Give Your Electrical Mining Machines a Voltage Boost!

Technology Update – Voltage Regulation Systems for Mining Equipment

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Abstract

This paper introduces a new application of a proven technology to provide dynamic, voltage regulation in underground mine electrical distribution systems. This technology acts to "stiffen" the electrical power feeding continuous miners and generally raise and improve the voltage regulation at the continuous mining machines which may be located over long cable distances from the mine incoming electrical substation.

This is extremely valuable for large underground continuous mining operations that use high power electrical mining machines fed over very long cable lengths (measured in 10s of km, from mine shaft to mine operating face). This new technology provides fast acting dynamic voltage regulation (voltage support) while starting continuous borers and extensible conveyor belts. Additionally, if the mine suffers from a lower distribution voltage due to long cable lengths, this new technology will raise the overall voltage at the mining machine, which can increased mining machine production and lead to longer motor life.

The technology is based on voltage source converters operating as static VAR compensators specially packaged for the harsh underground mine environment. While static VAR compensator technology has been successfully used in utility and large industrial applications for many years (including open pit mining and arc furnaces), it has not (until now) been applied in underground mining.

The paper will present the problem of poor voltage regulation in underground mines on weak electrical utility networks. It will then discuss some of the alternatives that have been used to resolve this voltage problem. It will then introduce the new technology used to solve the problem and review the issues involved in using this technology in the harsh underground environment. Finally, the paper will present preliminary performance results from an actual installation in a large underground continuous mining operation in Canada.

Introduction

A recent development in the mining industry may be extremely beneficial for mine operators who operate high power electrical mining equipment in their mine production process. This development is the Voltage Regulation System designed specifically for the heavy duty mine environment to provide high speed, dynamic voltage regulation for the mine electrical distribution systems. This paper discusses this new technology and provides some background regarding voltage drops experienced over long mine feeder cables.

Voltage Drops experienced at Mining Machines

"Maintaining adequate voltage is one of the more difficult problems in mining, and is often the main constraint on mine expansion from a point of power delivery to the operation." [1] This excerpt from the SME Mining Engineering Handbook indicates the seriousness of the problem encountered with "voltage limited" mine electrical distribution systems.

If a high power electrical mining machine (continuous miner, electric shovel, long wall mining system, etc) receives it's energy through a long feeder cable, there will be some voltage reduction across this long feeder cable. Figure 1 depicts a typical electrical distribution system encountered within an underground mine along with voltage profile showing the large voltage drop experienced across the long feeder cable.

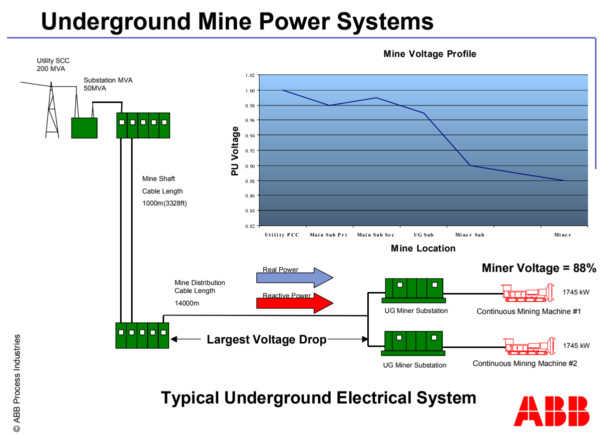

Figure 1 – Typical Underground Mine Electrical Distribution System

The voltage reduction consists of a voltage drop caused by real power (kW) flow (which is unavoidable), as well as a voltage drop caused by reactive power flow (kVAr). The real power flow consists of the electrical energy required by the mining machine to do it's work (rotate the cutter bits, rotate the hoist drum, etc) while the reactive power flow consists of the energy required to establish and maintain the mining machine motor's magnetic fields. Reactive power flow is necessary within the motor but does not directly contribute to the motor's real power output. The following simplified expression gives some insight into the voltage drop problem:

$$V\ drop = R(I \cos \theta) +/- X(I \sin \theta)$$

Where :
R = Resistance of mine feeder cables
X = Reactance of mine feeder cables (X is normally greater than R)
$I \cos \theta$ = Real power current
$I \sin \theta$ = Reactive power current
V drop = voltage drop across mine feeder cables

Voltage drops caused by real power cannot be avoided. If the mining machine is to do it's work, it will draw real power from the electrical network which will cause a voltage drop when transported across the mine feeder cable's resistance.

However, the voltage drop created by reactive power flowing across the long feeder cable may be reduced by injecting this reactive power, required by the motor's magnetic fields, right at the mining machine rather than transporting it across the long feeder cables. Since the long feeder cables supplying mining machines normally have a higher value of X than R (sometimes called the X/R ratio) the reactance component of the mine feeder cable has an amplified effect on the overall voltage drop. This means that voltage drop caused by the reactive current of a low power factor machine can be greater than the voltage drop caused by the real current. Therefore if, by injecting reactive power at the point of load, the mine can avoid drawing large quantities of reactive current across the larger reactance of a long mine feeder cable, the overall voltage drop experienced at the mining machine will be reduced.

Reactive Power Compensation

Currently, there are two methods of reactive power compensation: Capacitors and Static VAR compensators.
1). Capacitors
Capacitors have been used to supply the reactive power required by electric motors for their magnetic fields. Capacitors are fixed reactive power generators that are switched onto the circuit with either a circuit breaker or contactor. When they are switched onto the electrical network, they supply a constant, fixed quantity of reactive power to the electrical network, regardless of what the

electrical system and motors actually require. This means that when they are connected to the network, they can raise the voltage by a fixed amount. Their reactive power output is not adjustable and as such are not well suited for continuous voltage regulation.
2). Static VAR compensators
Static VAR compensators (SVCs) have been successfully used to regulate voltage in industrial plants for over 30 years. The term Static is used to differentiate SVCs from rotating VAR compensators (synchronous motors and generators). Their first major industrial application was in steel rolling mills and electric arc furnaces. Both of which have very high and very dynamic reactive power loads. Electric arc furnaces are particularly nasty in terms of the large reactive power swings over very short time periods resulting in voltage flicker (which when applied to electric lights can be quite irritable for humans). Static VAR compensators, unlike capacitors, can generate or absorb a continuously controllable quantity of reactive power. This means that when used in a voltage regulation system, they can generate or absorb the precise amount of reactive power required to maintain a stable and regulated voltage. Static VAR compensators use high speed electronic, power switching elements so they are capable of a fast response to a large reactive power change (and resulting voltage swing). Since static VAR compensators inject (or absorb) the precise amount of reactive power required by the load, they relieve the mine feeder cables from transporting this reactive power through their large reactance (X). Doing so, decreases the reactive power voltage drop and increases the “headroom” within the feeder cable to transport more real power.

Today, there are two main types of Static VAR compensators:

Thyristor Switched Capacitors (TSC), Thyristor Controlled Reactors (TCR)
Generally, TCR/TSC static VAR compensators are used for large industrial and utility applications. They are normally available at voltages above 5kV and typically start at 5MVA. Due to the large physical size of the water cooled thyristors, air core reactors as well as large capacitor bank racks, they are normally installed in fixed substation yards and generally are not suited for portable applications (although a low voltage version of a TSC has been successfully used on electric mine shovels).

Voltage Source Converters as Static VAR Compensators
A voltage source converter consists of a series of high power IGBT semiconductor switching elements connected in a three phase converter arrangement. When operated with the correct switching algorithm these high speed switches can convert a constant DC bus voltage into an adjustable voltage and adjustable frequency for operation on either a motor (Variable Frequency Drive application) or an incoming line (SVC).

Voltage source converters have been in use for years in the following applications
- ❑ Inverters in variable frequency motor drives
- ❑ Active front ends for multidrive and regenerative type drive lineups
- ❑ Power conditioners in wind generators

Today, voltage source converters can be applied as static VAR compensators. Using a voltage source converter as a static VAR compensator (VSC-SVC) is similar in concept to using a synchronous generator to provide controllable reactive power flow to and from a motor.

A voltage source converter (VSC) can generate a voltage across a load that is in phase with and at the same frequency as a utility voltage (or mine distribution system voltage) that is also applied across the load. Since these two applied voltages are in phase, adjusting the output voltage of the VSC either generates or absorbs reactive power. If the VSC applied voltage is less than the utility voltage, the VSC absorbs reactive power much like an inductive reactance (or motor). This will tend to reduce the overall voltage at the load. If the VSC applied voltage is more than the utility voltage, the VSC generates reactive power much like a capacitive reactance (or capacitor). This will tend to raise the overall voltage at the load. Since the quantity of the absorbed or generated reactive power is completely controllable within the nameplate rating of the VSC, the overall voltage at the load can also be controlled.

The VSC when applied as a static VAR compensator has a number of advantages over previous reactive power compensators.
- ❑ There is no large reactor that generates heat and losses as there is with a TCR
- ❑ The reactive power generated is completely and continuously controllable unlike a TSC
- ❑ There are no moving parts (except for cooling fans) unlike a synchronous motor

From this point on, we will refer to a voltage source converter operating as a static VAR compensator as a VSC-SVC.

The power circuit of a VSC-SVC consist primarily of high power semiconductor switches with minimal losses. Due to the modular nature of the VSC-SVC, the footprint required is smaller than that required of previous reactive power compensating device.

From the description, it seems that the VSC-SVC is an ideal solution for voltage regulation at mining machines.

VSC-SVC for use in Mine Voltage Regulation Systems
A properly designed and applied VSC-SVC can make an excellent reactive power compensation system capable of high speed voltage regulation at the mining machine terminals regardless of production load levels (high production, low production) network short circuit power levels and other factors affecting machine voltages. However challenges arise in designing a Static VAR compensator for use in the portable, rugged mining environment. Some of these challenges are as follows:

- Heavily dust loaded environment
- Continuously advancing mine production face requiring portability
- Vertical transport down the mine shaft
- Need for ruggedness & reliability

Underground Voltage Regulation System
Figure 2 depicts an underground voltage regulation system utilizing a VSC-SVC that was designed for use in an underground continuous mine in Western Canada to provide voltage regulation at the mining machines.

Figure 2 – Underground Voltage Regulation System

The underground voltage regulation system (UGVRS) is a ruggedly built, heavy duty static VAR compensator for use in the underground mining environment. The construction is such that the UGVRS can operate with little or no maintenance or operator attention within the harsh underground mining environment. It is normally located near the actual production face or continuous mining machines. The underground voltage regulation system designed for the above mentioned continuous mine has the following specifications:

- Incoming Voltage: 5kV Class
- Voltage Regulation Level (output): 4160V
- System Capacity: 3000kVAr
- Cooling System: Air Cooled
  with self cleaning filter system
- Operation Mode: Automatic
  Voltage Regulation to 4160V
- Electrical Topology: Parallel
  connection with mining machines
- Electrical Connections: Incoming &
  Outgoing, heavy duty mining plugs
- Voltage Regulation Level: Adjustable via
  setpoint control
- Total Harmonic Distortion: <1% Total
  Harmonic Distortion
- Protections: Multiple voltage, current
  and temperature protection
- Dimensions: 72" High x 72" Deep x
  306 Wide"
- Overall Weight: 23400 lbs

Benefits of a Voltage Regulation System
A properly designed and applied voltage regulation system will offer the mine the following advantages:

1). Larger Mine Production Area.
A voltage regulation system raises and regulates the voltage fed to the mining machine terminals. In a mine without a voltage regulation system, the length that the mine feeder cables can be extended is limited. As the production face advances further from the mine shaft (and mine substation), the voltage drop experienced across the mine feeder cables increases to the point where there is no longer sufficient voltage at the mining machine terminals to continue operation of the mining system. If a voltage regulation system is installed close to the point of load, the voltage drop experienced across the mine feeder cables is reduced, this means that the mine production face can continue to advance further from the mine shaft (and substation). In the case of the above mentioned underground mine, the voltage regulation system will allow satisfactory mining machine operation with a further 15km of mine feeder cable!

2). Higher Production Capacity
The torque developed by mining machine motors varies with the square of the applied voltage. If the voltage fed to the mining machine motor is reduced by 5%, the torque developed at the motor shaft is reduced 10%. If the voltage fed to the mining machine motor is reduced by 12%, the torque at the motor shaft is reduced 23%. Since

orebodies mined by electrical mining machines have a certain relatively consistent energy requirement for each ton of ore extracted, the reduction in shaft torque has a direct effect on mining machine production. A four rotor continuous mining machine with four 500HP head motors experiencing a 12% reduction in voltage will only have 1540HP available at the motor shafts. If the voltage regulation system is installed at a point close to the load, the voltage fed to the mining machine can be regulated to 100% nominal voltage, thereby increasing the shaft torque to design ratings. This allows full production from the mining machines.

3). Longer Motor Life

When a mining machine motor operates at less than nominal voltage, it's winding temperature increases resulting in a reduced motor life. A common rule of thumb is that for every 10 degree rise above maximum insulation temperature, the motor life is halved. If the voltage regulation system is installed at a point close to the load, the voltage fed to the mining machine can be regulated to 100% nominal voltage, thereby decreasing motor heating, which will result in a longer motor life.

In general, the above benefits can be attributed to operating the mining machines at their nominal or design voltage rating.

Application of Underground voltage regulation systems

An engineering study should be performed prior to the application of a voltage regulation system. An engineering study would include a load flow study, harmonic study, and a number of system simulations and system response studies to assist in the proper design and application of a voltage regulation system. These studies are necessary to ensure a sound engineering design of the voltage regulation system but as well to determine the effects the voltage regulation system will have on the mine electrical system during normal and abnormal conditions.

Once the electrical capacity as well as control system design of the voltage regulation system has been determined, it is then necessary to design the overall system taking into account the mine operating environment, operating practices as well as maintenance practices.

Actual Operation within an underground mine

Recently a UGVRS system was installed in an underground continuous mining operation. The system was sized and designed to maintain a constant voltage regulation at 4160V+/-5% during normal full load running conditions. Additional capacity was built into the system to allow the mining operation to extend their limit of mine production by approximately 15km. The continuous mining system had the following specifications:

- Mining Machine: 4 Rotor, Continuous Mining Machine
- Mining Machine Power: 2150HP
- Design Operating Voltage: 4160V
- Power Factor: Approximately 0.9

The underground electrical system had the following specifications:

- Mine Incoming Short Circuit Power: 276MVA Maximum
- Short Circuit Power at mining machine: 15 – 20MVA approximately
- Voltage range – light loads: 3900V – 4300V
- Voltage Range – Full Loads: 3600V – 4000V

Once the UGVRS was received at the mine site, it was lowered down the mine service shaft using normal equipment slinging procedures. The UGVRS was functionally tested and precommissioned in the underground electrical shop near the mine shaft. Once the functionality tests and precommissioning was completed, it was then "skidded" out to the mine production area. During the transport to the mine production shaft, one of the units overtook and collided into the hauling vehicle. Although there was a large dent in one of the units, there was no damage done to the UGVRS.

At the production face, normal, expected, minor commissioning bugs and problems were encountered but the system was fully functional after approximately 3 days.

The UGVRS contains two mine duty cable plugs. These plugs allow the UGVRS to operate in parallel with the continuous mining system. There is one incoming plug and one outgoing plug. Once the UGVRS is in the final operating location, it is connected to the mine underground electrical system via standard underground mine feeder cables plugged into the incoming and outgoing cable plugs.

The UGVRS includes a password protected, adjustable voltage setpoint level. This is the regulated voltage level and is normally set at the nominal voltage levels of the mine machine motors.

Operation of the UGVRS is very simple. Once the UGVRS is "plugged in", the main disconnect switch is closed. The UGVRS is then switched into the "automatic" mode of operation. At that point, the UGVRS immediately begins to regulate the voltage at the selectable voltage setpoint level. Any trips experienced with the UGVRS are easily reset once the fault is removed. The operator simply presses the reset button on the UGVRS and restarts the unit.

The preliminary results indicated the following performance of the UGVRS within the mine

- Voltage Range – Light Loads: 4160V +/- 3%
- Voltage Range – Full production loads: 4160V +/- 5%
- Maximum observed THD <1%
- Maximum operating temperature observed 73.6% of overtemperature trip level
- Normal temperature range Approximately 55% of overtemperature trip
- Normal UGVRS capacity utilized Approximately 47% of UGVRS system capacity

Figure 3 depicts the Underground Mine electrical system after installation of one UGVRS.

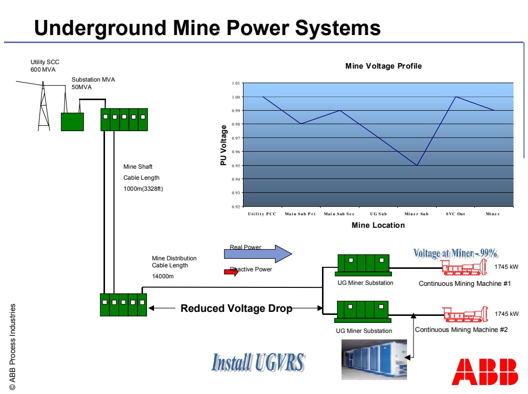

Figure 3 – Underground Mine Electrical System with UGVRS Installed

Figure 4 depicts a simulated voltage trend of this underground mine showing a simulated mining machine startup. While the simulation is not 100% representative of the actual mine, it is quite close. The red voltage trend depicts normal miner startup without a UGVRS. The blue trend depicts normal miner startup with a UGVRS. Note that the actual UGVRS installation does not experience the voltage overshoot shown on the simulation.

The UGVRS has been in operation for a number of months under normal mine production levels. Recently, the installed UGVRS experienced a true test of it's mettle. Due to some control problems experienced with the mine's incoming electrical meter, fifty percent of their surface power factor correction capacitors were switched off line. This meant that the mine incoming substation had to supply the reactive power normally generated by the now off line surface capacitors. This resulted in a very low voltage at the surface level and ultimately a much lower voltage in the underground distribution system. During this period, it was observed that the UGVRS was operating at it's maximum design capacity for a period of four days. The UGVRS operated well with no problems encountered during this period of maximum operation.

Conclusion

If a mining operation operates high power electrical mining machines over long mine feeder cables, it is quite likely that the mine is experiencing voltage drops at the mining machine terminals which result in lower production levels, higher rates of motor failures and a limited extent of mine production. Modern voltage regulation systems, if properly designed and applied can reduce the voltage drop across the mine feeder cables and effectively regulate the voltage at the mining machine terminals to their normal design levels +/-5%. Having the normal design voltage available at the mining machine allows for increased production and less motor overheating. Additionally, a properly designed and applied underground voltage regulation system can dramatically increase the extent of mine production at the facility.

1) LLOYD A MORLEY AND THOMAS NOVAK, Electric Power & Utilization , SME Mining Engineering Handbook, 2nd Edition, Volume 1 – Chapter 12.4, ppg 1205.