Recent Advances in Mining Haul Trucks

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***Abstract*—Electric mining haul trucks are one of the most challenging applications of power electronics in automotive systems. This paper presents some advances in very-high-power trucks used in copper mines. The special operational and environmental requirements for this application are highlighted. It is established that the use of inverter-fed three-phase induction motors with vector control is the preferred solution to reach the required high starting torque and good dynamic performance required by these vehicles. Packaging is a key issue and special attention is dedicated to the forced-air cooling system, because the air has a high dust level including conductive and corrosive materials. The truck's high-performance electric retarding system is described along with a novel use of trolley lines in a diesel boost mode as a way to increase the power and speed of the truck and reduce fuel consumption. Advanced features like remote monitoring, the use of global positioning systems and Internet diagnostics and troubleshooting are also discussed. The paper clearly shows that modern electric haul trucks are highly sophisticated systems that make full use of advances in modern technologies to increase safety and productivity levels.**

***Index Terms*—AC motor drives, automotive electronic systems, electronic packaging, global positioning, power electronics, traction motor drives.**

I. INTRODUCTION

ONE OF THE MOST demanding areas for automotive electronic systems is found on electric haul trucks used in the mining industry. These vehicles are employed for ore transportation under severe environmental conditions, stringent safety issues, and production requirements, including economies of scale that demand larger trucks.

Automotive systems are one of the most challenging fields for electronic systems design and applications, with embedded software for communication and control of sensors, actuators, microprocessors and networks. Recent advances in electronics systems state new system approaches for dealing with the new challenges [1]–[7]. Low- and high-speed networks are employed for noncritical and critical applications including real-time functions [5].

Safety critical applications—like air bags—are difficult engineering problems and require close co-design of hardware/software to meet high demand production of costs and development times in the competitive price-sensitive automotive domain [6].

Power electronics technology intended for traction drives has been driven by power switches [SCRs, gate-turn-off thyristors (GTOs), insulated gate bipolar transistors (IGBTs), integrated gate commutated thyristors (IGCTs)], ac adjustable drives, and machine control algorithms like field-oriented and DTC control [4]. Further improvements can be achieved through a system-level approach by developing further integrated power electronics modules (IPEMs) [2], [3] comprising power switches, control, protection electronics, and passive devices. An additional integration is obtained with drive-by-wire systems using electronics instead of mechanical means to control a system. This needs reliable data communication and control networks with fault tolerance [5].

Surface mines produce coal, copper, iron, and gold, and other materials essential for world industry. Open-pit copper mines are typically shaped like stadiums and can be very large. For example, the Chuquicamata copper mine located in northern Chile is 6 km long, 4 km wide, 1 km deep, and handles approximately 700 000 tons of ore per day [12]. The Morenci copper mine located in Arizona spans over 18 square miles has a 3000-ft vertical drop, and mines approximately 840 000 tons of rock each day [13]. Longer haulage distances and ramp slopes present a challenge for more powerful transportation systems. In addition, lower copper ore grades dictate processing increased amounts of ore to satisfy metal production goals.

Ore and rock transportation from mines to stockpiles or to crushers is made with haul trucks. For required productivity, the haul trucks must have fast run speeds uphill and downhill, the largest haulage capacity, and the most powerful drive systems to transport the ore and rock from mine to stockpiles for further mineral conveying and crushing processes. The main objective in designing a haul truck is to reduce the cost per ton of material hauled. In traditional haul trucks, power is transferred to the rear wheels via either a mechanical transmission or a dc electric drive system. One drawback of mechanical drive haulers is high maintenance and repair costs associated with their sophisticated and complex mechanical transmissions system. Elimination of the mechanical torque converter, transmission and differential is still one of the major advantages of electric haul trucks [3].

Diesel–electric haul trucks with dc drives are built up to 240 short tons. It was not feasible to develop a dc drive for 360-short-ton haulers, so high-power ac inverter-fed induction motor drives employed in locomotives have been developed for this application. Ruggedness and overloading capacity of three-phase induction motors, together with GTO (or IGBT) inverters offer a compact drive with higher power and high performance to meet the requirements of high reliability, con-

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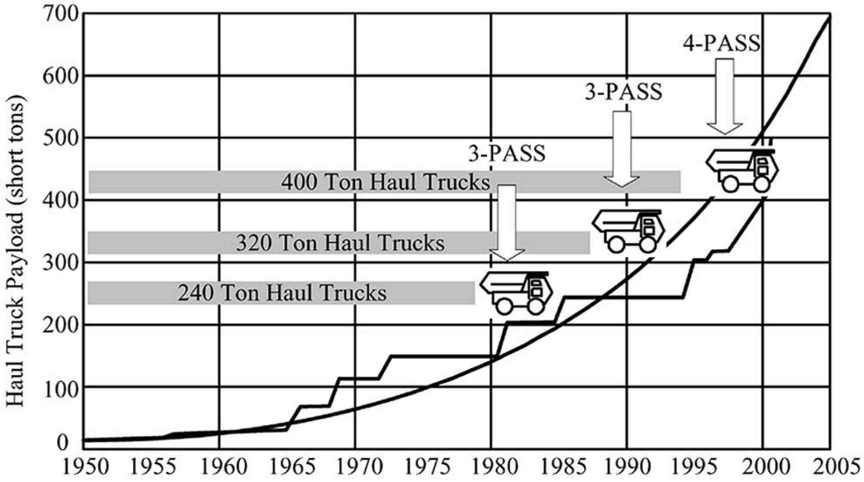

Fig. 1. Growth of payload capacity.

tinuous operation, high shock and vibration levels, temperature extremes, and cooling air with very high particulate levels. Vector controlled ac drives offer smooth stepless full-torque operation in motoring or braking at full operating speeds. A high starting torque and high top speed allow for more ore to be transported and at the same time giving the operator greater capacity for a given truck. Smooth and efficient electric braking offer improved safety and reduces the wear rates of the mechanical brakes. Powerful retarders (electric brakes) provide fine control down to standstill, with automatic blending between electric and service brakes below 2 km/h. The application of state-of-the-art electromechanical design, modern power electronics and sophisticated packaging makes these powerful haul trucks possible [8], [9].

Higher operating speeds, higher loading capacity, increased power density, higher reliability, greater efficiency, and lower maintenance give the chance for increased productivity. Availability is also improved by employing more advanced electronic systems that provide increased fault tolerance, contextual maintenance software that facilitates troubleshooting and remote diagnostic capability [9]. In addition, global-positioning-system (GPS)-based navigation systems are applied for dispatch control of the truck fleet, composed of more than 100 units in large open-pit mines as previously mentioned [12]–[14].

This paper shows the application of new technologies of automotive electronic systems for mining haul trucks, addressing the following issues:

- requirements for the trucks;
- power circuit of the drives;
- control and monitoring;
- trolley line operation;
- operational experiences.

II. REQUIREMENTS FOR THE TRUCKS

One of the major goals in productive industries is to increase efficiency. Mining enterprises are of no exception, and since one of the biggest mining tasks is the transportation of ore from the pit to the stockpile, the need to transport growing amounts of ore has pushed haul trucks to increasing sizes, as shown in Fig. 1.

Modern haul trucks can carry up to 360 short tons (793 000 lbs) at 64 km/hr (40 mi/h) and are able to climb an effective grade of 25% with full load [17], [18] for short distances. Typical effective grades are between 9%–12%.

This level of performance requires a huge power source (around 2000 kW) and maximum efficiency. Empty vehicle weight is kept as low as possible to maximize power available for ore transport. These conditions, coupled with very little space to mount the electronics, and the extreme environmental conditions make electronic packaging a fundamental part of a successful haul truck design.

Size and capacity are not the only necessities that have to be satisfied. There are other operational and environmental requirements:

- very high reliability—24 months mean time between failure (MTBF);
- continuous operation, with >95% electrical availability;
- minimal maintenance—no brushes, filters, or regular lubrication;
- high shock and vibration limits—2g in all directions;
- operation between −40 °C and +55 °C (−40 °F and 131 °F).

Forced air cooling with unfiltered air and very high dust levels (including coal, ore, salt, conductive, and corrosive materials)

Acceptance tests at mining facilities for assessing an effective operating performance.

III. POWER CIRCUIT OF THE DRIVE

Fig. 2 represents the simplified block diagram of the drive's electrical power system for haul trucks within the 240-360-tons payload range.

A. Diesel Engine, Generator, and Rectifiers

The power of the diesel engine is 2540–3380 hp, depending on the truck model and load to be transported [17]. AC power is generated in the alternator and rectified to produce a dc voltage of 2400 in the dc link. This voltage is filtered and supplied to voltage-source inverters, each of which powers one motor and a pair of tandem rear wheels. The rectifiers are nonregenerative

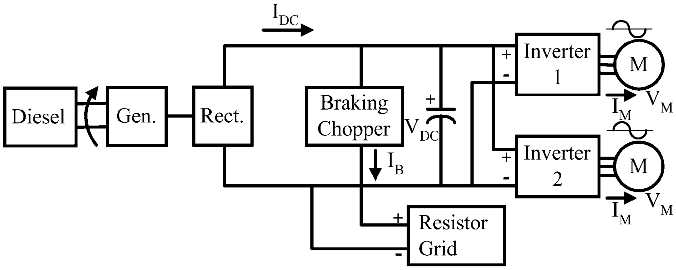

Fig. 2. Block diagram of the drive system.

so the control system ensures that the dc-link voltage will not reach an excessive value during the braking of the truck by operating the choppers to dissipate the electric braking energy in the resistor grid.

B. Main Power Inverters

Three-phase inverters deliver voltages with variable amplitude and frequency to control the traction motors. Smaller trucks (240 tons) use IGBTs as the main power switches. The use of IGBT devices brings important operational advantages: simpler and smaller gate driver circuits and more efficient overcurrent protection (by eliminating the driving pulses until the overcurrent disappears). In addition, IGBT driver circuits increase the overall reliability of the drive system to meet the harsh operating demands of the trucks.

Larger trucks (300 and 360 tons) use GTOs as the main power switches to meet higher power requirements. The inverters are built using 4500-V, 3000-A GTO devices installed in sealed modules, as can be observed in Fig. 3. The Fluorinert FC72 coolant used in the modules provides what is known as "evaporation bath" cooling whereby heat is transferred from the power devices to the inner walls of the module via a pumpless, low-temperature evaporation–condensation cycle. Unfiltered dirty air drawn across the external fins on the module removes the waste heat and cools the electronic components.

Evaporation bath technology is very compact and well suited for dirty environments because the modules are completely sealed. The resulting power density of the AC drive cabinet is approximately 1 $\mathrm{MW/m^3}$ (40 $\mathrm{hp/ft^3}$). Table I shows typical technical specifications of modern haul trucks equipped with ac drives (nominal payload capacity listed in short tons).

C. AC Motors

A three-phase squirrel-cage induction motor powers each set of the two-stage planetary wheel gears. The motors have integrated speed sensors and the only required maintenance is to grease the bearings once a year. Extensive design simulations ensured a good match between inverter, motor, and gear. The most relevant design factor for the motor–inverter combination was to select a motor impedance (determined by the number of turns) that would provide the required high starting torque without exceeding the peak current limit of the inverter.

D. Braking Chopper and Resistor Grids

The braking of the truck is a very critical part of the operation, due to the relatively high speeds and very high levels of energy involved. Wear of the mechanical service brakes has been all but eliminated by means of a very powerful electric retard system. During electric braking the motors act as generators and the inverters convert the truck's kinetic energy into electric power that is dissipated via high power grid resistors. Maintenance-free electrical braking choppers are used in place of mechanical contactors to channel this power to the grid resistors. Outstanding electrical brake performance has been accomplished using two GTO chopper modules. Each module contains two GTOs that are pulsed alternately at 50 Hz to produce a combined chopping frequency of 100 Hz. Both choppers are controlled to produce a combined switching frequency of 200 Hz on the dc link, minimizing the voltage ripple. The choppers are able to handle a power of 4500 kW (6000 hp) measured at the ground.

The ac traction motors are able to hold the vehicle stationary at full torque, but the control system is limited by the resolution of the motor speed sensors. Therefore, as the truck speed approaches zero, the traction control unit (TCU) simultaneously blends out the electric retard and blends in the service brake via a solenoid in the hydraulic line. The operator does not notice the transition and the TCU automatically sets the service/hand brake when zero speed is reached.

E. Cooling of the Power Circuits

Due to the high power involved, the cooling of the units is a very important issue. These trucks use an independent electric blower driven by a separate 70-kVA inverter coupled to an ac induction motor. The unit ratings were chosen so that it could maintain the blower at full speed, independent of engine speed, and alternator excitation level. The TCU manages the blower speed in response to actual cooling requirements, drive power level, components temperatures, and ambient temperature.

IV. CONTROL AND MONITORING

A. Drives and Control

As truck performance becomes more demanding, the need for advanced control algorithms becomes clear. In addition to the engine's integrated controller, the truck also has a sophisticated drive control unit to control truck speed, air cooling, vehicle dynamics, drive condition monitoring, etc.

The drive control unit, for example, in addition to executing vector control algorithms for the inverters and ac motors has three different control techniques to optimize the engine performance depending on the vehicle operating point (speed, load, and engine output power). The inverters and motors operate independent of each other, permitting different speeds on each rear wheel set. This makes it possible to implement a traction control system that includes an antilock brake (ABS) system to prevent wheel slide and a slip control function used during acceleration. Use of these control techniques common to the automotive industry are powerful tools that enhance the truck's dynamics, reliability, and efficiency. During normal operation, the operator only has to maintain the desired speed by pushing the throttle or retard pedals. The service brake pedal is used only for emergency stopping if the electric drive system fails. The accelerator/brake signals are fed directly to the TCU and used as reference values for the torque control loop.

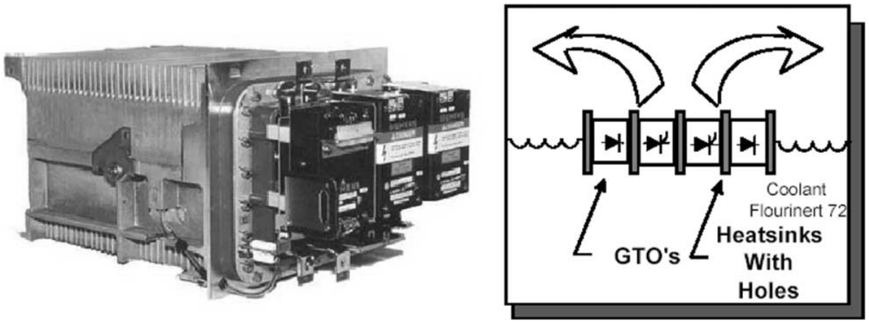

Fig. 3. Evaporation bath power module used in large ac trucks.

TABLE I
AC DRIVE SYSTEM MAIN SPECIFICATIONS FOR DIFFERENT TRUCK CAPABILITIES

	Notes	240 Ton	300 Ton	360 Ton
Engine Power	[HP] at flywheel	2540	2550	3380
Trolley Power	[HP] at ground	3770	3790	4700
Retard Power	[HP] at ground	4670	4690	6035
GVW	[lbm*1000] typical	860	1100	1250
Tire Size	[in] rolling radius	68.4	70.2	72.7
Gear Ratio	Typical, others optional	35.3	35.3	37.33
Gradient	Typical, varies with GVW	24.0%	21.5%	22.5%
Speed Limit	[mph] depends on gear ratio	40	40	40
Drive System	2 AC inverters	IGBT	GTO	GTO
Traction Motors	Squirrel-cage AC	2	2	2
Retard System	2 choppers	IGBT	GTO	GTO
Main Blower	Full-time variable speed	Dual centrifugal with AC motor		
Retard Grids	Standard (max 20)	14	16	18

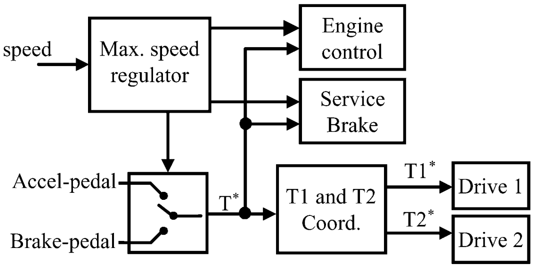

Fig. 4. Layout of the main control system.

The TCU determines the optimal operating point for the engine, generates the torque reference for each ac motor and activates the braking choppers as required. The layout of the main control system is shown in Fig. 4. The "Max. speed regulator" limits the speed that the truck can reach to a predefined value based on the manufacturer's design and mine policies. The "T1*" and "T2*" signals are the torque reference for each of the motor drives. These drives have a control system based on field orientation or vector control for ac machines, where torque and flux control is made separately. Fig. 5 shows a diagram of the control system.

Here, the flux ψ is calculated using a machine model based on the actual values of the stator currents and voltages and rotor position. The stator currents are transformed in a rotating reference frame oriented with the rotor flux (VT block), obtaining two currents, i_{f2} proportional to the torque and i_{f1} proportional to the flux. Both currents are controlled by proportional–integral (PI) blocks. Reference signals for each control loop come from the throttle, in the torque case, and from a fixed value for the flux. However, this reference value may vary due to field weakening if the speed of the truck is too high. The flux precontrol block is based on the magnetization curve and corrects any inaccuracies in the curve. A feedforward voltage drop compensator is also used, enhancing the tracking of the reference signal. The pulsewidth-modulation (PWM) modulator uses an optimized switching method to improve the stator current waveform and thus control the torque better.

B. Use of GPSs in "Smart Trucks"

Haul trucks are operated 24 hours a day, seven days a week, except as needed to change drivers, refuel, and perform maintenance. Under such operating conditions, it is desirable to monitor the position and status of the vehicle continuously so as to achieve maximum efficiency and determine when maintenance is required.

A GPS is a satellite navigation system used to pinpoint the exact position of an object by determining its latitude, longi-

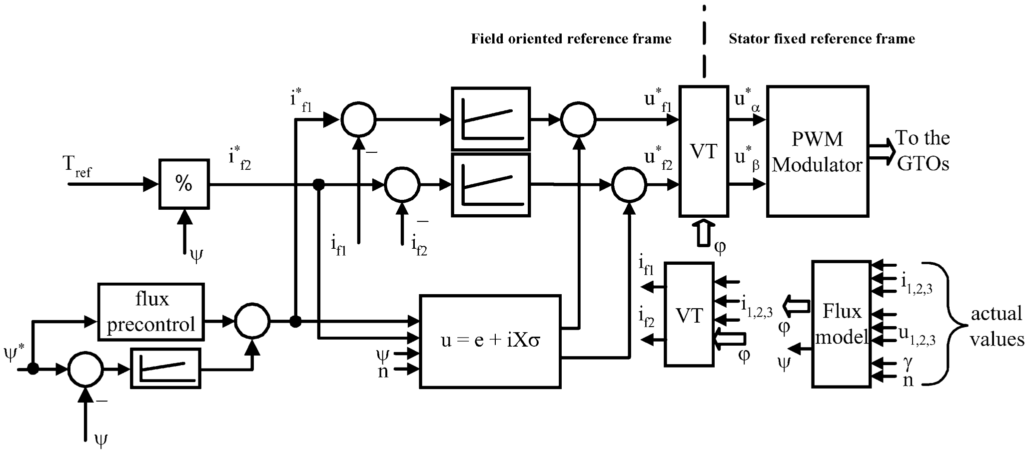

Fig. 5. Torque control Drive 1.

tude, and elevation (XYZ axis). Mining applications include surveying and tracking the position of mobile equipment such as shovels, trucks, or drills. Information technology tools integrate and enhance mine planning and production.

Using GPS-based systems, operators can know whether the shovel-load is ore or waste and direct the haul trucks accordingly. The Morenci copper mine, for example, has 16 shovels and a fleet of approximately 100 haul trucks, equipped with GPS systems. A GPS is used on the haul trucks to track and monitor position [13], [14].Theoretically, four satellites above the horizon are needed for position estimation [15], and five for real-time kinematics surveying. If some satellites are obscured by obstacles (buildings, mountains, trees) the situation gets worse. In the case of the Chuquicamata mine, about 130 haul trucks are employed. For a GPS system, six or more satellites are needed, because of signal loss inside the pit and closeness to the pit walls. In order to solve this visibility problem the Global Orbiting Navigation Satellite System (GLONASS), maintained by the Russian Republic, was also utilized. As with the GPS system, GLONASS also uses a 24-satellite network, but with lower cross-correlation interference [16] and better coverage at higher latitudes (because of higher orbit inclination than the GPS system). The use of a combined strategy enables the selection of satellites with the minimum position dilution of precision, leading to an improved accuracy and velocity of the resulting position. To date, the enhanced system has been fully operational and provides a very good solution. It is expected that the performance of the GPS/GLONASS system will be further optimized and applications for shovels and drills will be expanded and enhanced [12].

Truck routing follows the best path principle, which is determined using a computerized dispatch system. Continuously changing haulage ramps and roads are designed to meet both short- and long-term planning goals. In addition, crisis management can be carried out for completing tasks even in darkness or under foggy conditions.

Further developments are expected where the working efficiency may be improved without wasted activity of vehicles by enabling prompt change of a travel route at a time when it becomes necessary [21].

C. Local and Remote Monitoring

It is desirable that advanced and expensive machines such as haul trucks run 100% of the time. Of course, this is not possible so the goal is to reduce the causes of failure and the required repair time. This is of particular importance when the machinery, like haul trucks, is a fundamental part of the production process. Therefore the trucks are equipped with devices to monitor the status and performance, such as the display system, which informs the operator about the system status with text messages in a color LCD display.

Remote access technology makes it possible for maintenance experts to communicate with the truck control electronics via radio, telephone and satellite links in a more rapid form, reducing the time to detect and repair any fault, or to prescribe preventive maintenance procedures before failures occur. An application of this remote diagnostic capability is the use of the Internet for diagnostics and troubleshooting. This new technology has been successfully demonstrated in modern shovels and haul trucks [25]. The remote access allows authorized technicians all over the world to monitor, analyze, diagnose, and suggest a corrective action. It is even possible to make changes in the control software remotely.

This technology maximizes uptime and reduces service costs, increasing mine efficiency to a higher level. The monitoring system may be enhanced with higher robustness given by intravehicle communications systems [20].

V. TROLLEY ASSIST OPERATION

One of the advantages of using electric drives in haul trucks compared to a conventional mechanical transmission, torque converter and differential is the possibility to draw power from dc overhead trolley lines and bypass or supplement the diesel engine as the truck's source of power [11]. Fig. 6 shows a haul truck running under trolley lines. Overhead trolley lines are most commonly installed in mines that have a single road coming out of a deep pit or where fuel costs are much higher than the cost of electricity. The principal characteristic of trolley assist operation is that the power available for the traction motors is greatly increased. This allows the truck to

Fig. 6. Haul truck operating with trolley lines.

move up the grade faster, reduce the time needed to transport the mineral and, thus, increases production rates.

An advantage that ac drive haul trucks have over dc drive haul trucks when operating on trolley is that the ac inverters decouple the traction motor voltage and speed from the dc line voltage. This is very important because it ensures maximum utilization of the equipment. For example, overloaded dc trucks that are moving too slow cannot take the line because of the fixed voltage–speed relationship of dc drives and the resulting over current that would result. The ac-motored truck, on the other hand, can take the line at any speed and move on the line at any speed independent of the dc-link voltage. In either case, trolley assist enables mine operators to increase on-grade speeds up to 80% and reduce overall cycle times by as much as 20%.

There are two ways for ac drive haul trucks to connect to dc trolley lines. The first is a direct parallel connection and the second is a novel indirect method utilizing a series connection.

A. Direct Trolley Operation

This method is used when the trolley line voltage matches the maximum dc-link voltage of 2600 V. The connection sequence begins when the operator moves the truck under the lines (at any convenient speed) and presses a button to engage the system. The TCU raises the pantograph, checks the line voltage, raises the dc link to its maximum, moves S4 (Fig. 7) to position 2, closes the line contactor to connect the dc link in parallel with the trolley line, unloads the alternator, reduces the engine r/min to idle, and then raises the motor speed to utilize the full-rated trolley power. During direct trolley operation all traction power is drawn from the trolley lines, resulting in major fuel savings. Hauling uphill with the engine in idle greatly extends the operating hours between engine overhauls and increases the engine MTBF.

B. Diesel Boost Trolley Operation

This method is used in mines that already operate DC trucks on trolley lines and where the line voltage is between 1200–1600 V. Diesel boost operation has proven to be extremely practical because it accommodates operation of the new higher voltage ac drive system on existing low voltage trolley lines. Operation of the ac drive is made possible by connecting the dc trolley lines in series with the output of the truck's onboard power supply (engine/alternator/rectifier) to reach the 2600-V operating voltage. On-grade speed and performance are the same in both modes of trolley operation, but fuel consumption is lower during direct trolley than during diesel boost trolley operation. Fig. 7 shows the power system arrangement and the contactors used in the connection sequence for direct and indirect trolley operation. In this figure, two independent inverters feed two ac motors. When the truck is in diesel operation (not on trolley) switches S1, S2, S3, and S4 are in position 1, so that the rectifiers are connected in series and power is drawn from the engine. For direct trolley mode, switches S1, S2, and S3 are in position 1 and switch S4 is in position 2, the rectifiers are inactive, the diesel engine is at idle and the dc link is fed by the trolley lines. The connect/disconnect sequence is very straight forward and can take place under full diesel power.

For diesel boost trolley operation, the system must end up with switches S1, S2, and S3 in position 2, connecting both rectifiers in parallel, and switch S4 in position 1 connecting the trolley lines in series with the paralleled rectifiers.

The connection sequence starts from the diesel configuration as the truck moves under the line. After the operator raises the pantograph, the TCU checks the line voltage, adjusts the dc-link voltage to approximately twice the line voltage and closes the line contactor connecting the line in parallel with Rectifier 1. This reverse biases Rectifier 1, allowing S2 to be opened under no load and S1 and S3 to be moved to position 2, connecting Rectifier 1 in parallel with Rectifier 2. The TCU then raises the motor speed to utilize the full rated trolley power level, whereby a portion of the power is supplied by the diesel and the rest comes from the line.

This novel diesel boost arrangement and connection sequence allows the truck with a high-voltage ac drive system to smoothly make and break a series connection between the diesel and trolley power supplies in order to go on and off a low-voltage trolley line at any speed while operating under full diesel power [26].

The use of trolley lines along the most power intensive portions of the haul route results in a significant reduction in fuel consumption, saving up to approximately 30% [19], reduces the truck's maintenance cost and increases the mine's productivity.

Trolley assist does, however, have some disadvantages. There are high installation costs, the need to relocate lines and wayside equipment if the haul route is moved, and additional equipment maintenance and driver training. Even though feasibility studies often show very favorable economic payback periods, only a limited number of mines worldwide have installed trolley assist systems. In addition, considerations regarding safety should be observed [10].

VI. OPERATIONAL EXPERIENCES

Several tests were performed in 2002 at the Chuquicamata copper mine on trucks from different manufacturers. The selected truck was the Liebherr T 282, with 2610-hp engine output and 364 short tons of payload capacity with Siemens/Liebherr

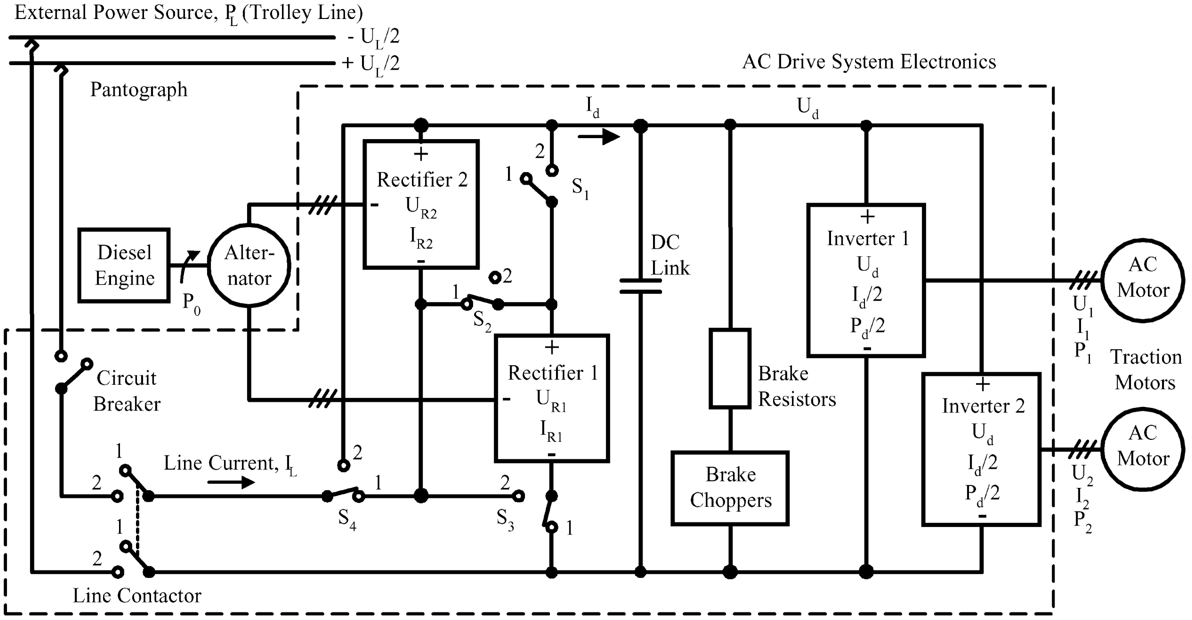

Fig. 7. Electrical connections of the power circuit.

ac motors. This truck was required to meet the mine's target of 10 km/h while on-grade. In fact, the speed developed by the T 282 was a healthy 11.2 km/h, indicating the drive system was more efficient than estimated and/or (as is more significant) the diesel engine was putting out more horsepower than specified.

A major effort, which has proved to be extremely valuable, was made to maintain the dynamic behavior of the truck's retard system at the high altitude of the mine. This was done by increasing the power/cooling capacity of the retard resistors and retard blower for the thin air found at this altitude. The results are very impressive. If the operator puts the retard pedal to the floor, one would be thrown from the seat if not wearing a seat belt, yet the empty truck can be maneuvered smoothly back and forth without the slightest lurch.

An advantage of ac drive haul trucks with a chopper-based retard system over dc drive haul trucks using contactor-based field reversal retard control is that there is no time delay when the operator presses the retard pedal. In addition, the truck can decelerate right to standstill in direct proportion to the operator's wishes. When the vehicle speed approaches zero, the service brake is set automatically. The truck responds so well that the driver can let off the pedal just as the speed reaches zero and gracefully come to rest without sloshing a cup of coffee. The automatic retard and brake system permits an operator to drive the truck in a manner that reduces the reliance on the service brakes as a means of vehicle speed control. By reducing the reliance on service brakes it is possible to go down hill faster and reduce the overall maintenance costs of the truck [22].

VII. COMMENTS AND CONCLUSIONS

Drive technology in haul trucks has shown enormous developments in recent years, yielding an important improvement in performance with increasing payload capacity.

A diesel–electric motor–generator system with inverter-fed ac induction motors is the only solution found in electric haulers 300 tons and larger. The use of IGBT transistors in place of GTO thyristors can reduce the cost, and increase the reliability of the power inverters, due to simpler and more compact driver circuits. It is foreseeable that IGBTs with higher voltage and current ratings will replace GTOs in larger trucks in the near future.

The use of sealed modules for power semiconductors is a key factor to increase the reliability of the drive, due to the high amount of dust in mining applications. Maintenance-free high-performance electric braking choppers have replaced mechanical contactors to connect the braking resistors. Vector-controlled induction motors provide very good control of speed including high starting torque and smooth controlled braking, in addition to very low maintenance requirements.

The use of ac drives for trolley assist provides more reliable performance than dc drives, especially when the trucks are overloaded. In addition, the connection scheme developed for diesel boost operation allows the new higher voltage ac drive to be connected under full power in series with existing low voltage trolley lines to provide high power trolley performance without having to change the installed line voltage.

The use of GPS-based dispatch systems increases the efficiency of the complete ore transportation process. The use of advanced and modern technologies like remote diagnostics and Internet troubleshooting maximizes up time, while reducing service costs.

According to experts, future improvements in the state of the art should be focused on increasing reliability methods, like extensive use of trolley lines and remote truck's parameters monitoring, making possible Internet diagnostic and troubleshooting capabilities. Initial steps in this way, like those shown in [23], open a very interesting field of research and development. Another advance will likely be automated (unmanned) haul trucks. It is expected that this feature will increase security levels and allow for more optimized path selection, as described in [24]. Capability to dispatch the appropriate truck to a given point is clearly related to the operator's ability to know the exact location of all the trucks at all times. This means that the use of GPSs will be a common tool in most open-pit mines.

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