

# FACTS for Cost-Effective Improvement of Power Feeding of Large Mining Complexes

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## II. FACTS

*Abstract-* Loads such as mine hoists, mining shovels, crushers, etc for mining are demanding and also sensitive to dips and fluctuations in feeding voltage, thereby depending on secure, high quality power supply. At the same time, mining complexes are often remotely located, where power is weak and unpredictable. A traditional way to deal with poor power supply is reinforcing the grid by building new lines, uprating voltages to higher levels, or building local power plants to supply parts or the total of the load. Such measures, however, are expensive and time-consuming, if at all permitted. A more cost as well as time effective way may be to introduce FACTS, thereby utilizing existing facilities more efficiently.

The paper highlights SVC and STATCOM for improving power supplies to mining industry, offers some salient design features, as well as gives examples of current, successful FACTS installations for the purpose in the world.

## I. INTRODUCTION

Feeding safe and reliable power to mining complexes can be a challenging task. Loads such as mine hoists, mining shovels, crushers, pumps, conveyor belts etc are demanding and also sensitive to dips and fluctuations in feeding voltage, thereby depending on secure, high quality power supply. At the same time, availability and reliability demands are high (production outages very expensive).

Mining complexes are often forced to operate in environments characterized by one or several of the following factors:

- Remote areas where power supplies are weak or inadequate
- Rough, inaccessible terrain, more or less unsuited for OH line construction
- Elevated or high isokeraunic activity

The picture is further complicated by modern industrial drives, derating the power quality of feeding grids, unless proper mitigating measures are taken.

A traditional way to deal with shortcomings in power transmission as well as with poor or insufficient power quality is reinforcing the grid by building new lines, upgrading voltages to higher levels, or building local power plants to supply parts or the total of the load. Such measures, however, are expensive and time-consuming, if, indeed, they are permitted at all. A more cost effective way may be to introduce FACTS, thereby utilizing existing facilities more efficiently.

The term “FACTS” (Flexible AC Transmission Systems) covers several power electronics based systems utilized in AC power transmission and distribution [1]. FACTS solutions are particularly justifiable in applications requiring rapid dynamic response, ability for frequent variations in output, and/or smoothly adjustable output. Under such conditions, FACTS is a highly useful option for improving the utilization of transmission and distribution grids.

FACTS devices can be sub-divided into three groups:

- Shunt devices such as SVC (Static Var Compensator) and STATCOM<sup>1</sup>
- Series devices such as Series Capacitors and Thyristor Controlled Series Capacitors (TCSC), not treated in this paper.
- Dynamic Energy Storage, also not treated in the paper.

With SVC and STATCOM, a number of benefits can be attained in power systems:

**Dynamic voltage control**, to limit over-voltages over lightly loaded lines, as well as prevent voltage depressions or even collapses in heavily loaded or faulty systems.

**Increased power transmission capability and stability** of power corridors, without any need to build new lines. This is a highly attractive option, costing less than new lines, with less time expenditure as well as impact on the environment.

**Maintaining power quality in grids** dominated by heavy and complex industrial loads such as large mining complexes.

Several examples of these benefits are demonstrated in the paper by means of ongoing or recent installations of FACTS devices in various parts of the world.

## III. DYNAMIC VOLTAGE CONTROL

The introduction of an SVC at a critical load point will serve as a powerful tool for dynamic voltage support that will enhance the stability margin. The capability for the SVC to maintain a constant voltage in the load point for a certain grid configuration is depending on the SVC rating and size of the load. This relationship is shown in Fig. 1.

The under-voltage control at faults and overvoltage control during light or no load conditions are key features for the SVC operation. Let us assume a generic case as shown in Figure 2. The load centre is fed through a transmission line and the load consists to a large extent of induction machine

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<sup>1</sup> Also known as SVC Light®

loads which are sensitive to under-voltage situations. In this case both active and reactive power to the load has to be supported through the transmission line. Apart from the ohmic losses this will generate in the system it will also show up as challenges at faults in the system.

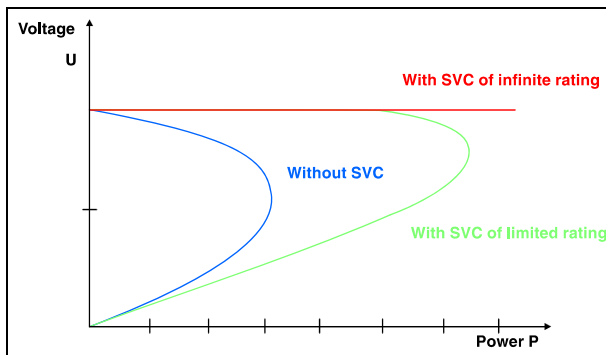


Fig. 1. Voltage variation at a load busbar as a function of loading, with and without SVC.

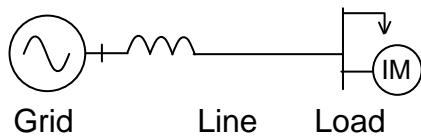


Fig. 2. Single line diagram of generic system.

#### A. Under-voltage Control

Under-voltage situations can occur at generator outages, starts of large induction machines or faults in adjacent feeders. The faults will typically be temporary, cleared after 100-150 msec. During the fault, the voltage will go down to a higher or lower degree.

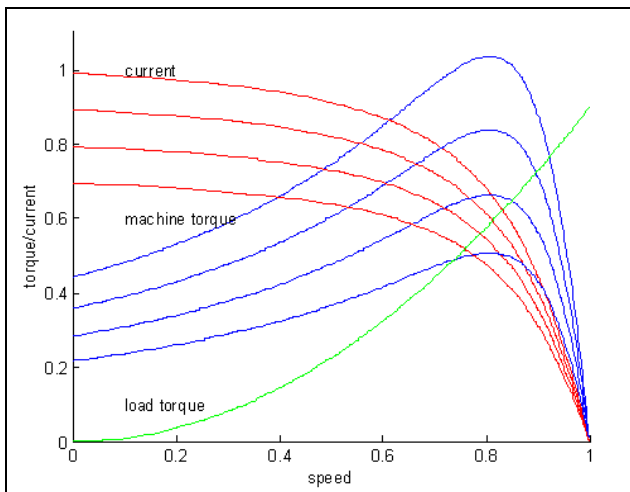


Fig. 3. Load torque and machine torques as functions of speed and machines currents.

Under-voltage situations are especially difficult when the load consists of a large percentage of asynchronous machines, such as motors for pumps or air conditioners. The situations

between the load torque and the produced electrical torque as a function of speed is shown in Fig. 3.

During the fault the asynchronous machines will slow down in speed which will affect the system when the fault is cleared. In the worst condition it might be so severe that the grid is not able to get a voltage recovery after this kind of fault. However, this challenge can be resolved through the use of a Static Var Compensator (SVC). The generic single line diagram after installation of the SVC is shown in Fig 4.

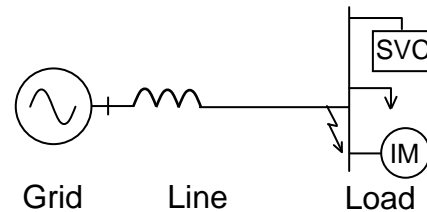


Fig. 4. SVC installed at a load centre.

With the help of an SVC that dynamically supports the situation during the fault through reactive power support, the case can be solved [2].

Other types of loads such as DC drives for mine hoists are voltage sensitive, as well, and may require dynamic voltage support for various load conditions. A recent example is given below in section V, sub-section C.

#### IV. SVC

An SVC is based on thyristor controlled reactors (TCR), thyristor switched capacitors (TSC), and/or harmonic filters. Two common design types, each having its specific merits, are shown in Fig. 4a and 4b.

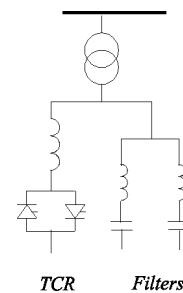


Fig. 4a. TCR/filter configuration.

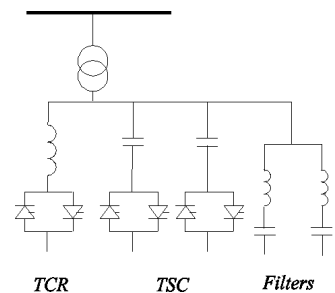


Fig. 4b. TCR/TSC/filter configuration.

A TCR consists of a fixed shunt reactor in series with a bi-directional thyristor valve. TCR reactors are as a rule of air core type, fibre glass insulated, and epoxy resin impregnated. A TSC consists of a capacitor bank in series with a bi-directional thyristor valve and a damping reactor which also serves to de-tune the circuit to avoid parallel resonance with the network. The thyristor switch acts to connect or disconnect the capacitor bank for an integral number of half-cycles of the applied voltage. The TSC is not phase angle

controlled, which means it does not generate any harmonic distortion.

A complete SVC based on TCR, TSC and harmonic filters may be designed in a variety of ways, to satisfy a number of criteria and requirements in its operation in the grid. In addition, slow vars by means of Mechanically Switched Capacitors (MSC) can be incorporated in the schemes, as well, if required.

#### A. SVC Characteristics

An SVC has a voltage-current characteristic (VI) as shown in Fig. 5. The SVC current/susceptance is varied to regulate the voltage according to a droop characteristic, or slope. The slope setting is important in coordination with other voltage control equipment in the grid. It is also important in determining at what voltage the SVC will reach the limit of its control range. A large slope setting will extend the active control range to a lower voltage, but at the expense of voltage regulation accuracy.

In Fig. 5, the voltage improving effect of the SVC is demonstrated for three different load cases by letting the SVC characteristic intersect with system load lines for the following cases (Slope:  $X_s$ ):

- 1: Nominal voltage & load
- 2: Under-voltage, e.g. due to generator outage
- 3: Over-voltage, e.g. due to load rejection.

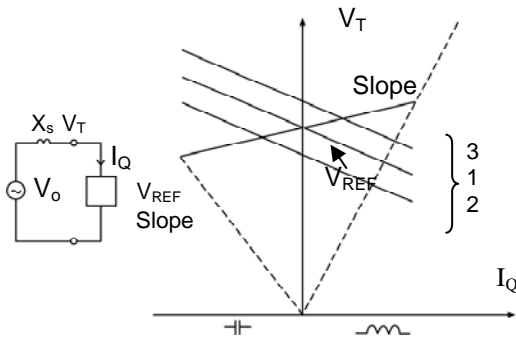


Fig. 5. System voltage correction by means of SVC.

#### B. Control System

The control of the SVC requires a fast acting and accurate control system to be able to counteract rapid changes in the bus voltage and control the TCR phase angle to the desired value. This is done by a micro processor based and highly flexible system that measures all necessary voltages and currents in the SVC, and determines the susceptance needed by the SVC. The output of reactive power is usually based on a positive sequence measurement of the three phase voltages at the Point of Common Coupling (PCC). For special undervoltage and overvoltage strategies, individual phase voltages are measured.

In some cases, where voltage unbalance is an issue and the loads are sensitive to unbalance, the SVC can be equipped with negative sequence control to individually regulate each

phase of the TCR valves [3]. It should be observed that with this regulator principle, the SVC will generate third harmonic when compensating unbalance, creating a need for a 3<sup>rd</sup> harmonic filter to be installed.

As mentioned previously, the mining loads are often located very remotely to weak networks with voltage stability issues. The control system must therefore be very sensitive to oscillations and carefully changing the SVC reactive power output not to cause severe overshoots in the network voltage. The voltage regulator can therefore be equipped with Gain Supervision functions that will detect oscillations in the response of the SVC. Oscillations can occur if the regulator gain is too large in comparison to the short-circuit strength of the network, for example due to a generator outage. The Gain Supervisor will immediately reduce the gain to a value that will give a stable operation of the SVC. Some SVCs also include functions for continuously measuring the strength of the network and adapting the gain of the regulator.

Operating in weak networks requires advanced control strategies for handling of undervoltages during faults or overvoltages after fault clearing. Special functions have been used in several installations to detect rapidly increasing voltages at fault clearing to be able to counteract within a few milliseconds.

#### 1. STATCOM

In cases where the conventional thyristor based SVC technology is not possible to use, STATCOMs with IGBT based voltage sourced converters will give additional control possibilities for weak networks and fast compensation of the voltages. These applications are however not discussed further in this paper.

#### C. Thyristor Valves

The thyristor valves consist of single-phase assemblies (Figure 6). The thyristors are electrically fired and the energy for firing is taken from snubber circuits, also being part of the valve assembly. The order for firing the thyristors is communicated via optical light guides from the valve control unit located at ground potential.



Fig. 6. Thyristor valve of BCT design.

Between thyristors, heat sinks are located. The heat sinks are connected to a water piping system. The cooling media is low conductivity water, sometimes mixed with glycol. The TCR and TSC valves each comprise a number of thyristors in series, to obtain the voltage blocking capability needed for the valves.

Of course, high power thyristors are normally able to conduct in one direction only. This is no serious limitation in most applications of the technology. In the case of SVC, however, thyristors conducting in both directions of the current cycle would definitely offer possibilities for savings in costs as well as space. This has now become a reality. In the most recent SVCs supplied, the thyristor valves are equipped with so-called Bi-Directional Control Thyristors (BCT). In such devices, two thyristors are actually integrated into one wafer with separate gate contacts [4].

The two component thyristors in the BCT function completely independently of each other under static and dynamic operating conditions. Each thyristor in the BCT has a performance equal to that of a separate conventional device of the same current carrying capability.

The valves comprise only one thyristor stack in each phase instead of two, which of course enables considerable compacting of the valve design.

## V. SOME RECENT CASES

### A. SVC for Dynamic Voltage Support of a Long, Weak Grid Feeding a Mining Complex in Australia

A large iron ore mining complex in Western Australia is fed over a more than 500 km radial 220 kV grid with generation at one end and the mining load plus additional generation at the other. The main part of the generation is located at the coast, whereas the main load is inland.

The 220 kV line connecting the load with the coastal generation area suffers from degraded availability due to outages caused by lightning.

The load is to 85% heavy mining loads with crushers, conveyors, pumps, etc. The remainder chiefly consists of air conditioning. The fault level at the 220 kV point of common connection (PCC) is low, dipping below 200 MVA in certain grid situations. During contingencies, the feeding voltage could drop to 0.8-0.5 p.u., tripping relays, and losing large motors as well as other vital functions.

To improve the power supply, as well as accommodate planned increases of ore extraction, an SVC has been installed at the 220 kV mining substation. The primary function of the SVC is to provide reliable reactive power support to the area and stabilise the 220 kV voltage under steady-state conditions as well as transient disturbances, keeping the system and loads online.

The SVC (Fig. 7) is rated at 75 Mvar inductive to 75 Mvar capacitive ( $\pm 75$  Mvar), with an overload capability of  $\pm 100$  Mvar for a duration of up to one hour. The SVC also controls two MSCs, each rated 220 kV, 25 Mvar, and located in the same substation.

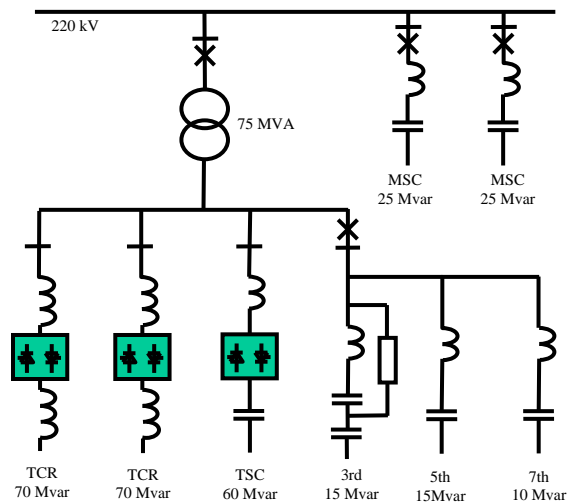


Fig. 7. 220 kV SVC plus MSC.

Experience from the initial test period shows excellent correlation between load drops which would have led to voltage rises, and the SVC going inductive to keep the feeding grid voltage at its set point. Likewise between load increases which would have led to voltage drops, and the SVC going capacitive to support the voltage.

### B. SVC for Voltage Support and Power Quality Control at a Mining Complex in Peru

A mining complex in North Central Peru has a daily production volume of 70,000 tons of ore. A prerequisite for this was the development of an adequate utility infrastructure to feed the mine complex, as detailed electrical studies indicated that the grid system would be inadequate to support the forecasted loading and several system configurations.

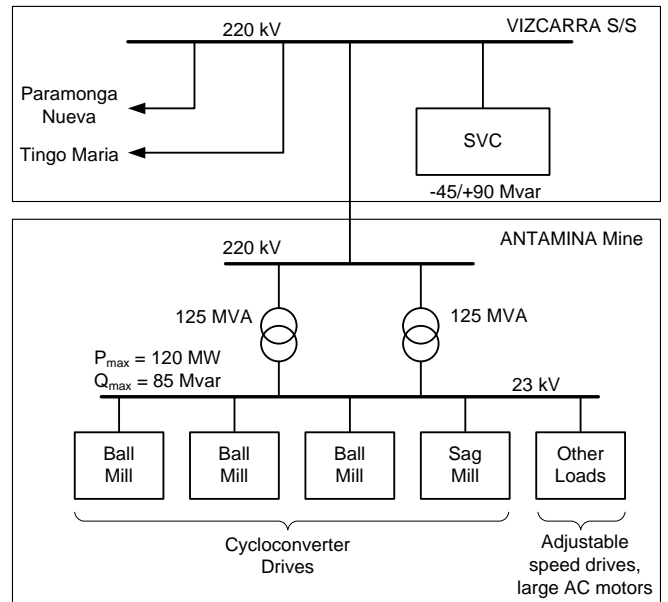


Fig. 8. Mining complex feeder and loads.

It was decided to implement FACTS to improve the existing 220 kV power system at the junction point of their connection with the interconnected utility. This was deemed the most attractive option to assure dependable power under all anticipated utility configurations. Based on this, a decision was made to install an SVC in the existing 220 kV switching substation some 50 km away from the mine, Fig. 8.

### 1. Main System Design

The selected SVC is rated at 45 Mvar inductive to 90 Mvar capacitive at 220 kV, Fig. 9. It comprises a TCR rated at 135 Mvar plus an array of harmonic filters rated together at 90 Mvar and comprising three parallel branches tuned to the 5<sup>th</sup>, 7<sup>th</sup>, and 11<sup>th</sup> harmonics. Its purpose is to stabilize the 220 kV bus voltage at the mine substation to within  $\pm 5\%$ , permitting the operation of very large machinery even under the most restrictive power system configuration. The SVC and power system were designed for a maximum load of 120 MW, of which the largest loading (approximately 70 MW) consists of four cyclo-converter drive mills at the concentrator complex. Additional drives for crushers and mine operations consist of variable speed drives and solid state equipment.

The design of the SVC took into account various scenarios of power transmission. Without the SVC, power disturbances such as lightning and ground faults in the 220 kV grid may cause load shedding due to the close voltage tolerances that the cyclo-converter drives of the mine have to operate at. With the SVC in operation, as long as the grid disturbances do not occur close-in to the SVC, the risk of load shedding is reduced. The SVC provides reactive power support of the AC transmission system in order to maintain a stable voltage during steady state and transient conditions. During transient and fast changing voltage conditions, the SVC helps prevent extreme over-voltages, voltage collapse and instabilities in the system.

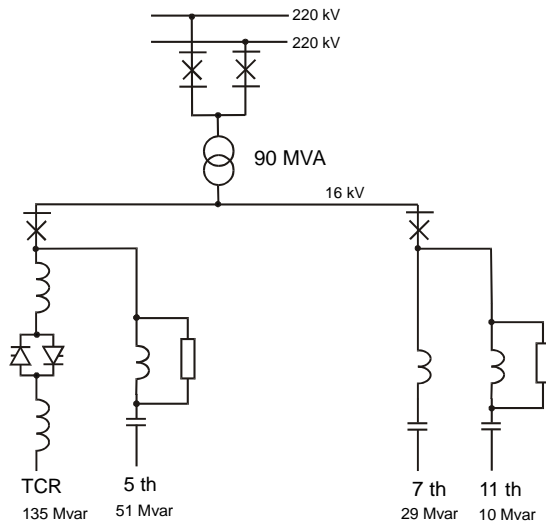


Fig. 9. Single-line diagram of the SVC.

### 2. Control System

The main objective of the control system is to keep the HV bus voltage close to a voltage set point, to provide dynamic,

fast response reactive power following system contingencies, and to maintain the magnitude of dynamic system voltages within 110% during disturbances. The voltage control used is a closed loop system. The automatic control can be switched off and the SVC operated manually. The network characteristic and the SVC characteristic together determine the operating point of the SVC.

A site photo of the SVC is shown in Fig. 10.



Fig. 10. Site view of the SVC.

### C. Improved Power Quality and Productivity at an Iron Ore Mine in Sweden

In 2009, an SVC was commissioned in the LKAB iron ore mine at Kirunavaara in the north of Sweden. The SVC, rated at 0-35 Mvar capacitive at 6.3 kV, has the purpose of improving power quality at the 145 kV Point of Common Coupling (PCC) as well as inside the mine by reducing voltage fluctuations and harmonics. As a direct benefit, with the SVC in operation, the ore hoisting capacity has risen, as well, making the extracting process more efficient than before [5, 6].

In the demanding environment of the iron ore mine, special focus was given to creepage distances of support insulators of outdoor equipment due to iron dust. Likewise, as the mine is situated north of the Arctic Circle, focus was given to snow clearance in winter time, as well as surrounding temperatures down to  $-50^{\circ}\text{C}$ .

#### 1. Mine Loads

In the underground mine of LKAB, iron ore is brought to the surface by a total of seven mine hoists, each driven by a 4.3 MW thyristor equipped 6-pulse DC drive and representing a fast varying load affecting the whole supply system. The load cycle consists of three different phases: acceleration, full speed operation and retardation. A typical load cycle duration is about 90 sec.

Before the advent of the SVC, due to insufficient strength of the feeding grid, simultaneous operation of the drives was seriously restricted, preventing the full capacity of the hoists to be utilized. Only 3% of voltage variations are permitted at the 145 kV PCC. Thus, to limit the voltage variations at the PCC to an acceptable level, only one mine hoist could be

started at a time, resulting in reduced productivity. With a planned extension of production capacity from 25 Mt annually to 35 Mt, the situation was aggravated further.

Due to the rapid load variations, conventional mechanically switched capacitors (MSC) were ruled out for voltage control of the drives.

With the SVC in operation, the voltage feeding the drives is supported at all times, with voltage sag never exceeding 3% at the 6.3 kV bus. Under these conditions, the mine hoists can be utilized more efficiently, cutting the total load cycle from previously 96 seconds to 72 seconds, an improvement of hoisting capacity by some 30%. One year of operational experience has corroborated this result, with a noted increase in hoisting capacity by 25-30%.

### 2. Main Design Features

The SVC consists of a Thyristor Controlled Reactor (TCR) rated at 6.3 kV, 35 Mvar, in parallel with three harmonic filters tuned to the 5<sup>th</sup>, 7<sup>th</sup>, and 12<sup>th</sup> harmonics (Fig. 11). The total reactive power yield of the filters is 35 Mvar at 50 Hz, giving the SVC an overall control range of 0-35 Mvar capacitive, continuously variable. For proper design of the harmonic filters, not only the grid impedance was taken into consideration but also the reactance of a 250 m cable connection between the feeding switchgear and the SVC. The 12<sup>th</sup> harmonic filter has a high-pass character, enabling it to damp the 11<sup>th</sup>, 13<sup>th</sup> and higher harmonics, as well.

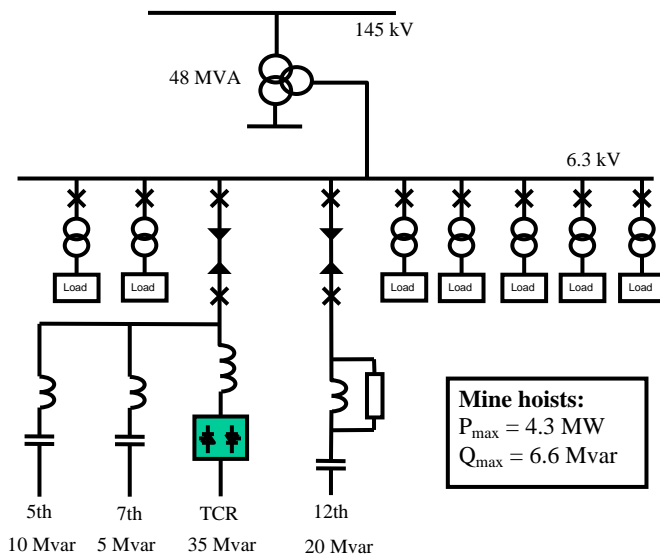


Fig.11. Single-line diagram, SVC and mine hoists.

### 3. Operational Experiences

The main goal of the SVC installation is to reduce voltage variations on the 6.3 kV and 145 kV bus bars. A comparison between the voltage variations on the 6.3 kV busbar without the SVC as well as with the SVC in operation at approximately 30 MW hoist load is shown in the graphs (Fig. 12 and Fig. 13). It can be seen that the voltage variations have been reduced from typically  $\pm 10\%$  down to  $\pm 2\%$ . An increase of hoisting capacity by 25-30% has been noted.

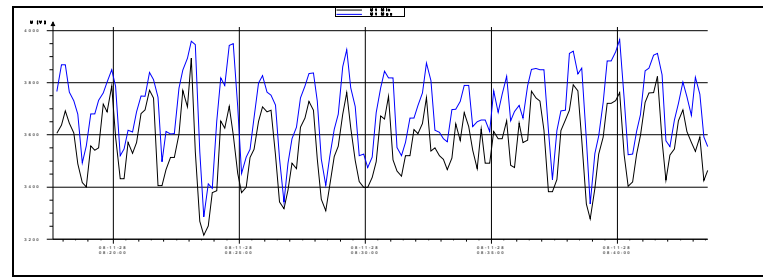


Fig. 12. Bus voltage variation without SVC. (Blue: maximum values; black: minimum values).

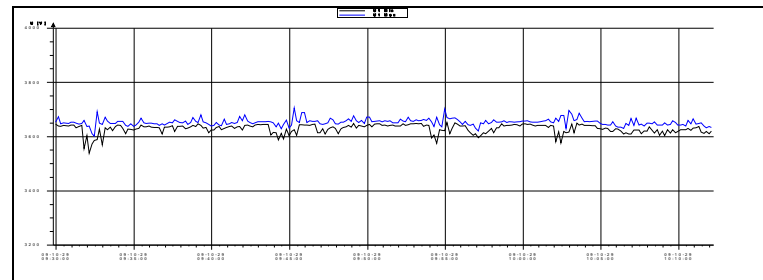


Fig. 13. Bus voltage variation with SVC. (Blue: maximum values; black: minimum values).

### 4. Performance Results

The contractual requirements on the performance of the SVC are listed below (Table 1), together with the actually measured values with the SVC in operation. As can be seen, the SVC fulfils its tasks, as well as actually surpasses them.

TABLE I  
PERFORMANCE

	Required values		Measured values	
	6.3 kV	145 kV	6.3 kV	145 kV
Max voltage variations	3%	3%	3%	1.3%
Power factor	0.98	-	0.998	-
Total harmonic distortion, voltage	4.8%	1.5%	3.2%	0.8%
Total harmonic distortion, current	5%	5%	2%	2%

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