Reduction of Network Peak Power and Power Swing Demand in Mine Hoist Applications

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ABSTRACT: A mine hoist is probably the worst load on the power network of a mine due to its frequently changing power demand. During every hoisting cycle lasting for about 1.5 to 3 minutes, the power demand changes many times, often at high change rate. The load variations cause severe disturbances on the network in the form of voltage variations. Mines in remote areas are often powered by local diesel generators or gas turbines that cannot change the generated power as fast as required. As a result, the network voltage and/or frequency will change, which may be unacceptable to the mine hoist and other loads. In addition, the power generation has to be dimensioned to the peak power demand which requires correspondingly high so called spinning power resulting in overall higher operating cost and lower efficiency. The paper presents a solution to reduce the peak power demand, power swing and power change rate using a flywheel connected to the voltage source converter that controls the torque and speed of the mine hoist. The method makes it even possible to achieve constant power demand during the entire hoisting cycle.

GENERAL

Mines are often located in remote areas with either long power lines from the supplying power grid resulting in low short-circuit power. In other cases, the mine has to generate its own electricity by either diesel generators or gas turbines also with relatively low short circuit power. The mining trend is that to be profitable, production needs to be higher than in the past. In addition, new ore bodies are often located deeper resulting in larger hoisting system with high power demand. Rated motor power of 10 MW with peak power of 20 MW is not unusual today.

The hoisting system is generally not the largest load in a mine. Other major loads such as ventilation and refrigeration systems, crushing and grinding could be requiring larger power but these loads are normally operating continuously giving a fairly constant load on the supply network. The power demand of a mine hoist varies over the hoisting cycle from zero during loading and un-loading to about 200% of the rated motor power at the end of acceleration. In addition, the power demand change rate, dP/dt [MW/sec] is often high during the hoisting cycle. Fossil fuel power stations at the mine cannot handle large power change rates without changing voltage and frequency. Such changes may exceed acceptable values. The power station must have what is called spinning power available for the peak power demand of the mine. This means that the generators running must be able to deliver the peak power when required. Starting another generator set from stand still status is obviously not the solution. This could mean that an additional generator set is required to run continuously just to deliver the peak power required for the short moments the hoist is at the end of its acceleration. The cost of keeping a generator set running continuously is considerable and there is consequently a potential for CAPEX and OPEX savings if this can be avoided.

TYPICAL POWER DEMAND GRAPHS

The motor power required for a defined production rate tonnes per hour with a defined hoisting distance depends on the hoist type. A double-drum hoist requires a larger motor than a friction hoist due to higher unbalance torque and higher inertia. Figures 1 and 2 show different hoist types but with the same production rate. The network load is also depending on the type of motor and drive used. A DC motor with DC drive and an AC motor with cyclo- converter drive both generate large amounts of reactive power whilst an AC motor with VSI drive (Voltage Source Inverter) with AFE, Active Front End, only demands from or delivers active power to the network. This paper only deals with hoists with VSI type drives.
Figure 1. Friction hoist power demand

Peak power 7.1 MW

Power swing i.e. $P_{\text{max}} - P_{\text{min}}$ 7.1 MW

dP/dt 4 MW/s

Figure 2. Double drum hoist power demand

Peak power 10.7 MW

Power swing 13.1 MW

dP/dt 4.5 MW/s

In both of the above cases, the peak power and power variation rate can be reduced by increased S-shape in the speed reference ramp but at the expense of the cycle time. Without any S the power demand change when changing from constant full speed to retardation is instantaneous i.e. the dP/dt is very high.
ALTERNATIVE METHODS TO REDUCE PEAK POWER DEMAND AND POWER SWING

Choice of Hoist Type
As shown in Figures 1 and 2, a friction hoist is a less demanding load on the network than a double-drum hoist with the same production rate. The example shows that using friction hoist reduces the peak power by 34% and the power swing by 46% compared to using double drum. The relations vary from case to case but are typical. The difference could have considerable impact on the capital and operational costs of a local power plant. It is believed that this normally not considered when planning a hoisting system.

Change of Hoisting Cycle Parameters
Increasing the S of the speed S-ramp reduces the peak power when approaching full speed. The speed ramp could also have a lower linear acceleration rate at higher speed. The same ramp shape at start of retardation from full speed will reduce the power change rate dP/dt. Lower acceleration/retardation near full speed will only increase the cycle time by fractions of a second. Large S at low speed is time consuming and has no effects on the power issues in this paper but may be required to control rope oscillations.

Changing the hoisting speed will change the peak power demand proportionally. The formula normally referred to for optimized hoisting speed is

\[ v = (0.5 - 0.6) \sqrt{as} \]  

Where

- \( v \) = hoisting speed m/s
- \( a = \frac{(acc + ret)}{2} \) m/s²
- \( s \) = hoisting distance m

(0.5-0.6) should be read as a constant between 0.5 and 0.6

Higher speed requires higher motor power but gives smaller production increase

Energy Storage
Using an energy storage system that delivers energy corresponding to the power demand of the hoist above a certain value and that recharges when the power demand is low reduces both the peak power demand from the network, power change rate and the power swing during the hoisting cycle.

Several solutions for energy storage are available on the market or are being developed. Most of them are used to stabilize the network or as standby energy source in case of power failure. The methods of storage are, for example, battery, super capacitor, magnetic storage using super conductivity, pump storage and flywheel. Wind mill farms are an increased market where energy storage is used to even out power output at varying winds.

Significant of the mine hoist cycle is the large power swings and their frequency. A mine hoist cycle (or trip) is typically 1.5 to 3 minutes and the power swing could be 20 MW for a large hoist. Batteries have limited life time when subject to large number of deep discharges. Super capacitor, magnetic and pump storage have also been eliminated in our study as candidates for mine hoist applications.

FLYWHEELS IN MODERN HOISTING SYSTEMS

Background
Flywheel energy storage in mine hoist applications is by no means a new thing. It has been successfully used in Ward-Leonard- Ilgner systems in which the flywheel is mounted to the shaft of the DC generator that powers the DC hoist motor. In the past decades, Ward-Leonard systems have become uncompetitive following the introduction of thyristor converters. Since the 1980’s, AC- motors are replacing DC motors.

Flywheels are installed in some mines, connected to the plant network via frequency converters as voltage stabilizers (see Figure 3). Such units are rather small, in the order of 1 MW peak power. Several such units would therefore be required if a large hoist is connected to the network. The peak load required by the
hoist motor is still delivered by the network but part of the power is delivered by the voltage stabilizer flywheel.

**Figure 3.** Counteracting peak power demand by voltage stabilization

**New Solution with VSI Drives with Active Front End**

**Figure 4.** Flywheel assembly as part of the hoisting system

Figure 4. shows a solution using a VSI drive with active front end. The peak power is delivered by the flywheel via the DC link to the hoist motor. This means that the network is only loaded up to a certain power. When the hoist duty demands higher power, the excess is delivered by the flywheel. When the power demand is lower the flywheel is charged by the network. Thereby the power swing is reduced in both ends i.e. lower peak demand and lower min power if charging is made also during standstill.
A brief description of the system function is shown in Figure 5. The max allowed power from the network is set at $P_{\text{max}}$. Before the hoist cycle starts, the flywheel is accelerated to full speed. The power is taken from the network (6) via blocks 4, 7, 8 and 11 to the flywheel motor (13). As the hoist starts and accelerates, the power is delivered by the network via blocks 4, 7, 8 and 9 until the hoist motor power demand has reached $P_{\text{max}}$. When the hoist motor requires more power than $P_{\text{max}}$, the excess power is delivered by the flywheel (14) via block 13 now acting as a generator, 11, 8 and 9. This continues until the hoist motor power demand is reduced below $P_{\text{max}}$. At that time, the flywheel is charged again. This is done so that the sudden drop of hoist motor power demand at start of acceleration is compensated by the charging of the flywheel hence reducing the network power change rate $dP/dt$. The control strategy is different depending on the level of flywheel power required. If only reduction of the peak power demand from the network is required, the flywheel will not charge the entire standstill time for loading and unloading. Network power input will then be zero when the flywheel is fully charged.

If, on the other hand, full power compensation is required so that the power delivered from the network to the hoisting system shall be constant during the hoisting cycle, the flywheel is also controlled to charge also during hoist acceleration until $P_{\text{max}}$ is reached at which time the flywheel instantly changes from charging to discharging mode.

Advantages of the Solution Described in Figures 4 and 5

Following are advantages of the flywheel being part if the hoisting system as per Figures 4 and 5 (here called the integrated solution) compared with a stand-alone flywheel voltage stabilizer as per Figure 3:

- The integrated solution requires only an inverter supply unit while the stand-alone system requires a full frequency converter, transformer and breaker. This is a cost advantage for the integrated solution.
- The efficiency of the integrated system is higher since the flywheel current is passing only two inverter supply units when delivering power to the hoist motor. The power through the active front end (7) and transformer (4) is limited to $P_{\text{max}}$.
- The integrated solution only loads the network up to the $P_{\text{max}}$ value. In the stand-alone solution, the full motor power has to be delivered by the network although compensated by the stand-alone solution. But if other loads on the network need more power than planned, the stand-alone system may not be capable of fully compensating the hoist peak power.
• The integrated solution is capable of delivering sufficient power and energy using a single flywheel with motor and inverter supply module while known stand-alone flywheels with motor and drive are only available in small modules. This means that several modules would be required for a large hoist. This should be an additional cost advantage for the integrated solution.
• The integrated solution can be customized to the specific installation.

Example Friction Hoist Installation with Constant Power Demand from the Network
Figures 6-8 below show a hoisting plant with 9 MW peak power demand.

Figure 6. Hoist motor power during hoisting cycle

Figure 7. Hoist motor and flywheel motor power during hoisting cycle.
Note: Energy is the surface between the curve and the x-axis. \( W = \int P dt \)

Figure 8. Network power to the hoisting plant including the flywheel (unbroken line)
The example illustrates that it is possible to fully eliminate the power demand during the hoisting cycle by selecting the flywheel inertia and controlling charging and discharging. This is obviously only feasible in automatic production hoist where the loading/unloading time is constant. In the example, the peak power 9 MW, power swing 9 MW and power change rate 4 MW/s without flywheel are improved when using flywheel to continuous power 3.6 MW, power swing 0 MW and power change rate 0 MW/s.

Flywheel Design

The flywheel has to deliver sufficient energy to cut the peak power demand from the network.

Basic formulae for inertia of a solid cylinder (J) and its rotational energy (W) depending on speed \( \omega \)

\[
J = \frac{mr^2}{2} \quad [\text{kgm}^2] \quad (2)
\]

\[
W = \frac{J \omega^2}{2} \quad [\text{Ws}] \quad (3)
\]

For the example above, a flywheel with the following main data will enable constant power demand:

Diameter 1.9 m
Max speed 1800 rpm
Total net energy (excluding losses) about 45 kWh
Total flywheel weight including shaft ends about 29 tonnes.

The speed range during operation is about 30-100%. At 30% speed, only 10% of the kinetic energy remains so there is no point in reducing the speed further.

From the strength point of view, it is favorable to design the flywheel as a solid cylinder with bolted-on shaft stubs. This is for two reasons: first, the stresses in the cylinder are smaller compared to a hollow cylinder. Second, it makes it easier to check that there are no inclusions in the flywheel.

Figures 9 and 10 show the stresses in a cylinder without and with center hole at 1800 rpm. \( D_y = 1900 \) mm, In Figure 9 \( D_y = 200 \) mm.

Figure 11 shows finite element analyses of the same cylinder without center hole with bolted-on shaft stubs.

Figure 12 shows typical dimensions of a flywheel assembly with bearings and motor.
Figure 9. Stresses in solid cylinder

Figure 10. Stresses in hollow cylinder

Figure 11. Finite Element analysis of stresses at 1800 rpm
SUMMARY

A mine hoist is a severe load on the electrical network with large and fast variations in power demand that a weak grid or a local power station has difficulties to handle and at the same time maintaining the required network quality required by other loads. The paper highlights the importance of selection of hoist type to reduce the negative impact on the network.

The use of a flywheel connected directly to the hoist motor drive as energy storage medium is a cost efficient method to improve network quality by reducing peak power demand, power swing and power demand change rate. The flywheel could considerably reduce the capital and operational expenditures of a local power station or enable full utilization of the hoist where the grid network is otherwise too weak.