Mitigation of Undervoltage in Distribution Networks Using an Automatic Load Shedding Scheme to Curtail Voltage Collapse

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Abstract- Undervoltage is still a power quality problem globally with several interventions like reactive power compensation in generation stations, transmission, and distribution lines. This issue still prevails in Uganda's power system network that has experienced five blackouts within five months in 2020. Most utility companies have resorted to automatic under voltage load shedding schemes as a safety net to mitigate undervoltage. This study purposely sought to develop and implement an automatic undervoltage load shedding relay in Physical Security Information Management (PSIM) software for mitigation of undervoltage in the distribution network. The study specifically was to design part of Uganda power system distribution network in DIgSILENT, develop an automatic undervoltage load shedding relay and lastly validate the undervoltage load shedding relay solution. The modelled network showed a percentage voltage deviation that was within the acceptable error margin.

The study results showed total distribution and transmission power output loss after network simulation with DIgSILENT software was 18.3% as compared with 21% loss from Umeme Limited (approx.17%) and Uganda Electricity Transmission Company Limited UETCL(approx.4%). It also shows a balance power system network after executing simulation that is load flow of active power 750.45MW, and reactive power 360.66 MVar is balanced with the simulated generation station power supply active power 769.46MW, and reactive power 246.28MVar. There is an excess of generation power to load demand of approximately 434.727MW. PSIM results showed that at a voltage below 118.8kV, 29.7kV, and 9.9kV for the voltage supply of 132kV, 33kV and 11kV respectively will shed off the lines/feeders. Validated PSIM results revealed 0.094% of total harmonic distortion (THD) compared to 3% (THD) for the 22kV to 400kV range according to Western Power Distribution. This is evident by 98% active power flow from the generation station to end-users. It implies that there is stability and good voltage regulation.

The study recommends the use of undervoltage load shedding relay in PSIM to improve the reliability of the power network. The technique Under Voltage Load Shedding Scheme (UVLS) is only activated as a final intervention/mitigation measure to shed offload after a sustained undervoltage for more than one minute.

Index Terms- *Automatic Undervoltage Load Shedding Relay, Distribution Network, Mitigation, Undervoltage, and Voltage Collapse.*

I. INTRODUCTION

Undervoltage is the phenomenon in the power network whereby the applied voltage drops to 90% of rated voltage, or less, for at least one minute [15]. It can be caused by several factors which can be categorized as power system overload and the equipment operations [5]. Therefore, an undervoltage load shedding plan can confine the voltage deficit in the generation or transmission within a certain allowable minimum geographical area [1].
Power system disturbances like undersized or overloaded utility and facility transformers, long distance electricity transmission, natural calamity, lighting, poor load balancing etc. [15] causes undervoltage as the load exceeds the supply thereby making the line voltage to drop, below the rated or generated value or level [19]. Considering sub-Saharan Africa, only approximately 28 percent of health facilities have access to reliable electricity and this is worsen by serious pandemic diseases like COVID-19 [20]. The electricity distribution requires a very robust, sensitive, coordinated, fast-acting, dependable, and selective advanced digital protection relay like automatic undervoltage load shedding relay for reliable power supply [22].

II. LITERATURE REVIEW

In Uganda, contemporary voltage control actions includes, an automatic voltage regulator (AVR) [16], Motor-Generator Set [21], shunt capacitor banks [8], [9], transmission line shielding [4], tap switching transformer[3].and uninterruptible power supply (UPS)[2]. The system frequency control and load shedding are done by the system operator [12]. The approach so far employed has not been able to mitigate many of the problems associated with undervoltage on the distribution power line. However many studies have demonstrated the successful application of undevoltage load shedding relay in mitigating this problem in distribution lines [7]. Undervoltage load shedding (UVLS) is based on the possibility of disconnecting some loads (or percentages of load) after a severe disturbance, in order to relocate the operating point far from the critical voltage value [14].

Many authors have proposed several UVLS scheme in literature reviews to load shed network lines when the voltage is completely out of operating range for our case ±10% for high voltage lines instituted by electricity regulatory authority of Uganda. A lot of classical strategies (constant amount or percentage of load are shedded off) have been explored [5]. However, these are not applicable for a complex system that is dynamic in nature. Several classical methods like use of centralized and decentralized load shedding and homogeneous load shedding were emphasize by authors [13]; [10]; [11]; [5]. Also other methods includes mathematical techniques such as linear programming (LP), nonlinear programming but the short fall is that, these algorithms require approximations of the power system model to reduce the calculation time [17]. Another optimization method used to improve load shedding automation was particle swarm optimization (PSO) quoted by Zomaya and Olariu, (2006); Kennedy and Eberhart, (1995), which were applied to improve load shedding automation [22]. A mixture or blended methods named heuristic technique (PSO and Generic Algorithm) by Amraee, et al (2007) was used to achieve an optimal load-shedding algorithm for ULVS scheme. These methods and techniques are good enough though its base on bus voltage magnitude. However, given the complex nature of modern network, it is really hard to attain power system operating conditions as contrasted by (Mozina, 2007).

III. METHODOLOGY

Research Design

The research design combined a mixture of both quantitative and qualitative designs. Largely the researcher interfaced with measurable and quantifiable data, which included; frequency, voltage, current, active & reactive power, impedances, Susceptance, GPS data, etcetera. This data formed a primary input which was used to describe the attribute of study.

Also the study utilized the case study method where only Kampala Industrial Business Park aka Namanve was considered for the study. Finally, modeling of the network using DIgSILENT and simulations of PSIM solution formed basis for experimental research.

Data Analysis and Presentation

The study used DIgSILENT (Digital Simulation of Electrical Networks) Software for modelling and simulating part of the Uganda power network system. Input data were from three-phase synchronous generators, generation, transmission and load busbar data, transformers data, load data, and lines data. The input and output provided an insight into power load flow in the different generation, transmission, and load bus bars. The output from DIgSILENT was then passed to PSIM for the implementation of the required UVLS scheme to mitigate the undervoltage in the distribution network.

PSIM is an acronym for physical security information management developed by Powersim and used to model and simulate undervoltage load shedding relay. It is electronic circuit simulation software with applications in power electronics and motor drives. Data presented in form of tables, graphs, snapshot pictures.

Chronological Undervoltage Load Shedding Algorithm

In the scenario where the measure network voltage is less than the minimum set voltage value, then undervoltage load shedding relay is activated and shed off some block of load. The undervoltage load shedding relay continues to shed off more load under abnormal condition not until the network become stable again. In case the voltage value is optimal to the set point, the network status remain normal with no load shedding action.

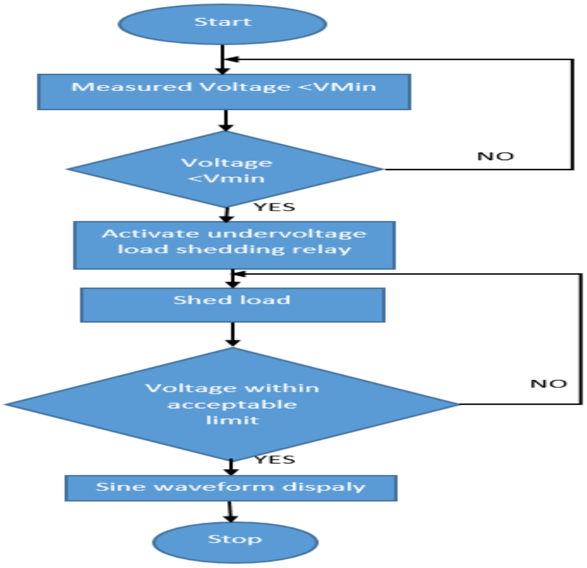

Fig.1. Shows undervoltage load shedding sequential algorithm

IV. PRESENTATION OF RESULTS

A. DATA COLLECTION.

Power system network modelling requires inputs data from generators, loads, step-up and step down transformers, generation and load busbars, and transmission and distribution lines data. Lots of data were collected to aid in modelling part of the Uganda network. These data were collected from Uganda Electricity Transmission Company Limited, Umeme Limited, the internet, and direct face-to-face interactions with the utility staff and workers in some industries within the Kampala Industrial Business Park aka Namanve.

Power Flow Analysis in DIgSILENT Power Factory

It is necessary to perform a load flow calculation to obtain voltage magnitude (V), voltage angle (J), active (P), and reactive (Q) power flow on nodal/bus branches to inform the researcher how well the networks are performing.

B. NETWORK DIgSILENT SIMULATION SOFTWARE.

All the technical data of lines, busbar, generators, shunt, and transformers were input in the DIgSILENT software and simulated as shown in the graphic diagram Fig.6.
Isimba synchronous machine is connected at the top via a three-phase step-up transformer (11/132kV) in an overhead bare conductor line to Bujagali generator double busbar arrangement. Bujagali synchronous machine is at the extreme top right of the graphic window and connected to the same generator busbar via a three-phase step-up transformer from 11kV to 132kV. Nalubaale& Kira synchronous machines are connected to Bujagali generator double busbar system via 132kV overhead bare conductor line as well. Other sources of power (solar, thermal etc.) are connected at the Namanve (2) 33kV substation for purpose of this study.
At the extreme bottom, are the industrial load which includes Roofing rolling mill, Orion, Steel & Tube, Rwenzori, Coca-Cola and Century bottling company that were selected for this study. There is two independent power supply circuit to the Kampala Industrial and Business Park. The first one is 132kV overhead bare conductor lines right from Nalubaale & Kira HPP to GIS Namanve 132kV substation. The second is the 132kV overhead bare conductor line from Bujagali 132kV substation to Kawanda, Lugogo and lastly to Namanve 132kV substations.

The simulated Load Results

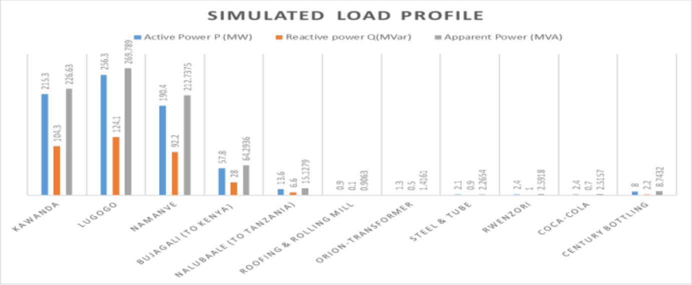

Fig.2. Bar graph showing the load active, reactive and apparent power at different busbars (e*xtracted from DIgSILENT Simulation*).

The bar graph indicates that the Lugogo busbar has the highest active load (269.789MW) and reactive load (124.1MVar) connected followed by Kawanda busbar reactive load (226.63MW) and reactive load (104.3MVar). The lowest load connection is at Roofing rolling mill with active load (0.9MW) and reactive load (0.1MVar).

Simulated Generation Power Flow Output

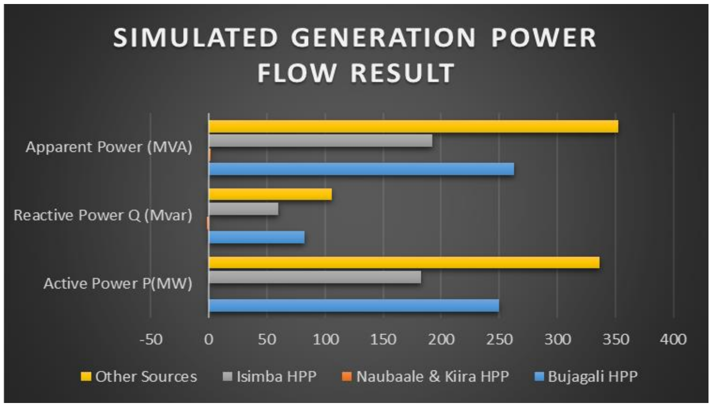

Fig.3. Bar graph showing generation stations active, reactive and apparent power in Uganda

The simulated generation results show that other sources (Solar, thermal, etc.) have the highest active power generation (336.46MW), reactive power (107.53 MVar) followed by Bujagali with active power (250MW), reactive power (82.2MVar). Isimba HPP active power (183MW), reactive power (60.1MVar) and lastly Nalubaale& Kira HPP not generating any active power but instead absorbing MegaVar of about (-1.55MVar).

Network under normal condition

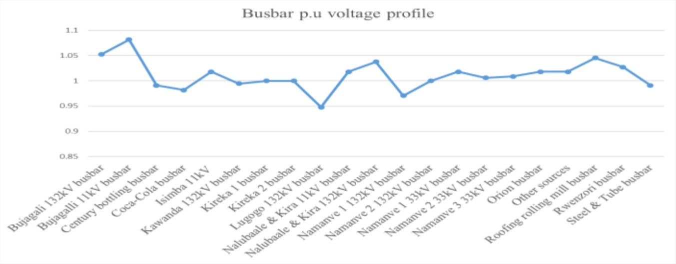

Fig. 4. The line graph shows a busbar p.u line to line voltage profile

The normal network condition line graph above indicates that Bujagali, Isimba, Nalubaale & Kira, Namanve, Orion, other sources (Solar, thermal etc.), Roofing rolling mill, Rwenzori, Century bottling and Coca-Cola line to line busbar voltage are higher than the design busbar line to line voltages of 132kV,33kV and 11kV. The Kireka 1&2, Lugogo, Kawanda and Steel & Tube line to line busbar voltages are lower than the design busbar voltages and would be the best candidates for disconnection except that they still fall within the ±10% regulated value by the Electricity Regulatory Authority of Uganda

Network under abnormal condition

The network behavior under supply side contingency condition is shown in fig. 5. When the faults originated from the supply side say Bujagali hydropower station disconnected from the grid and run in island situation or out of service, the network changes as indicated by red curve contrasted to original blue curve. Therefore Bujagali 132kV, Century bottling, Coca-Cola, Isimba 11kV and 1132kV,Lugogo 132kV,Nalubaale 11kV and 132kV, Namanve 2 132kV, Namanve 2 33kV and Namanve 3 33kV are weak busbars and qualified candidates for disconnection since are below the required voltage range (0.9 p.u.). Load shedding the load connected at Bujagali 132kV busbar, the network condition improved as seen in dark blue curve. Finally, load shedding

Bujagli, Kawanda and Nalubaale 132kV connected loads altogether normalizes the network approximately close to the original network condition (operating point) because practically it is impossible for the network to attain its previous status before disturbance as seen in orange curve.

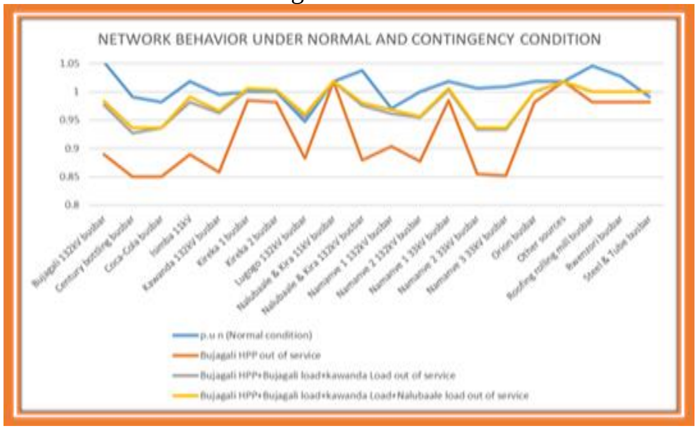

Fig.5. shows network behavior under normal and contingency condition

Experiment of Undervoltage Load

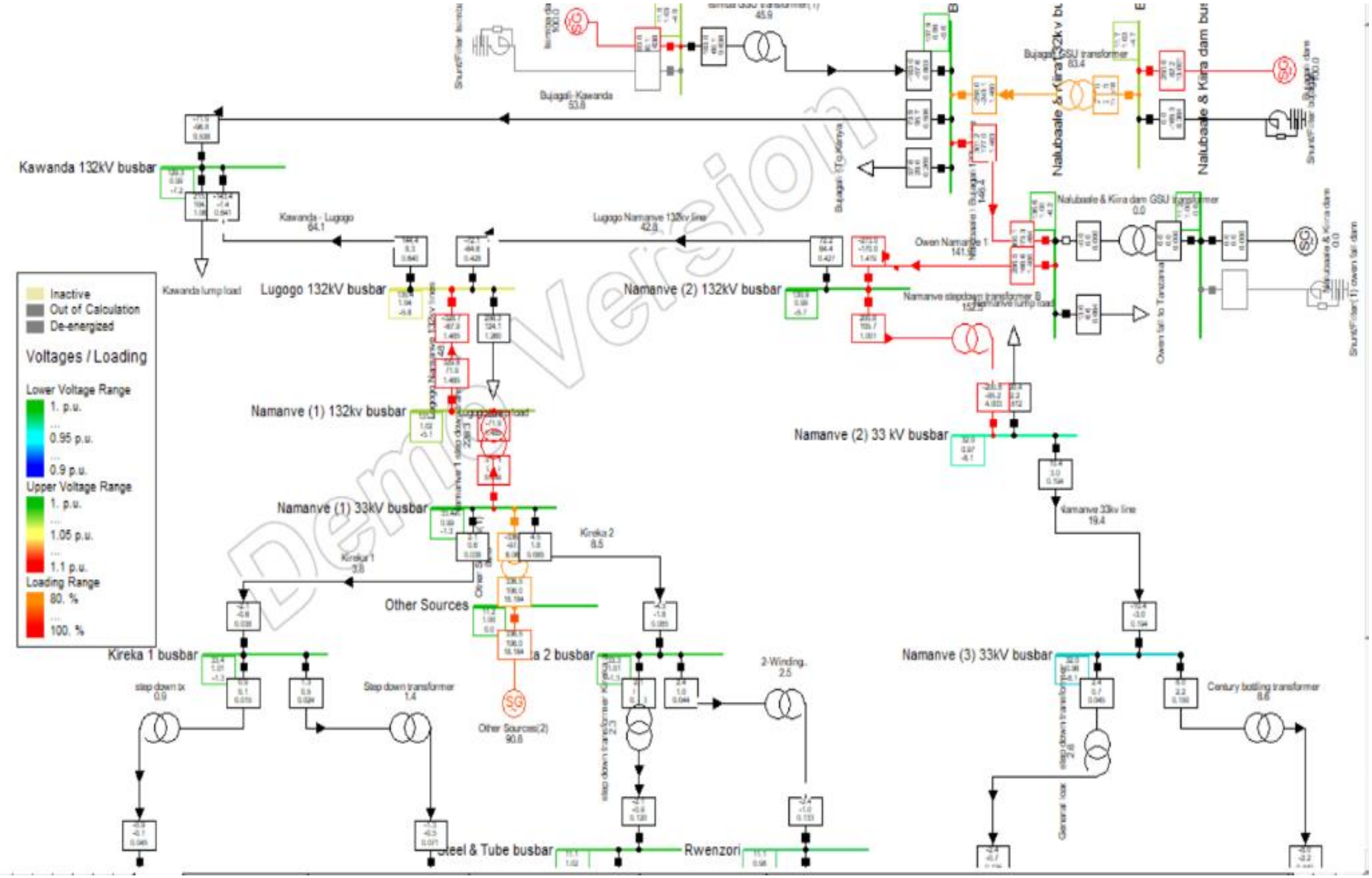

Fig. 6. DIgSILENT Simulation Results in Graphic Window

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In a scenario where the faults originated from the demand side in Fig.7, below, say Rwenzori busbar fault, the network condition changes as seen in blue curve and Rwenzori busbar loads became the candidates for disconnection. So it's the same with the Century bottling company in the yellow curve and Roofing milling company busbar indicated by dark green curve since they all fall out of the required voltage range of (0.9p.u).

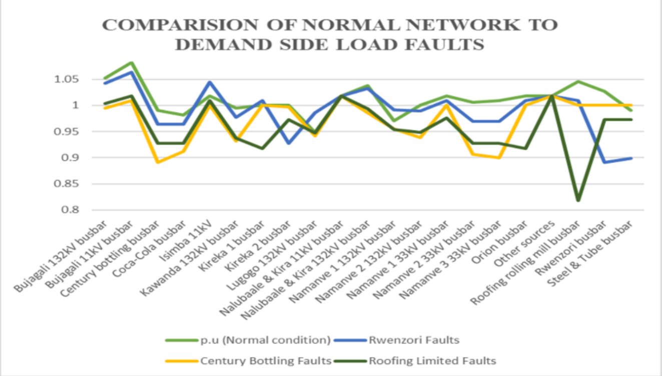


Fig.7. shows comparison of normal network to demand side load faults.

C. PHYSICAL SECURITY INFORMATION MANAGEMENT SOFTWARE (PSIM).

Development of an Automatic Undervoltage Load Shedding Relay

PSIM software was used to develop an automatic undervoltage load shedding relay in Fig.10. The undervoltage load shedding relays are installed at decentralized and centralized locations in the network. The network parameters like voltage, current, active, reactive power and power factors served as the inputs to the UVLS relay settings. The behaviors of the UVLS relay is directly dependent on the network characteristics/condition at a certain instant. Under normal power network conditions, the UVLS relay is not expected to disconnect any lines and voltage and current waveform output displayed in Fig.9 & Fig.10, respectively. However, for contingency conditions weak busbars/lines according to set criteria and guidelines (0.9 p.u) as illustrated in Fig. 6 & Fig.7, are disconnected hence no potential across the affected lines.

Simulation of an Automated Undervoltage Load Shedding Relay under Normal Network Condition

Load voltage

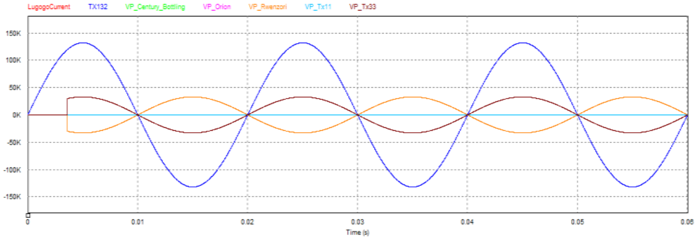


Fig. 8. Voltage Waveform under normal power network condition

Load current

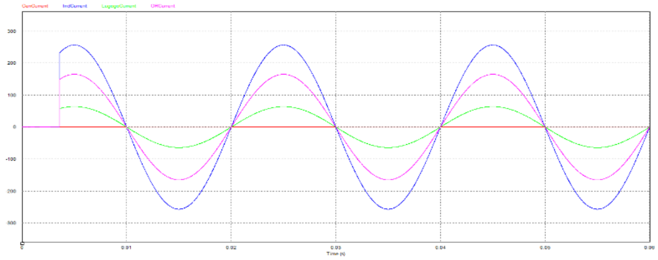


Fig.9.Current Waveform under a normal power network condition

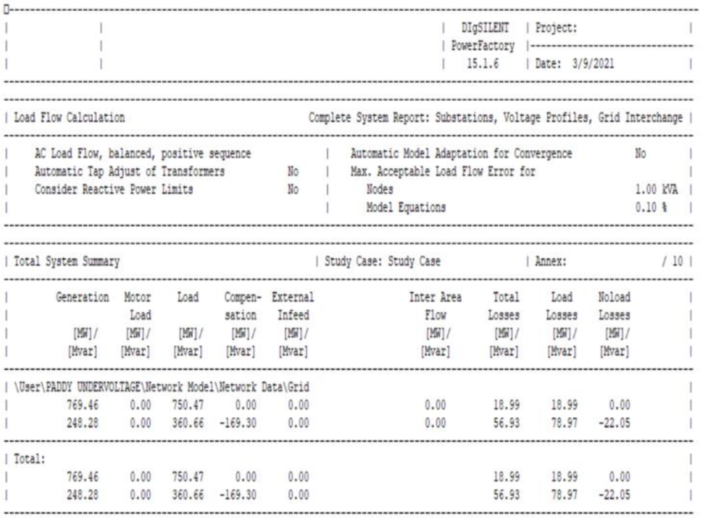
Simulation of an Automatic Undervoltage Load Shedding Relay during Network Contingency

Network contingency means either the network cannot evacuate power from generating stations to the loads due to network disturbances or the quality of power delivered is not good. When the supply voltage to the primary side of transformers is less than the lower limit of the circuit voltage of 118.8kV, 29.7kV, and 9.9kV, that is the regulated -10% voltage range by the Electricity Regulatory Authority of Uganda, it falls in the undervoltage region. It then by default becomes a candidate for disconnection from the power network. Therefore, there will be no voltage potential and current flow in the network after the undervoltage load shedding relay is activated.

D. VAIDATION OF THE UNDERVOLTAGE LOAD SHEDDING RELAY SOLUTION.

Power Loss Analysis

TABLE 1. Simulated power load loss analysis



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D----------------------------------------------------------------------------------------------------------
|                  |                                                      |   DIgSILENT   | Project:                    |
|                  |                                                      |  PowerFactory |-----------------------------
|                  |                                                      |    15.1.6     | Date:  3/9/2021             |
----------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------
| Load Flow Calculation                        Complete System Report: Substations, Voltage Profiles, Grid Interchange |
----------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence          |   Automatic Model Adaptation for Convergence          No    |
|    Automatic Tap Adjust of Transformers          No   |   Max. Acceptable Load Flow Error for                      |
|    Consider Reactive Power Limits                No   |     Nodes                                        1.00 kVA  |
|                                                       |     Model Equations                              0.10 %    |
----------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------
| Total System Summary                             | Study Case: Study Case               | Annex:               / 10 |
----------------------------------------------------------------------------------------------------------
|        Generation   Motor     Load    Compen-  External                 Inter Area    Total    Load    Noload       |
|                      Load             sation    Infeed                     Flow       Losses   Losses   Losses      |
|           [MW]/      [MW]/    [MW]/    [MW]/     [MW]/                     [MW]/      [MW]/    [MW]/    [MW]/      |
|          [Mvar]    [Mvar]   [Mvar]   [Mvar]    [Mvar]                    [Mvar]     [Mvar]   [Mvar]   [Mvar]      |
----------------------------------------------------------------------------------------------------------
| \User\PADDY UNDERVOLTAGE\Network Model\Network Data\Grid                                                        |
|          769.46     0.00   750.47     0.00      0.00                      0.00       18.99    18.99     0.00      |
|          248.28     0.00   360.66  -169.30      0.00                      0.00       56.93    78.97   -22.05      |
----------------------------------------------------------------------------------------------------------
| Total:                                                                                                          |
|          769.46     0.00   750.47     0.00      0.00                                 18.99    18.99     0.00      |
|          248.28     0.00   360.66  -169.30      0.00                                 56.93    78.97   -22.05      |
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Looking at the last row in the table above from DIgSILENT power loss analysis, no-load losses are (-22.05) MVar & 0MW and the load losses are 18.99 MW & 78.97MVar making total load losses of 18.99MW & 56.93 MVar.

The total Active power load loss = (18.99/750.47)*100%. Approx. =2.5%

The total reactive power load loss = (56.93/360.66)*100. Approx. =15.8%

Therefore the total load power loss =18.3%

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Experiment of Undervoltage Load Shedding Relay Simulation in PSIM

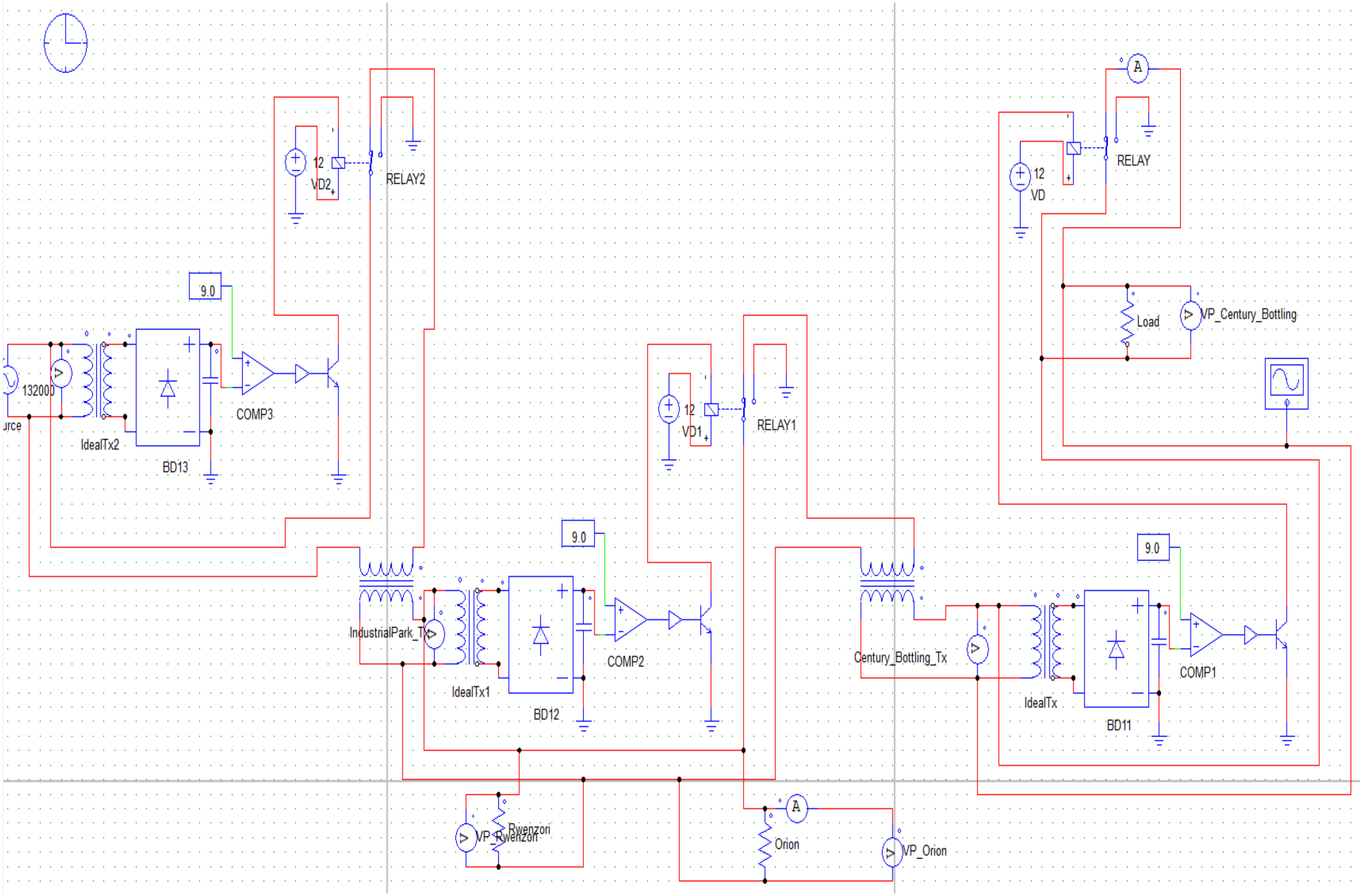

Fig.10. Undervoltage load shedding relay simulation diagram

Model Voltage Validation

The collected secondary data from Umeme Ltd & UETCL were compared with the simulated busbar data. The percentage voltage deviation was calculated. Line graph Fig.11, gives more representation of voltage deviation.

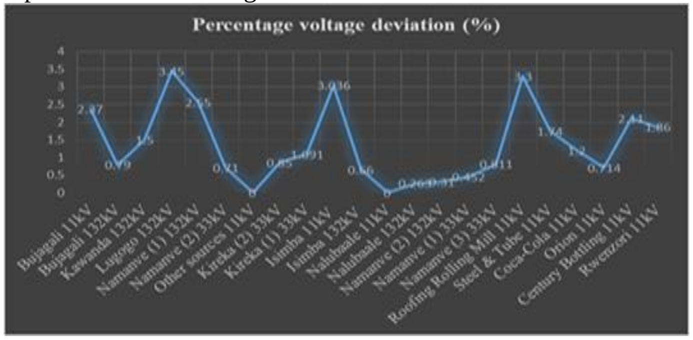

Fig.11.Line graph shows percentage voltage deviations

The line graph shows a percentage voltage deviation between actual Umeme Ltd & UETCL busbar and real DIgSILENT simulation busbar voltages. At Nalubaale 11kV busbar and other sources (Solar, Thermal etc.), the voltage difference gives zero percentage. Lugogo 132kV has the highest variation of 3.45% followed by the rolling mill busbar at 3.3%. The overall voltage variation range is (0-4) %.

Total Harmonic Distortion

Analyzing the total harmonic distortion (THD) in the voltage waveform in Fig.12, below, the voltage distortion of 0.00094114674 (0.094%) is output which is far much less than the THD for high voltage seen in table 2 below. The low THD imply that power quality is good with a low voltage drop in the PSIM simulation.

TABLE 2. Summary of THD planning level

System voltage at the point of connection	Design network application	THD Percentage limit
400V	LV	5%
6.6kV, 11kV & 20kV	6.6kV & 11kV (MV)	4%
22kV to 400kV	33kV, 66kV &132kV(EHV)	3%

Secondary source: (Western power distribution: power quality, nd)

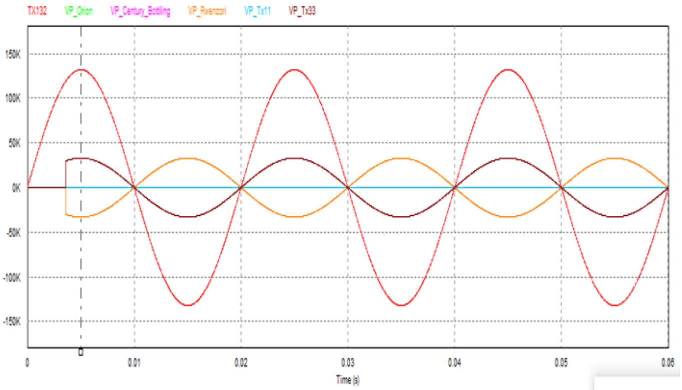

Fig. 12. Total Harmonic Distortion (THD) display

V. CONCLUSION

This research details a load shedding scheme that acts as a safety net (last intervention) for the power system network to curtail voltage collapse that would subsequently result in a power blackout. The network supplying power to Kampala Industrial and Business Park (KIBP) Namanve which doubles as an industrial hub and centre for economic development was modelled and simulated as a case study. This undervoltage load shedding solution can be applied to the whole Uganda network since it can easily be configured to work with any existing numerical relays in the network. Unlike the manual erroneous intervention by the system operator for load shedding, the undervoltage load shedding relays that are designed to be installed at decentralized and centralized locations in the network automatically disconnect the lines with faults prioritizing different networks according to the set criteria and UVLS guidelines. The restoration of the disconnected lines can only be possible after faults clearance by the protection team since this solution acts as a last resort.

The proposed use of undervoltage load shedding relay in PSIM technique is a good solution that optimally disconnects the weak busbars bringing back the network close to its operating point, and reduced total harmonic distortion thereby improving the voltage regulation of the distribution lines. However, it has issue of scalability because it cannot allow more than six electrical loads and it only considers the voltage as a base for load shedding. The automatic UVLS relay solution in PSIM can be used by the utility companies in Uganda to mitigate the undervoltage issues by knocking off weak busbars, reducing total harmonic distortion, improving voltage regulation, and increasing power grid efficient through improving the system power factor.

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