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RESEARCH ARTICLE

FACTS for Effective DER Integration into the Georgia Distribution Grids

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ABSTRACT

In recent decades, the integration of distributed energy resources (DER), primarily solar and wind, has transformed distribution grids from passive to active systems, creating challenges for grid controllability and asset utilization. Due to the intermittent and unpredictable nature of DER, expectations of improved voltage stability and profiles are often unmet in real-world operations. This has introduced significant issues for Distribution System Operators, particularly concerning voltage control and asset aging. Traditionally, voltage regulation relied on transformer tap changers, which are not equipped to handle the fast, dynamic changes caused by DER. Frequent tap adjustments accelerate transformer aging, while weak grid connections, such as in rural or mountainous areas, can lead to voltage collapse. Additionally, mismatches between generation and demand often cause active power flow to exceed infrastructure limits, leading to renewable energy curtailment or restricted grid connections. This study examines a weakly connected distribution grid in a mountainous region of Georgia, integrating 200 kW rooftop solar photovoltaic (PV) systems, a 200 kW ground-mounted solar plant, and a 200 kW hydropower plant. Due to the high costs and geographical constraints associated with network reinforcements in such regions, the study explores the deployment of distribution Flexible alternating current (AC) Transmission Systems (FACTS) devices, specifically Static Volt-Ampere-Reactive (VAR) Compensator (SVC) devices, as an effective solution. The study focuses on how improvements can be achieved through reactive power compensation and advanced voltage regulation, addressing voltage instability, and enhancing power flow management. Multidomain analysis highlights the effectiveness of SVC devices in managing the challenges of DER integration while deferring costly grid reinforcements.

Index Terms—Distribution grid, flexible AC transmission systems (FACTS), renewables

I. INTRODUCTION

In Georgia, the existing distribution system was originally designed for unidirectional power flow. However, the integration of generation sources into the distribution system has resulted in bidirectional power flow, transforming the previously passive distribution system into an active one. This shift has been particularly evident following the introduction of DER support mechanisms, such as the net metering system. Under the net metering system, any interested party can apply to connect Renewable Energy Sources (RES) with a capacity below 500 kW to the Distribution System Operators (DSO) for self-consumption. If excess electricity is generated, it can be supplied to the distribution company, and the generator receives reimbursement. The increasing number of Solar Power Plants (SPPs) under the net metering system has significantly accelerated this transition. However, the integration of DER into the distribution grid presents challenges for asset utilization and controllability for DSOs in Georgia. These challenges have a wide spectrum, including voltage fluctuations, load management complexities, and harmonic distortions caused by inverters, which impact power quality and system stability [1]. These issues are primarily caused by the variable and intermittent nature of solar energy, which constitutes the largest share of DER in the country [2].

Considering that the distribution grid was originally designed to be passive, voltage regulation was primarily handled by transformer tap changers. Generally, the tap changer position is adjusted based on voltage levels, which depend on nodal voltage and loading. However, with the integration of intermittent DERs, their rapidly changing active and reactive power patterns pose significant challenges. Transformer tap changers either cannot respond quickly enough or, if they do, experience accelerated aging. Such operational practices may lead to damaged or faulty assets, curtailed consumers, and a reduced level of electricity supply security. Additionally, the rural distribution network in Georgia is weak and already aged.

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During peak hours, it struggles to ensure bulk power transfer within its ampacity. Due to aging infrastructure, the overloading tolerance of these lines is very limited. As a result, DSOs must either curtail renewable generation or invest in grid rehabilitation. In mountainous regions of Georgia, harsh climate conditions and complex geographical terrain further complicate strengthening and adapting the distribution network. Such upgrades require significant investments and time.

Taking into account the above-mentioned challenges, it can be concluded that DER-dedicated voltage and power flow control, as well as distribution asset aging, are pressing issues in Georgia. To address voltage and power flow control challenges in a DER-integrated distribution grid, one of the distribution grid sections in Georgia will be modeled and simulated.

An effective solution proposed in the study is the deployment of distribution Flexible AC Transmission Systems (FACTS) devices. These technologies, which are not limited by geographical constraints, offer flexible and fast response times to enhance voltage profiles, improve power flow control, and mitigate asset aging. Static reactive power compensators (SVCs) play a pivotal role in enhancing the performance and stability of power grids. These devices dynamically regulate reactive power, thereby improving voltage stability, reducing power losses, and mitigating voltage fluctuations. The study presented in [3] investigates the impact of SVC integration on power grids, emphasizing its ability to stabilize voltage profiles during load variations and grid disturbances. The findings demonstrate that SVCs effectively enhance the grid's operational efficiency by ensuring optimal reactive power balance under diverse operating conditions [3].

In [4], the importance of SVCs in enhancing voltage stability and improving voltage profiles within power systems is emphasized. SVCs are recognized as vital components for dynamically managing reactive power to stabilize voltage levels. By mitigating voltage fluctuations, they play a crucial role in ensuring grid reliability, particularly during load variations and disturbances. The study highlights their rapid and adaptable compensation features, which strengthen overall system stability and help prevent voltage collapse.

A 2023 comparative analysis evaluated the dynamic performance of SVCs and Static Synchronous Compensators in mining expansion projects. The study demonstrated that both devices effectively enhance voltage stability, with SVCs providing a cost-effective solution for dynamic reactive power compensation, thereby preventing voltage collapse during load variations and disturbances [5].

In [6], the application of SVCs for improving power system voltage stability is analysed. The findings suggested that integrating SVCs enhances voltage control mechanisms, supporting the integration of renewable energy sources into the grid.

In [7], the impact of SVC integration on voltage stability in heavily loaded transmission networks was examined. The results highlighted that proper placement of SVCs minimizes power flows in overloaded lines, reduces system losses, and enhances the overall stability of the power grid.

Furthermore, a 2024 study investigated the enhancement of power system transient stability using an SVC based on a fuzzy logic controller (FLC). The findings revealed that the proposed SVC-FLC improved the system's transient stability by reducing the maximum rotor angle difference and settling time compared to conventional Proportional-Integral (PI) controllers. This improvement indicates a more stable and resilient power system capable of better handling disturbances and maintaining stability under fault conditions [8].

In [9], an optimization challenge is explored to minimize network losses by integrating hybrid system reconfiguration, expansion, and the placement of SVCs and shunt capacitors, considering time-varying electricity consumption. To address this, the paper proposes an efficient economic module for generating variable loads in large-scale network reconfiguration, expansion, and reactive power control. Tested on two real distribution systems, the model demonstrated faster computation, higher precision, ease of application, and cost-effectiveness compared to conventional peak-load and variable load-based approaches with fixed capacitors and variable VAR compensators.

The selected distribution grid is located in a mountainous region of Georgia, characterized by aged and weak infrastructure. This region also experiences harsh climate conditions, particularly in winter, when road closures restrict residents' access to the rest of the country. Therefore, ensuring a reliable and secure electricity supply in this area is critical for the well-being of local citizens.

Main Points

- Aging distribution grids often struggle with insufficient reactive power support, leading to voltage instability, especially with increasing renewable energy integration. Rapid voltage fluctuations from intermittent generation strain the system, causing operational challenges, particularly in regions with stressed infrastructure.
- Deploying Static Var Compensators enhances voltage stability, reduces transformer tap-changer operations, and mitigates overloading on critical distribution lines. These improvements ensure efficient grid performance under varying load conditions.
- Simulation results proved that Static Var Compensators provide a fast and flexible solution for voltage control in rural areas, strengthening grid reliability and enabling seamless renewable energy integration without major infrastructure upgrades.

II. SYSTEM DESCRIPTION

The portion of the distribution system modeled in this study is illustrated in Fig. 1. The modeled system includes one 200 kW Hydro Power Plant (HPP) and two 200 kW Solar Power Plants (SPPs), both connected to the grid through the same 10 kV busbar. The main radial system consists of a 35 kV transmission line, which links the modeled system to the 35 kV main distribution grid. Power is then transferred to consumers via a 10 kV distribution substation (S/S),

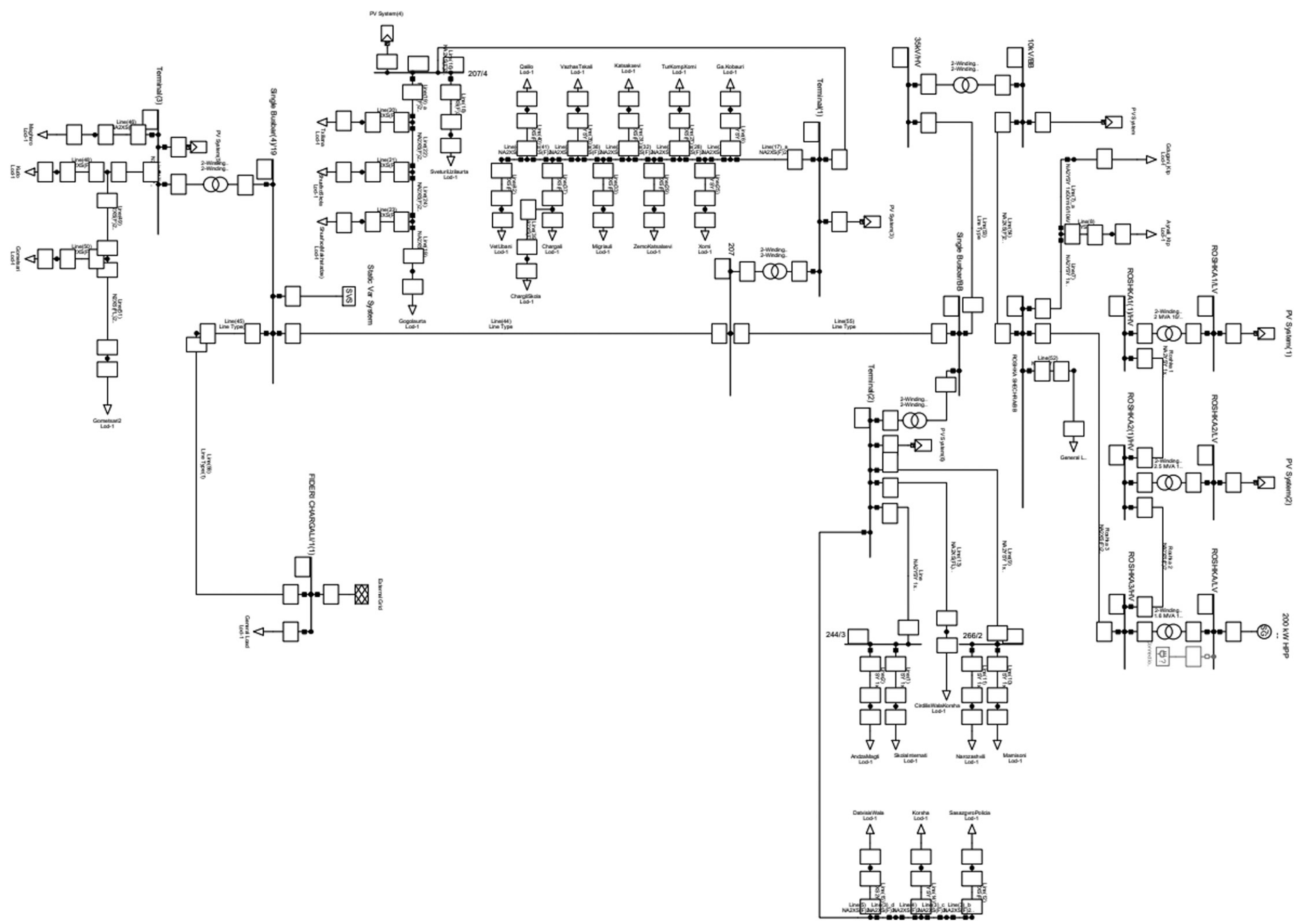

Fig. 1. Single-line diagram of the modeled distribution system.

where aggregated loads and rooftop solar PV systems are connected. An SVC, a FACTS device, is included in the model as a source of reactive power support.

III. SYSTEM MODELLING

The modeling of the existing grid components is based on real parameters and data from the distribution network. The HPP is modeled as a synchronous generator that regulates voltage at its node but provides limited reactive power support to the system [10]. Given the hydrology of the modeled region, its power generation is assumed to remain constant throughout the day.

The SPPs are modeled as constant direct current (DC) sources, with generation dependent on weather conditions and solar irradiation. The DC source control operates at a unity power factor. Weather and solar irradiation data were obtained from [11] for a typical summer day in the modeled region. The daily generation patterns of the large and small SPPs are depicted in Fig. 2.

The diagram of the modeled FACTS device is given in Fig. 3. The FACTS system contains three blocks [12]:

1. Thyristor Controlled Reactor – 30 kVAr
2. Thyristor Switched Capacitors – 400 kVAr
3. Fixed Capacitor – 250 kVAr

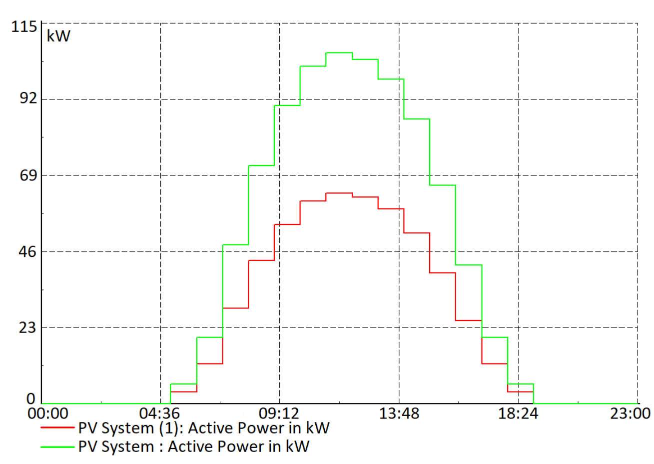

Fig. 2. Solar power generation pattern over a typical summer day.

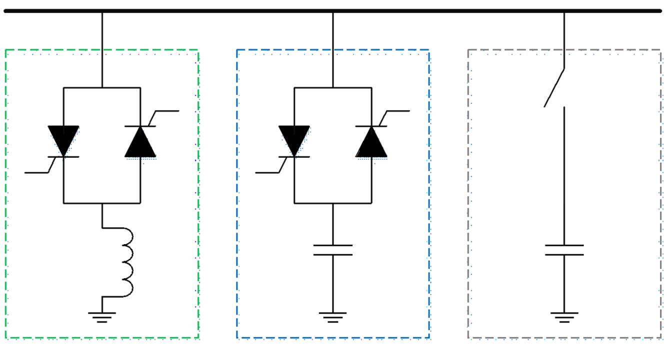

Fig. 3. Modeled Static Volt-Ampere-Reactive (VAR) Compensator.

The system is connected to the 10 kV bus of the modeled network. The control logic is balanced, meaning there is no separate control for per-phase compensation. This approach is justified because the network does not experience phase imbalance issues.

The primary challenge in the network is a low voltage profile caused by aging assets, such as cables, overhead lines, and transformers with limited transfer capacities. To address this, the introduced FACTS system is primarily capacitive, with a small inductive capacity reserved for rare cases when high voltage profiles occur during minimum load scenarios.

The main distribution grid is represented as an infinite bus that operates at 35 kV at 50 Hz. The 35 kV and 10 kV lines and cables were modeled with lumped parameters. All transformers connected to the grid are modeled as two winding transformers with automatic tap-changers that are set to control voltage automatically.

The system load connected at 0.4 kV was represented as an aggregated load on the 10 kV side. The typical load profile of the modeled distribution network is represented below in Fig. 4 below.

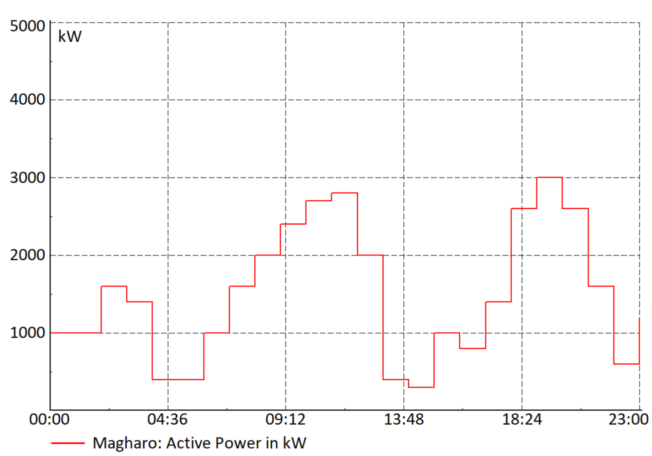

Fig. 4. System's typical daily loading profile.

IV. SIMULATION RESULTS

Different simulations were performed to analyze the performance of the existing distribution network with and without the FACTS device. Initially, an Electromagnetic Transients (EMT) simulation was conducted to evaluate the voltage profile under rapidly changing solar generation conditions caused by a cloudy day. In the first simulation, the FACTS device was switched off, and the simulation was run for 20 seconds. In the second simulation, the FACTS device was switched on, and the simulation was run for the same duration. Fig. 5 presents the results for the bus where the largest SPP and the largest load are connected.

As seen from Fig. 5a, the voltage profile is unstable and follows variations in solar generation. It is characterized by sharp changes in voltage magnitude and even violates the statutory limit (−10%) at the 17th second where the voltage magnitude is below 0.9 p.u. Such fast variations of the voltage profile negatively affect connected electrical devices and shorten their life cycle. At the same time, this results in the interruptions of the electricity supply to the load and contradicts the guaranteed security of the electricity supply.

This is mainly due to the lack of fast-acting reactive power support since the transformer tap-changers are restricted by switching time from one output to another and hence cannot provide such a rapid response.

On the other hand, Fig. 5b shows the voltage profile at the same busbar after switching the FACTS device, in this case, SVC. As observed, the voltage variation has a much more stable dynamic, it is not characterized by sharp spikes and the voltage drop does not exceed 4%.

In the second scenario, quasi-dynamic analyses for 24 hours were carried out to check the voltage profile in the system with and without the FACTS device.

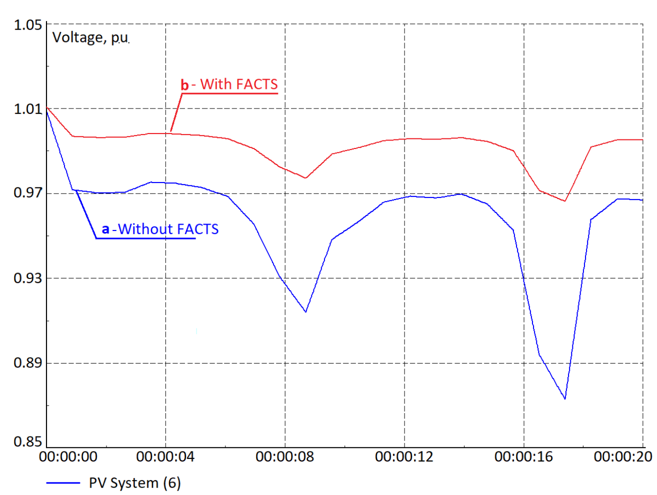

Fig. 5. Voltage profile during fast-changing solar generation a) without FACTS and b) with FACTS.

At first, the quasi-dynamic simulation was run for 24 hours to observe voltage magnitudes at the most loaded busbars without a FACTS device. The results are represented in Fig. 6 below.

As seen from Fig. 4, generally the modeled distribution grid is characterized by a lower voltage profile (below 1 p.u.). During the morning peak (09:00–12:00) voltage at all observed buses drops below the statutory limit (−10%) up to as low as 0.84 p.u. and it restores back only after a demand reduction and is kept within acceptable limits. During the evening peak (17:30–20:00) when the demand starts to increase, the voltage begins to drop below acceptable limits to 0.81 p.u. due to insufficient reactive power. Once the demand starts to decrease, the voltage magnitude recovers. It should be noted that during the morning peaks the voltage drop is lower compared to the evening peaks. This is because SPPs generation tends to reach its maximum output from 09:00 and at 17:30, when the evening peaks start, SPPs generation tends to decrease and reaches 0 kW at 18:30.

In addition to violating voltage statutory limits, such variations in the voltage profile cause transformer tap changers to adjust more frequently when other reactive power sources are introduced. Given the aging infrastructure of the existing network, this frequent adjustment significantly increases the probability of transformer failure.

As a next step, a quasi-dynamic simulation was conducted for 24 hours to observe voltage magnitudes at the same busbars as in the previous case, but with the FACTS device activated. The simulation results are presented below in Fig. 7.

As observed in Fig. 7, switching on the SVC significantly improves the voltage profile, ensuring it does not drop below 0.98 p.u., even during peak hours.

The third scenario investigated the impact of FACTS devices on the distribution network's loading. A 24-hour quasi-dynamic simulation was conducted to determine whether the lines connected to the largest loads could ensure the security of supply without requiring renovation or strengthening of the modeled network. Fig. 8 presents the simulation results without FACTS, while Fig. 10 shows the results with FACTS.

The simulation results Fig. 8 demonstrate that the 10 kV Line 46 is overloaded by 123% and 135% during morning and evening peaks, respectively. Similarly, the 10 kV Line Roshka 3 is also overloaded during evening peaks. In contrast, the 35 kV line operates at a more moderate load, reaching only 92% during evening peaks.

Despite the presence of transformers with tap changers, the network still suffers from insufficient capacitance, leading to overload on the 10 kV line that supplies the majority of the system load. Overloading and subsequent heating of the aging assets significantly increase the probability of grid infrastructure failure, ultimately reducing the level of security of the electricity supply.

Overloading of assets also contributes to increased grid losses. As shown in Fig. 9 above, the system losses in this scenario amount to 43.9 kW.

Fig. 10 illustrates the influence of the FACTS device on network loading. After switching on the SVC, line loading remains within the acceptable range (below 100%) throughout the day.

Additionally, network losses are significantly reduced, halving to 17 kW, as shown in Fig. 11.

V. CONCLUSIONS

The study aimed to evaluate the challenges of the existing distribution grid infrastructure in Georgia under the integration of DERs

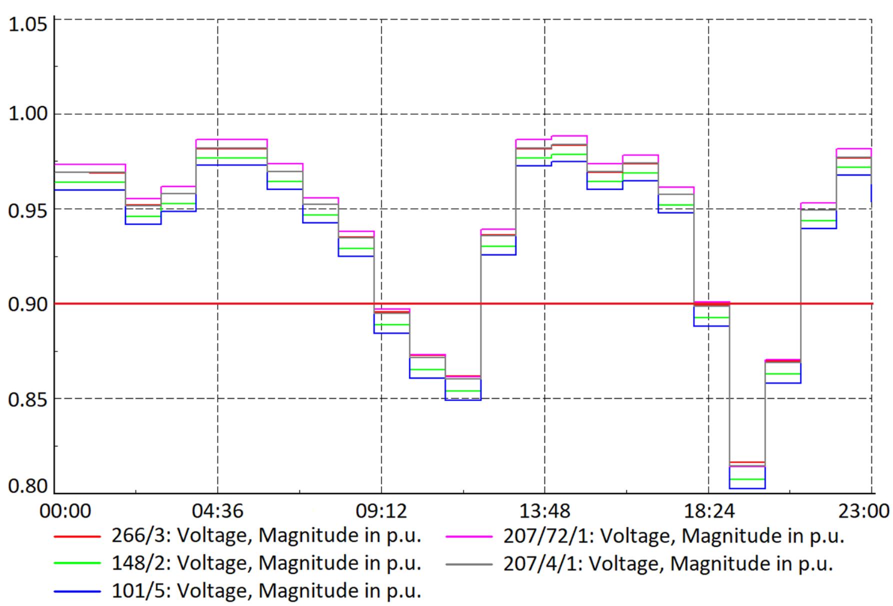

Fig. 6. Voltage profile at the most loaded busbars without FACTS.

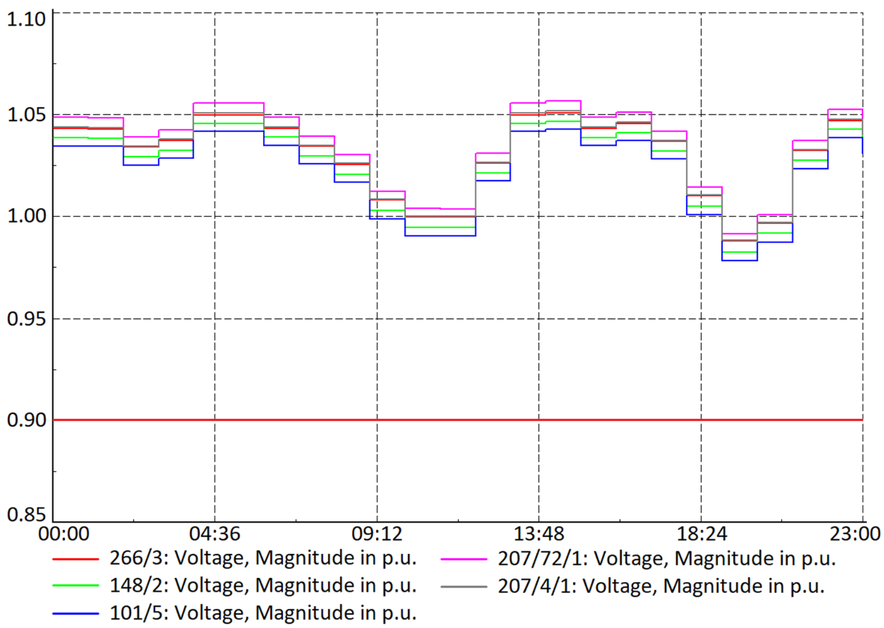

Fig. 7. Voltage profile at the most loaded busbars with FACTS.

and assess the impact of FACTS devices, specifically the SVC, on improving system performance. The following key findings were observed:

The existing grid struggles to ensure the security of electricity supply due to aging infrastructure and insufficient reactive power support. The integration of variable renewable energy sources like solar power causes rapid voltage fluctuations, further straining the system.

Introducing an SVC significantly enhanced the system's voltage profile, reduced the frequency of transformer tap-changer adjustments, and mitigated overloading on the most critical 10 kV lines during peak hours. After integrating the FACTS devices, line loading

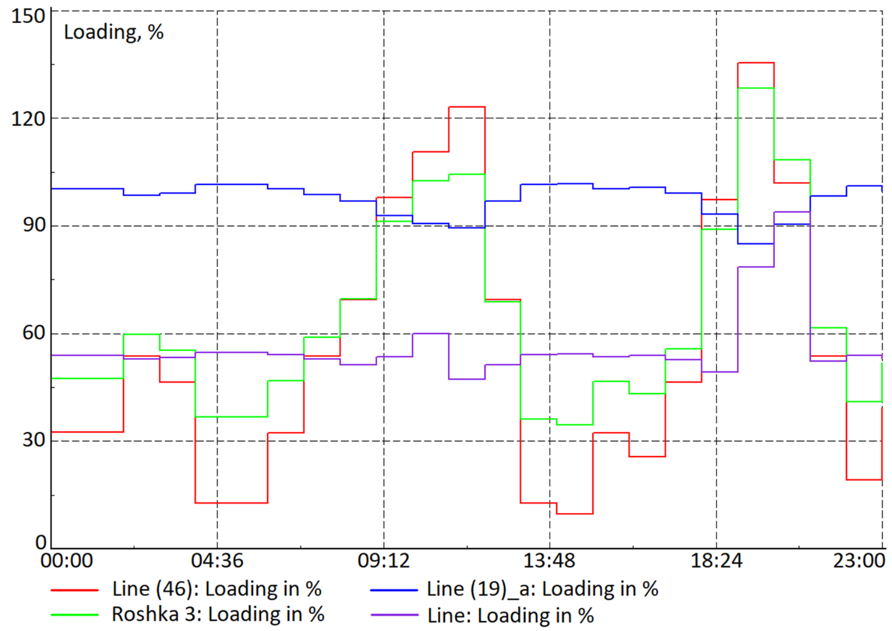

Fig. 8. Lines loading without FACTS.

```
------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                             | Grid Summary              |
------------------------------------------------------------------------------------------------------------------
|  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 %         |
------------------------------------------------------------------------------------------------------------------
| Grid: Grid                     System Stage: Grid         | Study Case: Study Case | Annex:         / 1        |
------------------------------------------------------------------------------------------------------------------
| Grid: Grid                                     Summary                                                          |
|----------------------------------------------------------------------------------------------------------------|
| No. of Substations       12  | No. of Busbars      15  | No. of Terminals       210 | No. of Lines         64  |
| No. of 2-w Trfs.          7  | No. of 3-w Trfs.     0  | No. of syn. Machines   1   | No. of asyn. Machines  0 |
| No. of Loads             33  | No. of Shunts        1  | No. of SVS             1   |                          |
|----------------------------------------------------------------------------------------------------------------|
| Generation             = 738.75 kW         -346.91  kvar       816.15 kVA                                      |
| External Infeed        = 0.00   kW        -4800.00  kvar      4800.00 kVA                                      |
| Inter Grid Flow        = 0.00   kW            0.00  kvar                                                      |
| Load P (U)             = 694.80 kW          587.86  kvar       910.12 kVA                                      |
| Load P (Un)            = 694.80 kW          587.86  kvar       910.12 kVA                                      |
| Motor Load             = 0.00   kW            0.00  kvar         0.00 kVA                                      |
| Grid Losses            = 43.95  kW         -936.31  kvar                                                      |
| Line Charging          =                   -984.03  kvar                                                      |
| Compensation ind.      =                      1.54  kvar                                                      |
| Compensation cap.      =                  -4800.00  kvar                                                      |
------------------------------------------------------------------------------------------------------------------
| Installed Capacity     = 1280.00 kW                                                                            |
| Spinning Reserve       = 301.25  kW                                                                            |
------------------------------------------------------------------------------------------------------------------
| Total Power Factor:                                                                                            |
| Generation             = 0.91 [-]                                                                              |
| Load/Motor             = 0.76 / 0.0 [-]                                                                        |
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Fig. 9. Grid summary without FACTS.

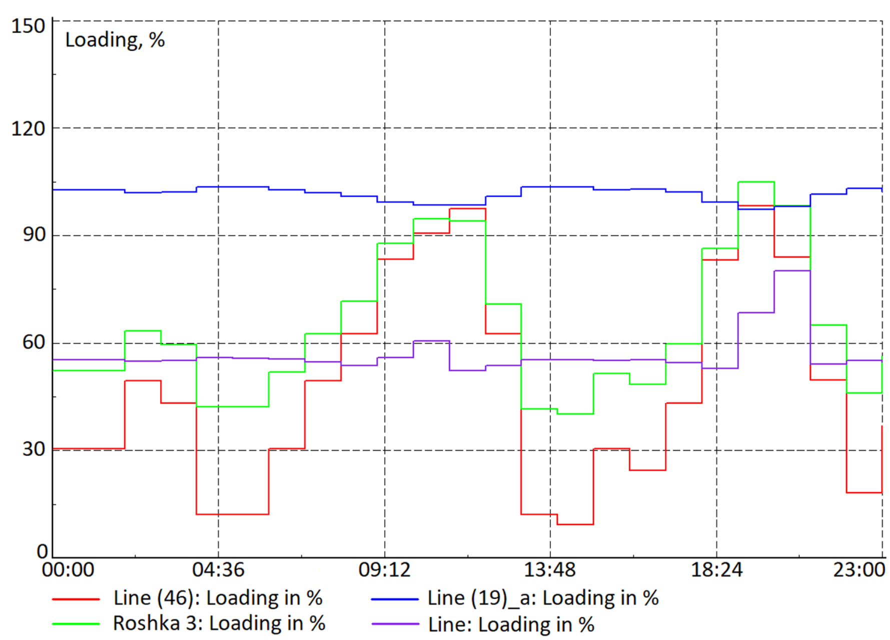

Fig. 10. Lines loading with FACTS.

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-----------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                           | Grid Summary                      |
-----------------------------------------------------------------------------------------------------------------------
|  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 %               |
-----------------------------------------------------------------------------------------------------------------------
| Grid: Grid                   System Stage: Grid          | Study Case: Study Case | Annex:       / 1                 |
-----------------------------------------------------------------------------------------------------------------------
| Grid: Grid                                  Summary                                                                  |
|----------------------------------------------------------------------------------------------------------------------|
| No. of Substations       12  | No. of Busbars     15   | No. of Terminals       210 | No. of Lines        64          |
| No. of 2-w Trfs.          7  | No. of 3-w Trfs.    0   | No. of syn. Machines     1 | No. of asyn. Machines  0       |
| No. of Loads             33  | No. of Shunts       1   | No. of SVS               1 |                                |
|----------------------------------------------------------------------------------------------------------------------|
| Generation             = 712.62 kW          -83.49   kvar      717.50 kVA                                           |
| External Infeed        = 0.00   kW        -4800.00   kvar     4800.00 kVA                                           |
| Inter Grid Flow        = 0.00   kW            0.00   kvar                                                           |
| Load P (U)             = 694.80 kW          587.86   kvar      910.12 kVA                                           |
| Load P (Un)            = 694.80 kW          587.86   kvar      910.12 kVA                                           |
| Motor Load             = 0.00   kW            0.00   kvar        0.00 kVA                                           |
| Grid Losses            = 17.82  kW         -545.21   kvar                                                           |
| Line Charging          =                   -569.41   kvar                                                           |
| Compensation ind.      =                      0.00   kvar                                                           |
| Compensation cap.      =                 -4926.14   kvar                                                           |
-----------------------------------------------------------------------------------------------------------------------
| Installed Capacity     = 1280.00 kW                                                                                  |
| Spinning Reserve       = 327.38  kW                                                                                  |
-----------------------------------------------------------------------------------------------------------------------
| Total Power Factor:                                                                                                  |
| Generation             = 0.99 [-]                                                                                    |
| Load/Motor             = 0.76 / 0.0 [-]                                                                              |
-----------------------------------------------------------------------------------------------------------------------
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Fig. 11. Grid summary with FACTS.

decreased by an average of 4–7%, while voltage levels improved by 4–5% in the downward direction and 12–15% in the upward direction. These findings align with the literature, which highlights that SVCs effectively maintain stable voltage profiles and improve system performance during rapid voltage variations, as discussed in [3-9].

The deployment of FACTS devices enables fast and flexible reactive power control, supporting the seamless integration of DERs without the immediate need for network rehabilitation. This solution is particularly advantageous for rural networks in mountainous regions, ensuring a reliable and secure electricity supply.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – G.A., T.E.; Design – G.A., T.E.; Supervision – G.A.; Resources – G.A.; Materials – G.A., T.E.; Data Collection and/or Processing – G.A.; Analysis and/or Interpretation – G.A., T.E.; Literature Search – G.A., T.E.; Writing Manuscript – G.A., T.E.; Critical Review – G.A., T.E.

Declaration of Interests: The authors have no conflicts of interest to declare.

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