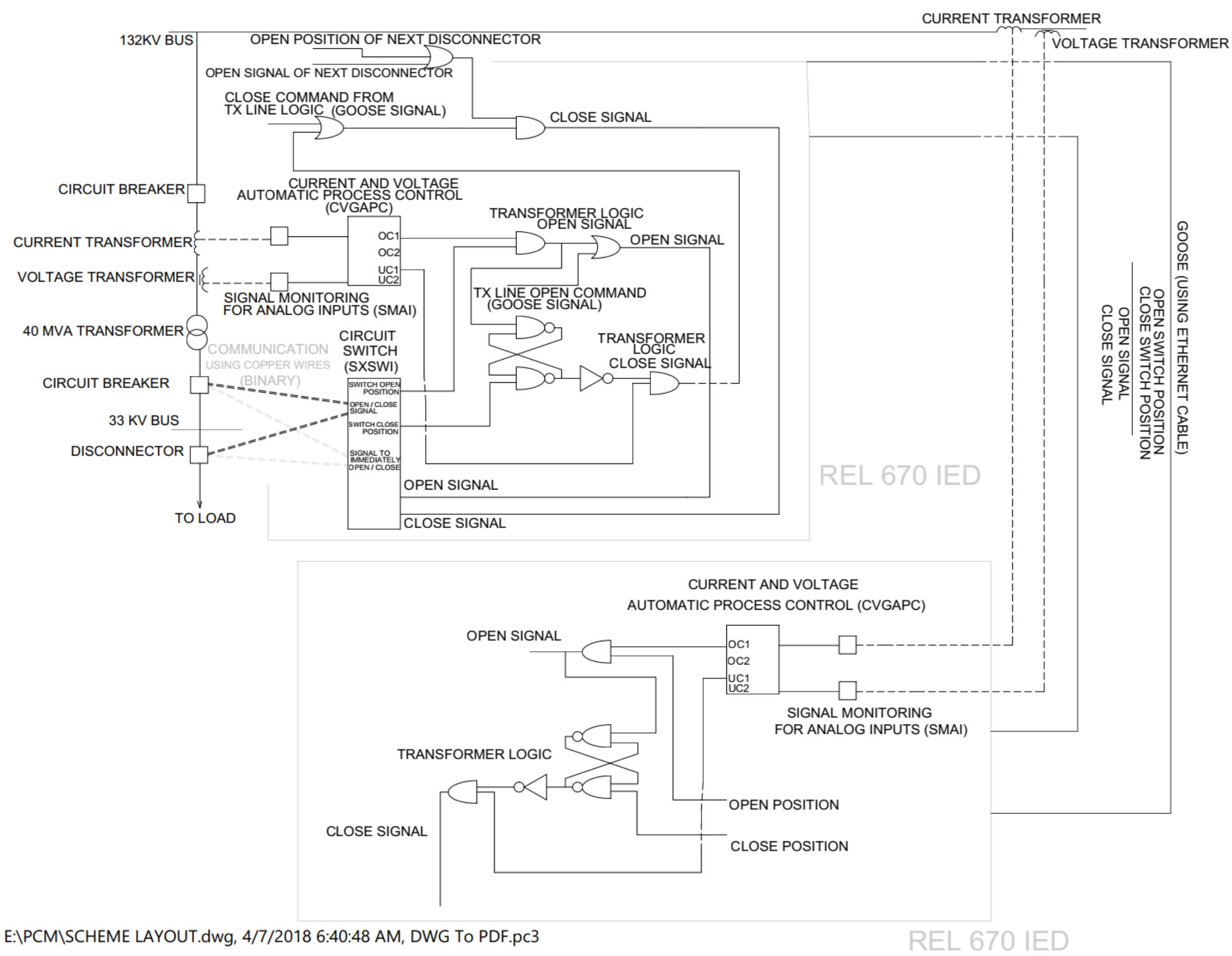


Figure 15: System configuration.

Matrix Tool (SMT). The two IEDs were fully configured to exchange GOOSE messages on the station bus. To ensure communication compatibility in hardware between the two IEDs, the IEC61850 communication was turned ON (in software), and the communication port that was to publish and to receive the GOOSE messages was turned on. GOOSEPortEd1 was set to 'AP_1' and RemSetCntrlEd_2 was disabled.

Hardware configuration

A 6U ½ 9 inch rack casing was considered for the relays REL670 and RET670. The hard ware configuration involves specifying the Card Space, Card Type, and Card Identifier. The Table 14 shows the configuration of the cards at the rear of the IED.

Signal matrix

Whereas the above table shows the available spaces on the cards for connection to other IEDs and any relevant hardware like circuit breakers, the signal matrix was used to specify the function blocks that connects with a particular card port. This ensures implementation of the designed logic because the output of a software function block directly affects the output of the card.

The signal matrix is sectioned into: Binary Input, Binary Output, Analog Input and GOOSE receive. The Binary Input maps the LDCM card to the function blocks like SXSWI and SMAI which can accept binary inputs. Similarly, Binary Output maps the LDCM card to the function blocks like SXSWI and SMAI which are capable of producing binary inputs. Analog Input mapped SMAI to the instrument transformers. Goose receive specified the link between the GOOGE receive function block (GOOSEBINRCV) and the GOOSE send function block (SP16GAPC1) in the other IED. Below are the settings made in the signal matrix.

The SP16GAPC1 function block of the REL670 was mapped to RET670's GOOSEBINRCV function block to convey the open and close signals when the measured values have exceeded the threshold values of the measurement function blocks. This configurations enables peer to peer communication between the two IEDs on the station bus.

IED SCout simulator: IEDScout simulator was used to simulate IEC61850 substations. The IEDs in the substation communicate via GOOSE over a process bus. To simulate an IED using IED scout, the SCL file of the IED was loaded into the simulator. This SCL file was obtained from PCM600 after developing the logics and setting the load, GOOSE, hardware configuration, and communication parameters. If the IED was available online, its IP address would have been fed into the simulator. The SCL files from the two IEDs were loaded into the simulator.

Cost benefit analysis

Below is the list of costs and benefits of the project which were used for assessment of the financial performance before recommendation for implementation (Table 15).

When this project is implemented, the system will continuously isolate the same feeders because the load shedding hierarchy is constant. The consequence is continued complaints from customers that could result into reduced interest for new connections. Given that the low priority feeders are supplying majorly domestic consumers, the direct revenue effects of reduced connection, and media outcry would not be very disastrous.

The current estimates for the costs associated with outages is shown in the table below. According to UETCL (2017), the peak bulk cost per MWh is UGX337200 and the profit made by UETCL per MWh is UGX292175. A minimum outage time of one hour was considered, Maximum outage time of two hrs, and an annual outage time of 13.85 hrs.

According to the 2017 outage statistics of the 40 MVA transformer at Lugogo substation, the average MW load on TX1 and Tx2 was 15.7MW and 16.6 MW respectively. The maximum load on TX1 and TX2 was 37.79MW, and the maximum load on the 11 kV bus was also 37.79MW [16].

Therefore, the computed annual loss is UGX 152,921,911.51. With the LMS in place, the loss will be reduced because the entire transmission line or transformer will not be de-energized but rather particular feeders. These feeders will only be out for a time corresponding to the duration when the load is above the threshold value. Averagely, when the first four feeders on the hierarchy are load shed, the transformer load will be restored [17]. The first four feeders on the hierarchy are CMB, Bugolobi, Kibuli, and Kitante Road- 2. These have a total load of 15.048 MW. With this LMS action, the annual loss will be reduced to UGX 60,893,594.19. Thus 39.82% of the computed annual loss is suffered if the LMS is not used. 60.18% will be saved which corresponds to UGX 92,028,317.32 [18].

S (CB position)	R (CB signal)	Q	Q	Q Inverted	K	A	Action
0	O	1	1	0	1	0	
0	1	1	0	1	1	1	CB close signal initiated
1	0	1	1	0	0	0	
0	0	1	1	0	0	0	

Table 13: Truth table for the close operation.

Card Space	Card Type	Card Identifier	Module
p1	PSM	PSM_1	Power Supply Module
p30	NUM	NUM_30	CPU Module
p30:1	SFP 100SFX_1	SFP_301	Ethernet SFP, Optical LC Connector
p31	ADM	ADM_31	ADM Converter
p31:1	SLM	SLM_311	Serial Communication Module
p31:2	LDCM 64 kbps Analog_1	LDCM_312	Line Data Communication Module, Analog 64 kbit/s
p31:3	LDCM 64 kbps Binary	LDCM_313	Line Data Communication Module, Analog 64 kbit/s
p40	TRM 9I + 3U	TRM_40	Transformer Input Module, 9I + 3U

Table 14: Hard ware configuration for RET670 and REL670.

Benefit	Cost	Impacts
Reduced power disruptions	Purchasing a REL at Lugogo	Minimum power disruptions
	Purchasing and installing ethernet cables.	
Reduced outage duration	Purchase and installation of copper wires	High Efficiency
	Purchase of other accessories; cable ties, lugs etc.	
IEC61850 compatibility	Logic development and testing by full time staff	Step to smart grid and modern Substation standardization
	Operation and maintenance cost	

Table 15: Impacts, benefits, and costs of the project.

Citation: Rwendeire A, Bakkabulindi G, Kizito R (2018) An Advanced Protection Scheme to Avert Blackouts due to Transmission Network Overload. J Electr Electron Syst 7: 283. doi: 10.4172/2332-0796.1000283

The project's costs and benefits were analyzed in the table below. These costs and benefits relate to the list shown in Table 16. The disadvantage of a constant load shedding hierarchy as mentioned in the above paragraphs cannot be easily quantified; therefore, no specific amount has been allocated to this disadvantage [19]. Below are the project costs, benefits, and payback period.

The initial investment has been assumed to be UGX 68 million. This will essentially purchase the required equipment and accessories for implementation. The initial investment together with the costs and benefits gave a cost benefit ratio of 1.647 and payback period of 1.28 years. The CBA is greater than one, thus the project should be pursued [20].

Discussion of Results

PCM600 logic

After setting the threshold configuration and GOOSE in PCM600, a GOOSE report was printed out. This report shows the GOOSE receives GOOSE control block, data sets, and logical nodes as presented below.

The report represents the physical devices (IEDs) as AA1J1Q01A1 and AA1J1Q01A2. The data attribute of the monitoring logical node is the status value (stVal). This GOOSE report also shows the sender and receiver IEDs as well as the GCB, data set and the subnet frame work for communication [21].

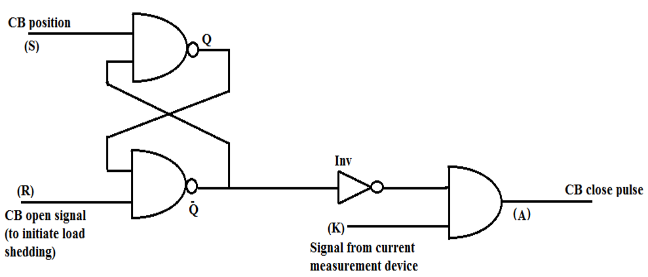


Figure 16: Close conditional logic NAND latch.

The GOOSE settings were also displayed: min publishing time = 10 ms, max publishing time = 500 ms. The report also specifies the list of all the data objects (the particular signal to be transmitted to/from the IEDs over LAN). This specification is done for the bi-directional GOOSE messages i.e. from the REL670 to the RET670 and vice versa (Figure 17) [22].

This clearly indicates the capability of the two IEDs to communicate together through GOOSE messages. Both IEDs are supposed to publish their status every 500 ms if there is no event, otherwise, they should send messages whenever there is an event such as a current value above the set threshold for a particular feeder. GOOSE communication and general IEC61850 standard was further simulated using IEDScout. The Configuration of function blocks to achieve the Load Management Scheme was validated by PCM600 design tool [23], thus the design is real and executable (Figure 18).

Cost	Amount
Purchase of line protection IED (UGX).	65,000,000
Purchase and installation of ethernet cables (UGX).	50,000
Purchase and installation of copper wires (UGX).	2,000,000
Purchase of other accessories; lugs, cable ties, screws .etc. (UGX).	300,000
Logic development and testing by full time staff (UGX).	10,000,000
Operation and maintenance cost (UGX).	1,500,000
Total (UGX)	78,850,000.00
Benefits	**Amount**
Reduced power disruption (UGX)	92,028,317.32
Reduced down time (UGX)	8,000,000
IEC61850 compatible Standard substation (UGX)	32,000,000
Total (UGX)	**132,028,317.32**
Profit (UGX)	**53,178,317.32**
Cost Benefit Ratio	**1.647**
Initial investment (UGX)	**68,000,000**
Payback period	**1.28 years**

Table 16: Financial analysis.

GOOSE Receivers

GOOSE Receiver: AA1J1Q01A1 (RET670)

Description: RET670

Access Point	GOOSE Sender	Control Block	Data Set	Subnetwork
S1	AA1J1Q01A2.S1 (REL670)	MON.LLN0.LtTX	MON.LLN0.ITtx	WA1

GOOSE Receiver: AA1J1Q01A2 (REL670)

Description: REL670

Access Point	GOOSE Sender	Control Block	Data Set	Subnetwork
S1	AA1J1Q01A1.S1 (RET670)	MON.LLN0.TXtL	MON.LLN0.txTI	WA1

Figure 17: GOOSE Report.

GOOSE Control Blocks

IED: AA1J1Q01A1 (RET670)
GOOSE Control Block: TXtL

LN: LLN0
LD: MON
AP: S1
Subnetwork: WA1

Category	Parameter	Value
Communication	Access Point	S1
Communication	App ID	0001
Communication	MAC Address	01-0C-CD-01-00-00
Communication	Subnetwork	WA1
Communication	VLAN ID	000
Communication	VLAN Priority	4
Data	Clients	System.Collections.Generic.List`1[ABB.PCM.Tools.ICE.Core.Data.IClientReference]
General	Config Revision	100
General	Data Set	txTl
General	Description	
General	Max Time	250
General	Min Time	10
General	Name	TXtL
General	Type	GOOSE
Substation	IED	AA1J1Q01A1
Substation	Logical Device	MON
Substation	Logical Node	LLN0
	Client 1	AA1J1Q01A2 (S1)

IED: AA1J1Q01A2 (REL670)
GOOSE Control Block: LtTX

LN: LLN0
LD: MON
AP: S1
Subnetwork: WA1

Category	Parameter	Value
Communication	Access Point	S1
Communication	App ID	0002
Communication	MAC Address	01-0C-CD-01-00-01
Communication	Subnetwork	WA1
Communication	VLAN ID	000
Communication	VLAN Priority	4
Data	Clients	System.Collections.Generic.List`1[ABB.PCM.Tools.ICE.Core.Data.IClientReference]
General	Config Revision	100

Project: MSc. project. phase 1	Responsible department: ABB Ltd.	Technical ref...	Document kind: IEC 61850 Config...	Doc. designation
Repla...	ABB	Created by	Title	Document id.
Rev. / Modification / Rel. date / Created by / Based on		Approved by		Rev. / Rel. date / Lan en / 2 / 6

Figure 18: GOOSE Report.

IEDScout

IEDScout was used to test the IEC61850 configuration and to demonstrate GOOSE communication between the two IEDs. Unicast (one to one) Ethernet/IP was implemented using LAN. The two IEDs used in this design were represented using two laptops. The two laptops were interconnected by a CAT6 straight-through Ethernet copper cables using RJ 45 connector. The reports produced by IEDScout in a .pcap file format were decoded and analyzed as explained in the next section [24].

IEDScout was loaded with, and accepted the Substation Configuration Description (SCD) file from PCM600. This SCD file carried all the settings, the logical nodes and devices, and the substation layout. The compatibility between PCM600 and IEDScout presents a way to analyze the logic design and coded setting in the function blocks of PCM600 [25].

Running the simulation generated a report containing GOOSE subscriptions and the general traffic on the ethernet cable. Note that, communication is one major component of IEC61850 because the standards' main aim is interoperability between different vendor IEDs using ethernet. This would not only reduce the number of hard wire connections between the IEDs but also increase communication speed to increase efficiency in monitoring, decision making, and action in case of violations and commands [26].

Citation: Rwendeire A, Bakkabulindi G, Kizito R (2018) An Advanced Protection Scheme to Avert Blackouts due to Transmission Network Overload. J Electr Electron Syst 7: 283. doi: 10.4172/2332-0796.1000283

Simulation results

IEDScout was used to demonstrate the ability of the design (obtained using PCM600) to perform inter-IED communication and so it proves adaptability to IEC61850 standard. This simulation tool was preferred because of its ability to simulate the GOOSE in the absence of an actual IED. The figure below displays when IEDScout identified and validated the logical node, LLN0.lt.TX. This logical node was set and specified in PCM600 as the logical node for the transformer differential IED RET670. IEDScout identified the same logical node before simulating the GOOSE communication (Figure 19).

The above identification and verification of the logical nodes was similarly done for REL670 on the simulating computer. Below is a representation of the real time data packet flow along the ethernet cable. This rhymes with the print out of the packet flow in Appendix eight (Figure 20).

IEDScout produced a simulation report in .pcap format. Wireshark was used to open the document. Wireshark is a GUI network protocol analyzer which enables interactive packet data (as flows through the Ethernet cable) browsing from a live network or from a previously saved capture file.

The Figure 21 shows the conversation on the ethernet cable from one computer (with IEDScout, simulating RET670) to the other (with

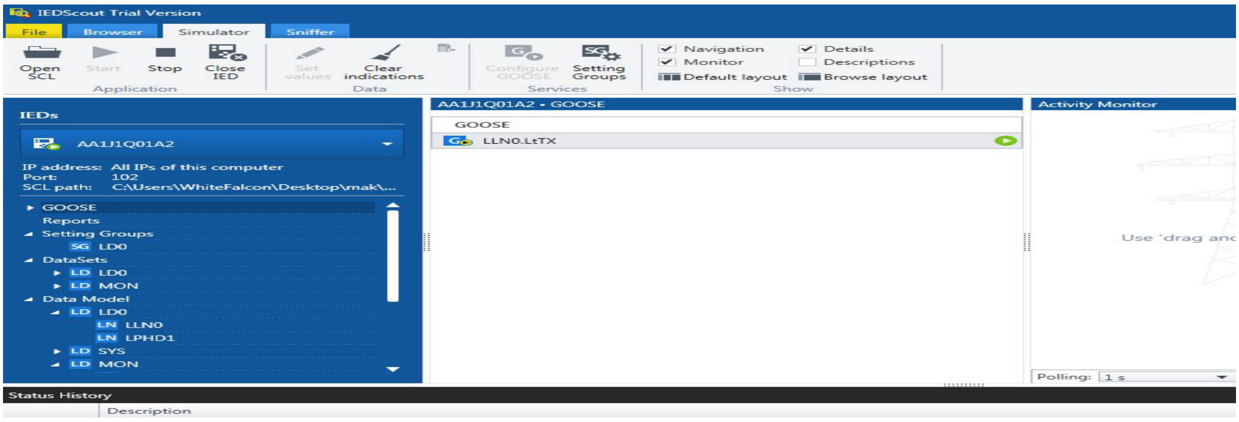
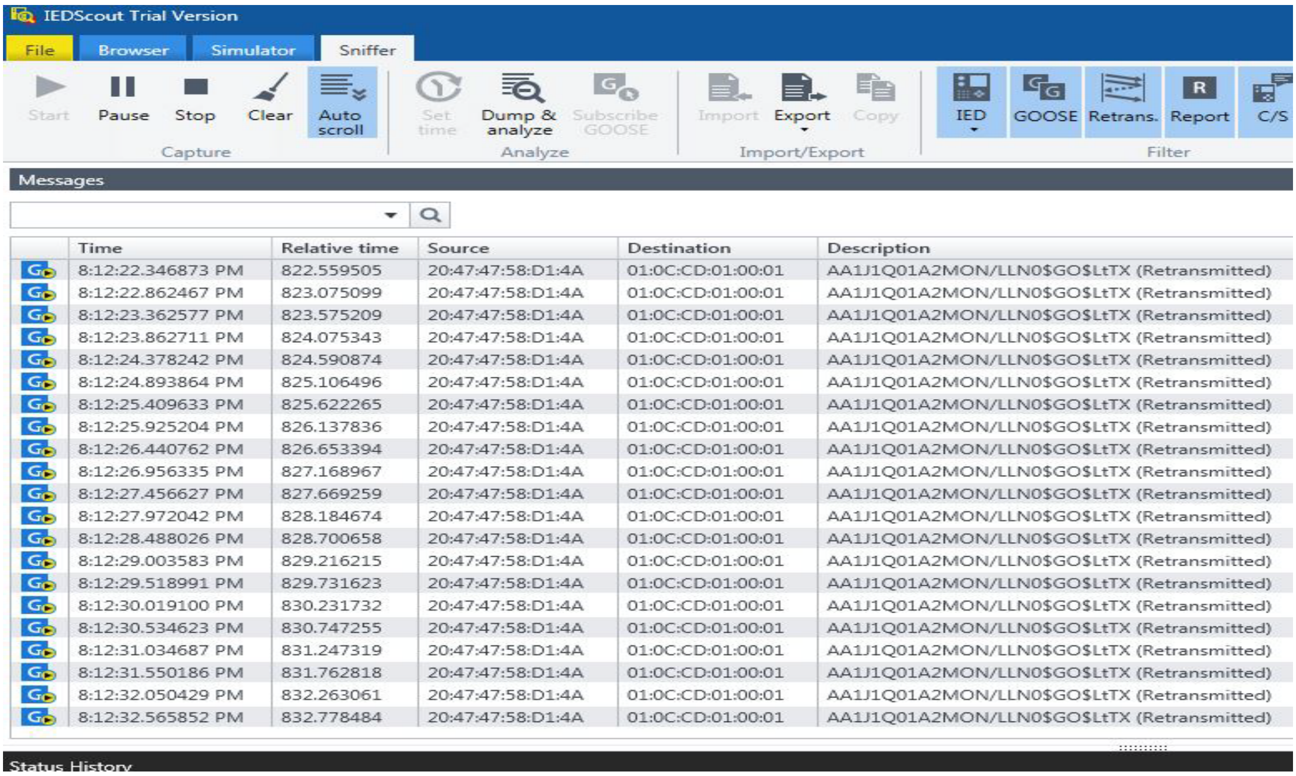


Figure 19: Simulating GOOSE in IEC61850 substation.



Time	Relative time	Source	Destination	Description
8:12:22.346873 PM	822.559505	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:22.862467 PM	823.075099	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:23.362577 PM	823.575209	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:23.862711 PM	824.075343	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:24.378242 PM	824.590874	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:24.893864 PM	825.106496	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:25.409633 PM	825.622265	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:25.925204 PM	826.137836	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:26.440762 PM	826.653394	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:26.956335 PM	827.168967	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:27.456627 PM	827.669259	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:27.972042 PM	828.184674	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:28.488026 PM	828.700658	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:29.003583 PM	829.216215	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:29.518991 PM	829.731623	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:30.019100 PM	830.231732	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:30.534623 PM	830.747255	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:31.034687 PM	831.247319	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:31.550186 PM	831.762818	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:32.050429 PM	832.263061	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)
8:12:32.565852 PM	832.778484	20:47:47:58:D1:4A	01:0C:CD:01:00:01	AA1J1Q01A2MON/LLN0GOLtTX (Retransmitted)

Figure 20: Published GOOSE for every one second (set time).

IEDScout, simulating REL670). Two simulations were carried out on the former, one generated 590 packets and the other 2443 packets of information which corresponds to 98 k bytes and 464 kbytes sizes respectively. The traffic above is due to the GOOSE packets flowing on the network. These packets were updated every half a second as shown below Figure 22.

Irrespective of the setting in IEDScout (1 second interval), PCM600s' 500 ms setting was by the GOOSE messages. The above packet flow graph demonstrates the time after which a new packet was released which reflects the exact time on the ethernet cable when the same packet transmitted. Below are the IO graphs from the two different computers as was used to simulate the design (Figure 23).

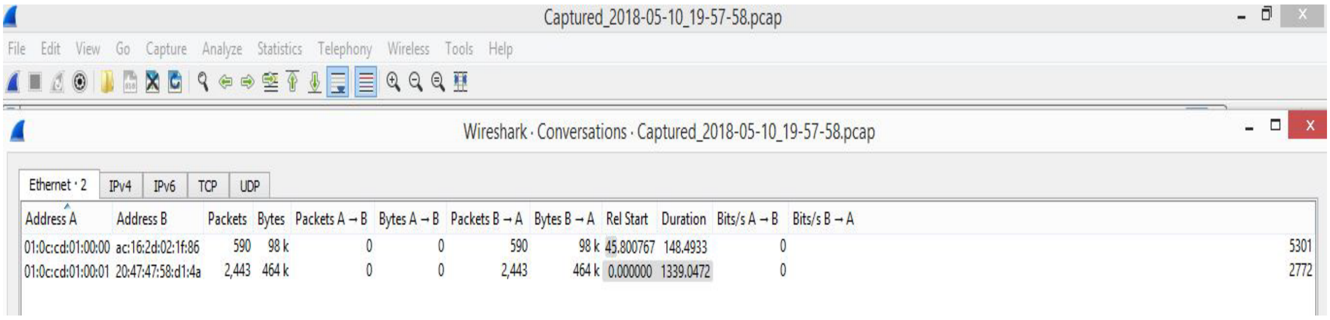


Figure 21: Ethernet conversation traffic.

Figure 22: IEDScout packet traffic.

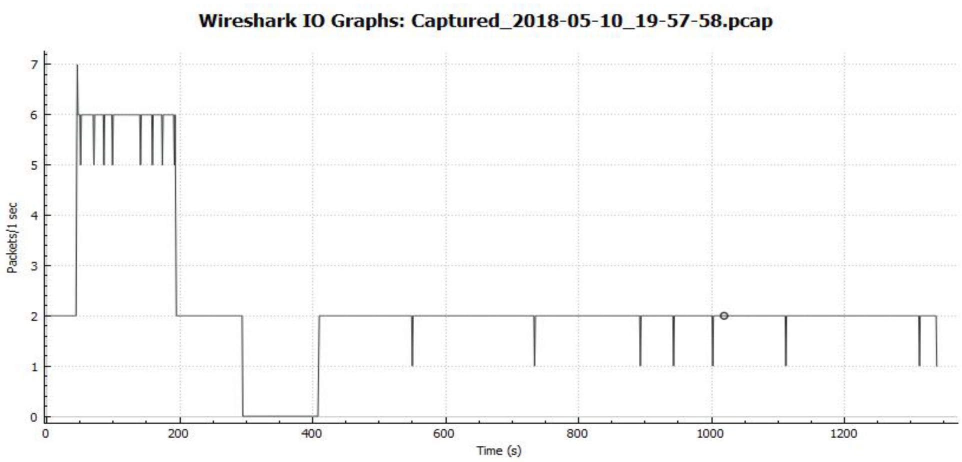


Figure 23: IO graph for RET670 simulation

In PCM600, the GOOSE message update time was set to half a second for each relay, therefore, from the above simulation graph, it is clear that the simulation packets are two per second. The first 200 seconds on the RET simulator correspond to the time when the ethernet cable was connected to the internet port, before connecting it to the other computers' ethernet port to allow serial communication. It should be noted that simulation could only be achieved when the ethernet cable was connected between the computers. However, the laptop was unable to receive the particular GOOSE from the other laptop because it lacked the firmware (as should have been in the IED) to read the GOOSE sent via ethernet. This is clearly demonstrated in the ethernet conversation traffic shown in Figure 24.

Economic analysis of the project

A cost benefit ratio of 1.647 was obtained. This illustrates that benefits are more than costs thus, the project is worth pursuing. The analysis of costs and benefits resulting from the utilization of the load management substation automation system show consistent possibility for application. The monetary and non-monetary costs and benefits were considered. Their present worth was estimated with the guidance of UETCL personnel.

Some aspects like the contribution of this research to encourage local contractors to undertake scheme design and substation implementation works were hard to quantify in terms of money, and so they were left out during the analysis [27].

Conclusion

This research presents unique load management techniques that have not been used anywhere on the Ugandan network. Currently, load monitoring and load-shedding are manual and are challenged by lack of efficiency, reliability, and split-second decision making. This dissertation presents a successfully developed automatic load management scheme for hierarchical load shedding of twelve feeders at Lugogo substation, on the 11kV bus. The GOOSE updates the circuit breaker status every 500ms to enable the IED to make timely decisions whenever the feeder load values exceed the preset threshold limit. The scheme also provides for re-energizing feeders following a Last Output First Input order.

According to the data obtained from UETCL, Naluubale substation had the highest number of outages. Given that Naluubale substation is a generation substation, a non-probability purposive sampling was done on the substation's outgoing transmission lines. Lugogo substation was obtained as the case study substation. The highest load on the 132/33 kV transformers at Lugogo substation is 1.12% greater than the rating of one transformer. Although Lugogo substation's bus bars are interlocked with the transformers, this scheme can be implemented in the same substation if the load grows or in any other substation that lacks interlocks, when the load has grown unexpectedly.

ABBs' PCM600 was used to develop the load shedding decision making logic using function blocks as shown in appendix three. The CID file from PCM600 was loaded into IEDScout which was used to simulate station bus GOOSE communication to demonstrate IEC61850. PCM600 produced the GOOSE report showing the GOOSE Control Block, sending and receiving logical devices, logical nodes, and data objects. The ability of the two IEDS (REL and RET) to communicate demonstrates IEC61850 standard and appreciates its benefits by effecting the load management scheme.

The auto load shedding and load reconnection decision making algorithm was simulated to demonstrate fast GOOSE messages that updates data sets whenever there is a change of state or after every 500 ms. The report produced by IEDScout demonstrated the station-bus traffic by showing a data flow rate of 2 kbps. Two data packets were sent every second through the ethernet cable, 464 k bytes of data packets were sent as messages on the station bus during the simulation. This communication speed and rate of data packet exchange on the station bus can be set and adjusted in the algorithm set in PCM600.

An economic analysis to determine the viability of the project

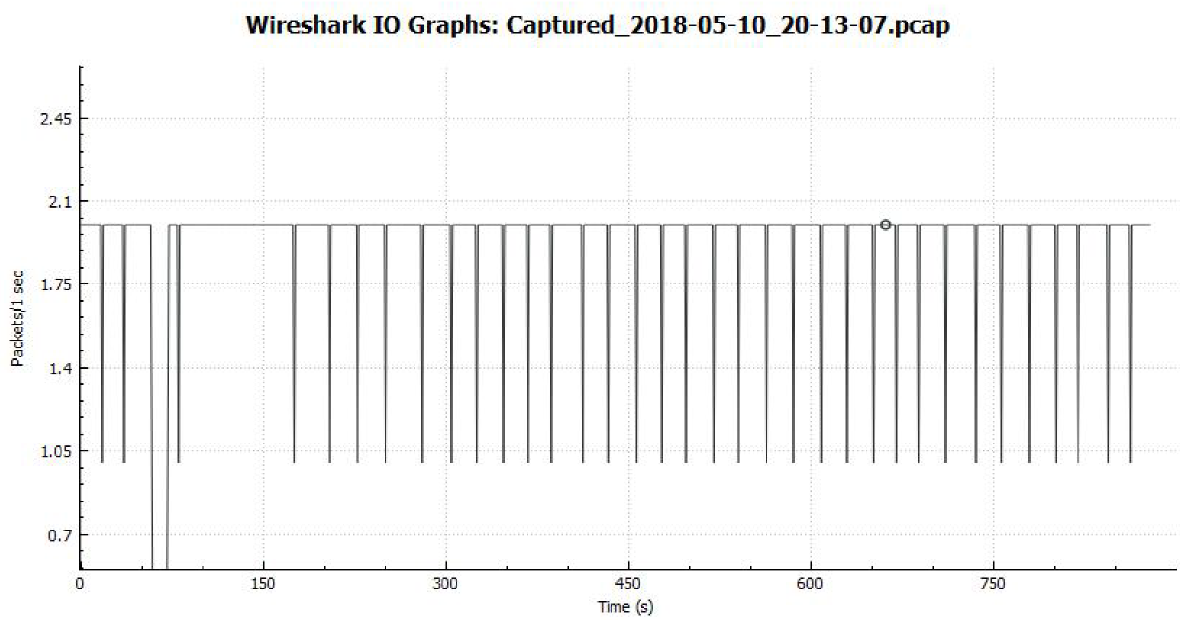


Figure 24: IO graph for REL670 simulation.

showed a CBR of 1.647, this is well above 1 and signifies a go-ahead to project implementation. The cost benefit analysis was performed on the basis of all advantages of the scheme including reducing downtime, reducing man hours spent investigating cause of transformer failure, operation cost of manual systems, increasing system efficiency by reducing human intervention. This system can be installed to prevent the uncommon but catastrophic conditions, before capital equipment like power transformers are bought and installed.

Recommendations

Recommendations to the utility

It is recommended that Uganda Electricity Company Limited adopts this scheme to increase system effectiveness to maintain availability of overloaded transmission line components. This scheme provides an immediate solution as the network planning team devises permanent solutions.

Lugogo substation already has a transformer differential protection IED but lacks a line distance protection IED. For implementation as a load management scheme on the transmission line and transformer, both IEDs must be in place. The REL IED can be used if the scheme is to be implemented as a load management scheme for only the transformer overload condition. Apart from the logic (as already developed in this dissertation), the other accessories like the ethernet cables (to link the IEDs), copper cables (to link the IED to the circuit breakers), and the manpower to implement the scheme have been fully priced in the cost benefit analysis. The scheme can be implemented as shown in Figure 20.

According to (Ssekide, 2018), UETCL could in the near future put up research laboratories to perform standard simulations. I highly recommend the utility to invest in these laboratories and simulation centers. These simulation centers will not only facilitate UETCL staff to develop well tested schemes but also to encourage research fellows to contribute fairly to the power industry.

Recommendations for future work

The developed load management system was tested using simulators. The test would have provided more realistic and practical results if an actual Intelligent Electronic Device was used. Simulators were used because Intelligent Electronic Devices are very expensive equipment that are not easily available.

This scheme can further be improved by merging it with the under frequency load shedding scheme to reduce on the cost of physical implementation as well as code development.

This scheme also does not fully consider the power system dynamics of economic dispatch, optimal power flow on a bus, and voltage profile. Including these components will make this scheme smarter and more effective.

This scheme can be further improved to explore the option of alternating the load shedding hierarchy so that feeder is not load shed in the same order whenever the load is above the preset threshold values.

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