

# Optimizing Power Quality and Efficiency of a Distribution Substation through Static Var Compensators: A Case Study of the 132 kV Qasimabad Grid Station, Pakistan

Shayan \*, Abdul Karim Shah, Muhammad Ashar, Faheemullah Shaikh

*Department of Electrical Engineering, Mehran University of Engineering & Technology, Jamshoro, Pakistan 76062*

\*Corresponding author: Shayan, Email: shayanriazakhund@gmail.com

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## ABSTRACT

The Qasimabad Grid Station has lost its efficiency due to increasing electricity demand and the aging of its infrastructure. This has resulted in frequent outages, overloading of transformers, degradation of the power factor, and bus voltages that are close to the minimum allowable values. To evaluate the performance of the grid, a power flow study was performed using the Electrical Transient and Analysis Program (ETAP) in accordance with the regulatory framework of the National Electric Power Regulatory Authority (NEPRA). The main goal of this study was to improve the performance of the grid system through the integration of Static Var Compensators (SVCs) in the modeled network. The first step in the research was to analyze system limitations to determine the reactive power needs of the system for proper SVC location and sizing in the network. This stage required data gathering and analysis during both high load and low load periods, paying particular attention to the number of transformer overloads experienced in June 2023, as well as underloads experienced in December 2023. The results further strengthened the findings of previous studies that SVCs are beneficial in improving grid reliability by maintaining nominal bus voltages, reducing transformer loading, and correcting the power factor.

## 1. Introduction

In recent years, Pakistan's electrical infrastructure has undergone increased stress. As a result, the overall performance, stability and efficiency of its power distribution network must be improved [5–8]. In response, the provision of reactive power balancing is important for maintaining voltage regulation and improving the power factor [9–12].

Flexible AC Transmission Systems (FACTS) technologies, particularly SVC, STATCOM, and D-STATCOM, are considered suitable approaches to compensate for reactive power. Among these, SVC is commonly adopted because of its economic viability and reliability, making it suitable for distribution networks with variable load conditions. SVC provides dynamic reactive power compensation through the regulation of thyristor-based reactors and capacitors, improving grid stability and the power factor [13]. STATCOM uses a voltage-source converter for swift and precise control over voltage regulation. D-STATCOM, a modified version of STATCOM, provides superior reactive power compensation for power distribution systems. However, it requires higher capital and operational costs. Hence, SVC provides a budget friendly yet optimal technical solution for reactive power compensation, thereby improving the

overall performance of electrical grids with fluctuating loads such as the Qasimabad Grid Station [13].

The 132 kV Qasimabad Grid Station consists of two sources. New Jamshoro serves as the primary source, and Hala Road acts as the backup. The substation comprises one slack bus and one PV bus, both separated by a sectionalizer as shown in Fig. 1. Additionally, four power transformers are available at the substation: one 40 MVA and three 26 MVA transformers. At the farthest end of the grid, there are four load buses, each connected to 25 distribution feeders. Furthermore, various protective and measuring instruments are available for proper monitoring and control.

Currently, the grid station is experiencing significant voltage fluctuations, which are adversely affecting the performance of the grid network. This situation has resulted in poor power quality, transformer overloading, a reduced power factor, frequent load shedding, and power outages.

Despite the installation of 7.2 Mvar capacitor banks within the Qasimabad Grid Station, there are different operational issues that are encountered. During the summer loading, the transformers at the substation are overloaded, and buses operate near the lower limit of the acceptable voltage threshold, contrary to the

expected support from the capacitor banks. In contrast, during winter loading there is a lack of power factor compensation available at the grid network, which results in a poor power factor.

This study was performed to address these problems through an ETAP based simulation of the 132/11 kV Qasimabad Grid Station with and without SVC technology. This analysis was primarily performed to assess the effectiveness of SVC integration in improving the Qasimabad grid's voltage profile, mitigating power losses, reducing transformer overloading, and improving the power factor.

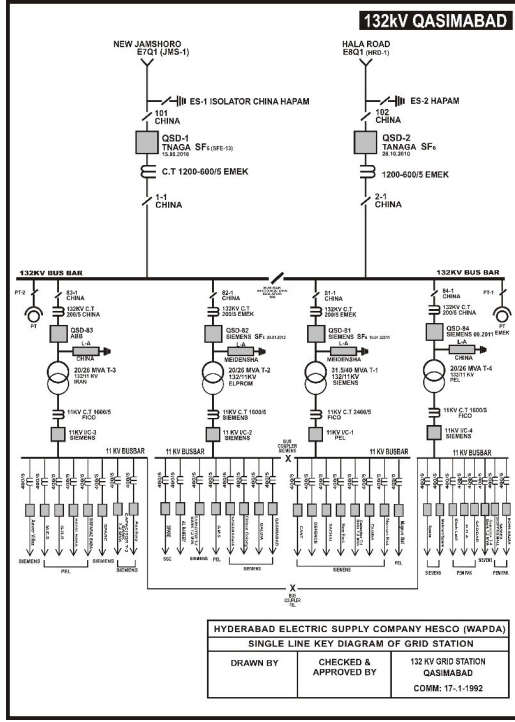


Fig. 1. Single line diagram of the 132 kV Qasimabad Grid Station

## 2. Methodology

A load flow analysis of the Qasimabad Grid Station was carried out using the ETAP software package to assess both the baseline scenario (without SVCs) and the compensation scenario (with SVCs).

### 2.1 Load Flow Simulation Setup

The electrical model of the Qasimabad Grid Station, considering the actual technical dataset such as transformer and bus voltages, as well as load characteristics, was simulated using the ETAP software. The simulation process was carried out using the following two steps:

**Step 1: Baseline Scenario (without SVCs):** In this step, the grid was simulated without SVCs under varying summer and winter load conditions. This step helped identify issues such as voltage deviations, overloading of transformers, and degradation of the power factor.

**Step 2: Compensation scenario (with SVCs):** In this step, SVCs were integrated into the existing grid system to analyze the improvements. The SVC parameters were precisely calibrated as per the grid's operational needs.

Finally, performance evaluation was carried out by comparing the baseline and compensation scenarios in terms of voltage stability, transformer loading, and power factor improvements.

### 2.2 SVC Design and Integration Process

The design of the SVC was based on deficiencies identified in the baseline scenario. The Mvar support at critical buses was quantified. The optimal ratings of capacitive and inductive reactive power needs were calibrated to achieve voltage stability across the network under varying load conditions.

### 2.3 Modeling Assumptions

The following critical assumptions were made to achieve the simulation objectives of this study.

- The model assumed steady-state load conditions with no sudden change in load.
- The model assumed a fixed rating for capacitor banks (7.2 Mvar) installed at the grid station.
- The voltages at the bus level were assigned fixed values corresponding to rated voltage levels.
- The system was modeled under fault-free conditions, given that the primary objective was to ensure voltage regulation and reactive power compensation.

### 2.4 Analytical Formulations

An iterative Newton-Raphson method was used to solve the non-linear power balance equations. The following two equations for net active power injection and net reactive power compensation were applied in the analysis.

$$P_i = \sum_{j=1}^N |V_i| \cdot |V_j| \cdot (G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)) \quad (1)$$

where

- $P_i$  Net active power injected at bus  $i$
- $N$  Total number of buses in the system
- $|V_i|$  Voltage magnitude at bus  $i$
- $|V_j|$  Voltage magnitude at bus  $j$
- $\theta_i$  Voltage phase angle at bus  $i$
- $\theta_j$  Voltage phase angle at bus  $j$
- $G_{ij}$  Conductance between bus  $i$  and  $j$
- $B_{ij}$  Susceptance between bus  $i$  and  $j$
- $\theta_i - \theta_j$  Angle difference

$$Q_{SVC} = Q_{TCR} - Q_{TSC} \quad (2)$$

where

- $Q_{SVC}$  Net reactive power of SVC
- $Q_{TCR}$  Reactive power absorbed by Thyristor Controlled Reactor
- $Q_{TSC}$  Reactive power supplied by Thyristor Switched Capacitor

### 3. Results and Discussion

The performance analysis in this study was carried out as specified in the NEPRA Distribution Code and IEC standards. As per the NEPRA Distribution Code, the permissible voltage regulation is required to be within  $\pm 5\%$  of the nominal voltage. This shows that the voltage level at each node must be maintained between 95% and 105% of the rated voltage to ensure stable grid functionality. According to the International Electrotechnical Commission (IEC) transformer loading standard, oil-filled transformers must not experience long-term loads exceeding 80% of their nameplate rating to avoid accelerated deterioration and maintain long-term dependability [15]. The NEPRA guidelines further specify a power factor of 90%–100% to minimize losses and improve system efficiency. These parameters were used as key performance indicators for evaluating grid performance and the effectiveness of the SVCs.

#### 3.1 Summer Analysis of Grid Performance Without SVCs

Initially, a load flow study for the Qasimabad Grid Station was performed under summer loading conditions. It was conducted using the Newton-Raphson method through ETAP as shown in Fig. 2.

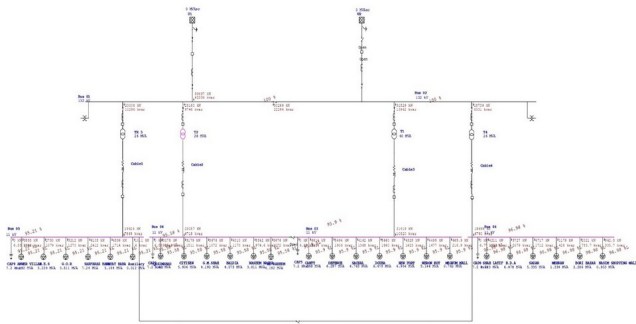


**Fig. 2.** Summer Load Flow Analysis of the Qasimabad Grid Station Without SVCs

The results from this subsection are summarized in Table 1. Several issues were identified through the load flow analysis at the 132 kV Qasimabad Grid Station: bus voltages approaching their minimum voltage limits, and overloading of transformers during the summer months.

Based on the analysis of the summer load, the system was subjected to heavy transformer overloading, particularly for transformer T2, which was operating at approximately 96.6% of its nameplate capacity. This type of overloading could reduce the operational life of this transformer as per the IEC standard [15]. Voltage sags were also observed at buses 3, 4, 5, and 6, which represented an exceedance of the  $\pm 5\%$  tolerance as defined by the NEPRA Distribution Code [14]. The simultaneous occurrence of these unusual conditions resulted in an unstable voltage profile and increased reactive power demand.

**Table 1**

(a, b, c): Load Flow Analysis results for summer loading without SVCs

a) Summary of general parameters for summer loading without SVCs

| Parameter       | Result |
|-----------------|--------|
| Power Factor %  | 91.09  |
| Generation-MW   | 93.44  |
| Generation-Mvar | 42.34  |

b) Summary of bus voltages for summer loading without SVCs

| Bus ID   | Nominal kV | Voltage (%) |
|----------|------------|-------------|
| Bus No 1 | 132        | 100         |
| Bus No 2 | 132        | 100         |
| Bus No 3 | 11         | 95.90       |
| Bus No 4 | 11         | 95.58       |
| Bus No 5 | 11         | 95.21       |
| Bus No 6 | 11         | 96.98       |

c) Summary of transformer loading for summer loading without SVCs

| Transformer | % Loading |
|-------------|-----------|
| T1          | 86.2      |
| T2          | 96.6      |
| T3          | 86.5      |
| T4          | 78.9      |

#### 3.2 Winter Analysis of Grid Performance Without SVCs

A load flow study for the Qasimabad Grid Station was performed under winter loading conditions. It was conducted using the Newton-Raphson method through ETAP as shown in Fig. 3.

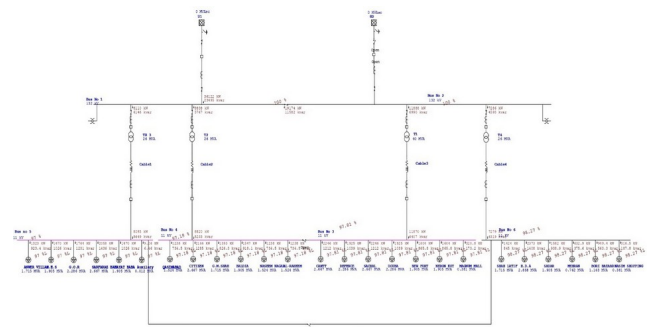


**Fig. 3.** Winter Load Flow Analysis of the Qasimabad Grid Station Without SVCs

The purpose of this analysis was to evaluate the voltage levels at various bus locations, the overall network power factor, the performance and loading of substation equipment during winter conditions without considering the effect of SVC integration. The results of the winter analysis are given in Table 2. The load flow analysis demonstrated that the 132 kV Qasimabad Grid Station suffered from poor power factor performance and faced significant operational difficulties.

Even though transformer loading did not exceed acceptable limits during winter loading, the system showed a power factor of 83.83% (Table 2); it remained below the NEPRA Code's required range of 90%–100%. A

**Table 2**

(a, b, c): Load Flow Analysis results for winter loading without SVCs

a) Summary of general parameters for winter loading without SVCs

| Parameter       | Result |
|-----------------|--------|
| Power Factor %  | 83.83  |
| Generation-MW   | 36.122 |
| Generation-Mvar | 23.495 |

b) Summary of bus voltages for winter loading without SVCs

| Bus ID   | Nominal kV | Voltage (%) |
|----------|------------|-------------|
| Bus No 1 | 132        | 100         |
| Bus No 2 | 132        | 100         |
| Bus No 3 | 11         | 97.81       |
| Bus No 4 | 11         | 97.18       |
| Bus No 5 | 11         | 97          |
| Bus No 6 | 11         | 98.27       |

c) Summary of transformer loading for winter loading without SVCs

| Transformer | % Loading |
|-------------|-----------|
| T1          | 34.5      |
| T2          | 40.6      |
| T3          | 39.1      |
| T4          | 33.1      |

power factor at this level represented poor performance of the grid, resulting in high system losses and a greater demand for reactive power compensation. Although the majority of the bus voltages were within acceptable ranges, the results indicated that the voltage regulation was inadequate (Table 2). Therefore, it was observed that compensation through SVCs must be provided to improve voltage stability and raise the overall power factor.

### 3.3 SVC Sizing

The first and most important step was to calculate the amount of reactive power required by each busbar to provide adequate compensation. The calculated Mvar values for each bus are shown in Table 3.

**Table 3**

Reactive power demands

| Bus   | Reactive Power Demand (Mvar) |
|-------|------------------------------|
| Bus 3 | 18.2                         |
| Bus 4 | 13.86                        |
| Bus 5 | 15.07                        |
| Bus 6 | 13.94                        |

Reactive power demand at each node was calculated based on voltage and current profiles at that particular node during peak summer and peak winter loading conditions. Table 3 summarizes the individual reactive power demand for each node, which is important for determining the proper SVC sizing.

The reactance limit methodology was subsequently used

to determine suitable capacitive and inductive ratings for the proposed Mvar compensation. This methodology also helped determine the operating voltage limits which helped ensure voltage stability across the network. The resulting parameters are shown in Table 4.

**Table 4**

SVC parameters for Qasimabad Grid Station

| Parameter | Value      |
|-----------|------------|
| $Q_L$     | -36.2 Mvar |
| $Q_c$     | +18.2 Mvar |
| $B_L$     | 0.30 S     |
| $B_c$     | 0.15 S     |

The grid model was modified to include the integrated SVC parameters. This framework helped in maintaining reactive power compensation and voltage standards throughout the seasonal load conditions. Subsequently, SVCs with these same parameters were integrated at each of the load buses, providing uniform reactive power compensation across the network.

### 3.4 Summer Analysis of Grid Performance With SVCs

This section discusses the performance of the Qasimabad Grid Station during summer loading conditions after the integration of the SVCs. A load flow simulation of the summer conditions using the SVC parameters as established in Section 3.3 was performed in ETAP. The results of this analysis were studied for voltage profile, power factor, and transformer loading. The results indicated improvements in these areas. Fig. 4 shows the ETAP simulation results from the summer analysis of grid performance with SVCs.

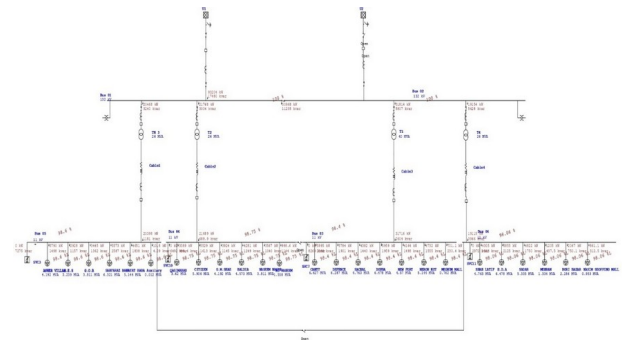


**Fig. 4.** Summer Load Flow Analysis of the Qasimabad Grid Station With SVCs

The power factor improved from 91.09% to 98.29% after incorporating the SVCs (Table 5a), an increase of 7.2 percentage points, due to reduced reactive power loss. Thus, the improvement resulted in system operation within the optimum range of 90% to 100% as stipulated by the NEPRA Distribution Code.

The bus voltage performance improved at all buses after the SVCs were connected as shown in Table 5b. Bus 3 increased from 95.9% to 98.4%. Bus 4, Bus 5, and Bus 6 similarly improved their voltage levels by 3.17%, 3.39%, and 1.08%, respectively. All of these voltage improvements helped maintain bus voltages within their nominal levels, in compliance with the  $\pm 5\%$  NEPRA voltage regulation limit.

The SVCs also directly affected transformer loading. The loading on transformer T2 was reduced from 96.6% to 84.5%, indicating a decrease of 12.1%. Similarly, the loading on transformers T1, T3 and T4 decreased to 80.8%, 79.7% and 76.6%, respectively. As a result of this reduction, the transformers could operate within acceptable limits set by IEC standards.

**Table 5**

(a, b, c): Load Flow Analysis results for summer loading with and without SVCs

a) Power factor improvement for summer loading with SVCs

| Parameter    | Without SVCs | With SVCs | Improvement |
|--------------|--------------|-----------|-------------|
| Power Factor | 91.09 %      | 98.29 %   | 7.2 %       |

b) Improvement of bus voltages for summer loading with SVCs

| Bus ID   | Nominal kV | % Voltage Without SVCs | % Voltage With SVCs | % Voltage Improvement |
|----------|------------|------------------------|---------------------|-----------------------|
| Bus No 1 | 132        | 100                    | 100                 | 0                     |
| Bus No 2 | 132        | 100                    | 100                 | 0                     |
| Bus No 3 | 11         | 95.90                  | 98.4                | 2.5                   |
| Bus No 4 | 11         | 95.58                  | 98.75               | 3.17                  |
| Bus No 5 | 11         | 95.21                  | 98.6                | 3.39                  |
| Bus No 6 | 11         | 96.98                  | 98.06               | 1.08                  |

c) Improvement of transformer loading for summer loading with SVCs

| Transformer | Without SVCs | With SVCs | Improvement |
|-------------|--------------|-----------|-------------|
| T1          | 86.2 %       | 80.8 %    | 5.4 %       |
| T2          | 96.6 %       | 84.5 %    | 12.1 %      |
| T3          | 86.5 %       | 79.7 %    | 6.8 %       |
| T4          | 78.9 %       | 76.6 %    | 2.3 %       |

### 3.5 Winter Analysis of Grid Performance With SVCs

A load flow analysis was performed with SVCs integrated under winter loading conditions. The simulation showed improvements in power factor, bus voltages, and transformer loading, as seen in Fig. 5.

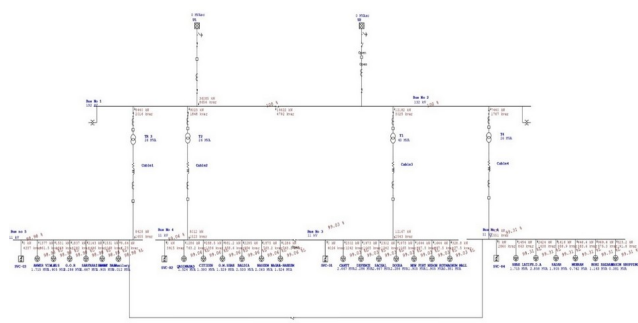


**Fig. 5.** Winter Load Flow Analysis of the Qasimabad Grid Station With SVCs

The integration of the SVCs improved all critical parameters as shown in Table 6a. The power factor increased from 83.83% to 97.24%, representing an increase of 13.41%. Resultantly, the SVCs provided reactive power support that ensured reliable grid operation.

Voltage levels also increased across all buses, as shown in Table 6b. Bus 3 increased from 97.81% to 99.03%.

Buses 4, 5, and 6 showed increases of 1.88%, 1.98%, and 1.04%, respectively. Consequently, all buses were within the  $\pm 5\%$  requirement set by NEPRA, which is critical to the operational stability and efficiency of the grid.

The overall performance of the transformers also improved with the integration of the SVCs into the electric power system. As seen in Table 6c, the loading on Transformer T2 decreased from 40.6% to 31.7%, a reduction of 8.9 percentage points. Similarly, the corresponding transformer loadings of Transformers T1, T3 and T4 decreased to 31.4%, 33.4% and 29.4%, respectively. These declines contributed to a lower risk of thermal overloads and protection against potential failure from persistent overloading, thereby improving the entire system's reliability.

**Table 6**

(a, b, c): Load Flow Analysis results for winter loading with and without SVCs

a) Power factor improvement for winter loading with SVCs

| Parameter    | Without SVCs | With SVCs | Improvement |
|--------------|--------------|-----------|-------------|
| Power Factor | 83.83 %      | 97.24 %   | 13.41 %     |

b) Improvement of bus voltages for winter loading with SVCs

| Bus ID   | Nominal kV | % Voltage Without SVCs | % Voltage With SVCs | % Voltage Improvement |
|----------|------------|------------------------|---------------------|-----------------------|
| Bus No 1 | 132        | 100                    | 100                 | 0                     |
| Bus No 2 | 132        | 100                    | 100                 | 0                     |
| Bus No 3 | 11         | 97.81                  | 99.03               | 1.22                  |
| Bus No 4 | 11         | 97.18                  | 99.06               | 1.88                  |
| Bus No 5 | 11         | 97                     | 98.98               | 1.98                  |
| Bus No 6 | 11         | 98.27                  | 99.31               | 1.04                  |

c) Improvement of transformer loading for winter loading with SVCs

| Transformer | Without SVCs | With SVCs | Improvement |
|-------------|--------------|-----------|-------------|
| T1          | 34.5 %       | 31.4 %    | 3.1 %       |
| T2          | 40.6 %       | 31.7 %    | 8.9 %       |
| T3          | 39.1 %       | 33.4 %    | 5.7 %       |
| T4          | 33.1 %       | 29.4 %    | 3.7 %       |

## 4. Conclusion

The ETAP based analysis of the Qasimabad Grid Station was performed to observe the effect of SVC integration on the grid parameters. Initially, the grid parameters did not meet IEC and NEPRA standards. The identified problems included low bus voltages, transformer overloading and a poor power factor. To address these issues, reactive power compensation was provided using SVCs installed at each load bus, which helped improve the overall performance of the grid station. At the end, this technology effectively reduced transformer overloading, improved bus voltages and corrected the power factor.

## Abbreviations

|       |                                              |
|-------|----------------------------------------------|
| FACTS | Flexible AC Transmission Systems             |
| SVC   | Static Var Compensator                       |
| ETAP  | Electrical Transient and Analysis Program    |
| IEC   | International Electrotechnical Commission    |
| NEPRA | National Electric Power Regulatory Authority |

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