Research Article

A Comparative Study of Static VAR Systems for Improving Voltage Stability in Expansion of Mining Projects with Gearless Motor Drives

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In the next decade, the demand for copper is expected to grow by 25%, posing a challenge for mining facilities to increase their production by opening new mines or upgrading existing ones. To optimize the electrical infrastructure of mining facilities, the integration of flexible AC transmission systems (FACTS) can be instrumental in mitigating voltage stability issues that may arise during the installation of new gearless motor drives (GMDs). The purpose of this paper is to conduct a comparative analysis of the dynamic performance of static VAR systems (SVSs) as a means of enhancing voltage stability in mining expansion projects, particularly in the context of the integration of new GMDs into the system. This paper presents a case study of an existing three crushing-line mine configuration that has been upgraded with two new GMD systems. The primary contribution of this research is a comprehensive methodology designed to enhance the stability of a mining system through the integration of an SVS, which includes the sizing of the SVS system, an analysis of costs, as well as a determination of the required installation surface and optimal placement of the SVS within the system. The simulation results conclusively demonstrate the effectiveness of the SVS systems in reducing the voltage drop by 2% upon activation of new GMDs, as well as mitigating the adverse impact of transient disturbances on the system. Specifically, the first oscillation voltage peak value is improved by 3.5%, following a three-phase short circuit of 1 second duration, while overvoltage is reduced by 1% in response to sudden load changes. When compared with the system without an installed SVS, these findings highlight the significant advantages and benefits of integrating SVSs into mining operations.

1. Introduction

Throughout history, the extraction of precious materials from the earth has held a tremendous value. As we enter the 21st century, the mining industry has become increasingly globalized, with large multinational corporations at the forefront of this sector. The industry’s impact on the environment and concerns regarding over-exploitation have prompted the implementation of regulations aimed at mitigating these issues. Mining operations are facing a competitiveness challenge as the world risks running out of copper due to a supply deficit and rising demand, with copper reserves currently at their lowest levels in the past 15 years following the pandemic. Furthermore, the demand for copper is expected to grow by 25% over the next decade. As a result, the copper price has suffered a revaluation of price higher than 28%, beginning 2021 at 7800 $/ton and reaching 10725 $/ton in May and 10652 $/ton in October (Figure 1). In the coming months, the price is expected to maintain its level around 9500 $/ton, and with this scenario, mine installations will be responsible for increasing their production to meet this exceptional demand, opening new mining exploitation or upgrading existing ones.
The mining industry of today is predominantly powered by GMDs, which represent the most robust and high-performance mill drive systems available for SAG, ball, and AG mills. GMDs use the combination of synchronous motors and cycloconverters, reducing the number of components, as couplings, intermediate gearboxes, and bearings [1]. Consequently, this approach leads to a 4% increase in energy efficiency and minimizes the need for spare parts. Latest trends in the mining industry are driving grinding mill sizes to greater levels than ever before. In the grinding step of the ore processing, GMDs have become a crucial component and their robust and proven design has been used for over 30 years, increasing reliability and efficiency in grinding [2]. It is worth noting that approximately 60% of the electrical energy consumed by mining installations is attributed to motors, particularly when new gearless motor drives (GMDs) are installed in an existing mine. This increase in active and reactive power consumption can cause power quality issues, particularly related to voltage stability. The primary objective of this study is to identify a FACTS capable of improving voltage stability in response to increased production demands and the installation of new motors in the mine’s electrical grid. Specifically, this research focuses on exploring the viability of an SVS as a solution for optimizing the existing grid performance and increasing mining production.

An SVS is defined as a combination of discretely and continuously switched VAR sources that are operated in a coordinated fashion by an automated control system. These VAR sources include SVCs and STATCOMs [3], members of FACTS controllers. SVSs can solve any power system dynamic performance problem (voltage stability, transient stability, voltage flicker, etc.) that can suffer in mining electric systems.

The assessment of the voltage stability improvement performance will encompass the evaluation of various FACTS device configurations and their compatibility with different power system structures. The literature shows some comparative studies of dynamic performance of aforementioned FACTS devices; for example, the authors in reference [4] compared the dynamic response and stability margin of SVC and STATCOM in weak and strong systems, the authors in reference [5] studied the influence in dynamic voltage stability during LVRT in wind farms, the authors in references [6–8] compared SVC and STATCOM in dynamic reactive power support in different conditions (wind speed variation and grid fault) in wind turbines, while the authors in references [9–12] showed the importance of reactive power compensation to improve transient stability margin and power quality. When looking for applications of these FACTSs in electric power networks, the authors in reference [13] read up on the best location of a STATCOM in the Pakistan power system to improve voltage stability, the authors in reference [14] studied different voltage variations when the 100/145 MVAr FACTS is connected after the tripping of one overhead transmission line, the authors in reference [15] combined the D-STATCOM and a low THD SVC to enhance power quality, reducing voltage flicker and THD in a distribution grid, and the authors in reference [16] compared the dynamic performance of SVC and STATCOM, showing reduction of the postdisturbance voltage recovery time after 3 phase faults. In reference [17], several series and shunt FACTS devices are combined in the Bangladesh power system to exploit the thermal limit but without the peculiarities of a mining installation.

If we refer to HPS, a comparison among STATCOM, SVC, and DVR can be found in reference [18], where it can be ascertained that reactive compensation devices increase voltage stability margin of the hybrid power systems, and in reference [19], a STATCOM is employed to meet the reactive power demand in an isolated hybrid microgrid, using the mine blast algorithm to tune the parameters of the FACT device. An isolated hybrid microgrid is a small-scale power system that combines two or more sources of energy to provide electricity to a local community or facility that is not connected to the main power grid. It typically consists of a combination of renewable energy sources, such as solar panels and wind turbines, and traditional fossil fuel generators, which work together to provide a reliable and sustainable power supply. The hybrid microgrid is “isolated” in the sense that it is not connected to the main grid and operates independently to provide power to the local
community or facility. The term “hybrid” refers to the fact that the system uses multiple sources of energy to generate power, allowing for greater flexibility and reliability. The reactive power effect on frequency and the active power effect on system voltage are examined in reference [20], when a STATCOM is simulated in an IHPS.

Mining power installations that utilize the FACTS have been documented in references [21, 22] where an application study of an SVC for improving the power factor and THD in mining complexes is conducted. STATCOM applications in mining are reviewed in references [23, 24], compensating quality problems (voltage sags, THD) in an underground mine, and in reference [25] where it is installed to support voltage during starting of an asynchronous machine in low voltage. Currently, there is a dearth of research on the application of FACTSs to expansion mining projects where the installation of new high-power motors, such as GMDs, poses a significant risk to the voltage stability of the electrical system.

Therefore, the main contributions of this paper are as follows:

(i) Stability analysis of an actual mining expansion project in Chile, which involves a dynamic simulation of the expanded electrical mine system with synchronous GMD motors and SVSs based on SVC and STATCOM technologies.

(ii) A methodology for selecting the most suitable SVS, which considers various factors affecting such projects, including performance, cost, and footprint.

This study adopts a methodical approach, consisting of a series of sequential steps, to achieve its objectives. The introduction section commences with the purpose of the study, followed by a literature review and an overview of the contributions of this work. Section 2 presents the case study, while Section 3 outlines the methodology proposed to improve voltage stability through the SVS. The modelling of the case study and the simulation procedure, including the main assumptions and model references, are provided in Section 4. The results are discussed in Section 5, while the main conclusions of this work are presented in Section 6.

2. Case Study

2.1. Description of the Electric Mining System. The mining industry plays a significant role in the Chilean economy, and Chile is the largest global producer of copper. In order to ensure the relevance and applicability of the study, a typical Chilean 3-line mine installation, as depicted in Figure 2, was selected as the source system for this research. It is composed by three level voltage buses, 220, 69, and 23 kV. The original mining setup comprised three crushing lines, powered by one 20 MVA motor and two 14.2 MVA motors. Recently, two more gearless motor drives (GMDs) were installed, one rated at 20 MVA and the other at 14.2 MVA. The aim of this study is to investigate the impact of these new GMDs on the power system and to explore how FACTS devices can enhance power quality.

2.2. Voltage Stability Problem. Mine electrical systems normally have low short-circuit power with low ratio reactance resistance (typical values for X/R ratios of these installations are from 4.5 to 7). Furthermore, the geographic location of mine infrastructures makes it even more difficult to control their voltage levels, characterized by low short-circuit power. These special characteristics make these facilities prone to short-term power quality problems, mainly voltage problems, which are due to the electrical distance between generation and loads and thus depend on the network structure [26]. Under these special conditions, a mine power system can exhibit a new type of unstable behavior characterized by slow voltage drops; these voltage drops will cause a significant decrease of the power drawn by other connected devices so that the total power consumed will decrease, and this could escalate to the form of a collapse [3]. The concerns show the significance of reactive power compensation devices, injecting reactive power and consequently maintaining the voltages of the system within nominal values. Reactive power compensation is often the most effective approach to improve both voltage stability and power transfer capability.

The capability of the combination of a FACTS (SVC or STATCOM) and MSCs to provide dynamic reactive power would prove to be useful in voltage stability (i.e., minimizing voltage drops) when a mine installation is optimized with new synchronous motors. However, the costs of these FACTSs increase in the same way as their capacitive rating. The literature comprises several studies of the costs of these systems. For example, the authors in references [27, 28] worked in the development of a methodology for finding a cost-effective FACTS solution, while in reference [29], it is demonstrated that the optimally allocated FACTS devices could contribute considerably to savings in generation cost while the payback period of the investment is less than the life expectancy of device. For comparison studies, references [30–32] can be used for the calculation of SVS’s costs, including costs for equipment, project engineering, and installation. If we focus on the cost for each kVAr installed in Table 1 (operation and maintenance costs are not included), it can be observed that MSCs have the lowest cost level; so, the bigger the number of these components installed, the more economical solution will be obtained in the SVS.

When considering the environmental impact of increased surface occupation, the size of the SVS can vary depending on the type of FACTS device and its power rating [33], as outlined in Table 2.

Table 2 shows that MSCs are the components which less surface occupy when a SVS is installed, so when lack of space is one constraint, MSCs would be a good solution. With the addition of the two new motors to the mining system, voltage stability is compromised, with voltage drops and a higher risk of voltage collapse during overloads. In steady-state operation, one way to prevent voltage collapse is to either reduce the reactive power load or add more reactive power compensation. The second option is calculated in Section 3.1, which determines the required reactive energy that the SVS must supply.
3. Methodology of Improving Voltage Stability in a Mine System through SVSs

Figure 3 illustrates the recommended design approach for selecting an SVS, which involves identifying the optimal solution while minimizing one of the primary cost drivers in power systems: either the cost of compensators or the footprint of the installation.

To begin, it is essential to conduct a simulation of the new motors within the electrical mining system. Upon completion of the simulation, a comprehensive evaluation of the voltage levels across all buses is required. Should the voltage level on any bus fall below nominal values or exhibit any power quality issues, a determination must be made regarding the need for additional reactive power. In such cases, the suitability of two primary reactive compensator alternatives will be analyzed, depending on the driving factor, as follows:

(i) For cost optimization of the installation, the combination of SVC and MSC is recommended.
(ii) If the primary concern is limited space and minimizing the footprint of the installation, the combination of STATCOM and MSC is a more suitable option to consider.

Once a suitable reactive energy compensator has been selected, the optimal location for the SVS installation must be determined. To achieve this, the analysis of the system voltage profile and PV curves is utilized to identify the best bus for SVS installation. Based on the selected bus, the requisite reactive energy necessary to compensate for voltage levels is calculated. Lastly, the control scheme for the SVS is designed, including the determination of the reactive energy contribution of each SVS component ($Q_{\text{stat}}$, $Q_{\text{svc}}$, and $Q_{\text{msc}}$).

3.1. Sizing of the SVSs. The lack of reactive power is one of the main causes of voltage instability [34]. The necessary reactive power to inject at a bus can be calculated from the following equation:

$$Q = P (\tan \theta - \tan \theta'),$$

(1)

where $P$ is active power, $Q$ is reactive power to install, $\theta$ is the power factor, and $\theta'$ is the power factor after reactive power compensation.

<table>
<thead>
<tr>
<th>Types of reactive power compensator</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanically switched capacitor (MSC)</td>
<td>10–20 €/kVAr</td>
</tr>
<tr>
<td>Static VAR compensator (SVC)</td>
<td>35–50 €/kVAr</td>
</tr>
<tr>
<td>Static synchronous compensator (STATCOM)</td>
<td>50–75 €/kVAr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Types of reactive power compensator</th>
<th>Necessary surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanically switched capacitor (MSC)</td>
<td>1–5 m²/MVAr</td>
</tr>
<tr>
<td>Static VAR compensator (SVC)</td>
<td>5–20 m²/MVAr</td>
</tr>
<tr>
<td>Static synchronous compensator (STATCOM)</td>
<td>3–5 m²/MVAr</td>
</tr>
</tbody>
</table>
Reactive power capacity of the SVS to install will depend mainly on the robustness of the grid at the POI [35]. The following equation could be used to determine the MVAr rating of the SVS:

\[ Q = \Delta U \times S_{cc}. \]  

(2)

\( Q \) is the reactive power of the SVS to be installed, \( \Delta U \) is the variation of the POI voltage with reference to bus nominal voltage, and \( S_{cc} \) is the short-circuit power at the bus where the SVS is connected.

In Figure 4, various buses are shown where the SVS can be installed, including 220 kV, 69 kV, and 23 kV. To determine the required SVS capacity for each bus, equation (2) must be applied. Table 3 displays the necessary reactive power needed for voltage compensation at each bus. The installation of new motors in the system results in varying voltage fluctuations across the buses (e.g., 2% voltage variation for the 23 kV bus versus 1.5% for the 220 kV and 69 kV buses).

Table 3 shows that in order to compensate for a voltage variation of 2%, 26 MVAr is required at the 23 kV bus, whereas at the 69 kV and 220 kV buses, 8.85 MVAr and
29.1 MVAr are required, respectively, to compensate for a voltage variation of 1.5%.

3.2. Placement of the SVSs. Finding the best location for providing reactive power support is important for the enhancement of voltage stability in electrical power systems [36]. Placing FACTS controllers at the proper place increases the loadability margin and hence the stability of the system. The best location for reactive power compensation for improving steady-state voltage stability margin is the weakest bus in the system [37].

Estimating the ideal bus for installing a reactive power compensator can be achieved through different techniques as follows:

(i) Power-Voltage (P-V) curves: The power-voltage (P-V) curves illustrate the relationship between load and bus voltage [38] by plotting the real power transfer at the constant power factor while monitoring bus voltages, highlighting the most critical buses. Figure 4 shows the voltage variation at different buses of the electrical mining system. It is evident that when power is increased, the voltage at the 69 kV bus decreases.

(ii) Figure 5 presents a comprehensive simulation model that analyzes the voltage profile of various buses in the system upon switching on the GMD motors.

Figure 5 reveals that the bus at 23 kV is the most vulnerable when GMDs are incorporated, as it exhibits greater voltage drops compared to the 69 and 220 kV buses. The selection of the 23 kV bus as the optimal location for the reactive power compensation has led to the decision to place a 30 MVAr SVS at this bus, which is expected to enhance the overall stability of the system.

After identifying the 23 kV bus as the optimal location for the SVS, two options for a 30 MVAr SVS are evaluated based on cost and footprint, as shown in Tables 1 and 2.

(i) The first SVS configuration comprises a 15 MVAr SVC and a 15 MVAr MSC, representing a more cost-effective solution driven by cost considerations.

(ii) The second SVS configuration consists of a 15 MVAr STATCOM and a 15 MVAr MSC, which is a more expensive option that is typically preferred when space constraints are a primary driver.

3.3. Strategy of the SVS. A static VAR system is, per CIGRE/IEEE definition, a combination of static compensators and mechanically switched capacitors and reactors whose operation is coordinated. The emphasis in a static VAR system is on coordination [39]. The strategy of the coordination between the SVS components will be essential to provide with the necessary reactive power after each VAR demand change in the system. In this case, the fast compensation will be provided by the FACTS (SVC/STATCOM). If the maximum capacity of the FACTS is reached, the compensator control would activate, in a predetermined sequence, the mechanically switched capacitor banks until the output of the compensator is reduced below that level, when it will switch off the capacitors [40].

Among the pros and cons of this control strategy, we can highlight the optimization of the compensation of reactive energy due to the FACTSs and, at the same time, the cost of the installation is minimized because of the presence of MSC components. Simultaneously, enhancement of system loadability is achieved [41].

On the other hand, MSCs introduce harmonics in the power system due to inherent operation and thus can amplify existing power system harmonic distortion [42]. Therefore, a power quality study has to be performed to detect possible resonances and design the proper filter solution.

4. Modelling and Simulation Procedure

4.1. Dynamic Models of the System Components. Detailed dynamic models for different components of the mine are presented in this section.

4.1.1. Synchronous Motors. GMDs are low speed units, operating in 9–12 r/min speed range and have an internal diameter between 10 and 15 meters, see Figure 6. With 60–72 poles, these motors are fed by a cycloconverter [29] which is a device that converts AC to a lower frequency AC with no intermediate DC link.

Synchronous motors are simulated as the standard model of synchronous machines with salient pole rotor [44–46]. The input parameters for these synchronous motors are the short-circuit parameters, listed in Table 4. The cycloconverters are not included in this simulation.
4.1.2. Loads. Loads have been modelled as general loads, with constant current and constant impedance for the active and reactive power consumption. Transformers are modelled as two-winding transformer models, and load flow calculation uses the detailed model of the transformer; all shunt and branch impedances are

<table>
<thead>
<tr>
<th>Names</th>
<th>$M_1$, $M_4$</th>
<th>$M_2$, $M_5$, $M_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MVA)</td>
<td>20</td>
<td>14.2</td>
</tr>
<tr>
<td>Nominal speed (rpm)</td>
<td>9.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Moment of inertia (kg·m$^2$)</td>
<td>34000000</td>
<td>27000000</td>
</tr>
<tr>
<td>Synchronous reactance $d$-axis nonsaturated $X_d$ (p.u)</td>
<td>0.89</td>
<td>0.93</td>
</tr>
<tr>
<td>Transient reactance $d$-axis nonsaturated $X_d'$ (p.u)</td>
<td>0.34</td>
<td>0.37</td>
</tr>
<tr>
<td>Synchronous reactance $q$-axis nonsaturated $X_q$ (p.u)</td>
<td>0.7</td>
<td>0.77</td>
</tr>
<tr>
<td>Subtransient reactance $q$-axis nonsaturated $X_{q'}$ (p.u)</td>
<td>0.7</td>
<td>0.76</td>
</tr>
<tr>
<td>Damper circuit time constant in $d$-axis nonsaturated $T_d$</td>
<td>0.029</td>
<td>0.03</td>
</tr>
<tr>
<td>Damper circuit time constant in $q$-axis nonsaturated $T_q$</td>
<td>0.028</td>
<td>0.03</td>
</tr>
<tr>
<td>Transient short-circuit time constant $d$-axis nonsaturated $T_{d'}$</td>
<td>3.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Subtransient short-circuit time constant $q$-axis nonsaturated $T_{q''}$</td>
<td>0.028</td>
<td>0.029</td>
</tr>
</tbody>
</table>
Table 5: Transformers and load characteristics.

<table>
<thead>
<tr>
<th>Names</th>
<th>Power (MVA)</th>
<th>Voltages (kV)</th>
<th>$Z_{sc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$, $T_2$, $T_3$</td>
<td>85</td>
<td>220/23</td>
<td>15</td>
</tr>
<tr>
<td>$T_4$</td>
<td>50</td>
<td>220/69</td>
<td>12.5</td>
</tr>
<tr>
<td>LOAD$_1$, LOAD$_2$</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 7: SVC-based SVS control block diagram.](image7)

![Figure 8: STATCOM-based SVS control block diagram.](image8)

Table 6: Parameters of SVC and STATCOM.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SVC</th>
<th>STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{p1}$</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$K_{i1}$</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$K_{p2}$</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$K_{i2}$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$Q_{max}$ (pu)</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>$Q_{min}$ (pu)</td>
<td>-1</td>
<td>—</td>
</tr>
<tr>
<td>$I_{max}$ (pu)</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>$I_{min}$ (pu)</td>
<td>—</td>
<td>-1</td>
</tr>
</tbody>
</table>

![Figure 9: Voltage profile at 23kV bus.](image9)
**Figure 10:** Switch on of MSC.

**Figure 11:** Reactive power delivered by STATCOM/SVC.
Figure 12: 23 kV bus voltage in p.u. after 1 second. Duration: 3 phase short circuit.

Figure 13: Reactive power delivered by SVSs.
considered appropriately in the positive- and zero-sequence systems [47].

Data of the transformers and loads are shown in Table 5.

4.1.3. SVC-Based SVS Dynamic Model. The model in Figure 7 accurately represents the behavior of the SVS-SVC system. Its objective is to calculate the necessary susceptance ($B_{svc}$) that the SVC must control to inject or absorb reactive power from the system. The model measures the voltage and reactive power in the bus to control.

4.1.4. STATCOM-Based SVS Dynamic Model. The STATCOM serves the purpose of regulating the bus terminal voltage by means of a PI control, which adjusts the AC side voltage to a predetermined reference value. The implementation of the SVS-STATCOM system is realized by means of a current injection model, depicted in Figure 8, where the STATCOM current is maintained in quadrature with respect to the bus voltage. In this case, the output of the model is the STATCOM current ($I_{q,stat}$) which can be positive or negative if the STATCOM behaves as a reactor or a capacitor, respectively.

The parameters of the dynamic models from Figures 6 to 7 are listed in Table 6:

4.2. Procedure and Scenarios of the Dynamic Simulations. An evaluation is conducted to assess the dynamic performance of the SVS based on SVC and STATCOM in their ability to enhance the voltage stability of a power system when new GMDs are integrated. This comparative analysis is carried out across the following scenarios:

(i) Scenario 0: simulation without SVSs
(ii) Scenario 1: the STATCOM-based SVS is simulated in the most insecure bus
(iii) Scenario 2: the SVC-based SVS is simulated in the most insecure bus

A comparative analysis will be presented to examine the diverse voltage profiles and the behavior of each component.

5. Results

5.1. Voltage Regulation after Motors Start-Up. To enhance the overall performance of the mining system, a strategic approach was implemented whereby the two new motors were activated at different time intervals during the simulation. Specifically, the 20 MVA motor was initiated at $t = 1240$ s, followed by the activation of the 14.2 MVA motor at $t = 2800$ s. Figure 9 illustrates the voltage profile at the 23 kV bus in various scenarios, specifically under two conditions: without any connected SVS (scenario 0) and with the integration of SVSs (scenarios 1 and 2). It is worth noting that upon activation of the new motors, voltage stability issues arise in the bus to which they are connected.

In scenario 0, it is evident that upon the activation of the motors, the voltage level in the 23 kV bus experiences a decline, dropping to 0.99 p.u. upon the initiation of the first motor and further decreasing to 0.98 p.u. once the second motor is operational. Under scenarios 1 and 2, the SVS control system detects any voltage discrepancies and addresses them by introducing reactive power to counteract the voltage drop, ultimately bringing the voltage back to its initial level of 1 p.u. In both of these scenarios, the FACT system responds by injecting reactive power up to its
<table>
<thead>
<tr>
<th>SVS configurations</th>
<th>Primary driver</th>
<th>Cost comparison</th>
<th>Space occupancy</th>
<th>Performance in transient stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVC + MSC</td>
<td>Cost</td>
<td>30% cheaper than 30 MVar SVC</td>
<td>60% more space than STATCOM + MSC</td>
<td>Satisfactory performance in reducing voltage peaks and overvoltage</td>
</tr>
<tr>
<td>STATCOM + MSC</td>
<td>Space</td>
<td>26% more expensive than SVC + MSC</td>
<td>75% less space than 30 MVar SVC</td>
<td>Satisfactory performance in reducing voltage peaks and overvoltage</td>
</tr>
</tbody>
</table>
maximum limit of 15 MVAr, after which the MSC takes over and continues with the compensation process.

The behavior of the FACTS system and its response to the connection of the MSC can be observed in Figure 10. Upon the activation of the capacitors, a micro peak is produced at \( t = 3398 \text{s} \) due to the connection of the MSC. A comparison of the STATCOM-based SVS and SVC-based SVS reveals that the former exhibits faster response times, with the MSC being switched on a few seconds later, resulting in slightly better performance:

If we focus on the reactive power delivered to the 23 kV bus, in Figure 11, reactive power delivered by the STATCOM/SVC is shown. When the first GMD is started, the STATCOM/SVC injects 9 MVAr to restore the voltage to 1 p.u. However, when the second GMD is connected, the required reactive power exceeds 15 MVAr. Thus, when the FACTS reaches its maximum reactive power compensation capacity of 15 MVAr, the MSC is activated and the reactive power injection by the STATCOM/SVC decreases to zero. This is illustrated in Figure 11, where a sudden change from 15 MVAr to 0 is observed. The MSC then provides the remaining 15 MVAr required for optimal system stability.

Zooming on the peak, it can be stated that STATCOM control is faster than the SVC and reverses before the limit of the FACTS, switching the MSC some seconds before:

(i) \( t = 3398 \text{s} \) in the STATCOM-SVS case
(ii) \( t = 3400 \text{s} \) in the SVC-SVS case

Simulation results indicate that both STATCOM and SVC are significant compensation devices in mining electrical networks. Nonetheless, the STATCOM exhibits a faster response time in delivering reactive power than the SVC.

5.2. Transient Stability Study after 3 Phase Short Circuit. Large motor’s transient stability is defined as the ability to return to its normal state when a fault occurs, depending mainly on the initial state and the severity of the disturbance [48]. During a fault, electrical power is reduced suddenly while mechanical power remains constant, thereby accelerating the rotor. With the aim of studying transient stability, a 3 phase short circuit in the weakest bus (23 kV bus) is simulated. According to Technical Annex of the Chilean National Standard [49] (where this installation is situated), the duration of the short circuit must be 1 second.

The voltage profile at the 23 kV bus is illustrated in Figure 12, following a 3-phase short-circuit simulation lasting 1 second, which occurred at \( t = 20 \text{s} \).

Following the disturbance, the synchronous motors experience transient voltage oscillations, which are prolonged due to their high moment of inertia. As illustrated in Figure 12, the following are the occurrence of the short-circuit event:

(i) In scenario 0, where the SVS is absent, the initial oscillation reaches 0.93 p.u., while the main oscillations hover around 0.98 p.u.
(ii) In scenarios 1 and 2, the SVS systems inject reactive power, reducing the magnitude of the first oscillation and keeping the voltage oscillations above 1 p.u.

In this type of phenomena, reactive power delivered during this short circuit can be seen in Figure 13; after the occurrence of the short circuit, the SVS delivers its maximum reactive power to restore the voltage level. Once the disturbance is cleared, both systems gradually reduce the reactive power injected into the system.

5.3. Sudden Load Change. Mine electrical networks are often weak networks, and their sensitivity to load changes is very high. A sudden change in the active load can cause voltage disturbances, and the SVS can help mitigate the effects. The study involves analyzing the effects of a sudden 50% reduction in the load at \( t = 20 \text{s} \), which leads to an overvoltage of 0.8% and voltage oscillations.

Figure 14 illustrates that, in the absence of the SVS, the system experiences sustained overvoltage upon the sudden load reduction at \( t = 20 \text{s} \). Upon the introduction of the SVS, voltage oscillations that arise immediately following the load reduction are mitigated and the SVS subsequently absorbs reactive power to stabilize voltage at 1 p.u.

6. Conclusion and Future Research Directions

This paper presents a comparative analysis of two static VAR systems (SVSs), namely, SVC- and STATCOM-based SVSs, as applied to a mining electrical system, within the context of FACTS technology. The paper explores the potential of SVSs in enhancing the stability of mining electrical systems, with a focus on comparing the performance of SVC- and STATCOM-based systems. The results indicate that both systems are suitable for strengthening grid stability. However, the STATCOM exhibits slightly better performance, delivering the maximum of its reactive power a few seconds earlier than the SVC. The study demonstrates the potential benefits of implementing SVSs in mining projects and highlights the importance of choosing the appropriate technology for the specific application.

Table 7 summarizes the results of the comparison between the two SVS configurations. It can be observed that when cost is the primary driver, the SVC+MSC configuration proves to be the most economical choice, providing a cost reduction of 30% compared to a 30 MVAr SVC and 26% less expensive than STATCOM+MSC. On the other hand, when space is the primary concern, the combination of STATCOM+MSC presents as the optimal solution, occupying significantly less space than the SVC+MSC option by 60% and even more compact than a 30 MVAr SVC by 75%.

In addition, both configurations exhibit satisfactory performance in transient stability scenarios, reducing the first oscillation voltage peak value by 3.5% in a 3-phase short circuit and minimizing overvoltage by 0.75% in load changes. The table shows that each configuration has its...
advantages and disadvantages, and the final decision should be based on the specific requirements of the mining electrical system.

It can be figured out that SVSs ensure grid stability and improve the system behavior against transient disturbances. By taking advantage of SVSs, new components as GMDs can be integrated in a mining power grid.

The results of this study should be considered in the context of certain limitations, such as the dearth of prior research on the use of FACTS to enhance mining operations. Nonetheless, the potential of FACTS to enhance mining productivity and their suitability for such applications represent promising avenues for future investigation.

As a future direction, exploring the synergistic effects of combining shunt and series FACTS devices is likely to yield more effective results than a single controller, making it a powerful approach for future studies. However, the complexity of control and coordination presents a challenge, and various control techniques such as bang-bang control, GA optimization, and moth-flame optimization should be evaluated and assessed to achieve better performance and explore new applications of the FACTS in mining installations.

An imperative task for future work is the verification of the SVS on a real-time platform prior to its implementation in a power system, as it is deemed indispensable for the triumph of the project.

**Abbreviations**

- \( Q_{\text{stat}} \): Reactive energy delivered by STATCOM
- \( Q_{\text{svc}} \): Reactive energy delivered by SVC
- \( Q_{\text{msc}} \): Reactive energy delivered by MSC
- POI: Point of interconnection
- P-V: Power voltage
- PI: Proportional integral
- \( K_p \): Proportionality coefficient of PI
- \( K_i \): Integral coefficient of PI
- \( B_{\text{svc}} \): Susceptance of SVC
- \( I_{q_{\text{stat}}} \): STATCOM current
- \( Q_{\text{max}} \): Upper limitation of PI controller
- \( Q_{\text{min}} \): Lower limitation of PI controller
- \( I_{\text{max}} \): STATCOM current upper limitation
- \( I_{\text{min}} \): STATCOM current lower limitation
- FACTS: Flexible AC transmission systems
- GMD: Gearless motor drive
- SVC: Static var compensator
- STATCOM: Static synchronous compensator
- SVS: Static var system
- LME: London metal exchange
- SAG: Semiautogenous
- AG: Autogenous
- LVRT: Low voltage ride through
- D-STATCOM: Distribution static compensator
- THD: Total harmonic distortion
- HPS: Hybrid power system
- IHPS: Interconnected hybrid power systems
- MSC: Mechanically switched capacitors
- GA: Genetic algorithm.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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