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Power Quality Enhancement of a Radial Distribution Network Using PV Systems, SVCs, and Single-Tuned Passive Filters: A Case Study of the KO5 Feeder of Mekelle's electrical distribution network in northern Ethiopia

تحسين جودة القدرة في شبكة توزيع شعاعية باستخدام الأنظمة الشمسية ومعوضات القدرة والمرشحات التو افقية: دراسة حالة مغذيKO5 لشبكة توزيع الكهرباء في ميكيلي بشمال إثيوبيا

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Abstract: This study investigates the power quality in the KO5 feeder in Mekelle's electrical distribution network in northern Ethiopia; the KO5 feeder has a bad voltage profile, excessive power loss, significant harmonic distortion, and a low power factor. A primary goal of this research was to improve the KO5 feeder's system performance by combining photovoltaic (PV) arrays, Static VAR Compensators (SVCs), and single-tuned passive filters (STPFs) as part of a hybrid solution. A model for the system was developed and run with simulations using ETAP 19.0 in both full-load (FL) and 70% partial-load (70% FL) operating condition. The optimal size and location of PV arrays at buses 106 and 109 was identified through simulation analysis, while eight SVC units were installed at the weakest buses in the network in order to improve voltage level and the flow of reactive power. The harmonic analysis indicated that the 5th and 7th harmonic contributed most of the distortion, therefore, STPFs were designed and implemented to the buses with the highest amounts of distortion. The proposed configuration resulted in a large drop in the total amount of power losses within the system from 1.474 MW to 0.270 MW at FL and from 0.647 MW to 0.096 MW at 70% FL. Furthermore, the minimum bus voltage increased from 78.1% per unit (pu) to 91.9% pu at full load, and from 85.6% pu to 95.6% pu at 70% full load, as well as an increase in the total system power factor. Therefore, these results indicate an improvement in reactive power management for the distribution system. In addition, the total harmonic distortion (THD) has been minimized below 5%; so that it complies with the IEEE 519-2022 standards, thus, the results indicate that the combined insulation of PV arrays, SCVs and passive filters is an economical method to enhance voltage stability, reduce energy loss, improve power factor, and improve overall power quality on radial distribution systems.

Keywords: Power quality, Distribution networks, Photovoltaic array, Harmonic distortion.

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المستخلص: تتناول هذه الدراسة تحسين جودة القدرة الكهربائية في مغذي KO5 ضمن شبكة التوزيع الكهربائي لمدينة مكلي في شمال إثيوبيا، والذي يعاني من ضعف في ملف الجهد، وارتفاع الخسائر الكهربائية، ووجود تشوهات توافقية، وانخفاض معامل القدرة. تهدف الدراسة إلى تحسين أداء النظام باستخدام نهج هجين يدمج الألواح الكهروضوئية، ومعوضات القدرة غير الفعالة من نوع(Static VAR Compensator (SVC ، والمرشحات التوافقية أحادية الضبط. تم نمذجة النظام ومحاكاته باستخدام برنامج ETAP 19.0 تحت حالتي التحميل الكامل (FL) والتحميل الجزئي (70% FL).أظهرت النتائج أن الحجم والموقع الأمثل للألواح الكهروضوئية تحقق عند العقدتين 106 و109، في حين تم تركيب ثماني وحدات SVC بشكل استراتيجي عند العقد ذات الجهد المنخفض لتنظيم الجهد وتدفق القدرة غير الفعالة. أظهر تحليل التوافقيات أن التوافقيين الخامس والسابع هما المساهمان الرئيسيان في التشوه، وبناءً عليه تم تصميم وتنفيذ مرشحات توافقية أحادية الضبط عند أكثر العقد تأثرًا. أسفر تطبيق الحل المقترح عن انخفاض ملحوظ في الخسائر الكلية من 1.474 ميغاواط إلى 0.270 ميغاواط عند التحميل الكامل، ومن 0.647 ميغاواط إلى 0.096 ميغاواط عند التحميل الجزئي. كما تحسن أقل جهد في الشبكة من 78.1% إلى 91.9% عند التحميل الكامل، ومن 85.6% إلى 95.6% عند التحميل الجزئي، إلى جانب تحسن معامل القدرة الكلي للنظام، مما يعكس تحسن إدارة القدرة غير الفعالة. إضافةً إلى ذلك، انخفض التشوه التوافقي الكلي (THD) إلى أقل من 5%، محققًا متطلبات معيار-IEEE 519. 2022وتؤكد النتائج أن الدمج بين الألواح الكهروضوئية، ومعوضات SVC ، والمرشحات التوافقية يوفر حلًا عمليًا وفعالًا لتحسين استقرار الجهد، وتقليل الخسائر، ورفع معامل القدرة، وتعزيز جودة القدرة في شبكات التوزيع الشعاعية.

الكلمات المفتاحية: جودة القدرة، شبكات التوزيع، مصفوفة الخلايا الكهروضوئية ، التشوه التوافقي.

1 INTRODUCTION

The increased number of nonlinear load and distributed generation units have caused significant concerns in the operation of today's power grids with respect to "power quality" (Bhuiyan, 2011; Ghorbani & Mokhtari, 2015), as poor quality will result in a variety of problems including voltage deviations, harmonic distortion, higher power loss, and lower than normal power factors resulting in reduced system reliability, decreased operational efficiencies, and significantly shorter life expectancy for electrical apparatus (Karimyan et al., 2016).Distribution Systems are especially vulnerable to the previously mentioned power quality problems, particularly those that operate radially at voltages of medium or low voltage due to their high resistance-to-reactance R/X ratio and very limited ability to regulate voltage (Karimyan et al., 2016).

The increasing demand for electricity and concerns over the environmental impacts of traditional central station generation have accelerated the adoption of distributed generation (DG) technologies, including PV systems. PV systems have gained significant attention as a source of renewable energy because they are relatively easy to integrate into an existing grid network, modular structure, and produce clean energy (Ackermann et al., 2001; Prakash & Khatod, 2016). The proper integration of PV systems into the grid can lead to a reduction in active power loss, improved voltage profile, and reduced greenhouse gases (Juma, 2018). However, the addition of large amounts of PV DG to the grid will also create several new technical challengesm such as the possibility of reverse power flow, voltage rise, a degraded power factor, and increased harmonic distortion due to the use of inverters (Khalid et al., 2024; Woldeyohannes, 2021).

The Reactive Power Compensation is very important to maintain the Voltage Stability and improve the power Quality in Distribution Networks. The static VAR Compensators (SVCs) classified as shunt Flexible AC Transmission System (FACTS) devices have been widely used to perform the Dynamic Reactive Power Control and the Voltage Regulation. SVC provides faster response, greater flexibility in the operation of the reactive power and better performance under variable load conditions compared with the traditional capacitor banks (Fernando, 2017; Molla & Kuo, 2020). In addition, some studies have shown the ability of SVCs to reduce power losses and improve voltage profiles in radial distribution systems (Alemu & Mesfin, 2025; Khan& Khalid, 2019). However, the Interaction between SVCs and inverter-based DG Sources, especially regarding the Harmonic Performance is still an important topic, which needs to be studied in depth.

Distortion from harmonics is a major problem with regard to power quality in present day power systems. Nonlinear loads and devices that utilize power electronics generate most of the harmonic content such as PV inverters, SVC thyristor-controlled reactors, adjustable speed drives and uninterruptible power supplies (Kazem, 2013). Excessive harmonic affects overall system reliability, leads to overheating of transformers and cables, malfunction of protective device, improper metering and decreased power factors (Omar, 2021). International Standards such as IEEE 519-2022 define strict limits on both voltage and current harmonic to maintain a safe and reliable system operating environment.

To reduce harmonic distortion many methods were implemented, including Active Filters, Hybrid Filters, Passive Filters. Among others, The Single-Tuned Passive Filter (STPF) is most commonly used due to its ease of implementation, lower cost, and the fact that it can provide both harmonic suppression and Reactive Power Compensation for the DG system (Mardawi, 2018; Yadav et al., 2022). STPFs, specifically, are very good at reducing dominant low order harmonics like the 5th and 7th, which are typically produced by Inverter-based DG Systems (Kahar & Zobaa, 2018).

There are many research papers that have evaluated the enhancement of power quality in the Ethiopian distribution systems. Gebregergs (2018) has used loss sensitivity factor and Particle Swarm Optimization to optimize the placement of DG units in the Mekelle distribution system; the results showed significant reduction in losses and improvement in voltage levels, however no consideration was given to the harmonic distortion. In addition to this Alemu & Mesfin (2025), and Khan. & Khalid (2019) examined the use of SVC for the purpose of voltage regulation and loss minimization, although they did not incorporate renewable DG units nor harmonic mitigation methods. Woldeyohannes (2021) demonstrated the major presence of the fifth and seventh harmonic in the grid connected photovoltaic systems in Ethiopia, thus proposed a passive filter solution, but without quantitative system-level validation

The majority of prior research have focused upon individualized solutions, such as PV integration, reactive power compensation, or harmonic mitigation in isolation thus, relatively little research has been conducted regarding a coordinated, hybrid solution which will simultaneously address power quality issues associated with power factor, harmonic distortion, voltage stability and power loss across various load levels. Thus, the primary objective of this study is to address this knowledge gap through the development of an integrated framework that includes optimally placed PV arrays, decentralized SVC units, and single-tuned passive filters. Utilizing the KO5 feeder of Mekelle's distribution system as a case study through using ETAP simulation based analysis, the results of this study provide a complete analysis of enhanced power quality within radial distribution systems while satisfying IEEE 519-2022 standards.

In this research, an integrated hybrid system is developed. The integrated hybrid system of PV generation with decentralized SVC based for reactive power compensation and single tuned passive harmonic filter are optimized to be used simultaneously to enhance overall voltage stability while reducing total power loss, improving the power factor and ensuring compliance with IEEE 519-2022 harmonic requirements in a radial distribution network during changing loads.

2 THEORETICAL BACKGROUND AND PROPOSED RESEARCH MODEL

2.1 Distributed Generation and Photovoltaic Systems

Distributed Generation (DG) refers to small-scale power generation units that are connected directly to the distribution network rather than the transmission system. DG technologies have gained increasing importance due to their ability to improve system efficiency, enhance voltage profiles, and reduce technical losses. Among various DG technologies, photovoltaic (PV) systems are widely adopted because of their clean energy production, modular structure, and suitability for integration into radial distribution networks. (TAKELE, 2020; Molla & Kuo, 2020; Fernando, 2017) . The common types and capacity of DGs that are applied to distribution network are illustrated in Figure 1.

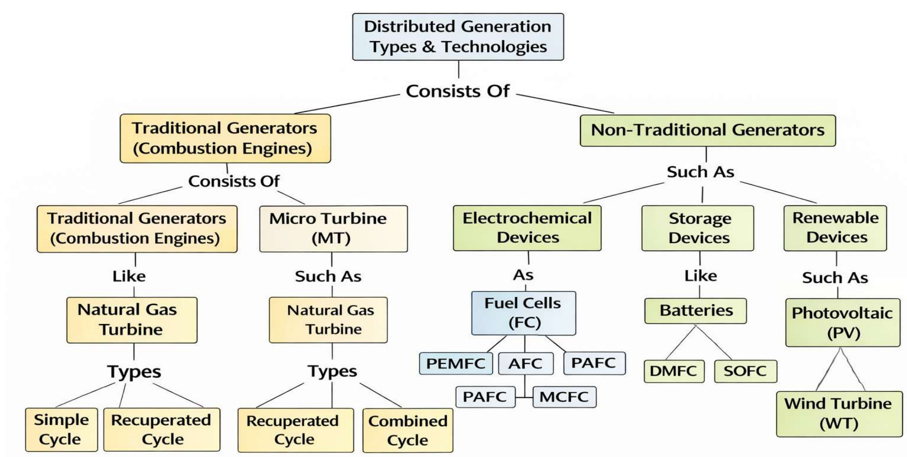


Figure 1. Types and Capacities of Distributed Generation (Fernando, 2017)

Solar Photovoltaics (PV) produce electricity through the Photovoltaic Effect, in which energy from sunlight energizes the electrons in a semiconductor material creating direct current (DC) electricity. A typical PV System consists of PV Cells that are connected to each other as Modules; the various modules can be connected together to create an array of PV's as shown in figure 2. The hierarchical structure of PV Systems allow for variable sizes of PV Systems to meet individual customer needs.

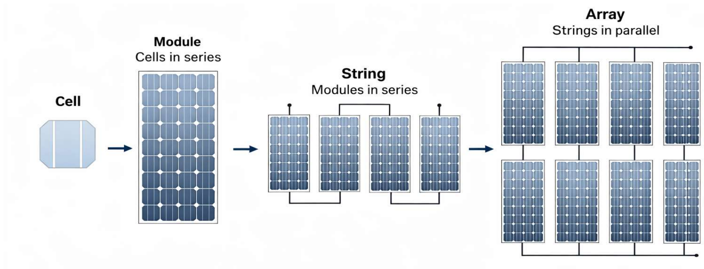


Figure 2. Configuration of PV Cell, Module, and Array (Alaa &Gharib ,2020)

From a power system perspective, the integration of PV-based DG reduces the active power demand supplied by the upstream utility, leading to lower line currents and reduced active power losses. The reduction in line losses can be expressed as (Mieraf, 2022). :

$$P_{loss} = I^2R \tag{1}$$

Where I represent the line current and R is the line resistance. By decreasing current flow through local generation, PV systems contribute significantly to loss minimization, particularly in feeders with high R/X ratios.

In addition to reducing losses, PV integration has a positive effect on voltage profiles for those buses that are farther away from a substation. Nevertheless, if too many PVs penetrate into a network it will result in the operational problems like "reverse power flow" and "voltage rise" during light load conditions. Consequently, the optimal size and location of PVs need to be identified to achieve the maximum benefit of PVs while ensuring that the system remains stable.

2.2 FACTS Devices and Static VAR Compensator (SVC)

FACTS Devices are a class of Power Electronic-Based Controllers that are used to Enhance Controllability, Stability & Transfer Capability of Electrical Power Systems. In Distribution Networks, FACTS Devices are Mainly Used for Voltage Regulation, Reactive Power Compensation and Loss Minimization. FACTS Devices can be classified into Shunt, Series & Combined Controllers; as seen in Figure 3. Among these devices, the Static VAR Compensator (SVC) is the Most Widely Used Class of Shunt FACTS Device Due to Lower Cost Compared to Other Types of FACTS Devices and Maturity of Technology, as well as Effective Performance Under Steady-State Conditions (TAKELE, 2020; Molla & Kuo,2020; Fernando,2017).

An SVC is connected in shunt to the power system and operates by dynamically injecting or absorbing reactive power in response to bus voltage variations. When the bus voltage drops below the reference value, the SVC operates in capacitive mode and supplies reactive power to the system. Conversely, when the bus voltage exceeds the reference value, the SVC operates in inductive mode and absorbs reactive power. This behavior allows the SVC to maintain voltage levels within acceptable limits. (Kumar, 2019). The steady-state voltage–current (V–I) characteristic of an SVC is illustrated in Figure 3. The relationship between bus voltage and SVC current is determine by (TAKELE, 2020):

$$V = V_{ref} \pm X_{slope} \cdot I_{svc} \tag{2}$$

Where V_{ref} is the reference voltage and X_{slope} represents the slope reactance of the SVC. This characteristic enables smooth and continuous voltage regulation within a predefined operating range.

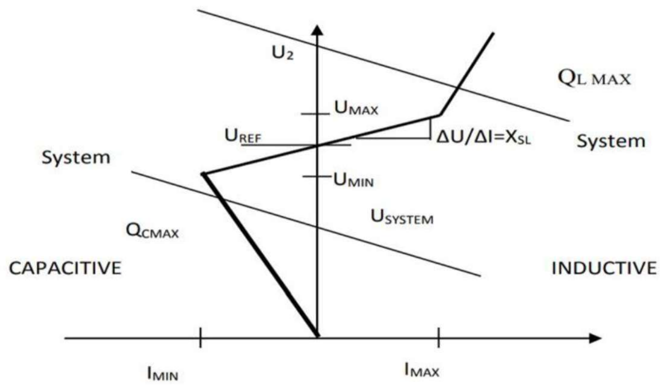


Figure3. V-I Characteristic and Control Ranges of SVC for Different Modes of SVC (TAKELE, 2020)

The reactive power injected or absorbed by the SVC can be calculated using (TAKELE, 2020):

$$Q_{SVC} = \frac{V^2}{X_{SVC}} \qquad (3)$$

Where V is the bus voltage and X_{SVC} is the equivalent reactance of the SVC. The proper sizing and placement of SVC units significantly enhance voltage stability, improve power factor, and reduce technical losses, especially in radial distribution networks with varying load conditions.

2.3 Power Quality and Harmonics

Power Quality is the ability of a network to maintain voltage and current waveform characteristics as near as possible to the ideal sinusoid with rated magnitude and rated frequency (Sannino et al., 2003). Any deviation from this condition constitutes a Power Quality Disturbance, which can include voltage fluctuations, voltage unbalances and waveform distortions. Among these disturbances, harmonic distortion has become one of the most critical issues in modern distribution networks resulting primarily from the growing number of power electronic device.

Harmonics are sinusoidal components of voltage or current whose frequencies are integer multiples of the fundamental frequency (Sood, 2018). Nonlinear loads such as PV inverters, adjustable speed drives, uninterruptible power supplies, and thyristor-based compensators draw non-sinusoidal currents, which introduce harmonics into the network .The presence of harmonics causes additional losses, overheating of transformers and cables, malfunction of protective devices, and deterioration of power factor. (Omar, 2021).

Total Harmonic Distortion (THD) is the most widely used index for quantifying harmonic distortion and is defined as (Bhuiyan, 2011):

$$\mathrm{THD} = \frac{\mathrm{sqrt}(\Sigma\, \mathrm{Fi}^2)}{F_1} \quad (4)$$

Where F_i represents the RMS value of the i^{th} harmonic component and F_1 is the RMS value of the fundamental component.

In addition to THD, Individual Harmonic Distortion (IHD) is used to evaluate the contribution of a specific harmonic order and is expressed as (Bhuiyan, 2011):

$$\mathrm{IHD} = \frac{\mathrm{F}_i}{\mathrm{F}_1} \quad (5)$$

International standards such as IEEE 519-2022 specify permissible limits for voltage and current harmonics to ensure safe and reliable system operation. For distribution systems operating below 69 kV, the voltage THD should not exceed 5%, while individual harmonic components should remain within specified limits

2.4 Single-Tuned Passive Filters

Single-Tuned Passive Filters (STPFs) are widely used for harmonic mitigation in distribution networks due to their simple structure, low cost, and effectiveness in eliminating dominant low-order harmonics. An STPF consists of a series RLC circuit tuned to a specific harmonic frequency, providing a low-impedance path for harmonic currents.

The required reactive power of the filter capacitor is determined based on power factor correction requirements (Ishaya et al., 2023):

$$\mathrm{Qc} = \mathrm{P}\left[\tan\left(\cos^{-1}(\mathrm{PF0})\right) - \tan\left(\cos^{-1}(\mathrm{PF1})\right)\right] \quad (6)$$

The capacitive reactance and capacitance of the filter are given by (Ishaya et al., 2023):

$$\mathrm{Xc} = \frac{\mathrm{V}^2}{\mathrm{Qc}} \quad (7)$$

$$\mathrm{C} = \frac{1}{2\pi \mathrm{fXc}} \quad (8)$$

The inductive reactance required to tune the filter to the h^{th} harmonic order is (Ishaya et al., 2023)

$$X_L = \frac{\mathrm{X}_C}{\mathrm{h}^2} \quad (9)$$

STPFs are commonly tuned slightly below the target harmonic frequency to avoid resonance and ensure stable operation under varying system conditions.

2.5 Proposed Research Model

Based on the theoretical framework presented earlier, this study introduces a research model integrating photovoltaic arrays; decentralized SVC units; and single-tuned passive filters to achieve simultaneous improvement in voltage stability and reduction in power loss, as well as enhancement in power factor and mitigation of harmonic distortion for radial distribution networks.

The framework for the proposed study will begin by performing a Load Flow Analysis on the Distribution System to determine the weak buses, and to evaluate system performance when operating under various loading conditions. Next, PV arrays will be optimized and located in an optimal manner to minimize the amount of Active Power loss in the Distribution System as well as to optimize Voltage Profiles within the system. After that, SVCs units will be strategically located throughout the Distribution System to manage Reactive Power and stabilize voltage levels. finally, Harmonic Analysis is performed to identify the Dominant Harmonics components within the system, and STPFs are designed and installed to assure compliance with IEEE 519-2022 Standards. The Methodological Flow Chart illustrating the sequential steps for the implementation of the model are shown in Figure 4.

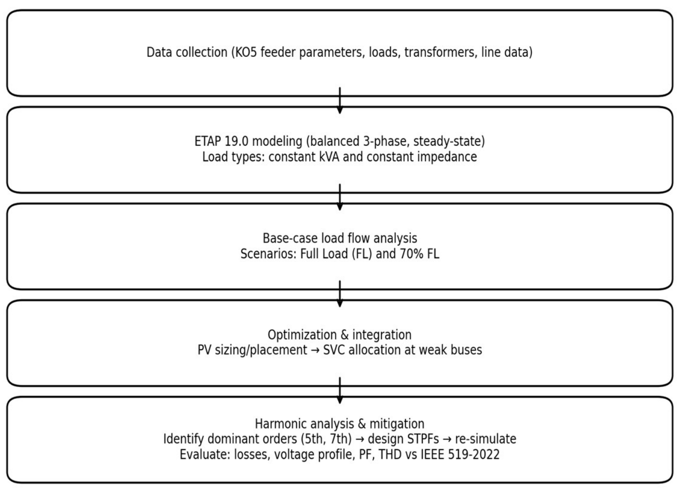


Figure4. Flowchart of the proposed methodology for coordinated PV–SVC–STPF power-quality improvement.

3 METHODOLOGY

The section will provide an overview of the methodological framework that is being utilized for assessing and improving power quality on Mekelle city's KO5 radial distribution feeder. The methodology for this study has been organized into a six-step structure: (i) data collection and characterization of the system, (ii) distribution network modeling in ETAP 19.0, (iii) base case load flow analyses under various loading conditions, (iv) integrated utilization of PV generation and SVC reactive power compensation, (v) harmonic assessment with passive filter design, and (vi) comparison of the results obtained from the previous steps against established standards for acceptable power quality limits.

3.1 Study Area and Feeder Selection

The research is carried out in Mekelle City, which is situated in the northern region of Ethiopia. The KO5 feeder is supplied from the Lachi substation and has a radial type distribution system that includes many buses and load points. Because this feeder is characterized by poor voltage profile, high technical losses, as well as harmonic distortion, which collectively motivate the need for integrated power-quality mitigation. Figure 5 shows the geographical location of Mekelle city within the Tigray Regional State of northern Ethiopia.

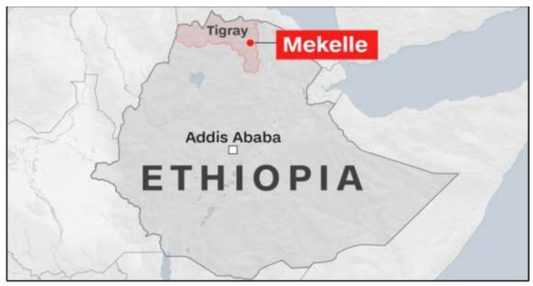


Figure5. Geographic location of Mekelle city (source: thesis).

3.2 Data Collection and Network Parameters

The KO5 feeder operates at a medium-voltage level of 15 kV and comprises 112 nodes and 111 line segments, serving 64 load points with a total load capacity of approximately 10.5 MW. The system experiences a real power loss of 1.474 MW and a reactive power loss of 1.552 MVAR (Gebregergs ,2018).

In addition, distribution transformers were represented as step-down units rated at 15 kV/0.4 kV, Figure 6 shows the layout diagram of the Lachi substation, where KO5 originates (Gebregergs ,2018).

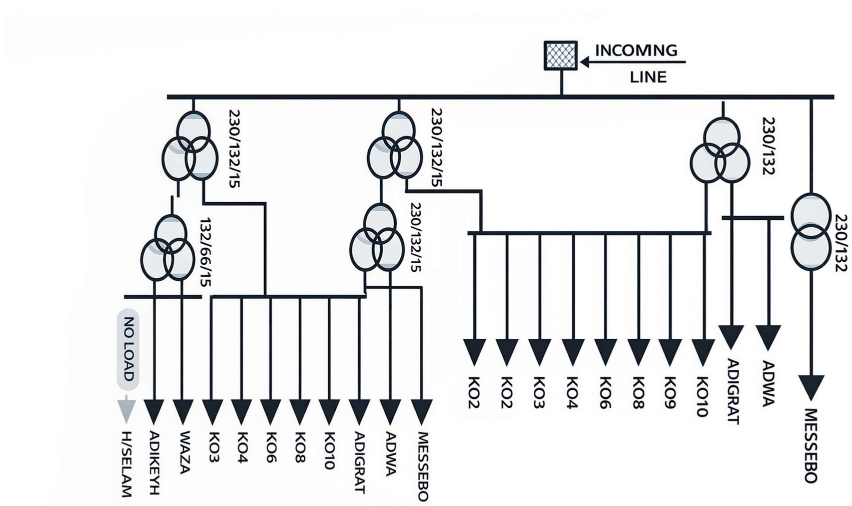


Figure 6. Single-Line Layout of Lachi Substation Supplying the KO5 Distribution Feeder (Gebregergs ,2018).

3.3 System Modeling in ETAP 19.0

Using ETAP software, we built and modeled the DN of the KO5 feeder based on data from Gebregergs (2018). The network was analyzed under the assumption of a balanced three-phase system operating under steady-state conditions. we included two types of loads: constant kVA loads and constant impedance loads. 44 step-down distribution transformers with a rating of 15 kV/0.4 kV were included in the system. Additionally, a typical transformer X/R ratio was applied in the simulation. Figure 7 shows the one-line diagram developed in ETAP 19.0.

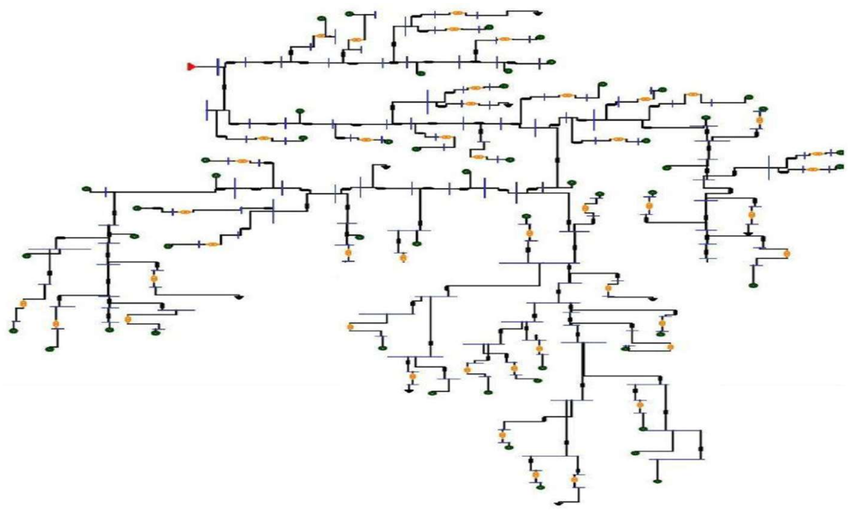


Figure 7. The Single-Line diagram of the KO5 Radial Distribution Feeder using ETAP.

3.4 Base-Case Load Flow Analysis

Load flow analysis was executed to quantify the base-case performance of the KO5 feeder and to identify weak buses. Two operating scenarios were simulated: full-load (FL) and partial-load (70% of FL). For each scenario, key indices were computed, including (i) bus voltage magnitudes (per unit), (ii) feeder active and reactive power losses, and (iii) overall power factor behavior. These results establish the benchmark against which all improvement actions are evaluated.

3.5 PV Integration Strategy (Sizing and Placement)

PV arrays were integrated as distributed generation sources to inject local active power and relieve upstream power transfer. The placement and sizing strategy aims to: (i) reduce feeder losses, (ii) improve the minimum bus voltage, and (iii) avoid adverse operational effects such as unacceptable voltage rise. In practice, candidate buses are evaluated through repeated simulations in ETAP to determine the locations that yield the highest loss reduction and voltage improvement under both FL and 70% FL scenarios. The final PV allocation is then adopted for the coordinated compensation stage.

3.6 Reactive Power Compensation Using SVC

SVC units were used as shunt FACTS devices to regulate bus voltages through dynamic reactive power injection/absorption. After identifying weak buses from the base-case load flow, SVC units were allocated to buses that exhibit the lowest voltage magnitudes or high reactive power demand. The SVC V–I characteristic enables smooth voltage control around a reference value, which supports improved voltage stability in radial feeders.

3.7 Harmonic Assessment and IEEE 519-2022 Compliance

Following the load flow improvement stage, harmonic analysis was conducted to quantify waveform distortion in the feeder. Harmonic sources in distribution networks typically include nonlinear loads and power-electronic converters (e.g., PV inverters and thyristor-based compensators). The analysis determines the dominant harmonic orders and evaluates the Total Harmonic Distortion (THD) at critical buses. Compliance is assessed against IEEE 519-2022 limits, where voltage THD in distribution systems is typically constrained to acceptable thresholds.

3.8 Design of Single-Tuned Passive Filters (STPFs)

Single-tuned passive filters were designed to mitigate dominant low-order harmonics, particularly the 5th and 7th, identified by the harmonic assessment. STPFs are implemented as shunt RLC branches tuned to a selected harmonic frequency to provide a low-impedance path for the targeted harmonic current. In addition to harmonic attenuation, the filter capacitor contributes to reactive power support, improving the displacement and true power factor.

In practical design, the tuning frequency is selected slightly below the exact harmonic frequency to reduce the risk of parallel resonance with the network.

3.9 Performance Metrics and Comparative Evaluation

The effectiveness of the proposed mitigation strategy is evaluated by comparing the base-case and improved cases for both FL and 70% FL scenarios. The main performance indicators include: (i) total active power losses, (ii) minimum and average bus voltages (per unit), (iii) system power factor, and (iv) voltage THD at critical buses. The coordinated solution is considered successful when it simultaneously improves the voltage profile, reduces losses, raises the power factor, and reduces THD to within IEEE 519-2022 acceptable limits.

4 RESULTS

This section presents detailed harmonic analysis and power quality results for the KO5 distribution feeder, based on ETAP 19.0 simulations under full-load (FL) and partial-load (70% FL) operating conditions. The results compare the base-case network with the improved configuration incorporating optimally placed photovoltaic (PV) arrays, Static VAR Compensators (SVCs), and single-tuned passive filters (STPFs).

4.1 OPTIMIZING PV ARRAYS AND SVC INTEGRATION

To determine the most effective location for PV array deployment, a series of simulation trials were conducted. Based on the simulation results, the optimal placement for the PV array is a decentralized configuration, with installations at buses 106 and 109. This configuration yields the best performance under both full load (FL) and partial load (70% FL) conditions.

In order to investigate the impact of the PV array size, we began with a capacity of 30% of the FL demand. table 1 presents various system parameters for different sizes of PV arrays.

Table 1: Impact of PV Array Size

PV%	Source (MW+j MVAR)	PV (MW+j MVAR)	Losses (MW+j MVAR)	Utility-PF	Min Bus Voltage-pu
0%	6.545+j 5.007	0+j0	.647+j.680	79.43% lag	85.6%
30%	3.367+j 4.743	2.927+j 0	.336+j.371	57.89% lag	89.9%
35%	2.864+j 4.727	3.419+j 0	.313+j .346	51.68% lag	90.4%
40.1%	2.361+j 4.718	3.915+j 0	.296+j .330	44.73% lag	90.9%
45.1%	1.873+j 4.711	4.399+j 0	.284+j .317	36.95% lag	91.5%
67.2%	- .069+j 4.770	6.562+j 0	.325+j .349	1.43% Lead	93.4%
73.5%	- 2.765+ j4.802	7.168+j 0	.528+j .553	48.32% Lead	94%

The results in table 1 indicate that increasing the size of the PV system reduces the power drawn from the grid and lowers system losses, while also enhancing voltage profiles. However, as the PV system primarily supplies active power, the grid compensates by providing reactive power, leading to a decline in the overall power factor. above 45% PV penetration level, system losses begin to rise and the power factor becomes leading and reverse power flow is observed so A PV penetration level of 45% is identified as optimal, as it effectively reduces losses without causing reverse power flow.

The optimal rating for the SVC-FC was identified as 13.8 MVAR through Optimal Capacitor Placement (OCP) analysis at FL performed in ETAP, ensuring improved system voltage profile. For effective placement, Based on the simulation results, the optimal SVC configuration is a decentralized configuration; consisting of eight units rated at 1.75 MVAR each. These units are strategically placed at the weakest buses in terms of voltage levels within the network.

4.2 HARMONIC ANALYSIS AND RESULTS

Under FL conditions, the integration of PV arrays alone leads to a significant increase in THD at buses 105, 106 and 107 (These buses were selected for analysis as they exhibit the highest THD levels in the system), rising from 0.45% in the base case to 10.82%. Similarly, under partial load conditions, THD increases from 0.56% to 11.95%. The subsequent addition of SVC unit's results in a slight reduction in THD levels under both loading scenarios, attributed to the harmonic filtering capabilities integrated within the SVC units.

The harmonic analysis results show that the 5th and 7th harmonics are the dominant contributors to THD at the pervious mentioned Buses, although higher-order harmonics such as the 11th, 13th, and 17th are also present to a lesser extent.

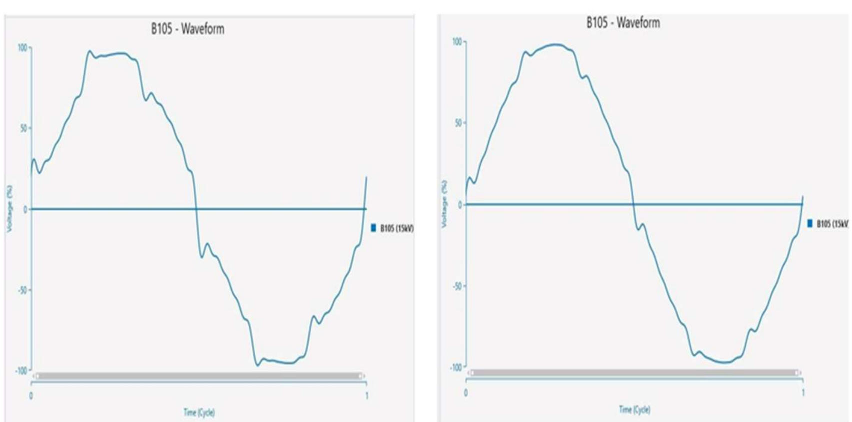
4.3 Harmonic Mitigation Using STPFs

To reduce THD and IHD to acceptable limits as defined by the IEEE 519-2022 standard, Single-tuned passive filters were designed and installed at buses exhibiting the highest harmonic distortion. Through a trial-and-error approach, the most effective mitigation strategy involved the installation of three STPFs: two filters targeting the 5th order at buses 106 and 107, and one filter designed to mitigate the 7th order at bus 107. After filter installation, voltage THD levels were reduced to below 5% across all monitored buses, ensuring compliance with IEEE 519-2022, table 2 shows Voltage distortion limits based on IEEE 519 -2022 standard.

Table 2: IEEE 519-2022, voltage distortion limits

Bus voltage at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Figure 8 illustrates the time-domain voltage waveform at Bus 105,(a) represents the distorted waveform before harmonic mitigation, showing clear deviation from an ideal sinusoidal shape due to dominant 5th and 7th harmonic components introduced by PV inverters and SVC operation. (b) Presents the voltage waveform after installation of the single-tuned passive filters (STPFs), where the waveform becomes nearly sinusoidal, indicating effective harmonic suppression and significant improvement in power quality.



(a) (b)

Figure 8. Voltage Waveform at Bus 105 (a) Before Installation of Single-Tuned Passive Filters (STPFs (b) after Installation of STPFs.

Figure 9 shows the harmonic spectrum of the voltage at Bus 105 ,(a) shows the harmonic spectrum before filter installation, where significant magnitudes are observed at the 5th and 7th harmonic orders, resulting in elevated Total Harmonic Distortion (THD). (b) Illustrates the harmonic spectrum after the implementation of STPFs, demonstrating substantial reduction in dominant harmonic components and the overall THD reduced below the IEEE 519-2022 limit.

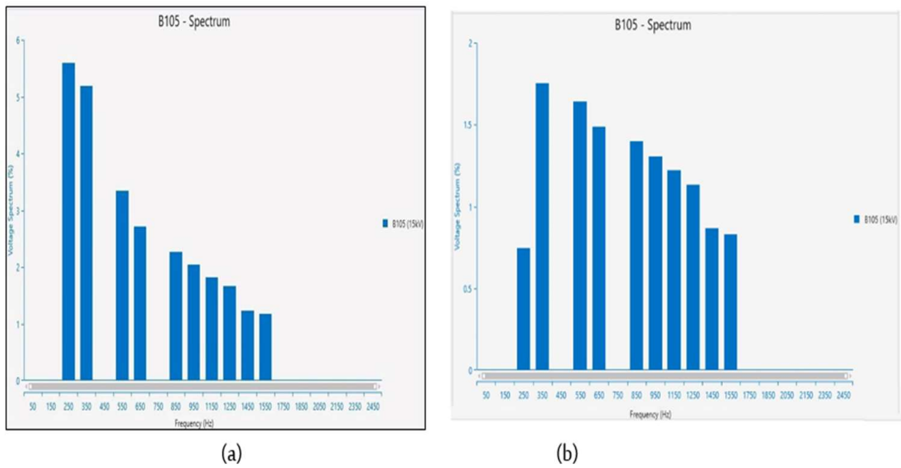


Figure. 9 Voltage Harmonic Spectrum at Bus 105 (a) Before Installation of Single-Tuned Passive Filters (STPFs) (b) after Installation of STPFs.

4.4 Power Factor Improvement

The combined effect of PV generation, SVC compensation, and filter capacitor reactive power contribution results in a significant enhancement of the overall system power factor. Under full-load conditions, the power factor improves from approximately 0.79 to 0.97, while under 70% FL it increases from 0.79 to 0.93.

4.5 Summary of Key Results

Tables 3 and 4 illustrate system performance under the four different scenarios: base case, with PV arrays only, with PV arrays and SVCs, and finally with PV arrays, SVCs, and harmonic filters. Each scenario is evaluated under both FL and partial load (70% FL) conditions.

Table3: Load Flow Analysis Final Results-FL

FL Case	Losses (MW +j MVAR)	Utility PF % Lagging	Min Bus Voltage % (pu)	THD (%)
Without PVAS,SVC and filters	1.474+j 1.552	78.79%	78.1%	0.45%
With PV arrays Only	.708+j .783	56.21%	85.4%	10.82%
With PV arrays and SVC	.305+j .378	86.3%	90.5%	10.25%
SVC and With PV arrays, filters	.270+j.341	97.33%	91.9%	4.2%

Table 4: Load Flow Analysis Final Results-70%FL

70% FL Case	Losses (MW +j MVAR)	Utility PF % Lagging	Min Bus Voltage % (pu)	THD (%)
Without PVAS,SVC and filters	.647+j.680	79.43%	85.6%	0.56%
With PVAs Only	.284+j.317	36.95%	91.5%	11.95%
With PVAS, and SVC	.128+j.162	60.16%	94.1%	11.33%
With PVAS,SVC and filters	.096+j.130	92.74%	95.6%	3.8%

4.6 Compliance with IEEE 519-2022

The final configuration of the KO5 feeder satisfies IEEE 519-2022 harmonic limits under both FL and 70% FL operating conditions. The coordinated integration of PV arrays, SVC units, and STPFs provides a comprehensive solution that improves voltage stability, minimizes losses, enhances power factor, and ensures acceptable harmonic performance.

5 DISCUSSION

The results from the harmonic and power quality assessments indicate that the use of the suggested integrated approach to coordinate PV array, SVC and STPF for improvement the overall performance of KO5 radial distribution feeder. This section discusses the simulation outcomes in terms of voltage stability, reduced power losses, improved power factor, and reduced harmonic distortion at both FL and 70% FL loads. The effects of the proposed system on voltage stability, power loss reductions, power factor improvements, and harmonic reductions under both full-load (FL) and partial-load (70% FL) operating conditions.

Under base case scenario, the KO5 feeder has a low voltage quality particularly for buses far from the substation due to its radial design and its high R/X ratio. As long as PV arrays reduce the amount of active power needed by the upstream network, there will be less current on the lines and an improvement in energy losses. Nonetheless, based upon PV array output alone, there is not enough generation to meet all of the reactive power needs of the system; therefore, additional reactive compensation is required.

Allocation of SVC units on weak buses is a method for providing dynamic reactive power support and improving voltage stability significantly. . The observed increase in the minimum bus voltage was increased by SVC implementation from 0.781 p.u. in the base case to 0.919 p.u. under FL conditions confirms the effectiveness of decentralized SVC. Improvements in minimum bus voltage were consistent across 70% FL conditions and show the robustness of this decentralized SVC placement strategy.

6 CONCLUSION

In this paper, a coordinated hybrid method was introduced to improve Power Quality in the KO5 Distribution Feeder of Mekelle City. Through simulations carried out in ETAP 19.0, the system was analyzed under both FL and partial load (70% FL) conditions, with a focus on improving power quality and overall system reliability. The effects of the of PV integration, SVC- based reactive power compensation, and Single Tuned Passive Filters have been investigated.

Simulation results show that optimal placement of PV arrays resulted in the significant reduction of active power losses, whereas the addition of SVCs greatly improved voltage regulation and reactive power management. Additionally, the successful mitigation of harmonic distortion and compliance with IEEE 519-2022 standards were achieved through the application of STPFs tuned to the dominant harmonic order.

The power losses dropped from 1.474 MW to 0.270 MW at FL and from 0.647 MW to 0.096 MW at partial load. Minimum voltage levels improved from 78.1% to 91.9% FL and from 85.6% to 95.6% partial load. The power factor also increased notably from 0.7879 to 0.9733 at FL and from 0.7943 to 0.9274 at partial load and the total Harmonic levels reduced to 4.09% at FL and 4.36% at 70% FL, achieving IEEE 519-2022 compliance.

Collectively, the coordinated application of PV arrays, SVC units, and passive filters achieved simultaneous improvements in voltage stability, loss reduction, power factor and harmonic performance. The proposed method could be applied by distribution utilities as an effective strategy to integrating renewable energy source into networks and maintain acceptable power quality.

Future studies may expand upon this study by investigating the effects of unbalanced loads, integrating Energy Storage Systems (ESS), and utilizing optimization methods to perform real-time control and planning.

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