Abstract—This paper presents an overview analysis and a discussion of field experience with different drive configurations used in shovel applications. The analysis includes different drive topologies, shovel duty cycles for a typical truck pass loading and energy regeneration capabilities. Special attention is given to the interaction between the high power shovel drives and the grid: harmonics injection, reactive power requirements, and voltage regulation. This paper presents operational experiences obtained in copper mine industries. The main characteristics of the newest shovels with Active Front End (AFE) at the line side are also included. Finally, a critical evaluation of the different topologies is presented, showing that the shovel drive operation strongly affects the behavior of the power distribution system and that the introduction of the AFE technology produces an important performance improvement.

Keywords—DC drives; AC drives; shovels; mining; Active Front End.

I. INTRODUCTION

Shovels are critical high power equipment in every mine industry and their operational availability has an important impact on production. Shovels are one of the key equipment used in the mobile material handling in open pit mines. In addition, their reliability is strongly dependent on the drive system. On the other hand, there is a continual economic push to increase the productivity reducing the cost per ton of material moved, which has led to an increase in the power of all equipment. For this reason, shovels are the largest power consumers throughout the mine [1].

Two drive technologies have been traditionally used in shovel applications: DC motors connected to phase-controlled thyristor rectifiers and AC motors controlled by gate turn-off thyristor inverters [1], [2], [3]. Both alternatives use line-commutated rectifiers at the input side and, in principle, they generate an important amount of input current harmonics and reactive power, which must be compensated to avoid problems with the quality of power during operation [4]. The need to regenerate power to grid, what is usual during shovel cycle operation, increases the demand on the rectifier’s performance in the case of shovels with AC motors. In addition, the operation of large equipment, typical in mining distribution systems, can produce voltage dips that can originate failures in the shovel rectifiers.

The generation of harmonics and reactive power at the shovel’s point of connection can be reduced by the use of an Active Front End Rectifier (AFE). In addition, an AFE allows for regeneration of power from the motors to the grid.

This paper presents the characteristics of the most important shovel drives including the main problems observed during their operation. The solutions found for these problems are also discussed. Finally, the paper addresses the main characteristics and performance of the newest shovels with recently introduced AFE rectifier.

II. TECHNICAL REQUIREMENTS FOR THE DRIVE.

Large shovels, like those used in mining applications, require large motion power ratings, which proportionally translates into high electrical power consumption.

Fig. 1 presents a typical shovel loading a large truck in an open pit mine. In order to fulfill the three-pass loading of the truck, the shovel drives must produce fast and smooth dipper movements. At the beginning of the swing movement the drive works in the motoring mode and energy is supplied from the source to the motors. At the end of this movement, the dipper must decelerate and its kinetic and potential

Fig. 1. Shovel loading a truck in an open pit mine.
energy have to be removed by the motors. In this part of the movement the motors regenerate active power.

Fig. 2 shows the active power consumption during the complete loading of a 280[Ton] truck. The truck is completely loaded with three shovel cycles. This figure clearly illustrates that the shovel includes a regenerative operation. During the regeneration mode, the drive and especially the converters must be able to deal with this energy, delivering it back to the grid or dissipating it in internal braking resistors. In addition, the converters must be able to handle momentary voltage fluctuations between +10% and –30% without shutdowns or component failures. To increase power system compatibility and meet regulations and standards, the drives must operate with a high power factor value and reduced input current harmonics. The motors and the converters must be dust and shock protected and the complete drive system should have a simple and reliable troubleshooting system to reduce unexpected downtimes.

Each shovel active power cycle is shown in Fig. 3. The loading cycle of the shovel is composed of 7 different movements. The identification of each movement is described in Table 1.

<table>
<thead>
<tr>
<th>Loading Action</th>
<th>Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The dipper is fully loaded with rocks.</td>
</tr>
<tr>
<td>2</td>
<td>The revolving frame rotates towards the truck.</td>
</tr>
<tr>
<td>3</td>
<td>Braking of the revolving frame (regeneration).</td>
</tr>
<tr>
<td>4</td>
<td>Mineral discharge and dipper lift.</td>
</tr>
<tr>
<td>5</td>
<td>The revolving frame rotates towards mineral side.</td>
</tr>
<tr>
<td>6</td>
<td>Braking of the revolving frame (regeneration).</td>
</tr>
<tr>
<td>7</td>
<td>Dipper lowered down (regeneration).</td>
</tr>
</tbody>
</table>

The amount of active power regenerated during one loading cycle is 15% with respect to the active power absorbed from the source. During the whole mechanical cycle of the shovel, the drive must adjust to the required active power taken from the grid to drive the different motors. In the case of drives powered by phase controlled rectifiers, the active power control is done by delaying the firing angles of the input thyristors, thus reducing the power factor. The measured power factor profile of a six pulse regenerative shovel during one loading cycle, without reactive power compensation, is shown in Fig. 4. This figure shows that the resulting power factor is very poor.

Different drive technologies have been developed and are available in the market, which use different approaches to deal with the regenerated power and low value of the power factor. The different drive alternatives and operating experience of each of them are discussed in section III.

III. TRADITIONAL DRIVE TECHNOLOGIES AND ASSOCIATED OPERATING EXPERIENCES.

A. DC drives.

1) Description of the drive

An important number of shovels use DC motors driven by phase-controlled thyristor rectifiers. One major manufacturer still produces shovels with DC motors. The controlled rectifiers use two 6-pulse three-phase bridges in anti-parallel connection, also known as dual converter, allowing full regenerative operation. The rectifiers include harmonic filters...
tuned to the 5th and 7th harmonics to compensate current harmonics. In addition, they use switched capacitor banks together with phase controlled reactors to improve the power factor. With filters and reactive power compensation these DC shovels work with a power factor equal to 0.93 lagging and a Total Harmonic Distortion (THD) below 11% [5]. The generic power circuit topology of this scheme is shown in Fig. 5.

B. 12-pulse non regenerative shovel with AC-drives

1) Description of the drive topology.

The typical configuration of AC drives used in shovels consists of a 12-pulse diode rectifier at the input to generate a common DC-Link. All induction motors required to drive the shovel are connected to the DC link through PWM voltage-source inverters. The ac drive topology with non-regenerative characteristics is shown in Fig. 6. For example, an 1.85 MVA shovel implemented with a 12 pulse rectifier is composed of 4 voltage-source inverters rated 790 kVA each driving 5 induction motors, one for each mechanical shovel movement. One induction motor rated at 1500 HP is in charge of the vertical displacement of the dipper (up and down) and for traction the shovel uses a 1070 HP motor. The rotation movement of the frame is done by two motors rated at 330 HP each, and finally, to load the dipper with rocks, a 390 HP induction motor is used.

The advantage of using a 12-pulse configuration instead of a 6-pulse converter, is that the harmonic content of the input current can be drastically reduced. One important disadvantage is that the configuration shown in Fig. 6 cannot regenerate power to the grid. This means that the power regenerated by the motors must be dissipated in order to maintain the DC bus voltage constant. The standard solution is to add a chopper-controlled resistor, which dissipates the regenerated energy. This configuration is also illustrated in Fig. 6. Obviously, this approach is not as efficient as a converter with full regeneration capabilities, such as the topology discussed in the next section.

From the load point of view, the DC-Link voltage can be used to generate the voltages required by the ac motors, using classical modulation techniques such as Sinusoidal Pulse-Width Modulation (SPWM) or Space Vector Modulation. In both cases the generated voltages present a constant switching frequency and a load-friendly frequency spectrum, which allows for high quality currents in the load due to the low-pass characteristics of induction motors. Commercially available drives for a 1.85 [MVA] shovel, use four GTO-based voltage-source inverters each of them rated at 0.79 [MVA].

2) Operating experiences.

It is important to mention that shovels with SCR inverters working with forced commutated circuits and analog controls are still in operation. These are the oldest shovels operating today and have quite satisfactory behavior.

A problem appears when the cable connecting 12-pulse non-regenerative shovels to the substation is too long. In this situation, the voltage drop in the cable reduces the input voltage of the shovel, forcing a trip in undervoltage protection. The problem has been solved by changing the tap in the substation or in the shovel transformer.
Another important problem can appear during the operation of the braking chopper. An oscillation is generated in the DC-link voltage, creating important variations in the amplitude of the motor currents, which can trip overcurrent protection. This phenomena has been observed in the swing motors and has been solved by introducing a limit to the maximum value of the torque reference and by increasing the pick up level of the inverters overcurrent protection.

C. 6-pulse regenerative shovel with AC-drive.

1) Description of the drive.

An obvious extension of the topology discussed in the previous section, is the addition of a dual converter at input, as shown in Fig. 7. This figure shows a fully regenerative 6-pulse shovel and indicates that in this case, a chopper is no longer required, because of the regenerative characteristic of the dual converter. This implies that the regenerated energy can be sent back to the grid and used to feed other loads. This scheme can operate with a power factor ranging from 0.82 to 0.93 and is commercially available for shovels rated at 2.35 [MVA], which uses six 0.795 [MVA] GTO-based voltage source inverters.

Fig. 7. Power circuit topology of 6-pulse regenerative shovel drive system.

The 2.35 MVA shovel uses 6 voltage source inverters rated at 795 kVA each, driving 6 induction motors. The vertical movement of the dipper (up and down) is powered by one motor rated at 2235 HP. This motor is driven by three voltage source inverters connected in parallel. The rotation of the shovel’s frame is driven by two motors rated at 505 HP, connected to two inverters in parallel. Traction is achieved with two 700 HP motors. Finally, the loading action of the dipper is powered by a 700 HP motor.

2) Harmonics in the input current.

One of the major problems with this configuration, is that the input current harmonics are very high, especially during the regeneration mode. Fig. 8 shows the current measured at the input of a 6-pulse regenerative shovel, where a high total harmonic distortion can be appreciated. The frequency spectrum of this current, Fig. 9, shows that the amplitude of the 5th harmonic reaches almost 50% of the fundamental component. It is important to mention that during regeneration the DC current is not continuous. This discontinuity generates an input current with large harmonic distortion, especially the 5th and 7th.

Fig. 8. Input line current waveform of the 6-pulse regenerative shovel

3) The commutation problem.

A serious problem with the configuration illustrated in Fig 7, is that regenerative drives with two or four quadrant line commutated thyristor rectifiers can have commutation failures when they are working in the regeneration mode. In fact, it is well known that line-commutated rectifiers are prone to commutation failure and fuses blow when they work in the regeneration mode. This is especially frequent in weak electrical power distribution systems with high power loads, such as shovels or excavators. At the beginning of operation in one company, a lot of fuses were blown and a study revealed that this situation appeared when the energy supplied by the substation was interrupted while the shovel was regenerating energy. The solution to this problem was to introduce resistor $R_L$ in series with the regenerative rectifier (see Fig. 7) to reduce the current level in this abnormal situation. Another important problem appeared when the input voltage of the shovel was reduced due to a large cable connection from the substation. Again the problem was a malfunction (commutation failure) of the regenerative rectifier. The
solution was to increase the tap in the substation. These facts confirm that failures in the commutation of the regenerative rectifiers are a key problem in regenerative 6-pulse shovels, which have an important impact on costs due to the expensive loss of production originated by non-programmed down times and the consequent low reliability of the whole extracting process.

4) Other operating problems.

The large amplitude of the fifth current harmonics at the shovel’s input current during the regeneration mode causes the tripping of negative sequence current relays, reducing power system reliability. This large component of fifth harmonic is interpreted as a serious imbalance in the line current, tripping the negative sequence current relay.

D. Passive filters to reduce input current harmonics.

Harmonic distortion is an important issue in power distribution systems since it contributes to reduce power quality index. For this reason, high power non-linear loads are forced to attenuate current harmonic components injected into the grid. The most used alternative, although not the most convenient, is the connection of passive filters. Passive filters tuned at a frequency equal to the order of the dominant harmonic generated by the shovel’s input rectifier have been used to reduce harmonic distortion. In shovels with six-pulse rectifiers (Fig. 7) a passive filter tuned at the 5th harmonic is normally used. However, the compensation performance of this filter changes according to the operation mode of the rectifier. Another aspect that influences the filter’s behavior is the equivalent reactance of the power source. This value is affected by the variable reactance of the shovel’s cable, which changes according to the distance between the shovel and the substation. The larger the value of the reactance, a better filtering performance is achieved. Also, filtering effectiveness depends on the rectifier firing angle and rectifier’s mode of operation, as shown in Fig. 10. This figure, has been obtained for a passive filter tuned at 250 Hz at the input of a 2.35 MVA shovel with a six-pulse rectifier. The parameters of the passive filter are shown in Table II.

Fig. 10 shows that harmonic distortion deteriorates when $\alpha$ increases. Moreover, a larger current distortion is obtained during the regeneration mode ($\alpha > 90^\circ$) as shown in Fig. 11, obtained without filter.

There are not many alternatives to reduce the harmonic distortion of the shovel’s input current for all the operational conditions described in section II. One alternative is to increase the filter capacitance value, but in this case the rectifier presents commutation problems, especially for low load operating conditions, which increase the voltage distortion across the DC bus. Another solution is to connect a reactor in series to the DC bus in order to reduce the ripple factor of the DC current. This alternative is better, since it allows for a reduction of the THD of the input current. In this case the size and cost of the reactor are significantly reduced, and the THD of the shovel’s line current during regeneration is always below 15%. The inductor value used in the 6-pulse regenerative shovel is equal to 458.67 mH. In this case the DC reactor eliminates the discontinuity of the DC current during regeneration, which reduces the line input current harmonics significantly.

The other alternative to reduce harmonic distortion in the shovel’s input current is by using active front end rectifiers, whose principal characteristic is the generation of sinusoidal input current with adjustable power factor. The characteristics and principles of operation of this converter are described in Section IV.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Apparent Power</td>
<td>400 kVA</td>
</tr>
<tr>
<td>Rated Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Capacitor</td>
<td>1989.44 [F]</td>
</tr>
<tr>
<td>Inductor</td>
<td>230.56 [H]</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>235 Hz</td>
</tr>
</tbody>
</table>

Fig. 10.- Total Harmonic Distortion of the shovel’s input current for different rectifier’s firing angle ($\alpha$).

Fig. 11. Input line current waveform of the 6-pulse shovel drive in regeneration mode.
IV. REGENERATIVE AC SHOVELS WITH ACTIVE FRONT END RECTIFIER.

A. Power circuit configuration of a single AFE rectifier.

The most important disadvantages of line-commutated thyristor rectifiers used at the input of AC drives can be overcome by using a rectifier with high power gate-controlled semiconductors (IGBT or IGCT), commutated at high switching frequency. Fig. 12-a shows the power circuit of the AFE used in modern shovels with 3.3 kV IGBTs as semiconductor switches. It is important to notice that the power circuit topology of the AFE corresponds to the same power circuit configuration of the three-phase voltage-source inverter. The DC link voltage is boosted to a value higher than the voltage produced with a diode rectifier.

The AFE takes advantage of the source voltage and input transformer reactance to control the input current waveform. A closed loop scheme is used to control the DC bus voltage and the inverter input power factor. The block diagram of the control scheme is shown in Fig. 12. The control system consists of two closed loops: one to control the active power required to keep the DC bus voltage constant, and the other to control the rectifier input power factor. The rectifier control scheme uses Park transformation to calculate the current components in $d-q$ reference frame. By adjusting the amplitude of $I_d$, the amount of active power is controlled and therefore $V_{dc}$ is kept constant. On the other hand, the converter input power factor is adjusted by controlling the amplitude of $I_q$.

B. Power circuit topology of the shovel with AFE rectifier.

Fig. 13 shows the power circuit topology of the shovel using AFEs at the input side. Power flows from the line through the input transformer and the input reactance into four AFE modules, creating a common DC bus. The inverters take energy from the common DC bus to control the induction motors for the different movements: swing, crowd, hoist and propel. The DC capacitor is loaded by an appropriate control system to avoid inrush currents. To achieve good load sharing each AFE must deliver 25% of the total power demanded or regenerated by the motors. This is achieved through a DC voltage controller in common operation with a load sharing strategy.

C. Performance.

Since the AFE actively controls the waveform of the input current, the power factor is very close to 1 and the current THD is equal to 3.5 %. With this low harmonic distortion value it is not necessary to install passive filters. Fig. 14 shows the frequency spectrum of the rectifier input current operating at rated power, illustrating the low amplitude of the different harmonic components, compared to the values shown in Fig. 9. It is very important to point out that the AFE topology shown in Fig. 12-a) allows for fully regenerative operation, resulting in a very fast and reliable power reversal.

---

**Fig. 12.** Three-phase AFE rectifier topology. (a) Power circuit configuration. (b) Control scheme.

**Fig. 13.** Block diagram of a modern high power shovel with AFE rectifiers.
Fig. 14. Harmonics in the resulting input current of the shovel with AFE rectifiers.

D. Operating experiences.

It is important to comment on the semiconductor technology used in AC shovels. GTO-based shovels use large driver circuits for the thyristors, with an important amount of components, presenting frequent failures difficult to detect and to repair. On the other hand, modern IGBT-based shovels have very simple and small driver circuits for the transistors, resulting in a more compact cabinet for the inverter. In addition, it must be said that IGBT transistors allow much more efficient overcurrent protection, which can be obtained by eliminating the driving pulses until the overcurrent disappears. This is an important advantage as compared to GTOs and significantly reduces unexpected shutdowns of the shovel. Very good evaluations concerning the reliability of the newest shovels with IGBTs have been observed in Antamina (Perú) and Alumbrera (Argentina).

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support given by Fondecyt, through the 1010096 project and of the Research Department of the Universidad Federico Santa María. In addition, the valuable field experience contributed by Mr. Vladimir Fierro of Minera Escondida is greatly appreciated.

REFERENCES


