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Optimal Location and Sizing of FACTS Devices to Improve Voltage Profiles on a 132 kV Mwanza-Musoma-Nyamongo Transmission Line

Fausta Manga, Peter Makolo†, and Francis Mwasilu

Department of Electrical Engineering, University of Dar es Salaam, TANZANIA
†Corresponding author: makolo.peter@gmail.com; ORCID: 0000-0002-3595-8468

ABSTRACT

Recently, utility companies have desired to supply quality, stable and reliable power to customers, and ensure they meet the demand. Flexible AC Transmission Systems (FACTS) dynamic compensator devices such as Static Synchronous Compensator (STATCOM), Static VAr Compensator (SVC) and Unified Power Flow Controller (UPFC) are an impeccable choice, however, cost is one of the limiting factors following these technologies. In addition, using FACTS devices in the system requires a detailed steady state, dynamic and optimisation analysis to effectively meet the purpose and ensure reduced cost. This paper proposes using an optimised FACTS device to improve voltage profile, power transfer, system stability, and reduce system losses on 132 kV Mwanza–Musoma–Nyamongo transmission line. The analytical and Particle Swarm Optimisation technique was used to obtain the FACTS device's optimal size and location. The optimized FACTS device is incorporated in the system model and implemented using PSS/E software version 35. The model was analysed with the 132 kV Mwanza–Musoma–Nyamongo transmission line loaded to its capacity, the network was observed to have an improved voltage profile, the voltage deviation lowered by 84% as compared to the current network voltage deviation of 0.2 p.u. Also, the transmission line transfer capability increased by 32 MW from the current transfer capability without distortion of the voltage profile and with an improvement on system stability. The ± 60 MVAr optimized STATCOM was observed to lower the system losses by an average of 14%. Furthermore, analysis concerning with the operation costs was observed that with maximum transfer the FACTS device investment payback period is thirteen (13) months demonstrating the system's financial viability.

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INTRODUCTION

Generally, grid outages or failures that relates to voltage collapse are mainly caused by inability of the system to meet the reactive power demand, which could help the system to rapidly restore to a new stable state following occurrence of disturbances in power network (Kihwele, 2019; Mhagama et al., 2021). The electric power distribution network and consumption are rapidly growing and the power generation expansion is limited to the location and availability of resources (Philip et al., 2023). The power system stability and efficiency are crucial concern of the utility company in ensuring reliable delivery of power to consumers or customers (Khan et al., 2021).

In the 1990s the Tanzania electric power grid generation was mostly from the hydro power plants that were located in the south-western highlands. In 2006 power rationing was practiced in Tanzania following an extended drought. The government of Tanzania together with the utility company, Tanzania Electric Supply Company (TANESCO) Limited, added thermal (natural gas and diesel) power plants (Kainkwa, 2008). Also in the same year, two static VAr compensators (SVCs) were installed at Singida and Shinyanga for voltage stability improvement in the northern grid. Furthermore, in 2011, 2013, 2015 and 2018 TANESCO added Ubungo II, Nyakato – Mwanza, Kinyerezi I and Kinyerezi II thermal plants, respectively (TANESCO, 2025).

The location of the power plants in Tanzania grid is observed to be located in the southern highlands and eastern part of the country. The north-western grid is part of the network located about a thousand kilometers from the generations. Most of the loads in this region are mining, requiring quality power; however, this part of the network suffers from voltage disturbances. Therefore, the Nyakato (heavy oil or diesel fuel) power plant operates for network support especially during peak load hours. Recently in 2024, the north-western grid was connected to Rusumo hydropower power plant (AFDB, 2024) and started getting about 20 MW. Despite the effort made the voltage disturbance is still a challenge in the north-western grid, especially in the remote ends of the radial transmission lines and the same increases with increase of load demand. The system disturbance scatter plot as created from TANESCO provided power-quality (PQ) log file, indicating the severity of the system disturbances for the months of May to August 2024 using NRS048-2:2015 standard is shown in Figure 1.

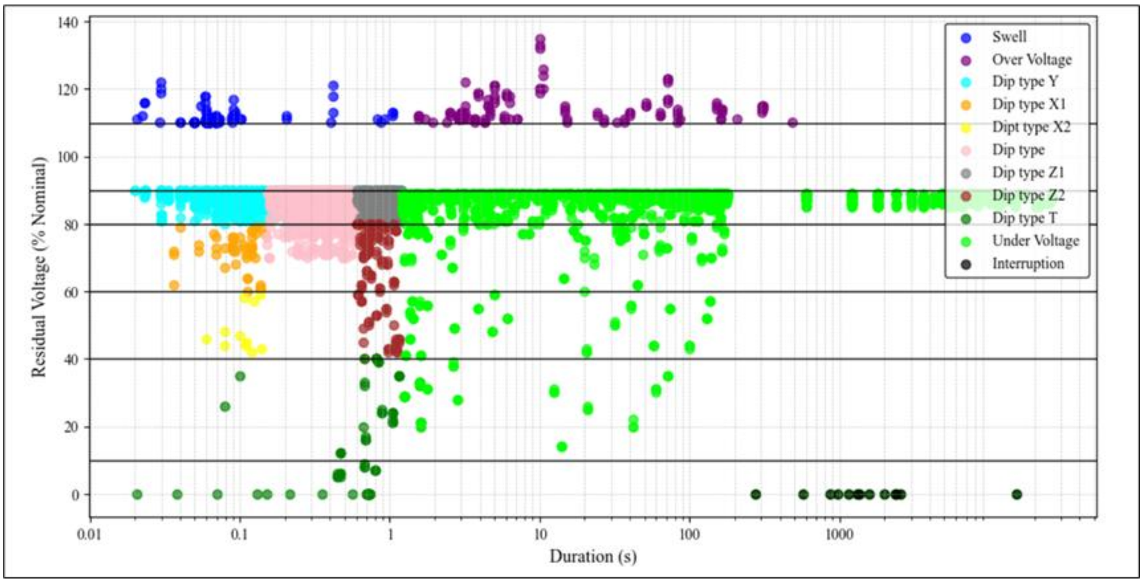


Figure 1: Distribution of PQ disturbances by its duration and magnitude (May to August 2024).

Currently, the promotion of Flexible AC Transmission System (FACTS) device such as SVC, Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) is high due to the desire of utility companies to supply quality power to end users (Ali, 2017) as the far away generator sources cannot deliver the demanded reactive power. The shunt dynamic VAR compensators predominantly SVC and STATCOM have shown to strongly impact on the voltage control (Saha et al., 2012). However, the optimal sizing of FACTS devices is required since the undersized FACTS may not give the preferred benefits and oversized FACTS may lead to high operation cost of the electric power network (Marouani et al., 2023).

In this paper, sensitivity analysis has been carried out initially through the Voltage Collapse Proximity Index (VCPI) and by constructing Power-Voltage (PV) curves of load buses to determine ideal locations for SVC or STATCOM. The buses prone to voltage collapse are easily determined by PV curves and VCPI. Placing FACTS at such buses can highly improve power system stability by providing reactive support and increasing loading capability. The validation of placement of FACTS, and sizing of the devices are presented through the particle swarm optimization algorithm (PSO), the objective being minimized total system operational cost which includes the cost of active power loss and cost of installation of FACTS. The presented methodology is applied to PSS/E 132 kV Mwanza–Musoma–Nyamongo power network.

Existing Literature Analysis

FACTS devices play a crucial role in improving transmission system stability and efficiency. Existing literature has mentioned the use of different FACTS devices for power systems performance improvement. In Pereira et al. (2017), the importance of the FACTS devices in controlling the voltage stability of a power system is studied. Different dynamic simulations were carried out in order to analyse the performance of SVC and STATCOM technologies in the dynamic voltage stability control of an electric power network. In Wonodi et al. (2023), using load flow analysis (LFA) and ETAP 19.0 software with Newton-Raphson numerical approach, reactive power losses were compensated and improved the voltage profile by using the SVC. Nadeem et al. (2020) used a novel method for the optimal placement and sizing of multiple types of FACTS devices. Initially, sensitivity analysis was carried out to find ideal locations of FACTS by using line stability (L_{mn}) index, voltage deviation, and higher active power loading being ideal for thyristor-controlled series capacitor (TCSC), SVC and UPFC placement, respectively. After optimal placements of FACTS in the network, optimal settings of fitness function variables were determined by the whale optimization algorithm (WOA). The research considerably reduced the total system operating costs and transmission line losses; however, did not consider optimal coordination of FACTS in the presence of renewable sources.

Similarly, Khan et al. (2021) researched to improve the performance of the national grid for both the present and the forecasted by the placement of FACTS devices. Initially, analysis was carried out to find optimum locations of FACTS devices using L_{mn} and voltage collapse proximity indices (VCPI) for SVC. Lines with the value of L_{mn} and VCPI index close to unity were considered as weak lines and weak buses respectively; thus, candidate locations for TCSC and SVC respectively. The optimal sizes of these devices were determined using PSO. Results show that an optimized solution significantly reduces power system losses. Adeniji and Mbamaluikem (2017), applied Newton-Raphson Power flow analysis and conducted a study on Nigerian 330 kV with and without the UPFC using MATLAB to improve voltage profiles and reduce transmission losses. Also, Samimi et al. (2011) determined the optimal location and size of the SVC device in order to minimize voltage deviation and the active power losses in the power network using the PSO technique. Moreover, Ali, (2017) used PSO based approach for allocation of the static synchronous series compensator (SSSC) devices in Iraq national grid system in order to obtain the minimum real power losses of the system and improved the voltage profiles.

Flexible AC Transmission Systems Devices

Flexible Alternating Current Transmission Systems are advanced power electronic devices designed to improve the power transfer capacity and controls. FACTS installation in power networks improves voltage stability, power transfer capability, transient stability, and power system reliability (Odion et al., 2023). The modern electric power system in the 21st century includes more renewable energy resources and critical infrastructure, making it vital for utilities to enhance power quality to end-users (Baby et al., 2022). Stability issues in the transmission and distribution networks are associated with reactive VAR power management, which ensures voltage support, load balancing, harmonic suppression, and mitigation of voltage fluctuations (Kolhe et al., 2003). Equation (1) expresses the reactive power flow between two buses with bus voltages V_1 and V_2.

$$Q = \frac{-V_1^2}{X} + \frac{V_1 V_2}{X} \cos(\delta) \quad (1)$$

Static VAR Compensator

A practical SVC mostly contains both thyristor switched capacitor (TSC) and thyristor-controlled reactor (TCR). The SVC also includes tuned filters to suppress harmonic current from flowing into the AC system (Hossain et al., 2018). The SVC's connection is parallel (shunt) to an AC line or busbar through a step-down transformer. In order to ensure improved power transfer and voltage, the SVC is normally placed in the middle of a transmission line (Marouani et al., 2023). With SVCs installed close to loads is more effective in providing voltage support, thereby avoiding voltage instability (Pourhossein & Najafi, 2017). The chief characteristic of the SVC is that it either absorbs reactive power from the bus or injects reactive power into the bus where it is connected (Pourhossein & Najafi, 2017). The SVC static V-I characteristic is shown in Figure 2.

With SVC being connected at the bus, the respective reactive power and current are given by equations (2) and (3).

$$Q_{SVC} = -V_S^2 B_{SVC} \quad (2)$$

$$I_{SVC} = jB_{SVC} V_n \quad (3)$$

where I_{SVC} is absorbed current by SVC, B_{SVC} is susceptance of SVC, Q_{SVC} is absorbed reactive power by SVC that is equal to injected power into connected bus n and V_n is the bus voltage where SVC is connected.

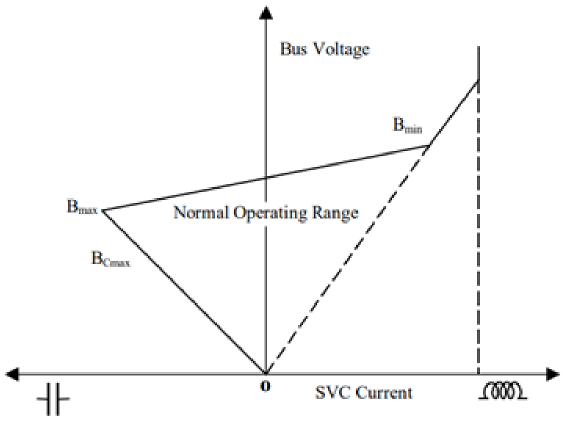
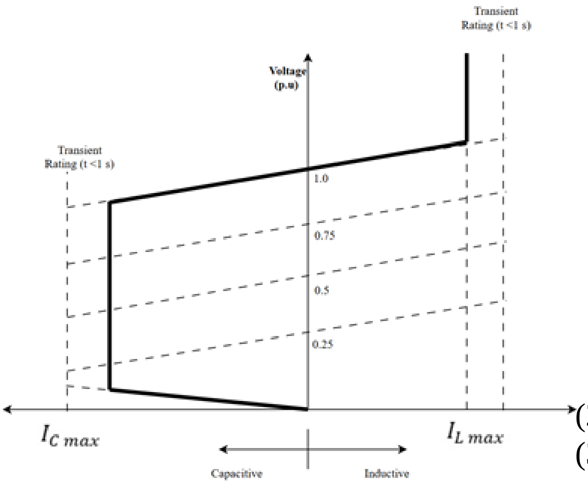


Figure 2: SVC static V–I characteristic (Pereira et al., 2017).

(1)

Static Synchronous Compensator

STATCOM is a voltage source converter-based FACTS that is used to offer reactive power support to maintain the voltage magnitude of a bus within its voltage security limit (Reddy & Devi, 2018). This device does not require passive elements like inductors and capacitors (Gandoman et al., 2018). STATCOM is always placed on a PQ (Load) bus and this PQ bus is converted into a PV bus and thus works as a (alternator) synchronous generator with real power output being zero and its voltage is set to some reference value (Reddy & Devi, 2018). The STATCOM V-I characteristic is shown in Figure 3.



(2)

(3)

Figure 3: STATCOM V–I characteristic (Gandoman et al., 2018).

The voltage at the STATCOM bus is expressed as per equation **Error! Reference source not found.**).

$$V = V_{ref} \pm IX_{SL} \quad (4)$$

where V_{ref} is reference voltage and X_{SL} is the controller droop and the inductive mode or capacitive mode of STATCOM is identified by using the positive and negative sign, respectively.

Optimal Allocation and Sizing of FACTS

FACTS devices are optimally allocated and sized on power distribution and transmission networks to achieve specific objective such as cost reduction, power losses reduction and voltage profile improvement (Ngei & Moses, 2023). Based on the previous studies, optimization techniques for FACTS devices in power systems can be classified into four different categories that is Classical Optimization, Meta-heuristic, Sensitive or analytical and mixed methods.

Analytic Optimization Method

This approach uses sensitivity analysis to locate critical buses where FACTS devices need to be placed. The advantage of using analytic methods to optimize FACTS devices is that they are efficient (Ngei & Moses, 2023).

Analytical optimization for placements of SVCs uses Voltage Collapse Proximity Index (VCPI) which finds out unstable buses in a transmission system (Khan et al., 2021). The buses with index values closer to 1.0 are considered weak (Khan et al., 2021). Therefore, such buses are the candidate locations for placing FACTS. The VCPI works on the principle of maximum power transfer via line defined in equation (5).

$$VCPI = \frac{P}{P_{max}} \quad (5)$$

Where P and P_{max} are defined in (6) and (7).

$$P = V_r I cos\emptyset \quad (6)$$

$$P_{max} = \frac{V_s^2 cos\emptyset}{Z_s 4cos^2(\frac{\theta-\emptyset}{2})} \quad (7)$$

V_s is the source voltage, Z_s is line impedance, θ is the impedance angle and Ø is the angle difference between the sending and receiving end bus.

Optimal locations of SVCs are also determined by power versus bus voltage (P–V) analysis curves, however this method is highly time-consuming (Liang et al., 2022). The P–V curves are constructed using the continuation power flow (CPF) technique. In P–V analysis, the weak bus is the one that is closest to the turning point or "knee" of the curve. Equivalently, it is the one that has a large ratio of differential change in voltage to differential change in load (Nadeem et al., 2020).

Optimal Allocation of STATCOM

The approach uses sensitivity analysis to locate critical buses where FACTS devices need to be placed (Ngei & Moses, 2023). For the case of optimal placement of the STATCOM, the buses that transmit the higher voltage fluctuation are determined, furthermore, the STATCOM is placed on buses with larger SI (Samimi & Golkar, 2011; Baby et al., 2022). The sensitivity index method is mathematically expressed in equation (4), representing the rate change of voltage fluctuation concerning the bus j and i.

$$SI = \sum_{j=1}^{j=i} \frac{\delta V_j}{\delta Q_I} \quad (8)$$

Meta-Heuristic Optimization Techniques

Meta-heuristic optimization techniques use stochastic algorithms to optimize the size, types, location, and number of FACTS devices in a power system (Ngei & Moses, 2023). These algorithms are widely used in FACTS device optimization problems because of their superiority in accurately optimizing multi-objective functions with many constraints (Marouani et al., 2023). The Particle Swarm Optimization (PSO) technique which has attracted the attention of several researchers when solving the FACTS device optimization problem in power systems because of its advantages in computation (Marouani et al., 2023). The PSO is a powerful metaheuristic optimization technique that guarantees optimal solutions when used for optimization of FACTS devices (Ngei & Moses, 2023). Many researchers have applied this technique to optimize different FACTS devices with different objective functions (Odion et al., 2023).

Model of the Network without FACTS Devices

Network model was created using PSS/E, as shown in Figure 4, based on the calculated line parameters and the calculation of the power system grid equivalent parameter. The resistance, inductive reactance and susceptance were the parameters of the line between the substations. The network was designed, and parameter limits were set, with the normal voltage operation limit ±5% and emergency voltage operation limit ±10% (EWURA, 2017).

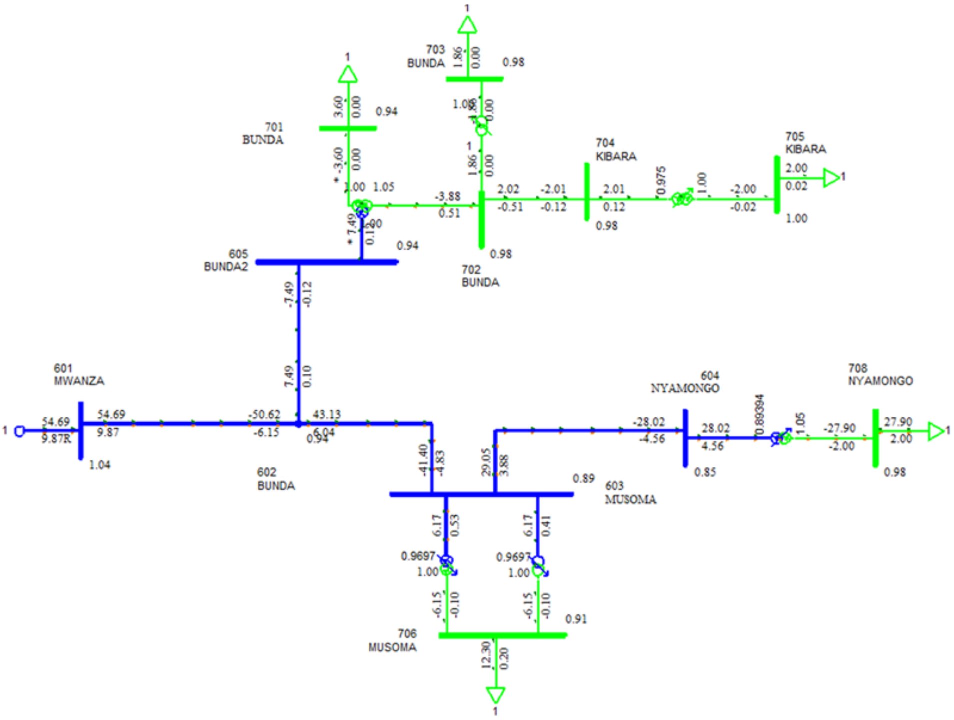


Figure 4: PSS/E Network model without FACTS.

The network was designed presenting an equivalent network generator as swing bus (code 3), Mwanza bus number 601 and other busses being load buses (code 1). Stepdown transformers were modeled as per the provided transformer details, including capacity and impedance. The loads were connected on the low-voltage side of 132/33 kV or 66/33 kV transformers on respective substations.

FACTS Devices Optimization

FACTS device optimization was conducted using two methods; sensitive and metaheuristic method. This approach was selected to ensure accurate Optimization. The optimization by sensitive method used the VCPI index to find the optimal location. The load flow results were compared with the real system operation parameters which are voltages and power flow between substations for network validation. The load flow results were then used to calculate the stability indices to obtain optimal FACTS location. The buses with index values close to 1.0 were considered close to instability or weakest point, therefore, such buses are the optimal locations for placing FACTS (Khan et al., 2021).

Optimization by metaheuristic was conducted by using Particle Swarm Optimization (PSO) algorithm where by the created problem was solved by linking Python with Mealpy modules and PSS/E. The FACT devices selected for Optimization of the location, size or MVAr rating were STATCOM and SVC.

Optimization by Sensitive Method

The Calculation of VCPI index used equation **Error! Reference source not found.** and results are as shown in Table 1.

Table 1: Voltage proximity indices for the Network without FACTS.

Transmission Line	Sending Voltage	Receiving Power	∅ rad	θ rad	VCPI	Rank
Mwanza - Bunda	137.4 kV	50.6 MW	0.168	1.175	0.428	3rd
Bunda -Musoma	123.9 kV	41.4 MW	0.091	1.175	0.780	1st
Musoma - Nyamongo	117.5 kV	28 MW	0.080	1.175	0.502	2nd

The optimum size obtained by conducting PV analysis with FACTS installed and loading the line to its capacity (Liang et al., 2022). Considering the configuration of the network under study, the 132 kV Mwanza-Bunda line section is the one that limits the power transfer. Calculating the line capacity using the given line design ampacity I = 405 A and system voltage U = 132 kV, gives line loading capacity of 88 MW.

Optimization by Particle Swarm Optimization Method

The requirement was to determine the optimal location, type and rating of the FACTS device to be installed to ensure an improved voltage profile, reduced system losses and thus, optimal operational cost on the 132 kV Mwanza-Musoma-Nyamongo transmission line. To achieve this, the problem was formulated and a Particle Swarm Optimization algorithm was implemented. The flow chart for optimization algorithm is shown in Figure 5.

Problem Formulation

The current system operation cost depends on the power generated by diesel generator and power losses cost. With the FACTS device installed, the system operation costs will depend on the Cost of FACTS and the system losses.

Objective Function

The objective function (f_x) of the system given in equation (9), considering the fact that the voltage deviation account for power losses and thus account for cost. The objective is to ensure the system voltage profile is improved, power losses are reduced and cost is optimized.

$$f_x = \min[C_{loss} + C_{FACTS}] \tag{9}$$

where C_{loss} is the real power losses cost given in equation (10) and C_{FACTS} is the cost of FACTS device.

$$C_{loss} = (P_{l0ss})x\left(\frac{0.115\ USD}{kWh}\right)x365x24 \tag{10}$$

where by $0.115\frac{USD}{kWh}$ is the Tanzania average electricity cost (TANESCO, 2017).

Cost characteristic of FACTS, SVC and STATCOM based on Siemens database are given in equation (11) and (12) (Nadeem et al., 2020), where q and Q are the sizes of SVC and STATCOM in kVAr.

$$C_{SVC} = 0.0015q^2 - 0.7130q + 127.38\left(\frac{USD}{kVAr}\right) \tag{11}$$

$$C_{STATCOM} = 553\,[0.0004Q^2 - 0.325Q + 127.38]\left(\frac{USD}{kVAr}\right) \tag{12}$$

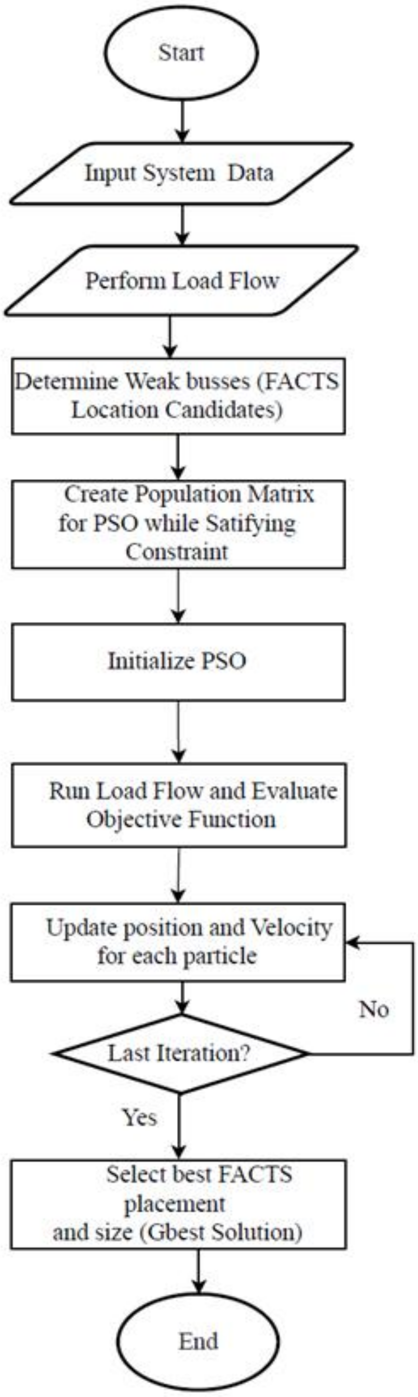


Figure 5: Optimization of FACTS Devices Location Flow Chat.

Optimization Constraints

Constraints that need to be satisfied are presented in (13) – (19).

Bus voltage constraints:

$$|V_i - 1| \leq 0.05 \quad (13)$$

Generator's reactive power supply constraints:

$$Q_{g,min} \leq Q_g \leq Q_{g,max} \quad (14)$$

Generator's Real power supply constraints:

$$P_{g,min} \leq P_g \leq P_{g,max} \quad (15)$$

SVC size constraints:

$$-100 \leq q \leq 100 \quad (16)$$

STATCOM size constraints:

$$-100 \leq Q \leq 100 \quad (17)$$

Cost Constraint:

$$C_{FACTS} = \begin{cases} C_{SVC}\ x\ q \\ C_{STATCOM}\ x\ Q \end{cases} \quad (18)$$

Device type constraints:

$$\frac{c_{STATCOM} - c_{SVC}}{c_{SVC}} \leq 0.5 \quad (19)$$

Model of the Network with FACTS

The system was designed with a FACTS device for the improvement of the voltage profile, system stability and reduction of system power losses as shown in Figure 6.

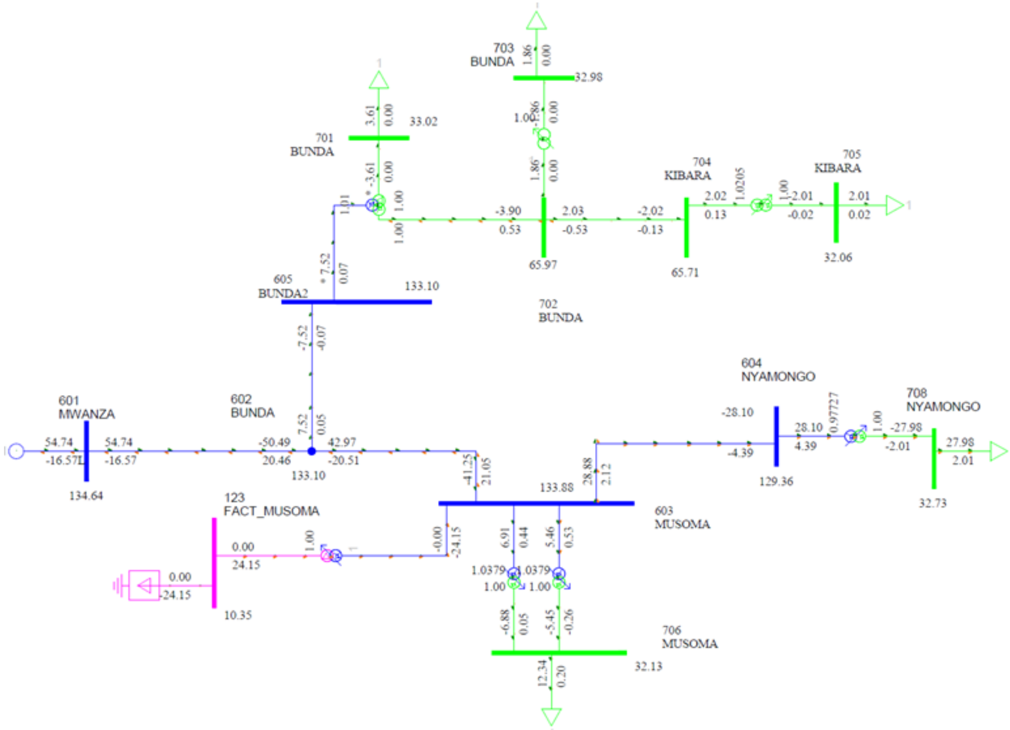


Figure 6: PSS/E network model with FACTS.

RESULTS AND DISCUSSION

PSS/E software requires steady state and dynamic parameters for modelling and studies. The dynamic parameters are responsible for device's response to system disturbance. The generators and switched shunts or FACTS are among the equipment requiring dynamic modelling parameters. Dynamic modelling parameters of the equivalent network generator is depicted in Table 2.

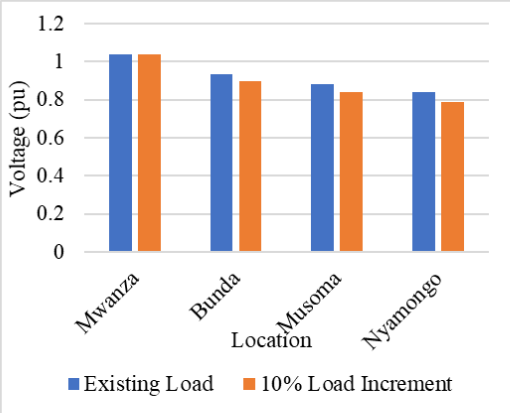
Table 2: Equivalent Network Model Parameters.

Parameter	**Value**
Model	GENCLS
Inertia Constant	2.87913
Damping	1

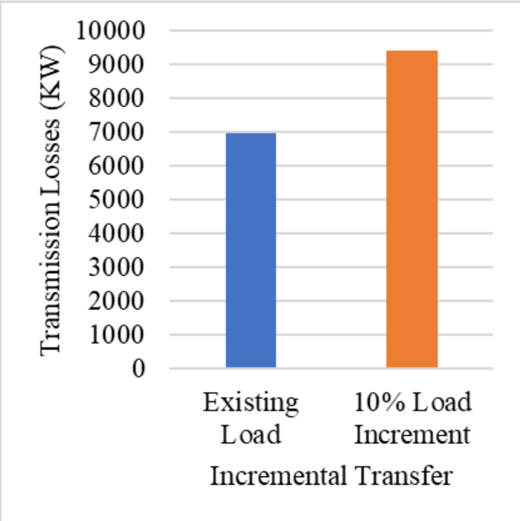
Analysis of the Network without FACTS

The load flow analysis of Case 1 (Current existing network) and Case 2 (network with 10% load increment) were conducted. Case 1 analysis, observed that some busses are violating voltage limits that is 0.85 p.u. For case 2 the voltages were below the limits for all busses with 0.79 p.u. at Nyamongo Substation. Therefore, the power quality to customers is deprived. Furthermore, with a load increased by 12% (6.5 MW) of the current network the network did not converge indication a system collapse. Figure 7(a) shows the voltage profile of a network without FACTS for both case 1 and case 2. The system power losses increase by 36.2% in case 2 as compared with case 1 as indicated in Figure 7(b). The PV analysis observed that at about 6 MW increment the drops much and voltage is out of limits which lead to system collapses. Figure 7(c) gives the bus voltages record of 132 kV Bunda, Musoma and Nyamongo during PV analysis.

The voltage stability analysis was conducted by applying a load drop of 20 MW at Nyamongo Substation. Before the disturbance, the system was stable however the voltage were below the normal operation limits, during load drop the voltage raised to 1.25 p.u. before it stabilizes to a new steady state level of about 1.06 p.u. as seen in Figure 7(d).



(a)



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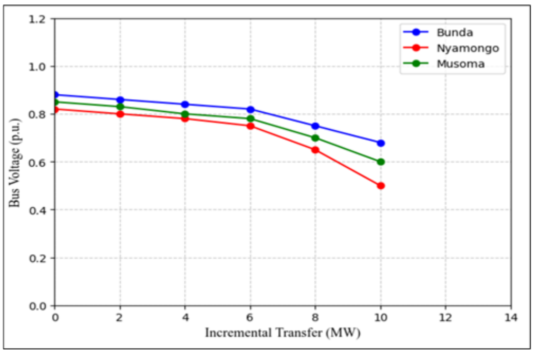
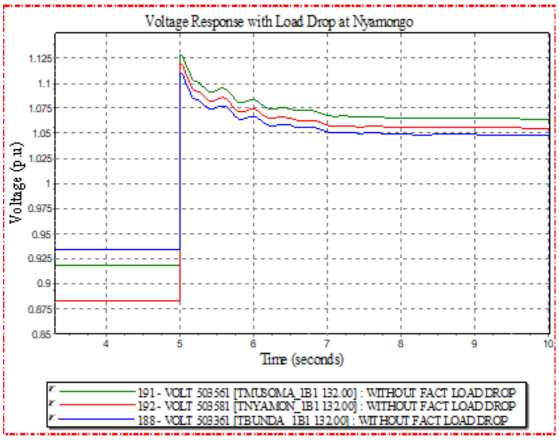


(c)



(d)

Figure 7: Simulation results for the network without FACTS (a) Voltage profile, (b) System power losses (c) PV analysis and (d) Stability analysis.

FACTS Devices Optimization

The stability indices were evaluated in the network without FACTS devices to identify weak buses that are candidates for FACTS device allocation. Following the study, the identified weak buses were the 132 kV Bunda bus number 602, the 132 kV Musoma bus number 603 and the 132 kV Nyamongo bus number 604. Therefore, optimization was conducted using these buses as candidates. The optimization techniques employed were sensitivity analysis and PSO.

Optimization by Sensitive Method

The load flow study was conducted with FACTS devices at Bunda, Musoma, and Nyamongo locations to observe the system voltage improvement and reduced power losses. The power losses following FACTS placement at different locations are observed to be slightly higher with the FACTS located at the Nyamongo substation as seen in Figure 8.

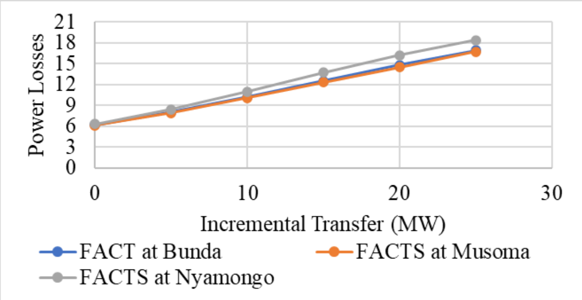


Figure 8: Power losses comparison with FACTS at different locations.

The PV analysis observed the reactive power requirement with FACT at different location, as seen in Table 3.

Table 3: Reactive Power Requirement During PV Analysis.

Incremental Transfer (MW)	MVAr Requirement - FACT at Bunda	MVAr Requirement - FACT at Musoma	MVAr Requirement - FACT at Nyamongo
0	16	23	21
5	30	30	26
10	35	35	31
15	44	40	37
20	50	48	42
25	60	56	50
27	64	59	54
30	70	63	60

Reactive power requirement, which determines the size of FACTS, is observed to be less at Nyamongo, followed by Musoma, and lastly at Bunda however the power losses are higher at Nyamongo.

Particle Swarm Optimization Technique

The optimized STATCOM was modelled with a short-time overloading capability to simulate its dynamic performance during severe system disturbances, such as three-phase faults. Specifically, the STATCOM is designed to inject up to 2.5 times its nominal rated current for a duration of up to 100 milliseconds. This capability is crucial for providing rapid reactive power support to the grid, preventing deep voltage sags, and ensuring that the system's transient stability limits are not exceeded. During a fault, the STATCOM's fast-acting control system utilizes this overcurrent capacity to quickly restore the bus voltage, which in turn helps to prevent generators from losing synchronism and the system from experiencing a cascading failure. By incorporating this short-time overloading feature, simulation results demonstrate a significant improvement in the critical clearing time of faults and a more robust recovery of the grid, thereby enhancing the overall reliability and security of the TANESCO network, particularly during peak demand periods when the system is most vulnerable.

The developed optimization process uses the PSO technique to choose type, locate and size the FACTS device (STATCOM or SVC). The 132 kV Mwanza-Musoma line has a power transfer capacity of about 88 MW, but carrying its maximum capacity without any compensation was not possible as the voltages were collapsing. The costs of the real power losses are 0.115 $\$/kWh$ (TANESCO, 2017), this encounters for the operation cost. The optimization results are described in Table 4.

The 132 kV Mwanza-Bunda line was identified as the initial limiting factor primarily due to its relatively low voltage profile and high-power transfer during our base case load flow analysis. This line's loading approached its thermal limit, and it exhibited a high voltage drop, particularly under contingency scenarios such as the loss of another key transmission line. While the Mwanza-Bunda line was the bottleneck for power transfer, our detailed sensitivity and transient stability studies revealed that voltage instability issues were most pronounced at the Musoma substation bus. The Musoma bus, being at the end of a long transmission corridor and serving a significant load center, experienced the most severe voltage sag and was the critical point for voltage collapse under stressed conditions. Therefore, while alleviating the Mwanza-

Bunda line's loading was a major objective, placing the STATCOM at the Musoma bus provided the most effective and comprehensive solution for enhancing overall system voltage stability and improving the transient response of the entire north-western grid, thereby indirectly but significantly increasing the power transfer capability of the Mwanza-Bunda line.
Following the above, it is observed that the obtained FACTS ratings satisfy the system's operation and reduce the overall system's cost at different line loading conditions, however, it is observed that is necessary to invest with the size that will cater 100%-line loading and the FACT device should have capabilities for short time overloading. Therefore, the selected FACTS is STATCOM with size of ±53 ±10% to be located at Musoma Substation.

Analysis of the Network with FACTS

The study observed that the losses of the line, increases with increase of the line loading despite the availability of FACTS device in the network, however the same is lower by an average of 14% as compared to model without FACTS which has 9.4 MW power loses for Case 2. The voltage profile measured by the voltage deviation improved by 83.4% as compared with the network without FACTS which had a total system voltage deviation of 0.2 p.u. The system voltages as monitored on different busses is as shown Figure 9(a).

Table 4: FACTS Optimization Analysis Summary.

Description	Case 1: Current Model	Case 2: Forecasted Model 10%	Case 3: Forecasted Model 50%
Transferred Power (MW)	54.2	60.4	88
Optimal FACT device	STATCOM		
Optimal Location	Musoma Substation		
Reactive power (MVAr)	23.7	26.8	53
Energy losses With FACTS (kWh)	55,188,000.00	68,328,000.00	144,540,000.00
Diesel generators energy generated (kWh) (as per 2024 records)	21,334,128.00	21,334,128.00	21,334,128.00
Energy losses Without FACT S (MW)	61,057,200.00	82,344,000.00	168,192,000.00
Cost of energy lost (USD/kWh)	0.115	0.115	0.115
Cost of Energy lost with FACTS (USD)	6,346,620.00	7,857,720.00	16,622,100.00
Cost of Energy lost Without FACTS (USD)	9,475,002.72	11,922,984.72	21,795,504.72
Total cost of STATCOM (USD)	3,081,000.00	3,484,000.00	6,890,000.00
Operation cost With FACTS (USD)	9,427,620.00	11,341,720.00	23,512,100.00
Operation cost Without FACTS (USD)	9,475,002.72	11,922,984.72	21,795,504.72
First year benefit (USD)	47,382.72	581,264.72	-1,716,595.28
Payback period	less than a year	less than a year	1 year + 1 month

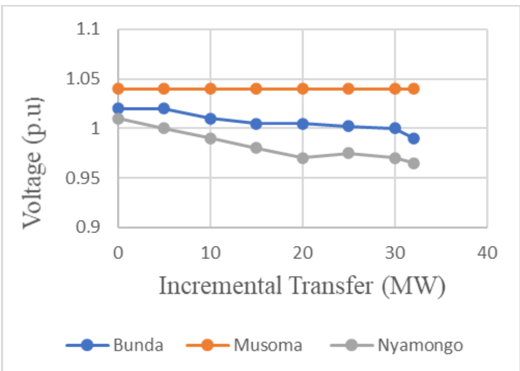
The P–V analysis conducted with 60 MVAr STACOM connected at Musoma shows the capability of line to transfer 88 MW with the system voltage within the limits. Figure 9(b) shows the voltage of Bunda and Nyamongo with a power increment to 34 MW.

The system stability assessment done by conducting the dynamic study with the network being subjected to disturbance scenario. Prior to disturbance the system was stable with voltage at Bunda being 1.02 p.u. (blue), Musoma 1.03 p.u. (green) and Nyamongo 0.985 p.u. (red) as described below;

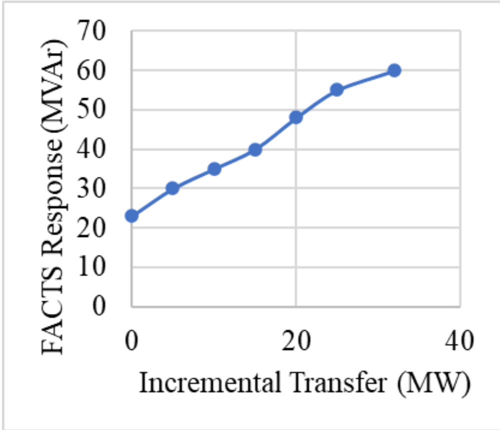
Scenario 1 increase of 10 MW load at Nyamongo: During the disturbance at 5 sec a load of 10 MW was switched in the disturbance as seen in Figure 9(c) the voltage at all substations drops and immediately rises and stabilizes at their new steady-state values. All the system voltages for pre-disturbance and post-disturbance are within the limits.

Scenario 2 tripping of 132/66/33 kV, 15 MVA transformer at Bunda Substation: During the disturbance at 5 sec a 132/66/33 kV,15 MVA transformer tripped as seen in Figure 9(d), the voltages raised to 1.1 p.u. and immediately lowered and stabilized at their steady-state values which is similar to the original steady state values. The voltages at pre-disturbance and post-disturbance are within the limits and the FACTS device response stabilized the network.

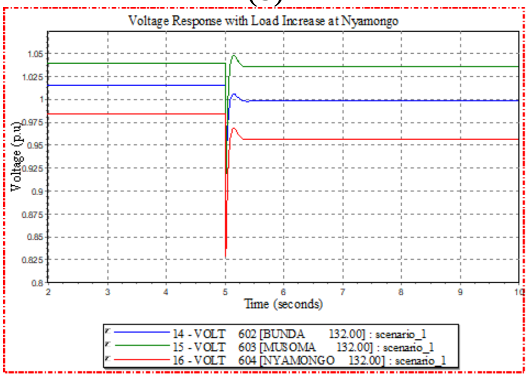
Scenario 3 three phase fault on 33 kV network at Musoma substation: The fault was applied for 120 ms then cleared, and the system was simulated for 12 sec. During the three-phase fault at 5 sec the voltages fluctuate and immediately gained its stability as seen in Figure 9(e). The response of the FACTS device by injecting or absorbing the reactive power plays a great role in stabilizing the system as seen in Figure 9(f).



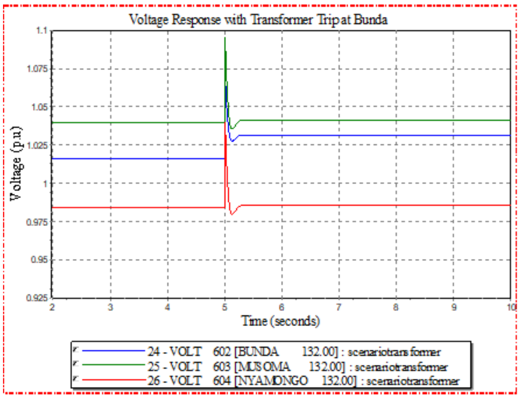
(a)



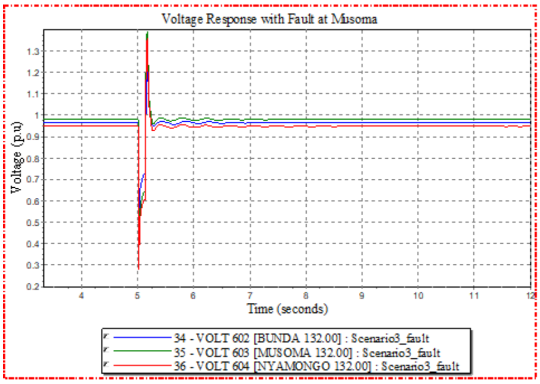
(b)



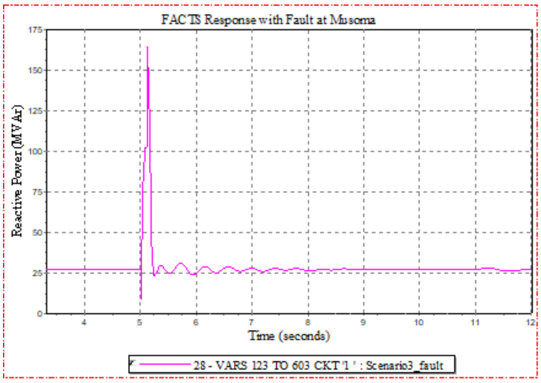
(c)



(d)



(e)



(f)

Figure 9: Simulation results for the network with FACTS (a) Voltage profile, (b) P–V analysis FACTS response and (c), (d), (e), (f) stability analysis.

CONCLUSION

In this paper, modelling and optimization of the FACTS device for 132 kV Mwanza-Musoma-Nyamongo power network was presented. This network was observed to have poor voltage profile and doesn't support increase of system load due voltage collapse. Therefore, it required the compensation in order to ensure an improved voltage profile, support load increase and reduce system losses. To attain these, the optimization of FACTS device was necessary to ensure accurate sizing and location of the compensation. The optimization was conducted by both the Sensitive method and particle Swarm Optimization (PSO) technique, finding the optimal location, size and type. The optimization results shows that the PSO technique is more precise and less time consuming as compared to the sensitive method.

The 132 kV Mwanza-Musoma-Nyamongo network with a 60 MVAr STATCOM at Musoma was then modelled and studied. The system was built and tested using PSS/E software Version 35. Different scenarios were successfully tested to validate the performance of the entire system. The optimized FACTS device observed to improve the system stability, the system power losses reduced by 14% and voltage deviation improved by 84%. Additionally, the economic analysis confirms that reducing transmission losses translates into significant cost savings for the utility. The payback period observed to be 13 months, making the investment in FACTS devices a viable solution for TANESCO. The Enhanced voltage stability will minimize disruptions and supports power grid reliability, which is essential for sustainable economic development and industrial operations in Tanzania.

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