Chapter 26
Electric and Hybrid Drive Systems

Objectives

After studying this chapter, you will be able to:

- ✓ Explain how an alternator generates electricity.
- ✓ Describe the different types of traction motors.
- ✓ Explain the operation and unique features of electric-drive mining trucks.
- ✓ Explain the operation of electric-drive wheel loaders.
- ✓ Explain the operation of electric-drive dozers.
- ✓ List examples of electric and hybrid-electric excavators.
- ✓ Describe safe practices for working on machines with electric drive.

Off-highway equipment manufacturers have produced electric propulsion systems (electric-drive systems) for decades. Electric locomotives date back to the 1870s. General Electric (GE) was the first to manufacture an electric drive for mining haul trucks in 1963 with the introduction of the 772 electric drive. See **Figure 26-1**.

Electric drives are continuing to gain popularity. Some manufacturers use a diesel engine to drive one or more electric generators that produce(s) electricity primarily for propulsion. Examples include locomotives, haul trucks, dozers, and wheel loaders.

Some machines use high-capacity batteries in place of diesel engines to power the machine. The batteries are designed to deliver enough power to complete up to an eight-hour shift and then require recharging. Some hybrid machines use batteries or capacitors to capture energy during cyclical machine functions like shuttle shifting wheel loaders, swinging an excavator boom, or lowering an excavator boom. The time it takes to charge the batteries is one of the challenges for the industry. Manufacturers

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Figure 26-1. This GE 772E DC electric drive motor was used to propel an electric-drive haul truck.

are continuously investigating methods to decrease downtime and increase machine's availability time. Some solutions have technicians swapping out discharged batteries for charged batteries in place of discharged batteries. Another solution is for technicians to use fast mobile electrical charging stations that can be hauled to the job site. The weight of the batteries also poses challenges and requires manufactures to redesign the machine's weight distribution.

Robert LeTourneau, a key electric propulsion innovator in heavy equipment, developed diesel electric-drive wheel loaders, scrapers, and haul trucks. Joy Global purchased LeTourneau Technologies in 2011. Komatsu purchased Joy Global in 2017 and continues to manufacture electrically propelled machinery. In the 1970s, Euclid manufactured a unique electric-drive haul truck that was powered by a gas turbine.

Although construction equipment manufacturers have predominantly chosen powershift, mechanical drive, and hydrostatic drive propulsion systems, new electric-drive technology has been developed to help meet stringent emission requirements and increase fuel economy. A diesel-electric propulsion system uses a diesel engine to drive a generator. The ***generator*** converts the engine's mechanical rotational energy into electrical energy (electricity). The electricity is used to drive electric motors.

The electric propulsion system can also be used for braking, powering accessory drive systems, or for load testing the diesel engine. In addition to electric-drive mining trucks and locomotives, manufacturers produce numerous other types of electric-drive equipment. A few examples include wheel loaders, dozers, excavators, shovels, on-highway semitrucks, mobile cranes, and backhoes.

Fully electric machines eliminate the diesel engine and are 100% emission free. The machines can be operated indoors or underground without the hazard of diesel exhaust fumes. Electric-drive machines can lower the time required to perform maintenance and reduce the total operating costs. They have reduced vibrations and can deliver instant torque rather than have a lag as a diesel engine ramps up to its rated speed. This allows them to provide more consistent performance. They also eliminate the difficult cold-starting issues that accompany diesel engines.

Electric-drive machines eliminate the engine oil and filter, diesel fuel and filters, air filters, mufflers, and engine after-treatment systems such as diesel exhaust fluid, EGR, and diesel particulate filter systems. Although engine coolant and radiators are no longer needed with the absence of an engine, electric drives still might use coolant to cool inverters, brake resistors, generators, and drive motors. Some electric motors and generators are air-cooled with a fan that is driven by a hydraulic motor requiring lots of hydraulic horsepower. Some generators and electric motors are cooled using their own dedicated hydraulic reservoir, coolers, and pumps.

Electric-drive machines can operate in environments that are off-limits to noisy diesel-powered equipment, such as urban locations like hospitals or schools. The in-cab noise can be reduced by four decibels. On average, the outside noise level of an electric machine can be ten decibels lower than for equivalent diesel-powered machines, and for every increase of three decibels, the overall volume is increased two times.

One target of the zero-emission machines is the rental equipment business. Some machines are battery-powered while others are powered by an AC electrical power cable. In the largest mining applications, an electric-powered shovel can only be used at a mine site that has affordable electrical power available and allowable for that mine site. The machine is less nimble than a diesel-powered shovel that can traverse throughout the site without being tethered to high-voltage power cables.

Alternators

The most common type of electrical generator is the alternating current (AC) generator, also known as an ***alternator*** or *traction alternator*. See **Figure 26-2**. The alternator is coupled to the diesel engine, which drives the alternator's rotor proportional to engine speed.

The alternator's ***rotor*** is an electromagnet consisting of a rotating, star-shaped iron core. Multiple coils of wire, called field poles, are placed around the rotor. See **Figure 26-3**. The alternating poles form north pole and south pole magnets when electricity is applied to the rotor. This is known as *exciting the field*.

The rotor spins inside a stationary housing called a ***stator***, which has multiple fixed windings. As the excited rotor passes by the stator's stationary windings, a voltage is induced in the windings. The voltage's waveform alternates from a positive voltage to a negative voltage. The alternating wave is known as an ***AC sine wave***, **Figure 26-4.** One sine wave is called a ***cycle***. The machine's electronic control module (ECM) controls the electrical output of the alternator by controlling the rotor's field current. The field current is the amount of amperage applied to the rotor's field coils. A larger amount of field current causes the rotor to exhibit a larger amount of magnetism, resulting in more electrical current being induced in the stator's windings.

Note

The number of pairs of poles determines the number of AC sine waves that are generated for every rotor revolution. For example, if the rotor has eight poles—four north poles and four south poles—it will produce four AC sine waves per rotor revolution.

Diodes are electronic devices that allow the flow of current in one direction only. Diodes are used to ***rectify*** AC sine waves; in other words, to convert the alternating current to direct current (DC) flow. Even if a machine uses AC electric drive motors, manufacturers commonly rectify the alternator's AC current to DC current. To operate AC electric drive motors, the DC current must then be inverted back to AC current. Manufacturers that use AC motors prefer rectifying the AC generator's current to DC, and then inverting the DC back to AC because of the difficulty in being able to accurately control the speed and torque in a straight AC generator to AC motor circuit. This process will be explained later in this chapter.

A diode acts in a similar manner to a hydraulic one-way check valve, allowing current to flow in one direction (forward) and blocking current flow in the opposite direction (reverse). A diode allows positive current to flow (known as *forward biasing*), but blocks a negative current trying to flow in a reverse direction (*reverse biasing*). A diode can block the negative portions of AC sine waves, leaving only the positive portions of the waves available to perform electrical work. See **Figure 26-5**. This is called *half wave rectification*. The challenge of half wave rectification is that the current pulses, making it impractical for performing electrical work.

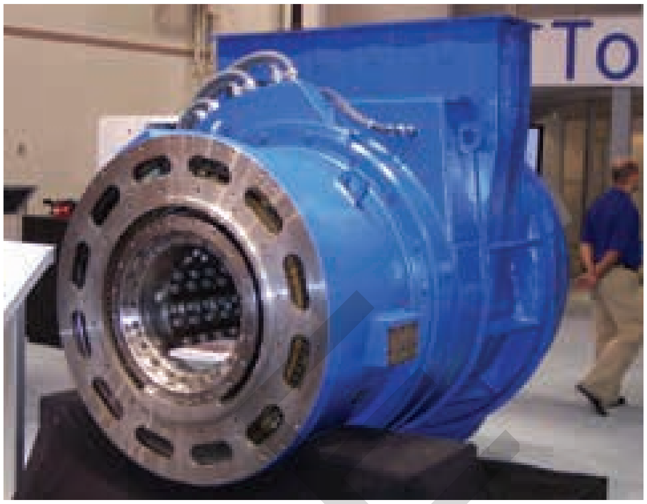

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Figure 26-2. This GE alternator is used to drive mining haul truck drive motors.

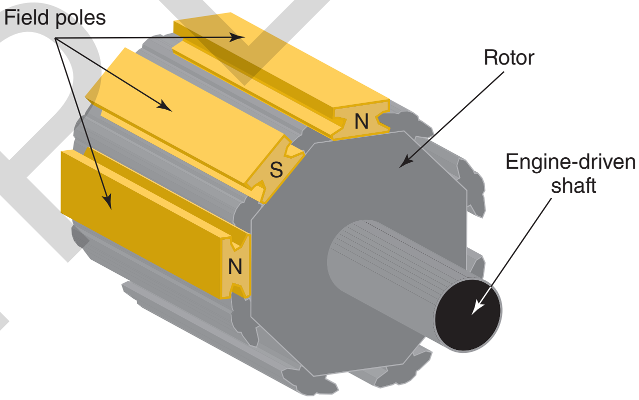

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Figure 26-3. An alternator contains a rotating iron rotor assembly that has multiple field poles. Every other field pole is wound in opposite directions to form alternating north and south electromagnetic poles. The stator windings are not shown.

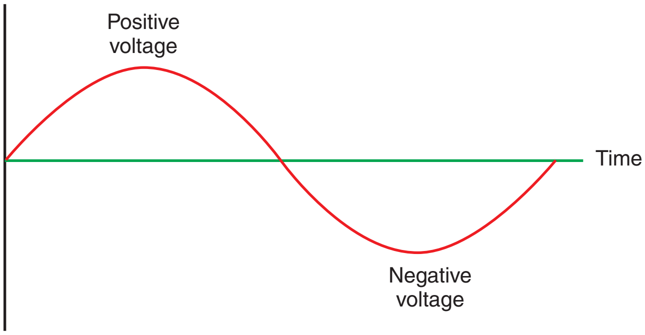

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Figure 26-4. A single-phase AC sine wave rises to a positive peak and then alternates to a negative peak. The single wave that starts from zero volts to maximum positive volts to maximum negative volts and back to zero volts is known as a *cycle*.

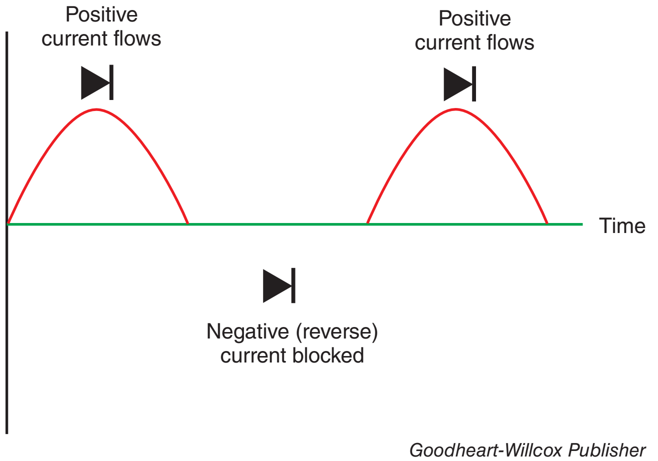


Figure 26-5. A diode can be used to rectify an AC sine wave by eliminating the negative current flow.

As the rotor's north and south poles alternatively pass by the stator, the current induced in the stator reverses direction. A ***bridge rectifier*** can be used to rectify reversed current flow into positive current. For single-phase AC, the bridge rectifier contains four diodes in a series block design.

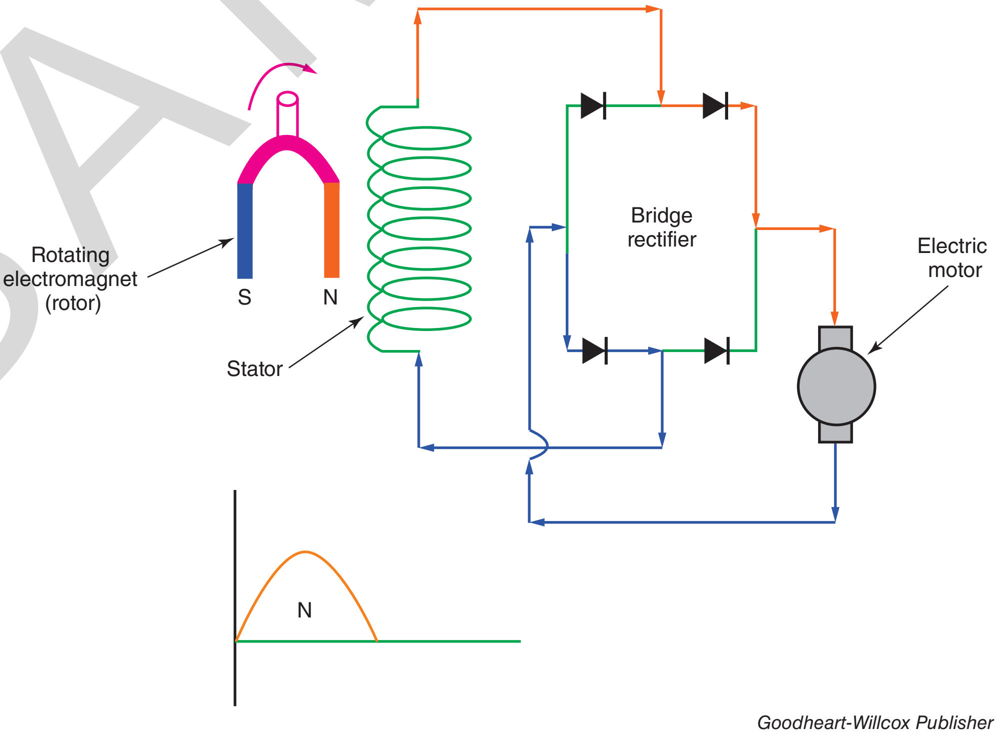
In **Figure 26-6**, two of the diodes rectify the first half of a sine wave, delivering a half wave to drive the electric motor. Note that the rotor is depicted as a rotating horseshoe-shaped magnet to simplify the drawing. The other two diodes rectify the current that is flowing in a reverse direction. As the rotor's south pole passes by the stator, current is induced in the stator, which directs the current in the opposite direction to the bottom of the bridge rectifier. See **Figure 26-7**. The lower right diode directs the current to the electric motor. The electric motor directs the remaining current flow back to the bridge rectifier, where the upper left-hand diode directs the current back to the stator.

Note

Bridge rectifiers for single-phase AC consist of four diodes. Six diodes are used in a bridge rectifier to rectify three-phase AC.

As an electro-magnet with one north pole and one south pole makes a revolution within a single stator, two half waves are generated, with zero volts where the half waves meet. Manufacturers can alleviate this problem by designing alternators to produce three separate phases of current flow. Three different stator windings are used to produce ***three-phase AC***, **Figure 26-8**. The three AC phases are then rectified to produce

Figure 26-6. When the north pole passes by the stator, a positive current exits the stator and enters the top portion of the bridge rectifier. The top right diode directs the current to the electric motor to drive the motor. After the load, the current is directed back through the bridge rectifier through the bottom left diode, and back to the stator.



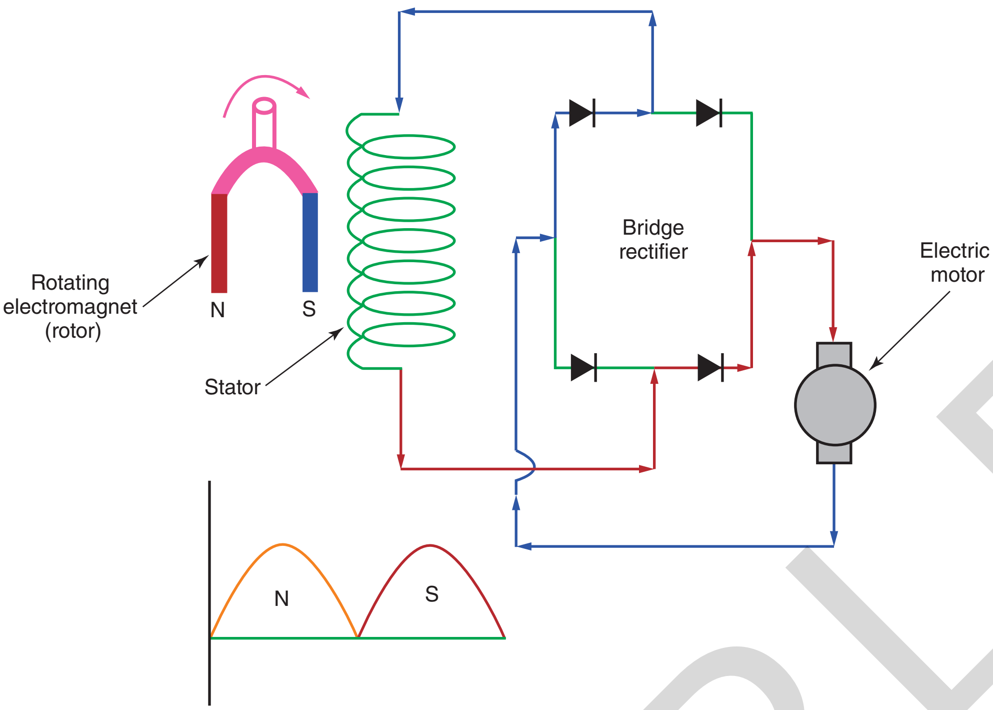


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Figure 26-7. The graph shows the half of the sine wave produced as the north pole passed by the stator plus the half wave produced as the south pole passed by the stator. If a single diode is installed between the stator and motor, the part of the sine wave produced by the south pole would be blocked. However, both portions of the sine wave are usable if a bridge rectifier is placed in the circuit. The graph shows how a sine wave induced by a single north and south pole magnet can be rectified into two positive half waves.

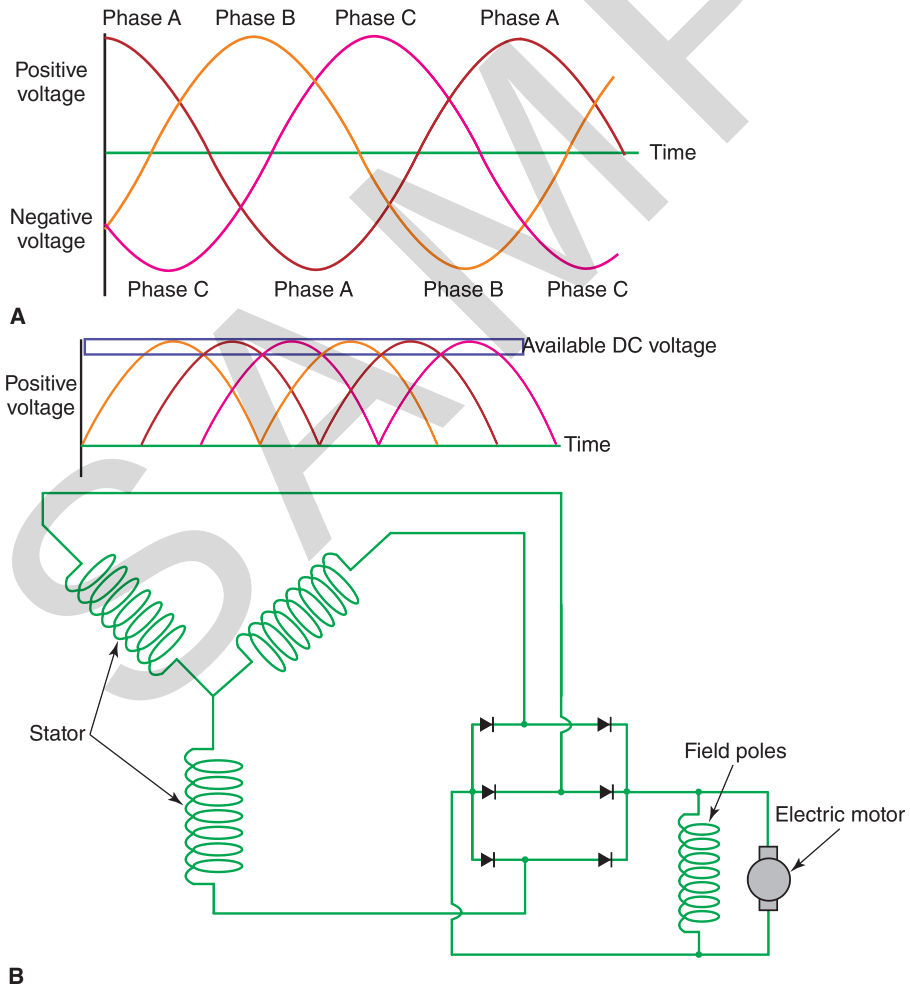

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Figure 26-8. Traction drive systems often use alternators that produce three phases of current flow. A—Notice that the three phases alternate across a period of time. B—A six-diode bridge rectifier rectifies the three-phase AC into positive DC.

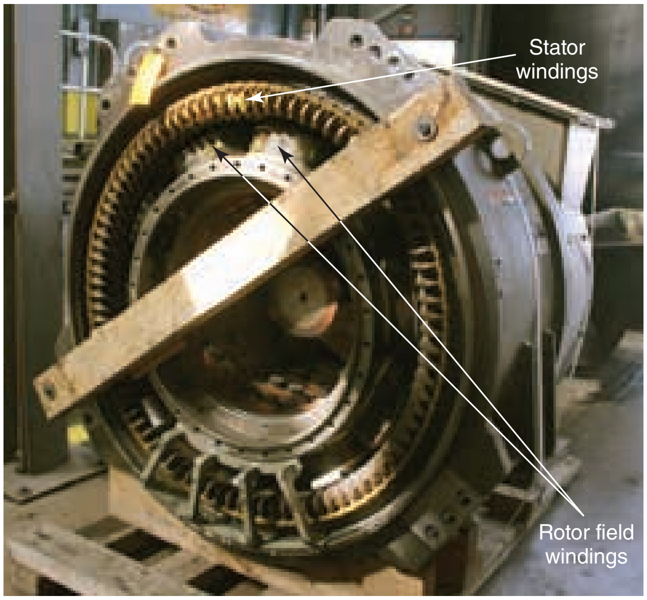

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Figure 26-9. This traction alternator has a rotating rotor with multiple field windings. The rotor spins inside a stationary set of conductors called *stator windings*.

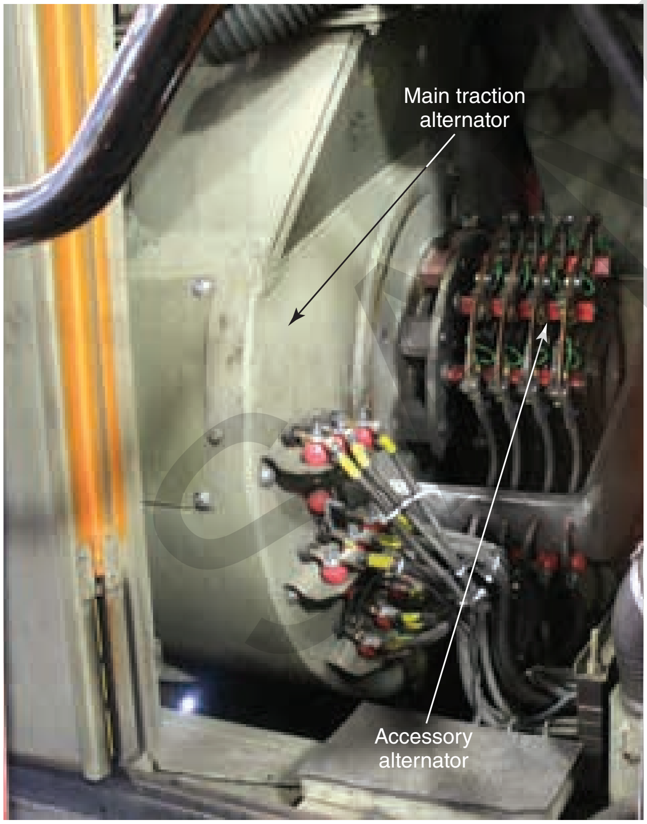

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Figure 26-10. This locomotive alternator powers six traction motors and the locomotive's accessories. The large portion on the left drives the locomotive. The portion on the right provides electrical current for the accessories.

a DC current flow with a consistent positive voltage. The alternator in **Figure 26-9** provides a view of the rotor windings and stator windings.

The locomotive traction alternator in **Figure 26-10** generates electrical energy to drive six traction motors and accessories. The larger portion of the alternator is used to drive the traction motors. The smaller accessory alternator, located on the rear, excites the main alternator's field, charges the locomotive's batteries, and powers the locomotive's accessories, such as the three-phase radiator fan.

Traction Motors

Electric-drive systems can employ different motor designs. Motors are designed to be driven by AC or DC. Most electric motors normally deliver power to some type of gearing that increases their torque. On a locomotive, the traction motor often drives an external-tooth pinion gear that drives an external-tooth bull gear on the drive axle. In a mining truck, the electric motor commonly drives a planetary gear set's sun gear.

The following are examples of drive motors:

- DC motors.
  - Brush-type.
  - Brushless.
- AC traction motors.
  - AC induction.
  - AC brushless.
- Reluctance motors.
  - Switched reluctance motors.
  - Synchronous switched reluctance motors.

DC Traction Motors

DC traction motors are the oldest design and were the preferred motor used in locomotives for decades. DC motors are now rarely used in electric-drive systems. DC motors can have several different designs. Two distinct classifications are brush-type DC motors and brushless DC motors.

DC motor speed is controlled by varying the voltage to the motors. When the DC voltage is increased, the current flow in the windings is increased, resulting in a larger electromagnetic force that causes the motor's speed or torque to increase. The motor's direction is reversed by reversing the polarity (reversing the current flow).

Brush-Type DC Motors

The ***brush-type DC motor (BDCM)*** contains an ***armature*** (sometimes called a *DC rotor*) that consists of several loops of large copper conductors connected to copper commutator bars. See **Figure 26-11**. The ***brushes*** are electrical contacts made of carbon and are wear items, **Figure 26-12**.

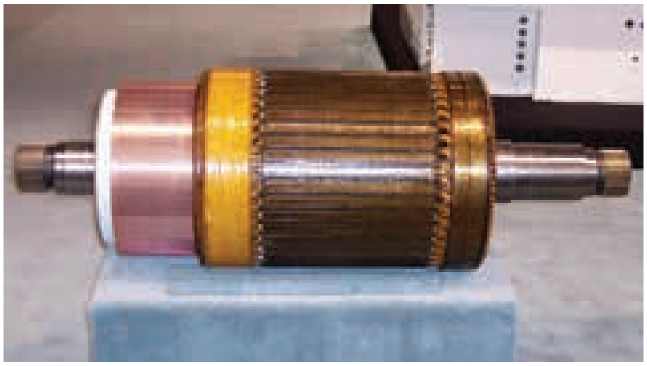

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Figure 26-11. This GE armature is used in a DC electric drive motor for a mining truck.

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Figure 26-12. This brush is used in a locomotive's DC traction motor.

A ***commutator*** bar is a copper bar that serves as an electrical contact that transfers electrical current between one brush and one end of an armature's electrical conductor. A group of commutator bars are arranged around the circumference of a DC motor. See **Figure 26-13**. A commutator receives electrical current from a positive brush. Each commutator is connected to one of the armature's hard wire conductors. DC current is passed from the brush to the commutator through the hard wire conductor. The DC current is then directed through a commutator bar located 180° from the other commutator bar. The current is directed out of the armature through the negative brush. See **Figure 26-14**.

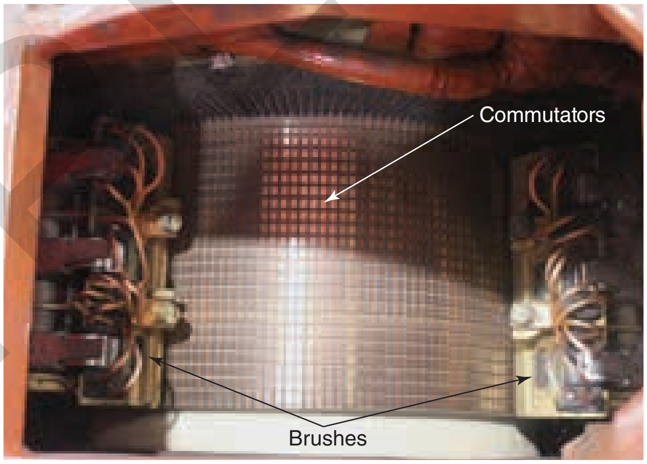

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Figure 26-13. The six brushes and commutators are viewed by removing the access cover on this DC traction motor.

The current sent through the armature's conductors causes the conductors to form electromagnetic poles and emit electromagnetic lines of force. The armature is located inside a group of fixed windings known as a *stator*. The stator's windings (called *field windings*) are arranged around the inside circumference of the motor housing. Stator windings, when energized, become electromagnets, forming north and south pole magnets. The magnetic force of the armature and the stator causes the electromagnetic forces between the armature and the stator to attract, causing the armature to spin. The armature is splined to the motor's output shaft.

Note

Two magnetic poles that are alike (two north poles or two south poles) repel each other. Opposite poles attract to one another. As current passes through the armature, the armature tries to move away from poles that are alike and move toward the opposite poles, causing the armature to rotate. As the armature spins, the commutators rotate past the brushes, allowing the current to flow through the next armature conductor. This sequencing action of current flowing through the next set of commutator bars is known as ***commutation***. Commutation enables the motor's armature to generate the correct polarity of electromagnetic force, resulting in a continuous armature rotation.

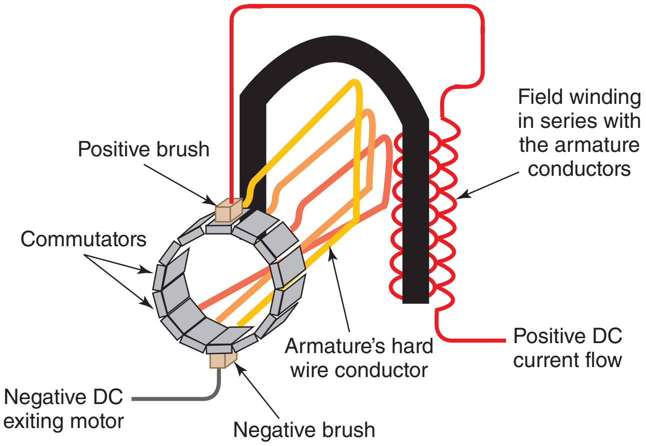

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Figure 26-14. A BDCM contains an armature with copper commutator bars connected to hard wire conductors. Brushes direct current through the armature's wires. As the stator windings are energized, a magnetic field is created. This field forces the armature's current-carrying conductors to spin away from the magnetic field, causing the motor to rotate. The laminated steel stampings are not shown to better view the armature's wire conductors.

The brushes wear as they ride along the rotating commutator bars. For this reason, BDCMs require more service than other traction motors and are seldom used in modern electric-drive systems. Some locomotive manufacturers still offer BDCM drives in overseas applications.

The armature's core consists of numerous steel laminated stampings placed against one another. The stampings have slots to hold the hard wire conductors. The laminated stampings improve the magnetic field generated by the armature's hard wire conductors. Individual laminated stampings are used in place of a single iron core to improve the magnetic efficiency of the armature. A solid iron core armature would generate eddy currents, causing the motor to lose efficiency. Eddy currents are current flow resulting from counter-electromotive force that is induced in the armature's core and works against the motor's rotation.

BDCM designs are based on how the motor's windings are wired in conjunction with the armature's conductors. These designs include the following:

- Series.
- Shunt.
- Compound.
- Permanent magnet.

The series BDCM is the design used in traction motors. Series BDCMs provide maximum torque from a stop (excellent low-speed torque). In a shunt-type DC motor, the windings are connected in parallel with the armature. A compound BDCM has a series-parallel design. Permanent magnet motors do not have stator field windings. The shunt, compound, and permanent magnet DC motors are used in lower-horsepower applications. These applications include fan blowers, windshield wipers, and some small engine starter motors.

Brushless DC Motor

The rotor of a ***brushless DC motor (BLDCM)*** has a rotating permanent magnet surrounded by pairs of coil windings. The motor's electronic controls energize the coil windings, causing the rotor to spin. This is known as ***electronic commutation***. As the coil windings are energized, the magnetic fields created cause the rotor's permanent magnets to spin the rotor. As previously mentioned, like magnetic poles repel and opposite poles attract.

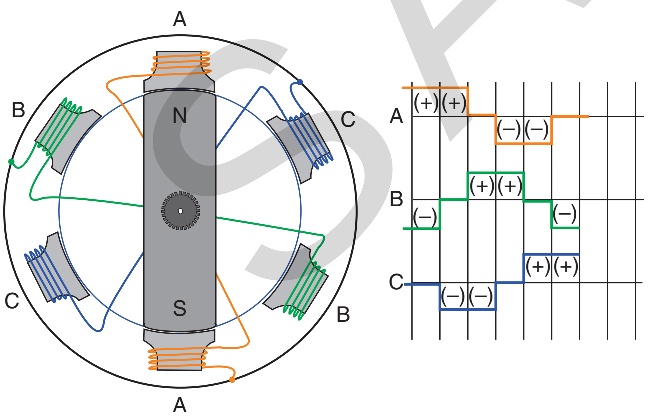

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Figure 26-15. A BLDCM contains a magnet that is rotated when the windings are energized in the proper sequence. Electronic controls are used to correctly energize the windings with the correct polarity. The pairs of windings are labeled A, B, and C.

The electronic commutation of a BLDCM energizes a pair of coil windings that are 180 degrees opposite each, wound in opposite directions, and are connected in series to form an electromagnet. See **Figure 26-15**. When they are energized, one coil winding becomes the north pole magnet and the other coil winding becomes the south pole magnet. The electronic commutation energizes the coil windings in sequence with the correct polarity to cause the permanent magnet to be spun due to the pulling force or pushing force of electromagnetic coils. See **Figure 26-15**. BLDCMs are most commonly used in smaller-horsepower applications. BLDCM weigh less than BDCM for a given output, and do not experience sparking that can occur when brushes wear.

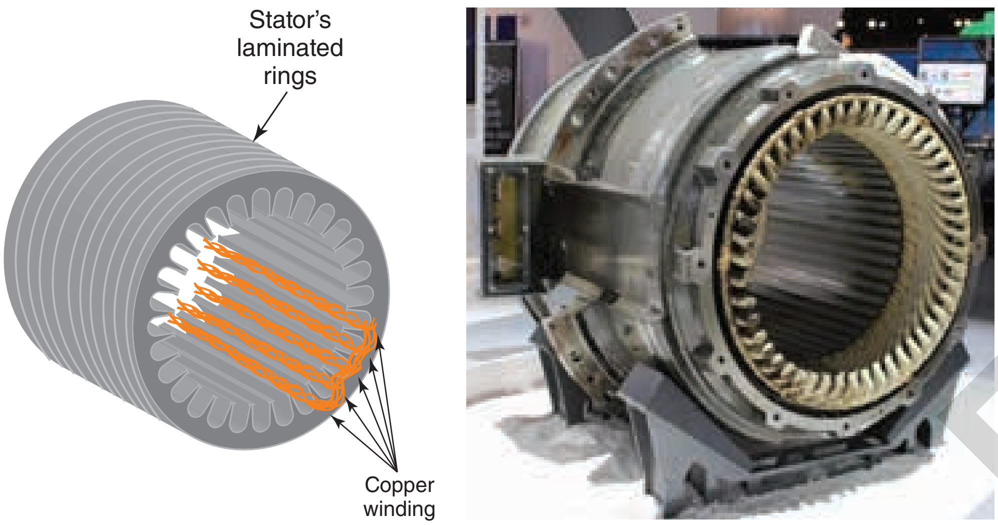

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Figure 26-16. An AC induction motor contains a stationary stator. A—The stator has numerous laminated steel rings placed next to each other. Copper wire is placed in channels inside the body of the stator. B—This stator is from a Liebherr KDF 1501 AC induction motor. It is rated at 2000 hp (1500 kW) and operates at 1310 volts and 770 amperes.

AC Traction Motors

The brushes used in BDCMs wear over time, requiring the motors to be repaired. As a result, some manufacturers choose to use ***AC traction motors*** that are driven with AC drive systems. AC traction motors have two different designs—traditional AC induction traction motors and AC permanent magnet motors. Both types are found in diesel electric propulsion systems.

AC Induction Motor

One of the first types of AC traction motors employed in electric drives is the ***AC induction motor***, which does not use commutators or brushes. An AC induction motor contains two primary components—a stationary stator and a rotating rotor. The stator is composed of numerous laminated stamped steel rings that are placed next to each other. Copper wire is wound and placed in channels inside the laminated stator body. The stator's windings have a clear resin coating. This coating insulates the conductors and prevents them from shorting with each other and the iron stator housing. See **Figure 26-16**. Multiple phases of AC electrical current (for example three-phase) is applied to the stator's copper windings, which results in a rotating magnetic field (rmf) that causes the rotor to rotate. The multiple phases of alternating current flowing through the field cause a uniform magnetic field to rotate. The speed of this rotating uniform magnetic field is known as synchronous speed.

A rotor, resembling an iron squirrel cage, is located inside the stator. See **Figure 26-17**. The ends of the rotor are made up of steel rings. Numerous bars, known as *conductor bars*,

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Figure 26-17. An AC motor's rotor resembles a squirrel cage assembly that allows a current to be induced, causing it to rotate. The rotor's conductor bars can be parallel to the axis of the rotor, or arranged helically around the axis of the rotor. A—This rotor is from a Liebherr KDF 1501 AC induction motor. Note that the conductor bars are parallel to the rotor axis. B—A cutaway of an AC induction motor inside a belt drive used in a mining application. The conductor bars are arranged helically around the rotor axis.

connect the two rings, forming the cage. When alternating current is applied to the stator's windings, the rotating magnetic field (RMF) generates current in the conductor bars, which creates another magnetic field around the rotor. The attraction and repulsion between the stator's magnetic field and the rotor's magnetic field cause the rotor to rotate. Because the induction of current in the rotor causes the rotor to spin, the motor is known as an *AC induction motor*. The core of the rotor is made up of laminated steel discs, similar to those in the armature of a DC motor, to reduce the eddy currents.

Manufacturers commonly take the rectified DC current and invert it back into AC. Varying the speed and torque of an AC motor requires electronic controls to vary the AC ***frequency*** (number of cycles per second). This variable AC electric drive is often called ***variable frequency drive (VFD).*** A VFD is an electronic controller that varies the AC frequency sent to an AC motor. By varying the AC frequency, the VFD effectively controls the AC motor's output speed and torque. As the VFD reduces the AC frequency, the motor's speed is reduced. As the AC frequency is increased, the motor's speed increases. It is difficult to vary the frequency of three-phase AC for the purpose of controlling the speed of an AC motor. Therefore, manufacturers first rectify the alternator's AC into DC, which is easier to work with, and then invert it back into AC of the desired frequency.

Note

Advancements in modern electronics made variable frequency drives cost-effective and practical. Without these advancements, the majority of traction motors would still be BDCMs, which require less electronic sophistication to drive. Sophisticated AC drives require electronic controls that can rectify the AC to DC, invert the DC back into a variable AC output, and be able to handle high current flow (1000 or more amps) and high voltages (2600 or more volts).

An AC induction motor is also known as a *frequency motor* or ***asynchronous motor***. The term *asynchronous* means the rotor spins at a speed slower than the speed of the induced magnetic field. The slower speed of the rotor is described as *rotor slip*. Locomotives; Caterpillar 794AC, 796AC, 798AC mining trucks; Liebherr T 236, T 264, T 274, and T 284 mining trucks; Komatsu 730E, 830E, 860E, 980E mining trucks; Hitachi EH3500AC, EH4000AC, and EH5000AC mining trucks; and Hitachi EX1900E-6 through EX8000E-6 electric-drive excavators use AC induction motors.

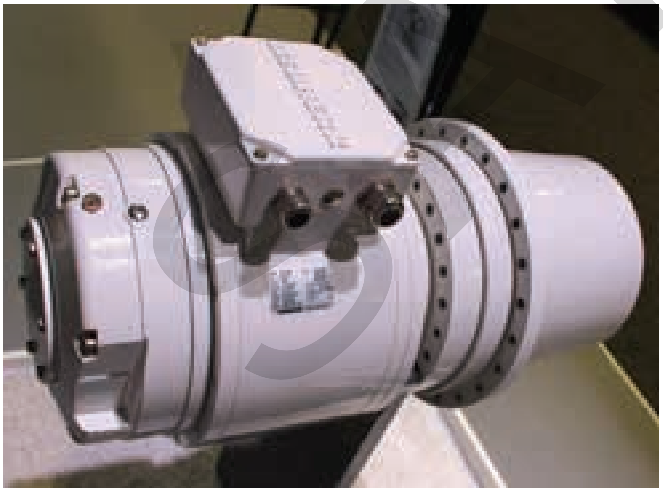

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Figure 26-18. This Liebherr electric-drive travel motor is equipped with an AC permanent magnet drive motor that powers the planetary reduction final drive. The electric-drive motor is used in place of the traditional hydraulic motor. It is found in mining diesel electric drives, such as those on mobile crushers and mobile screens.

Permanent Magnet AC Motors

A ***permanent magnet AC (PMAC) motor*** is also called a *permanent magnet synchronous motor* and a *brushless AC motor*. See **Figure 26-18**. Like the brushless DC motor, a PMAC motor contains stationary coil windings in the stator and a rotating rotor with permanent magnets. However, the BLDC motor's coil windings are wound around individual stator iron poles and the stator in a PMAC motor is similar to a traditional AC induction motor stator with slots that hold the multiple phases of coil windings. Another difference is that a PMAC motor is driven with AC sine waves instead of DC trapezoidal square waves. One negative trait of BLDC motors occurs when the electronic controls commutate the coils, (shut off one coil and energize the next), the motor exhibits torque ripple, small decreases or increases in torque, due to the square wave DC coil energization. The PMAC motors use a smooth AC sign wave that eliminates the torque ripple associated with BLDCs.

Compared to AC induction motors, PMAC motors in general offer a wider operating speed range, higher efficiency, and cooler operation that results in longer life of components. A PMAC motor also has more ***power density*** than an AC induction motor, meaning that it delivers more horsepower for a given motor size. The rotor also rotates at the same speed as the magnetic field making it a synchronous motor as compared to the asynchronous AC induction motor. Like other AC motors, a PMAC requires a VFD to operate. The John Deere 644K /644X wheel loader uses a PMAC motor.

BLDCMs and PMACs use rotors with permanent magnets. When the rotor is spinning, a backward ***electromotive force (EMF),*** also known as ***back electromotive force (BEMF)*** and ***counter-electromotive force (CEMF),*** is induced (generated) in the stator windings. EMF is voltage. When no current is applied to a BLDCM or PMAC, the permanent magnet rotor can be spun due to the machine's inertia. As the magnets spin inside the stator's housing, they cause a voltage to be produced. As a result, the motor acts as a generator and produces a voltage acting in the opposite direction as that normally used to drive the motor. If the motor is allowed to overspeed due to inertia, it can cause the voltage to increase to a damaging level.

If the motor is being electrically driven (due to current being applied to the motor), the motor still produces a CEMF. However, the voltage level of the CEMF is less than the voltage used to drive the motor. The motor's output torque is a function of the difference between the voltage being applied to the motor minus the CEMF created by the rotating motor.

Reluctance Motors

Another style of electric drive motors are reluctance motors. The two types include the switched reluctance and the synchronous reluctance motor.

Switched Reluctance Motors

A ***switched reluctance motor (SRM)*** has a rotor and a stator. The motor is simplistic and economical. The rotor does not have windings or permanent magnets. A SRM has an iron rotor with multiple poles. The rotor is made of many thin steel plates laminated together. The poles are magnetically permeable and have no conductors. The stator windings are separate individual coils, also known as concentrated windings, that can be replaced individually rather than requiring the entire stator winding to be replaced. The stator design can be called dual pole due to the opposing stator poles with concentrated coil windings. The only wear items on this type of motor are two bearings. Compared to AC motors, SRMs are heavier and noisier. SRMs also exhibit high torque ripple.

Although the motor is simplistic, the electronic controls are sophisticated and expensive to develop and produce. The control module energizes each pair of the stator windings independently. Reluctance (magnetic resistance) is developed between the aligned and unaligned rotor poles and stator poles. As the controller energizes pairs of stator windings (ahead of the rotor poles) in a synchronized fashion, the rotor is pulled, causing the stator poles to align with the rotor poles and resulting in rotation. The movement of the rotor results from the rotor taking the path of the least magnetic reluctance. Electronic controls synchronize the engagement of pairs of stator windings. This consecutive energizing of windings is called *sequential switching*. See **Figure 26-19**.

Switched reluctance (SR) is continuing to gain more popularity in the electric-drive sector. Caterpillar 988K XE wheel loaders, R1700XE LHD loaders, and D6XE dozers use SR. The John Deere 944K wheel loader uses four

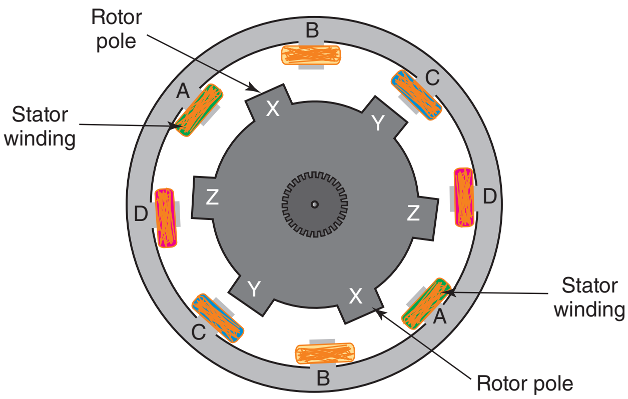

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Figure 26-19. In a switched reluctance motor, the stator contains windings that are energized in pairs, causing the rotor to turn along the path of least reluctance. The control module energizes the *A* stator windings to pull the rotor *X* poles counterclockwise. When the poles align, the control module next energizes the *B* stator windings, which pull the *Y* rotor poles into alignment with them.

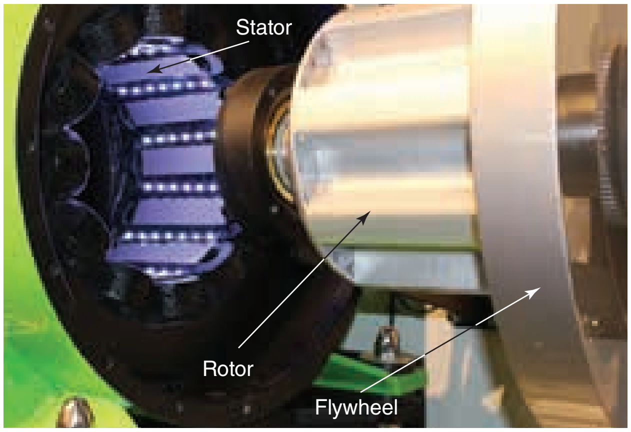

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Figure 26-20. This Joy Global SRM has a rotor with a flywheel used to store energy. The stator and rotor are formed from numerous laminated steel plates.

switched reluctance motors. Joy Global/Komatsu Mining electric mining machines also use SRMs. The rotor within a Joy Global/Komatsu Mining SRM is made from the same steel stamping as the stator. The centers of the plates are cut out and laminated into a single rotor and the outside of the plates are laminated into the stator. The rotor assembly has no windings or permanent magnets. The stator uses independent wound coils as compared to traditional AC induction motors that have overlapping wire in the stator coils. The rotor in **Figure 26-20** has a flywheel used to store energy. This type of rotor is explained later in the chapter.

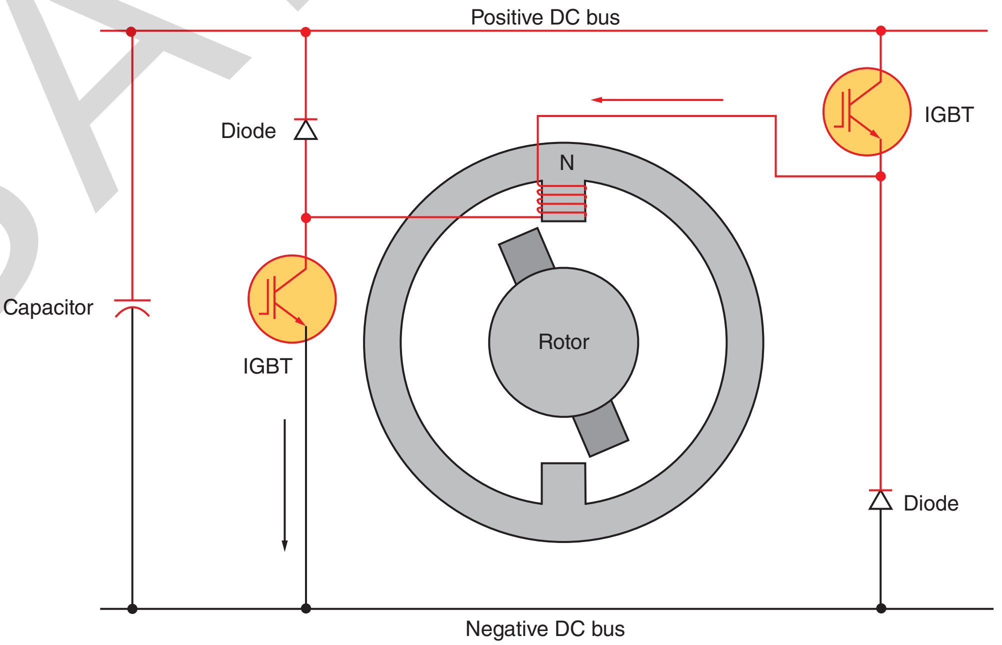
SRMs can also be used as generators during braking. During braking, the SR motors generate electrical current that is delivered to the SR generator, which acts like a motor assisting the engine to provide loader hydraulic functions. During braking, if the electrical energy generated by the motors becomes excessive, the controls will deliver electrical energy to the braking grids where it is dissipated as heat energy.

Controlling Switched Reluctance Motors

The torque of a switched reluctance motor is varied using insulated-gate bipolar transistors (IGBT) that act like on/off switches to apply DC electrical current to energize the motor stator's coils sequentially. The IGBTs are not variable, they are either switched fully open or fully closed. One IGBT is used to supply positive DC current from the positive DC bus to a stator coil. The DC bus is the electrical conductor that receives the rectified DC current. Another IGBT is used to direct the current exiting the stator coil to the negative DC bus. See **Figure 26-21**.

The Joy Global DC positive bus can have voltages as high as 700 DCV. One IGBT can handle 75 amps of current flow, therefore multiple IGBTs are connected in parallel to handle the amperage needed to drive a SR motor.

Figure 26-21. This simplified drawing shows that IGBTs are used as "on/off switches" to direct current through the SRM's stator coils.



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Synchronous Switched Reluctance Motors

The ***synchronous switched reluctance motor (SynRM)*** or (RSM) uses the same style stator that is used in traditional AC induction motors. It contains multiple phase stator windings distributed around the iron stator. The stator is sometimes described as a single salient pole with distributed windings. The rotor can be one of two types. Both rotors look similar from the end view. See **Figure 26-22**. One is made of stampings laminated axially with curved cavities (flux barriers) to provide magnetic reluctance and the cavities are surrounded by iron curvatures (known as flux carriers). The other type is assembled from radial laminations of steel and insulators rather than air pockets. The stator is energized with traditional AC inverters. The motor was first introduced in the 1920s.

A SynRM has less torque ripple than SRM, and the inverter and electronic controls are less sophisticated. The SynRM has excellent torque output and efficiency. The SRMs struggle to self-start (rotate), which requires the electronics to initially slowly start the RMF. The electronics slowly increases the frequency of the current to the coils. As the rotor begins to spin, the electronics synchronously increases the RMF to cause the attractive force to increase rotor speed. As the rotor experiences a load, it causes the rotor to slow behind the RMF. The electronics software continuously monitors the position of the rotor and adjusts the RMF as needed. SynRMs spin at synchronous speed and run cooler and produce more torque than AC induction motors. SynRM is used in public transportation locomotives. A variation of the SynRM with permanent magnets inside the rotor is used in automobiles.

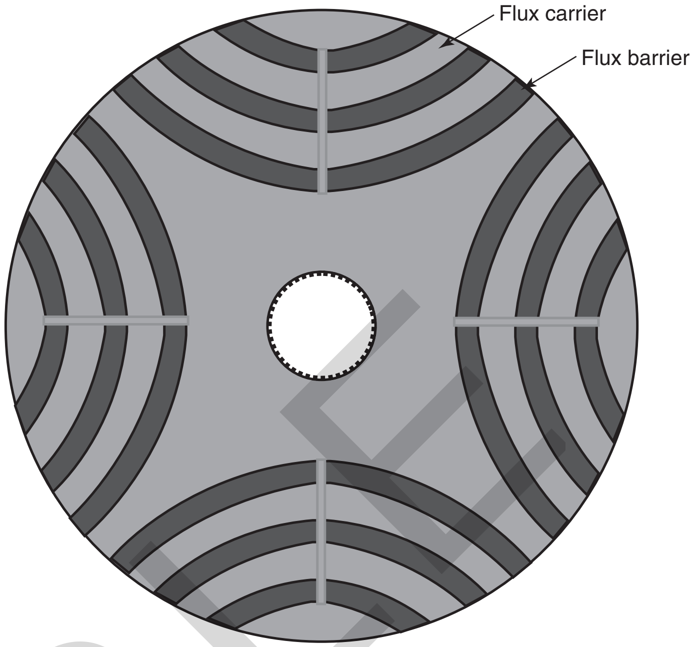

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Figure 26-22. An end view of a synchronous reluctance motor's rotor.

Electric-Drive Mining Trucks

The mining industry has been using electric-drive equipment for decades and continues to use it today. Most electric-drive mining trucks use a pair of traditional AC induction motors in the rear axle. Each AC motor drives a planetary final drive, which drives a pair of wheels. The motors, when produced by a high-quality manufacturer and operated in the right environment with good maintenance practices, can achieve a very long life, such as 30,000 hours, and over 50,000 hours in some extreme cases.

Caterpillar AC Mining Truck

Caterpillar's 794 AC, 795F AC, 796 AC, and 798 AC mining trucks are electrically propelled, **Figure 26-23**. The 794 AC has a

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Figure 26-23. A 794 AC Caterpillar electric-drive haul truck being shown at MineExpo.

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Figure 26-24. An 795F AC generator is located at the rear of the truck and is driven by the engine through an isolation coupler (damper assembly) and drive shaft.

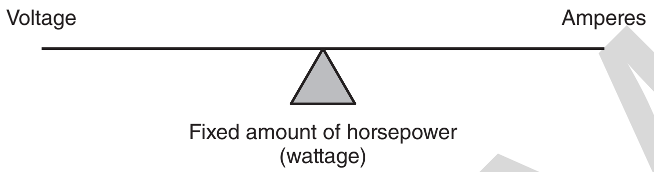

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Figure 26-25. Electrical horsepower exhibits an inverse relationship between voltage and amperes. If one variable is increased, the other is decreased.

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Figure 26-26. A Caterpillar 794 AC and 795F AC electric-drive truck's power control inverter cabinet is located beside the operator's cab.

320-ton payload capacity. The 795F AC truck has a 345-ton payload capacity. The 796 AC replaced the 795F AC and has a 360-ton capacity. The 798 AC has a 410-ton capacity. Caterpillar is the first manufacturer to offer a sole-sourced AC-powered truck. Caterpillar singularly designed and produced the electric-drive truck (795F AC) using several components from the mechanical 797 truck. Caterpillar dealers are the only entity needed to service the truck. The 794 AC is a product of Caterpillar purchasing Bucyrus, converting a MT 5300 Unit Rig truck to a 794 AC using the 795F AC electric drive train. All three 794 AC, 796 AC, and 798 AC truck use a C175-16 3500 hp tier-4 diesel-powered electric AC drive truck for low altitudes. The 798 AC high-altitude truck has a C175-20 4000 hp tier-2 engine and is used in South America.

A C175-16 diesel engine drives an AC generator at the rear of the 795F AC truck, **Figure 26-24**. The truck's electric drive operates at 2600 volts. Electrical power, measured in watts, is computed by multiplying the voltage times the current flow (amperes). For a given amount of wattage, an increase in voltage allows the engineers to decrease current flow. If the engineers designed the truck to operate on half the voltage, current would be doubled.

Amperage and voltage have an inverse relationship for a fixed amount of power (watts), **Figure 26-25**. For a given amount of electrical power, if a lower voltage is used, much larger electrical conductors would be required to accommodate the larger amount of current flow. High voltage and lower amperage reduces heat and increases component life.

The 2600 volts AC are rectified into 2600 volts DC. A control power inverter cabinet, **Figure 26-26**, converts the 2600 volts DC into a three-phase AC voltage that drives the right and left AC drive motors in the truck's axle housing. The control power inverter cabinet uses IGBT modules for controlling the truck speed and direction. IGBT modules are further discussed later in this chapter. The inverter cabinet directs the three-phase AC voltage to two AC induction traction motors in the truck's rear axle assembly. See **Figure 26-27**.

The Caterpillar AC trucks use a radial grid for braking. The ***radial grid*** converts the mechanical kinetic energy into heat energy, **Figure 26-28,** and acts like a brake resistor for slowing the truck. A ***brake resistor*** converts the electrical energy developed during a braking application into heat energy to be dissipated into the atmosphere. All three trucks have a hydraulic motor that drives a large fan that draws air into and through the electronic cabinet, blows it through the generator, and directs it to the two AC motors in the axle for cooling as needed. After startup, the air cooling is not always used or needed, depending on the climate.

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Figure 26-27. A Caterpillar 795F AC truck has two AC induction motors in the truck's axle housing.

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Figure 26-28. The radial grid acts like a brake resistor. It is located beside the control power inverter cabinet and has its own cooling fan.

Hitachi EH 4000 AC 3

Hitachi also manufactures electric-drive trucks. The EH 4000 AC 3 truck has a payload capacity of 243.6 tons and a rating of 2500 engine horsepower. See **Figure 26-29.** This truck has a single AC alternator and rectifies its output to DC. The DC is then inverted into AC and sent to two AC induction motors, one for the right drive and one for the left drive. The drive motors deliver power to a planetary final drive, which drives the left- or right-side dual wheels. A spring-applied caliper style parking brake is located at each drive motor. See **Figure 26-30**.

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Figure 26-29. This Hitachi EH 4000 AC 3 electric-drive haul truck has a 243-ton payload capacity. Its resistor grid boxes dissipate energy during braking and are visible above the engine's exhaust, just right of the operator's cab.

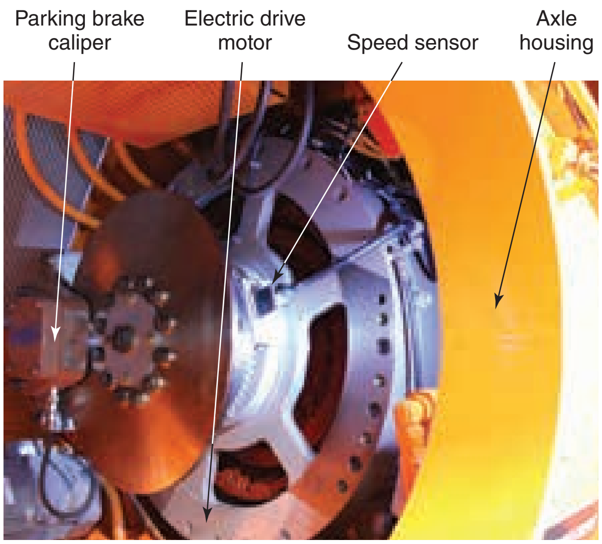

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Figure 26-30. The Hitachi EH 4000 AC 3 mining truck has spring-applied caliper-style parking brakes attached to each electric-drive motor. The brakes are accessible by removing the rear axle cover.

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Figure 26-31. The Komatsu 930E electric-drive truck uses GE's AC electric drive. The AC control cabinet is located beside the operator's cab.

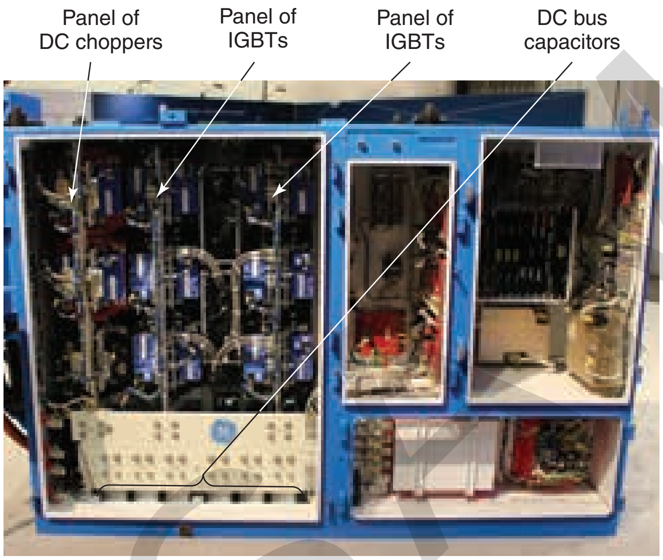

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Figure 26-32. This GE control cabinet contains the 12 air-cooled IGBTs that control the AC drive motors in the Komatsu 930E mining truck.

The truck is equipped with three advanced control features:

- ***Slip/slide control***. This feature uses front wheel sensors, suspension and steering sensors to provide traction control and antilock brake control in slick conditions.
- ***Pitch control***. This feature controls the AC drive motors to limit the amount of chassis bouncing that occurs in rough road conditions.
- ***Side skid control***. This feature controls the two AC drive motors to improve turning when operating in slick road conditions.

Komatsu 930E

The Komatsu 930E truck shown in **Figure 26-31** has a 320-ton payload and uses the GE electric-drive propulsion system. The trucks have an AC generator and two AC motors. As in most electric-drive mining trucks, the AC is rectified into DC and then inverted back to AC so the frequency can be more accurately varied to control motor speed and torque.

The control cabinet, **Figure 26-32**, has three rows of IGBTs. IGBTs are used as braking choppers and AC inverters. A ***braking chopper*** is an electrical switch that limits the DC voltage by diverting the high voltage to braking resistors. The other two rows of IGBTs are dedicated to control the AC three-phase variable frequency to the AC induction motors. Located below the IGBTs are DC bus capacitors that are used to stabilize the DC bus voltage. In a VFD drive, the DC bus supplies the DC current that is inverted back into AC and controlled by the VFD. DC bus capacitors store excess charge and release the stored charge if voltage drops to maintain a stable DC bus voltage.

Komatsu Autonomous Truck

Komatsu has developed an ***autonomous*** electric-drive truck that can haul and deposit loads without an operator. The truck is designed to drive by itself and has no operator's cab. The Komatsu Autonomous Haulage System (AHS) operates using onboard electronic control systems, GPS technology, and an obstacle detection system. See **Figure 26-33**.

The autonomous truck offers the advantage of nonstop operation. The trucks reduce or eliminate operator risks at high altitudes or in other remote, dangerous locations, such as mine sites. The truck is also uniquely equipped with four independent electric drive motors, providing four-wheel drive and four-wheel steer. Unlike human-operated trucks, an autonomous truck can be driven straight to a load site and reversed straight to the dump site without having to turn around, because the truck is not dependent on the operator viewing the road.

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Figure 26-33. The Komatsu four-wheel drive, four-wheel steer truck does not have an operator's cab. A—A photo of the back of the truck. Without an operator's station and with four-wheel steer, the truck drives the same in forward and reverse. B—A close-up view of the steerable drive wheel.

Trolley Electric-Powered Mine Trucks

Mining trucks that must travel up long uphill grades can get a boost from an overhead electrical power supply. This system is called ***trolley assist.*** See **Figure 26-34**. When ascending a hill, trucks with trolley assist can extend current collectors into contact with overhead power lines. When electrical contact is made, the truck's engine speed is brought down to an idle, and the truck is driven by power from the overhead lines. The electrical power from the overhead lines enables a truck's electric propulsion to operate with increased horsepower, up to 90% more horsepower than could be achieved if the electric drive was powered by the diesel engine. At the end of the grade, the truck disconnects from the grid and the diesel engine takes over.

To reap the benefits of this system, the truck must have an electric drive and be equipped with trolley assist. A loaded truck with trolley assist can travel much faster up a grade than a diesel-electric truck without trolley assist. The engine is allowed to idle, so engine life is increased. The truck also spends less time under extreme load, so drive motor life is also extended. Many electric-drive mining truck manufacturers offer trolley assist as an option.

Electric-Drive Wheel Loaders

Wheel loaders are a common type of electric-drive machine due to their cyclical operation. A common application has the loader driving forward into a pile to load the bucket, backing up to reposition the loader, then driving forward to dump its bucket into a truck. Some loaders are electric drives while others are hybrids that recover and store the energy during the cyclical braking operation.

Joy Global SR/Komatsu Mining

Joy Global began offering switched reluctance (SR) electric-drive wheel loaders in 2002. Komatsu purchased Joy Global. SR electric-drive machines include underground mining wheel loaders, open pit wheel loaders, and shovels. WE1150-2, WE1350-3, WE1850-3 and WE2350-2 wheel loaders are electric drive. Their WE2350-2 wheel loader is the world's largest, with a 70-cubic-yard bucket.

Hitachi Construction Machinery (Europe) NV

Figure 26-34. An electric truck with trolley assist enables the haul truck to connect to overhead power lines, providing the truck high horsepower for long, steep grades.

SR Generator

Joy Global electric drives are unique in that they use an SR generator instead of a traditional AC generator. The single diesel-driven SR generator is controlled to send current flow to a pair of front end converters, which delivers power to the DC bus. The DC bus sends power to the load side converters, which deliver power to four independently controlled SR electric drive motors. The Joy Global SR drive uses a lower switching frequency than traditional AC induction drives, which increases component life.

Kinetic Energy Storage System

Joy Global underground mining hybrid loaders can be equipped with the hybrid ***Kinetic Energy Storage System (KESS).*** Instead of traditional high-capacity batteries or capacitors, the KESS uses a SRM rotor flywheel to recapture energy. As the brakes are applied, that energy drives the SRM rotor flywheel, which greatly increases the loader's ability to capture energy. This type of flywheel was shown in **Figure 26-20**.

John Deere 944K Electric-Drive Wheel Loader

The John Deere 944K electric-drive wheel loader's engine runs at three speed ranges, low (1200 RPM), mid (1500 rpm), and max 1800 RPM, to offer choices in fuel efficiency and reduction of emissions. The engine drives two 3-phase 480-volt AC permanent magnet generators that feed electrical power to the power electronics devices, which comprise six inverters that use IGBTs. A separate inverter is used for each of the four drive motors and each of the two generators. Based on operator commands and machine operating conditions, the power electronics independently control four electric switched-reluctance drive motors. Each of these motors drives a planetary final drive that propels a single drive wheel and tire. See **Figure 26-35.**

The loader can individually power one, two, three, or four wheels. The electric drive replaces the traditional torque converter, powershift transmission, front axle, and rear drive axle. Unlike a traditional loader power train, the 944K electric drive allows the machine's ground speed to be controlled independently from engine speed.

26.4.2.1 Dynamic Braking

John Deere originally called the 944K electric-drive wheel loader a hybrid electric loader. However, by most definitions, a hybrid has a storage device, such as a bank of batteries or capacitors, for capturing and later releasing energy. The 944K does not contain any high-voltage energy storage device. John Deere plans to label future models E-drive instead of hybrid.

Consider that a loader's operation often involves frequent forward and reverse cycling. When the 944K operator presses the brake pedal, the machine electronically controls the electric drive motors to brake. Instead of dispersing this energy as heat, which occurs in conventional braking applications, the loader is capable of ***dynamic braking***. This means the motors, acting as generators, convert the machine's mechanical energy back into electrical energy. This electrical energy is sent to the generators, which act like electric motors to help the engine maintain its speed rather than lugging.

The recaptured energy helps the engine perform other functions, such as hydraulically controlling the loader lift, bucket curl, and articulated steering. This energy savings, along with the efficiency gained from the electric drive, increases the loader's fuel efficiency.

If the machine is not performing any other useful work, such as operating the loader or bucket, during dynamic braking, the power electronics send the electrical energy from the electric motor to two liquid-cooled brake resistors at the rear of the machine. See **Figure 26-36**.

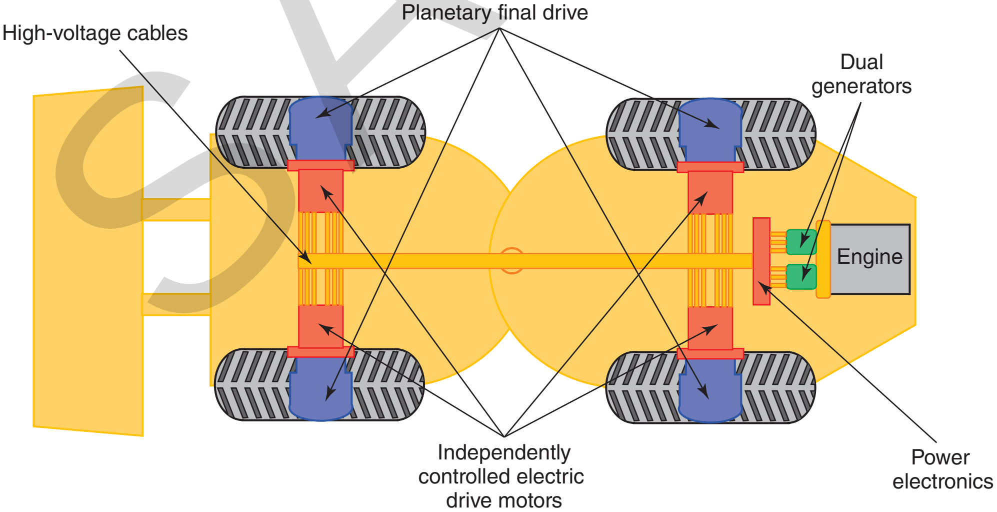

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Figure 26-35. The John Deere 944K electric-drive wheel loader has two engine-driven generators that send power to the power electronics, which are responsible for independently controlling four electric-drive motors.

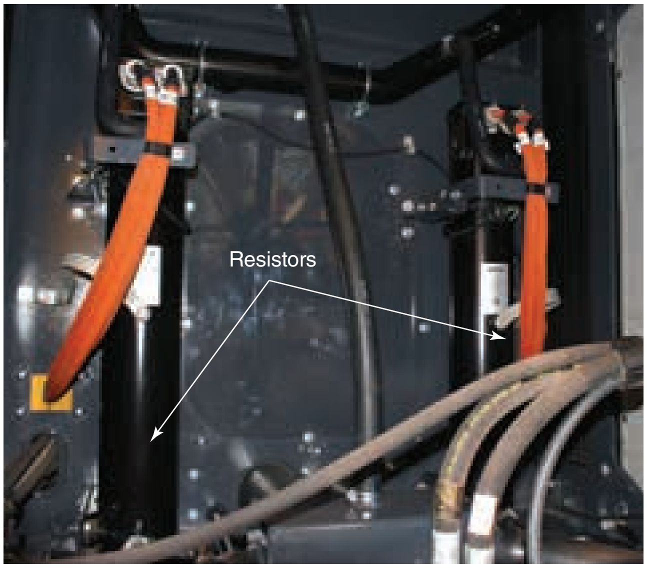

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Figure 26-36. The John Deere 944K has two liquid-cooled brake resistors at the rear of the machine, accessible through the rear compartment access cover.

The brake resistors convert the electrical energy developed during a braking application into heat energy that is dissipated into the atmosphere.

Locomotives, like electric-drive wheel loaders, use brake resistors, known as resistor grids, to dissipate heat. However, locomotives generate tremendous heat when they bring a long train of cars to a stop. As a result, their resistor grids must be designed to dissipate much more heat than the brake resistors in other types of electric drives. See **Figure 26-37**.

In addition to having dynamic braking, the 944K loader contains a traditional multi-disc parking and service brake assembly in each of the final drives. Each final drive brake is used for both service brakes and parking brakes. The service brake is hydraulically actuated and oil cooled. The parking brake is spring applied and hydraulically released.

Electronic Traction Control

The 944K has ***electronic traction control***, which monitors all four of the wheel motors to determine if any of the wheels begin to slip. When slip is detected, the electronic controls limit power to all four drive motors to reduce the machine's wheel slip. The loader has true four-wheel drive because it has no open differential.

The largest advantage of traction control is the reduction of costly tire wear. Loaders are notorious for spinning their tires while loading. The operator uses the machine's propulsion for driving into the face of the material being loaded. Some material is exceptionally harmful to slipping tires. An example is ***shot rock***—rock that has been blasted or hydraulically hammered but has not yet been crushed. Although all tire slip increases tire wear, sharp shot rock dramatically decreases tire life during wheel slip.

Each generator drives two diagonally opposed wheels. One generator drives the front-right and rear-left wheels, and the other generator drives the front-left and rear-right wheels. This is strategy is based on a loader digging its bucket into a pile. The load is placed on the front axle and those tires have all the traction and the rear wheels will easily spin. The diagonal distribution of electrical current to the motors distributes the load diagonally.

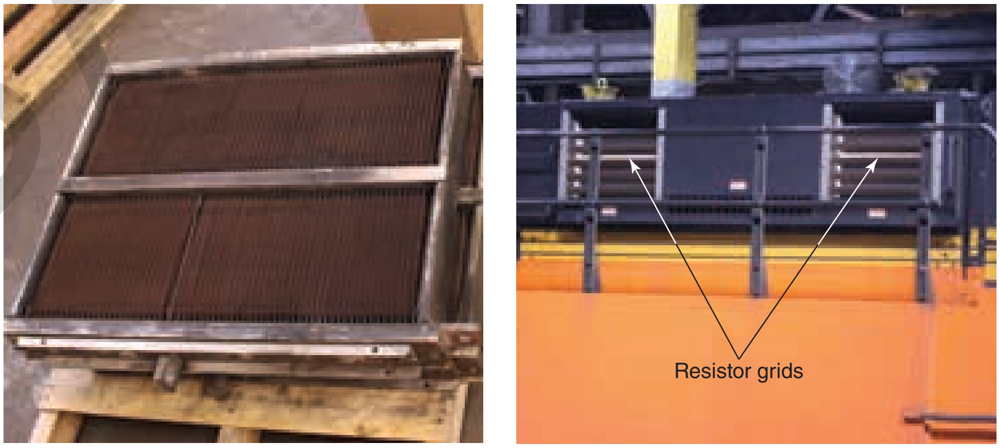

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Figure 26-37. Resistor grids are used on locomotives to convert braking energy into heat energy. A—These brake resistor grids are two of ten that can be used on one locomotive. B—Resistor grids are placed at the top of the locomotive.

Note

If a 944K's rear wheels lift off the ground when the machine drives into the face of a stock pile for loading, the machine will sense rear wheel slip and reduce power to all four drive wheels. Although you can see the wheels ratchet during the initial movement, they will not spin. Because the 944 has a separate inverter for each motor, it can actually control each motor individually if needed. The wheel speeds can be varied while steering so the outside wheels and inside wheels can turn at different speeds so the tires do not scrub like they do with a locked differential.

The loader has rim pull control with adjustable settings to limit the torque to the wheels to avoid slipping tires on soft and slippery applications.

944K Advantages

The 944K has no traditional axle or transmission fluids. It has a 13.5-liter engine compared to its competitor's mechanical-drive loader of the same size, which has an 18-liter engine. The electric motors are produced by Nidec, a Japanese locomotive company, and weigh approximately 1700 lb (780 kg) each. They have been engineered to limit heat buildup in the motors and use ceramic bearings. The motors have long service life and routinely last the life of the machine. A 944K can use up to 33% less fuel than a conventional loader of the same size and can be up to 8% more productive than a conventional loader. The inverters, including the internal IGBTs, also typically last the life of the machine. The loader has an 8-year, 20,000-hour hybrid-electric-drive warranty. At 15,000 hours, the loader's engine and electric-drive power cables should be replaced and the gearbox inspected. A similar service is performed at 30,000 hours, but the generators and motors typically do not need to be replaced or rebuilt at either interval.

Philip McNew

Figure 26-38. A John Deere 644K electric-drive loader.

John Deere 644K and 644X-Tier Electric-Drive Wheel Loader

John Deere produces an electric-drive wheel loader originally called the 644K, **Figure 26-38**, but now called the 644X E-Drive. The electric drive uses a constant-speed diesel engine to drive a brushless, 3-phase, 480-volt, permanent-magnet AC generator, which converts mechanical energy into electrical energy. The generator sends electrical power to an inverter. An early style inverter is shown in **Figure 26-39**. The current model wheel loader is the 644X-tier.

The inverter sends power to a brushless, 3-phase, 480-volt, permanent-magnet AC motor. The electric motor delivers power to a three-speed transmission, which delivers power to the front axle and rear axle. The mechanical three-speed transmission does not select neutral, forward, or reverse, which are achieved with the electric drive. The purpose of the transmission is simply to transfer power and change gear ratios. In

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Figure 26-39. An early version of the 644K inverter. The loader's inverter is liquid-cooled. The inverter controls the AC electric motor.

this application, the electric drive has replaced the torque converter. The electric drive allows the machine's ground speed to be controlled independently from the engine speed. See **Figure 26-40**.

The John Deere 644K electric drive is also labeled a hybrid electric loader, but like the 944K, it does not have an energy storage device. The 644K offers dynamic braking, allowing the electric drive to use braking energy to maintain engine speed. If the machine is not performing any other useful work during the dynamic braking, such as operating the loader or bucket, the inverter sends the electrical energy from the electric motor to a brake resistor. The brake resistor converts the electrical energy developed during a braking application into heat energy that is dissipated into the atmosphere. The brake resistors are also cooled with engine coolant. The integration of the brake resistor extends the life of the service brakes.

The inverters on the 644X and 944K are cooled by John Deere CoolGard II coolant with their own separate system, rather than the engine coolant. They have a dedicated electric water pump and their own cooler because they need to run at a lower temperature than the engine. The engine runs at a set speed and provides predictable hydraulics because of the fixed hydraulic pump speed. The engine speed of a mechanical-drive loader can be drawn down during operation. The 644K (644 X) loader performs similarly to a conventional 724 loader and costs less to ship than a 724 loader. It can save up to 5% in overall operating costs over its service life compared to the operating costs of a traditional 644 loader. If operating in a V-pattern when loading a truck, the loader can be up to 12% more fuel efficient than a conventional machine.

Hitachi ZW220HYB-5 Hybrid Wheel Loader

Hitachi was the first to mass-produce a hybrid electric wheel loader when they manufactured the ZW220HYB-5 in 2015 for the Japanese market. The loader has an engine-driven electric generator/motor assembly, two inverters, a capacitor, and two electric-drive motors. See **Figure 26-41**. The generator delivers electrical power to the left-side inverter, which sends power to the right-side inverter. The right-side inverter sends electrical power to the two drive motors. A capacitor assembly stores electrical energy that is captured when the machine is moving or during dynamic braking. The two electric-drive motors are responsible for driving the front and rear axles.

Philip McNew

Figure 26-40. The John Deere 644K AC permanent magnet motor is visible at the articulation joint.

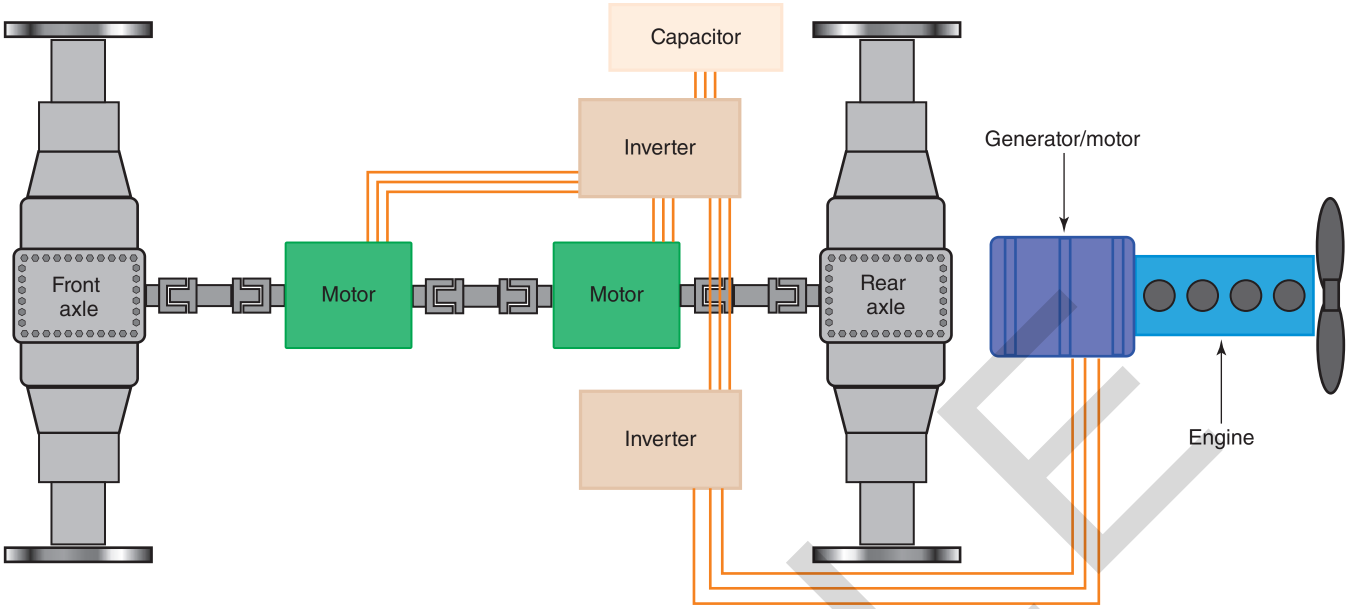

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Figure 26-41. The Hitachi ZW220HYB-5 hybrid wheel loader uses an engine-driven generator that supplies power to two inverters. The inverters can direct energy to be stored in the capacitor or direct electrical energy to the two electric drive motors.

Volvo Battery Electric Wheel Loader

The Volvo L25 wheel loader is a battery electric wheel loader that uses a 48-volt, 39-kilowatt-hour battery pack to power the loader. The machine can be operated in continuous use from three and a half to six hours. The batteries can be fast charged in just two hours and do not have to be fully discharged (deep cycled) to be charged. They can be charged anytime. The machine includes an onboard 3-kilowatt charger that can fully charge the machine in 12 hours. A permanent-magnet AC motor powers the hydraulic system, including steering. An AC induction motor is coupled to the rear axle and used to propel the loader.

Caterpillar 988K XE Electric-Drive Wheel Loader

In 2017, Caterpillar introduced the 988K XE electric-drive wheel loader. In the machine, the mechanical transmission and torque converter have been replaced with an electric drive. The loader is an electric-drive machine that does not use any high-voltage, high-capacity battery or capacitor to store or recover electrical energy. Nor does it use any type of brake resistor.

The C18 engine drives a switched-reluctance generator. The generator sends power to an inverter (integrated power electronics). The inverter sends power to drive a switched-reluctance electrical motor, which sends torque to a drop box. The drop box delivers power to the front and rear axles. When the machine is slowing down, the motor acts like a generator and the generator acts like a motor.

Caterpillar R1700XE Battery Electric Underground Loader

Caterpillar produces an underground battery electric loader, the R1700XE, on a limited basis. It is labeled a load, haul, dump (LHD) loader. It uses SR technology for propulsion and hydraulics. Like the 988K XE wheel loader, this electric-drive loader also has traditional drive axles. The loader's batteries can be charged in 20 minutes using two Caterpillar MEC500 mobile equipment chargers. These portable chargers can be brought to the machine on the job site, much like a fuel truck, which can drive up to and refuel a machine.

Electric-Drive Dozers

Dozers are another machine that can be equipped with electric drives. Caterpillar has produced the D7e and D6XE dozers. It has also developed a D11XE prototype dozer.

Caterpillar D7E Electric-Drive Track-Type Dozer

The D7E is Caterpillar's first electric-drive dozer, introduced 2009. Much like a locomotive, the machine has a diesel engine that is responsible for driving the electric motors in series. The tractor does not use a high-capacity electrical storage device, such as a high-voltage battery or capacitor. It also does not have a torque converter or a powershift transmission. The power train consists of a C9.3 ACERT diesel engine coupled to a flywheel clutch, which drives the rotor of an AC generator. The electric drive operates at 480 V. The generator delivers the three-phase current through three high-voltage, high-current wires (conductors) into a power inverter. See **Figure 26-42**.

The power inverter controls the electrical output. It delivers both AC and DC power. The power inverter also sends high-voltage DC current to the accessory power converter, which is responsible for delivering DC electricity to the air-conditioning compressor, to traditional starting batteries to keep them charged, and to a hazardous voltage present lamp (indicator) that alerts the technician that high voltage is present.

The power inverter also propels the tractor by sending high-voltage and high-AC current through six wires to two infinitely variable electrical drive motors. The two drive motors drive a single bull gear that drives the differential steering's planetary carrier to provide the propulsion input into the track differential steering system. A dedicated steering hydraulic motor provides the steering input into the differential steering gear set to control the tractor's steering direction and steering speed. The axles deliver power to a right and left final drive assembly. See **Figure 26-43**.

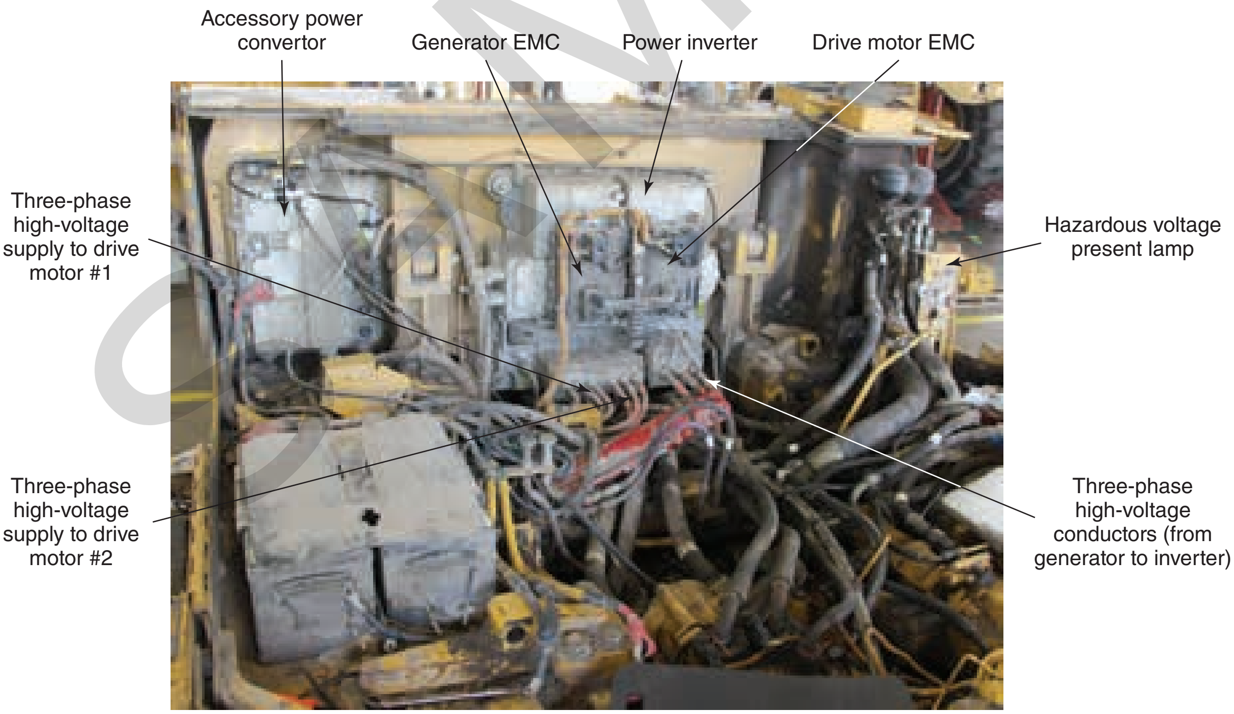

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Figure 26-42. The power inverter receives high voltage, high current from the AC generator. The inverter then delivers high voltage, high current through six wires to the two individual electrical-drive motors. The motors provide an infinitely variable input to the machine's axle.

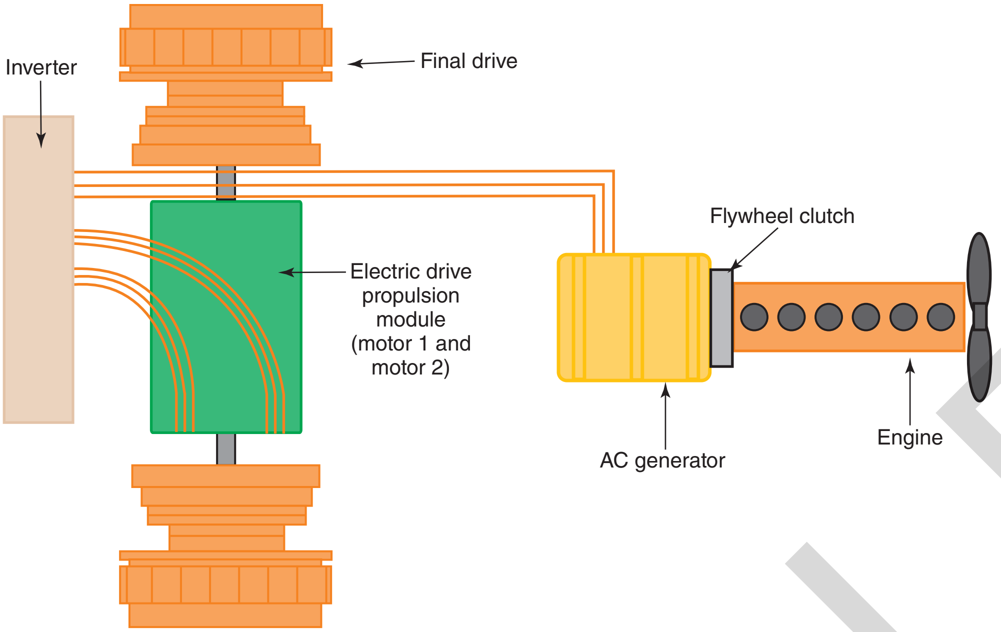

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Figure 26-43. The D7E engine drives an AC generator that sends current to a power inverter. The inverter drives the tractor by controlling two AC drive motors in a propulsion module. The tractor uses hydraulic differential steering. The inverter also sends DC power to the accessory power converter to operate the air-conditioning compressor and charge the traditional starting batteries.

The D7E tractor does not have a hybrid drive even though it has an electric drive. This means that the system does not store or recover high voltage or high current in any type of capacitor or battery.

D7E Electric Drive Advantages

The electric-drive system in the D7E dozer provides machine owners with the following advantages:

- An engine designed to operate at speeds within a narrow power band, which extends the life of the engine and enables the tractor to use up to 25% less fuel.
- It can lower operating costs.
- It has good straight-ahead dozing capacity and maneuverability in tight spaces (similar to hydrostatic drive and differential-steered dozers).
- It does not require gear shifting (similar to a hydrostatic drive).
- The electric-drive system has 60% fewer moving parts compared to a powershift transmission.
- The electric-drive powertrain components are expected to last up to 50% longer than traditional drive components (in similar conditions) and are configured in replaceable modules.
- It has no engine accessory drive belts, which improves machine serviceability.

The D7E is configured with a low oval-shaped undercarriage. In 2020, Caterpillar introduced the new D7 with elevated tracks and traditional mechanical powershift powertrain.

Caterpillar D6XE Electric-Drive Track-Type Dozer

In 2019, Caterpillar offered the first elevated-sprocket electric-drive dozer, the D6XE dozer. It is a differential steer tractor. The dozer does not use a high-capacity electrical storage device, such as a high-voltage battery or capacitor. Nor does it use any type of brake resistor.

Unlike the D7E, the D6XE uses a SR generator to drive one SR motor that drives a propulsion planetary carrier inside the differential steering gearbox, instead of two electrical motors. The SR generator sends three-phase, pulsed DC current to the power inverter, which directs three-phase, pulsed DC current to the SR motor. The pulsed DC current varies from –715 V to 715 V.

The D6XE has a 20,000-hour, 84-month electric power train warranty. The generator and motor bearings and seals must be replaced before 12,000 hours in order to maintain the warranty. The D6XE inverter is designed to last the life of the machine. However, if needed, unlike the D7E, the D6XE inverter is serviceable by Caterpillar technicians.

Caterpillar D11XE Electric-Drive Track-Type Dozer

Caterpillar is testing a prototype electric-drive in its largest dozer, the D11XE. It is the largest electric-drive dozer in the industry. The electric drive makes the dozer capable of a power turn, unlike traditional D11 dozers that use steering clutch and brakes. The D11XE also has no transmission gears to shift, as there are in a traditional D11.

Electric and Hybrid Electric Excavators

Manufacturers offer several types of electric-drive excavators: electric-powered compact excavators and loader backhoes that receive power from a battery or power cord, large mining electric-drive excavators and shovels that receive their power from an external AC electrical power supply, and diesel-powered excavators with hybrid electric slew drives.

Electric-Drive Compact Excavators and Loader Backhoes

Several manufacturers offer compact electric-drive excavators. Two manufacturers produce electric-drive loader backhoes.

Electric-Drive Mini and Compact Excavators

Numerous manufacturers produce prototypes or manufacture electric-powered mini excavators. Some are battery powered and some are powered with a plug-in power cord. Examples of prototype battery-powered compact excavators include the Yanmar CE SV17e compact excavator and Hitachi ZE19 and ZE85 models. The Hitachi machines are designed to operate for four or more hours with a one-hour rapid charge.

JCB manufactures the 19C-1E, E-TECH battery-powered mini excavator. When configured with the four-battery pack, it delivers up to five hours of operation, which is generally the amount of time a compact excavator is operated for a traditional day's work. The three-battery pack provides up to four hours of operation. The machine can be charged with 110 V AC, 230 V AC, or 415 V AC.

Volvo builds the ECR25 battery-powered electric-drive excavator. It uses three battery packs that provide 20 kilowatt-hours of energy. One ***kilowatt hour*** (kWh) equals the amount of power it takes to power an electric device that uses 1000 watts for one hour. The machine delivers four hours of work on a fully charged battery pack. A completely drained battery requires five hours to charge. It weighs 440 pounds (200 kilograms) more than the diesel-powered excavator. Volvo states that a traditional diesel-powered ECR25D excavator generates the noise equivalent of 8 to 10 ECR25 electric-powered machines. The battery is designed for 6000 hours of use, which is the equivalent of up to 10,000 hours on a diesel-powered machine due to the typical 40% idle time. The battery can handle up to 2000 charges and discharge cycles, which is the equivalent of one cycle per day for 200 days in a year times 10 years. The electric motor is designed to last the life of the machine.

Kato manufactures the 9VXB and 17VXB battery-powered compact excavators. They offer up to eight hours of operation on a full battery charge. The Kato 17VXE electric-powered mini excavator is powered by a three-phase, 50-amp, 480-volt AC power cable.

The Caterpillar 300.9D mini excavator can be powered by its own diesel engine or by a separate electric-powered hydraulic power unit (HPU). The HPU300 is a three-phase, 16-amp, 480-volt power source that supplies hydraulic power to the 300.9D mini excavator. When powered by the HPU, the mini excavator produces no exhaust emissions. The HPU300 has a front hitch bracket that allows the excavator's dozer blade to lift and carry the HPU when the mini excavator is being powered by its diesel engine.

Komatsu and Honda have partnered to produce the PC01E electric-drive micro excavator for overseas markets. The excavator is powered by Honda's mobile power pack (MPP). The PC01E is based on the diesel-powered PC01, which weighs only 661 pounds. The micro excavator can fit in the back of a truck. If the charge runs low, the drained MPP can be swapped with a charged MPP.

Load Backhoes

John Deere has partnered with a large utility company, National Grid, to test a prototype battery-powered loader backhoe, known as E-Power. The backhoe is labeled a 310-X tier. Deere is using X to denote hybrid and electric drive. The target is to provide eight to ten hours of operation on a fully charged battery. The battery charge time is also being tested, including a fast charge and recharge times when mobile quick chargers are used. The 310-X is approximately 25% quieter than the comparable 310L diesel-powered backhoe.

Case partnered with Moog, and in 2020 introduced the first fully electric-powered backhoe loader, the 580 EV, also known as project Zeus. Its 90-kilowatt-hour, 480-volt lithium-ion battery pack is designed to power the machine for eight hours in traditional backyard operations. A completely drained battery requires an eight-hour charge time. The battery pack is recharged with a three-phase, 220-volt charger.

Large Mining Electric-Drive Excavators and Shovels

Hitachi electric-drive excavators and Caterpillar electric-drive rope shovels receive their power from an external AC electrical power supply. The machines are environmentally friendly and run emission free because there is no diesel engine and exhaust system. They also have less daily maintenance. Because there is no diesel engine, there is no need to check the engine oil, air filters, or engine coolant.

Hitachi EX1900E-6 through EX800E-6 Electric-Drive Excavators

Hitachi EX1900E-6 through EX8000E-6 electric-drive excavators use a single three-phase AC induction motor that powers the machine's hydraulic system, HVAC, and electrical accessories. The electrical input to the motors ranges from 6600 to 6900 volts at 60 hertz. Their output ranges from 805 US horsepower (600 kilowatts) to 3218 US horsepower (2400 kilowatts).

Caterpillar Electric-Drive Rope Shovels

Caterpillar electric-drive rope shovels also use an external AC electrical power supply offering the same advantages as the AC electric-powered Hitachi excavators. Two machine model examples include 7395 and 7495. The shovel receives 7200 volts of power at 50/60 hertz. The high-voltage electrical power supply cord requires a carefully chosen approach for truck loading. The following are few examples and a few factors to consider:

- Single truck back-up loading.
  - Does not require overhead cable towers.
  - Good when working in close quarters
  - Requires minimum driver skill.
  - Requires extended spotter and truck exchange time.
  - Inability to load while the dozer is cleaning the work site
- Double truck back-up loading.
  - Requires twin overhead power cable towers.
  - More driver skill is necessary.
  - One truck can get into a loading position while the other truck is loaded.
  - Can load while the dozer is cleaning one of the work sites.
- Drive-by loading (undercarriages are parallel to wall and can move forward)
  - Good for belly-dump trucks and coal sites.

- Modified drive-by loading (undercarriages are parallel to wall and can move forward and the trucks back into loading site at an angle).
  - Is good for end-dump trucks and popular for coal sites.
  - Requires high driver skill.

Diesel-Powered Excavators with Electric Hybrid Slew Drives

Some examples of electric hybrid excavators are Hitachi ZH210-5, Kobelco SK210HLC, and Komatsu HB 215LC-A and HB 365LC-3. The hybrid technology is not used for propulsion, but for ***slew***, which is swinging or rotating the excavator's house to the left or right. A generator and electric motor in conjunction with large liquid-cooled capacitors or batteries recover energy as the excavator swing comes to a stop. In hybrid excavators manufactured by Caterpillar and Volvo, hydraulic accumulators, rather than electrical capacitors, recover the energy. Depending on the design, hydraulic accumulators can be charged when slowing the slew (Caterpillar) or when lowering the boom (Volvo EC300E).

Electric/Hybrid Safety and Service

In electric propulsion and hybrid power systems, the high-voltage conductors are orange cables. The tremendous amount of voltage and current required to propel these large off-highway machines can easily cause a fatality. Technicians must be properly trained prior to servicing or repairing off-highway electric-drive systems.

Even if a machine does not have high-capacity batteries or capacitors, the system can still retain high voltage for a period of time after the machine has been shut down. Take the following precautions:

- Never perform any service or repair work on the electrical propulsion system while the machine is running or operating.
- After the machine has been shut down, follow the manufacturer's steps for de-energizing the electric-drive system.

On hybrid systems with high-energy capacitors or batteries, the system still contains a tremendous amount of energy stored in the capacitor or batteries, even when the machine is shut down. Take the following precautions:

- Never attempt to service or repair a charged battery or capacitor.
- Always follow the manufacturer's service literature for servicing and repairing hybrid and high-voltage systems.

Note

Manufacturers' diagnostic service tools and machine monitors can display high-voltage readings.

Some manufactures provide specific instructions for cleaning terminals with an alcohol and water solution any time the conductors are removed or installed from an electric-drive component. Some manufacturers specify always installing new hardware when reattaching the conductors to the component.

Gloves

Most electric-drive manufacturers require technicians who service their equipment to use special insulated rubber gloves designed for working with high voltages. Six different classes of gloves are available, based on the amount of voltage they can safely handle. See **Figure 26-44**. The gloves are often rolled from the cuff toward the fingers to see if they will hold air. If a hole or crack exists, voltage can leak through the glove and endanger the

Class	Max AC use voltage	Max DC use voltage (average)	Color of Label
00	500	650	Tan
0	1,000	1,500	Red
1	7.500	11,250	White
2	17,500	25,500	Yellow
3	26,500	39,750	Green
4	36,000	54,000	Oange

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Figure 26-44. Matrix of voltages and classes of insulated gloves.

technician. Leather gloves, specified by ASTM standards, are placed over the insulated rubber gloves to protect the rubber gloves.

Electric-drive machines should not be serviced or repaired any time high voltage is present. Prior to working on a high-voltage electric-drive system, technicians must follow the service literature for shutting down the system and depleting the high voltage. In an abundance of caution, a technician should double check that the system has had its high voltage properly depleted. The insulated gloves are worn while double checking for high voltages in electric-drive components.

Ground Fault, Low Isolation

The electric-drive's internal copper-core drive wires have a shielding that isolates the conductors from the machine's chassis ground. A cross-sectional drawing of a drive wire from a Caterpillar D6XE is shown in **Figure 26-45**. The internal conductor is made of copper and surrounded by wire insulation. The insulation is surrounded by Mylar tape. Braided stainless-steel grounded shielding surrounds the Mylar tape. The grounded shielding is surrounded by an orange nylon braided cover.

The stainless-steel shielding that surrounds the drive cables is grounded to the machine's chassis ground. The internal drive wires are isolated from the shielding and chassis ground. During start up on the D6XE, the electronics look for ground faults between the copper conductor and the grounded shielding. If no fault is detected, the machine will slowly step up voltage until it reaches the normal operating range.

During startup and normal operation, the electronics on the 644X and 944K Deere wheel loaders look for continuity from the internal core drive wires to the outside shielding. Normally there is 2,000,000 ohms of resistance. The machine is allowed to operate if the resistance is 500,000 ohms or above. However, if the resistance drops any lower, the machine will not operate, and a low isolation fault code will be set. A technician will have to repair the fault before the machine can operate.

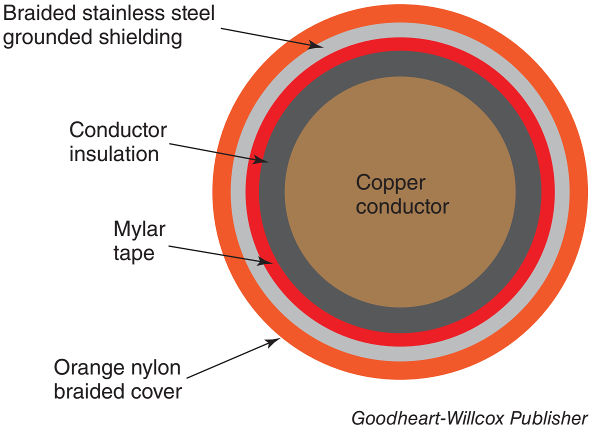

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Figure 26-45. A cross-sectional drawing of an electric drive cable.

Summary

- Alternators use a rotating electromagnet inside a stationary winding (stator) to develop three phases of AC flow.
- Bridge rectifiers are used to rectify AC to DC.
- DC traction motors have an armature consisting of wire conductors. Current passes through the field windings, carbon brushes, copper commutator bars, and armature conductors.
- Brushes wear over a period of time.
- AC traction motors do not require the use of commutator bars and brushes.
- Two types of AC motors are induction and permanent magnet.
- In switched reluctance motors, the stator coils are energized sequentially to pull the rotor, causing it to rotate.
- Electric-drive mining haul trucks use large resistor grids to dissipate the heat energy that occurs during braking.
- The John Deere 944K electric-drive wheel loader uses two AC generators to independently control four separate electric-drive wheel motors, providing independent drive, traction control, and dynamic braking.
- The John Deere 644K electric-drive wheel loader uses an engine-driven generator to drive an electric motor, which sends power into a three-speed transmission. The electric drive replaces the traditional torque converter.
- The Hitachi ZW220HYB-5 wheel loader uses a capacitor to recover energy.
- The Caterpillar D7E electric-drive dozer has an AC alternator that delivers power to an inverter, which sends electrical power to two electrical drive motors. The electrical drive motors send power to a bull gear in the differential steering assembly, which powers the left and right final drives.
- Hitachi, Kobelco, and Komatsu hybrid excavators use capacitors to recover energy.
- Electrical/hybrid machines can retain high voltage for a period of time after the machine has been shut down. Technicians working on these systems must be properly trained and take the necessary precautions.

Technical Terms

AC induction motor
AC sine wave
AC traction motor
alternator
armature
asynchronous motor
autonomous
back electromotive force (BEMF)
brake resistor
braking chopper
bridge rectifier
brushes
brushless DC motor (BLDCM)
brush-type DC motor (BDCM)
commutation
commutator
counter-electromotive force (CEMF)
cycle
diode
dynamic braking
electromotive force (EMF)
electronic commutation
electronic traction control
frequency
generator
kilowatt hour
Kinetic Energy Storage System (KESS)
permanent magnet AC (PMAC) motor
pitch control
power density
radial grid
rectify
rotor
shot rock
side skid control
slew
slip/slide control
stator
switched reluctance motor (SRM)
synchronous switched reluctance motor (SynRM)
three-phase AC
trolley assist
variable frequency drive (VFD)

Review Questions

Answer the following questions using the information provided in this chapter.

Know and Understand

1. In an alternator, the _____.
   A. rotor is an electromagnet
   B. field poles are stationary
   C. stator rotates
   D. All of the above.
2. In an alternator, the _____ determines the number of sine waves generated for every rotor revolution.
   A. total number of field poles
   B. total number of pairs of poles
   C. number of stator windings
   D. strength of the field current
3. A three-phase AC bridge rectifier contains _____.
   A. two diodes
   B. three diodes
   C. four diodes
   D. six diodes
4. Modern electric propulsion systems *rarely* use _____.
   A. BDCM traction motors
   B. AC traction motors
   C. switched reluctance traction motors
5. Traction motor brushes are made of _____.
   A. aluminum
   B. carbon
   C. iron
   D. titanium
6. Commutators enable electricity to be transferred from the _____.
   A. field pole to the stator
   B. brush to the stator
   C. rotor to the armature's conductors
   D. brush to the armature's conductors
7. _____ causes an AC motor's rotor to rotate.
   A. An engine-driven pulley
   B. Magnetism generated by the field poles
   C. Induced magnetic force from the stator
   D. Magnetism generated from the brushes and commutators
8. Caterpillar's AC-powered electric truck operates at _____.
   A. 260 volts
   B. 600 volts
   C. 2600 volts
   D. 6000 volts
9. For a given amount of electrical power, if the voltage is increased, the amperage _____.
   A. decreases
   B. increases
   C. remains the same
10. Which of the following statements about trolley assist is *false*?
    A. Increases machine life.
    B. Allows faster travel speeds when loaded.
    C. Increases horsepower.
    D. Can be equipped on a mechanical drive truck.
11. John Deere's 944K wheel loader uses what type of high energy storage device to recover dynamic braking energy?
    A. None.
    B. Battery.
    C. Capacitor.
    D. Accumulator.
12. John Deere's 644K wheel loader uses what type of high-energy storage device to recover dynamic braking energy?
    A. None.
    B. Battery.
    C. Capacitor.
    D. Accumulator.
13. What does the John Deere 644K wheel loader use to assist with dynamic braking?
    A. Brake resistor.
    B. Hydraulic retarder.
    C. Radial grid.
    D. Wet service brakes.
14. Caterpillar's D7E accessory power converter sends DC power to all of the following, *EXCEPT*:
    A. air conditioning compressor.
    B. traditional starting batteries.
    C. hazardous voltage present lamp.
    D. traction motors.
15. Caterpillar's D7E propulsion system operates at _____.
    A. 12 volts
    B. 24 volts
    C. 480 volts
    D. 2600 volts

16. AC electrical propulsion systems normally _____.
    A. rectify AC to DC, then invert it back into AC
    B. use the AC generator to directly drive the AC motors
    C. use brushes and commutators
17. Hitachi, Kobelco, and Komatsu hybrid excavators use what type of high-energy storage device to recover energy when the swing is slowing to a stop?
    A. None.
    B. Battery.
    C. Capacitor.
    D. Accumulator.
18. Which of the following statements about electrical propulsion and hybrid power systems is *false*?
    A. Training is required in order to service or repair these systems.
    B. Repair work on the electrical propulsion system can be done while the machine is running.
    C. A machine that does not have a high-capacity battery can still exhibit high voltage after the machine has been shut down.
    D. High-voltage conductors are identified with orange cables.

Apply and Analyze

19. An alternating electrical wave of current flow is also known as an AC _____ wave.
20. One sine wave is also known as one _____.
21. In an alternator, the _____ form the north and south magnetic poles.
22. The process of converting AC electricity to DC electricity is known as _____.
23. A(n) _____ is an electronic device used to convert AC to DC.
24. A(n) _____ motor is simple and economical but requires complex and expensive electronic controls to drive the motor.
25. The Caterpillar AC electric truck uses a(n) _____ to dissipate heat during braking.
26. John Deere's 944K wheel loader uses a total of _____ electric-drive traction motor(s).
27. John Deere's 644K wheel loader uses a total of _____ electric-drive traction motor(s).
28. Caterpillar's hybrid excavator uses a(n) _____ to recover and store high energy when the swing is slowing to a stop.

Critical Thinking

29. Explain the electrical drive differences between a Caterpillar D7E dozer and a Caterpillar D6XE dozer.
30. What advantages do 100% electric-drive excavators offer over diesel-powered excavators?
31. What is a difference between a permanent magnet DC motor and a switched reluctance motor?