SR Theory of Operation

Section 06–03–02 Gen2

Section Version 0000

Table of Contents

This Page Intentionally Left Blank

List of Figures

This Page Intentionally Left Blank

Preface

This Manual is provided as a guide to personnel involved with the operation, maintenance and repair of Komatsu Mining Corp. equipment. We recommend that such personnel review and become familiar with the general procedures and information contained within this manual. In addition, we recommend that this manual be kept readily available for reference when repairs or maintenance are necessary.

Read and become familiar with this Manual and any other general safety practices before attempting any procedures.

Due to the complexities of mining equipment and the environment in which it operates, situations may arise which are not directly discussed in detail in this Manual. When such a situation arises, past experience, availability of equipment and common sense play a large part in what steps are to be taken. In addition, a Komatsu Mining Corp. service center representative is available to answer your questions and assist you upon request.

Komatsu Mining Corp. reserves the right to continually improve its products and associated documentation. Therefore, physical alterations to Komatsu equipment may not be identified in this Manual. Revisions may be frequently made to this Manual in an effort to ensure that information contained within is current as alterations occur to the equipment. If you find an error or have other feedback regarding this Manual, please contact Product Training and Publications at *Pro.Train.Pub@mining.komatsu*.

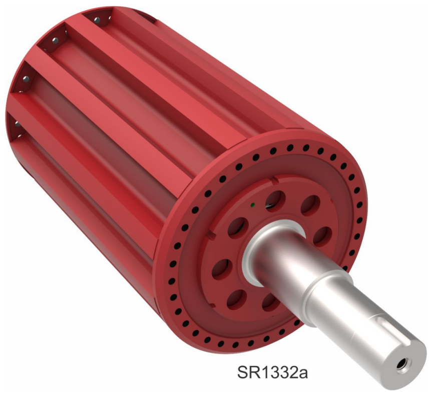
Copyright

This Page Intentionally Left Blank

Scope of This Publication

Theory of Operation covers the basic principles of switched reluctance operation, providing the basic operations and principles of the P&H wheel loader SR drive system.

Figure 1: SR Components



This Page Intentionally Left Blank

Safety

This publication contains special instructions that pertain to safety, operation, maintenance, and repair of the machine. Listed below are the signal words and symbols that precede these instructions and their meanings:

⚠ DANGER

The danger label indicates a hazardous situation which, if not avoided, will result in death or serious injury.

⚠ WARNING

The warning label indicates a hazardous situation which, if not avoided, could result in death or serious injury.

⚠ CAUTION

The caution label, used with the safety alert symbol indicates a hazardous situation which, if not avoided, could result in minor or moderate injury (includes the safety alert symbol ⚠).

CAUTION

The caution label (without safety alert symbol) is used to address practices not related to personal injury – only equipment damage.

NOTICE

The notice label indicates areas of importance to the reader that are not related to personal injury or machine damage.

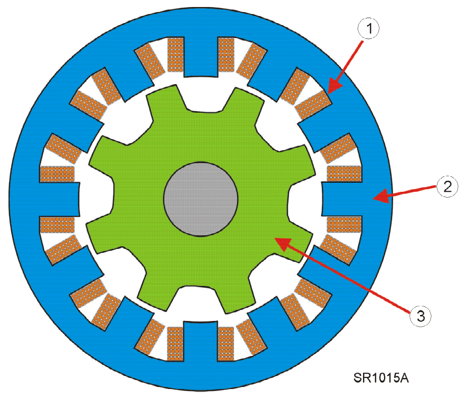
This Page Intentionally Left Blank

Introduction to Switched Reluctance Motor Drive Technology - Basic Motor Design

Komatsu has implemented a new and unique generation of motors and motor drives for mobile mining equipment, called switched-reluctance. The switched-reluctance motor (SRM) utilizes electro-magnetic principles to produce torque on the rotor of the motor.

- The SR motor is a member of the family “reluctance motors” (Fundamental torque-producing mechanism).
- Reluctance is defined as the resistance of a material to a magnetic field.
- The SR motor is operated by switching groups of coils on and off with respect to the rotor angle – hence “switched reluctance” motor.

Figure 2: Simplicity of SR

All Coils Stationary **Simple Coil Design** **Rotor Is Simply A Stack Of Lam Steel** **Bearing Is Only Wear Part** **Different Number Of Poles On Rotor And Stator**	 **1)** Windings, **2)** Stator, **3)** Rotor

A switched reluctance motor has a rotor that has no magnets or windings of any kind and is effectively a piece of shaped iron, creating an arrangement of salient poles (poles that stick out). The rotor can have various numbers of poles.

The switched reluctance stator is similar to an AC motor stator with multiple salient poles. Each of the poles contains a separate winding with no overlap between windings, similar to a field of a DC motor.

Some of the outstanding benefits of SR technology include:

- The motor is more robust than an AC or DC motor, since there are no coils on any of the moving parts of the motor.
- The rotor inertia is much lower than a DC rotor, giving benefits to gearing life, especially if there is frequent stopping and starting.
- No commutator maintenance - there are no brushes or brush rigging.
- Stators are very similar to DC motor field poles.- Simple to wind and install
- Smaller than DC motors with comparable horsepower.
- Simple and robust electronic controls compared to variable frequency AC.
- High level of fault tolerance.
- Continuous low speed torque output of a conventional DC motor
- High Speed - high speeds can be achieved, limited only by bearing and electromagnetic timing constraints.

- Low Speed - can operate at low speed providing full-rated torque down to zero speed (for a short time).
- System is four-quadrant and can run forward or backward as either a motor or generator simply by changing the timing of energizing the coils. The direction of current in the coils does not change.

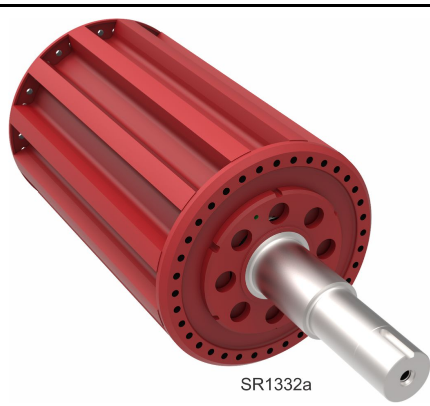
The technology was developed and put to use in the 1970’s due to the following advancements that enabled the control of an SR motor:

- Computers to allow design of non-linear systems
- Signal-level control
- Economic (solid-state) power electronics

The success of switched-reluctance technology has been made possible by today's digital control techniques. The transistor switches used to energize the stator coils are called IGBTs (insulated gate bi-polar transistors). IGBTs are now available in the current and voltage ratings needed for high horsepower applications. The availability of these devices also paved the way for today’s proliferation of AC drives.

However, unlike the AC drives, the SR drive has a motor coil in line with each IGBT. This system impedance gives more capability to control any type of system fault. Therefore, the “shoot-through” fault possible in AC systems is not present, resulting in a much more robust drive. Also, the generally lower switching frequencies in a SR system result in a more efficient drive.

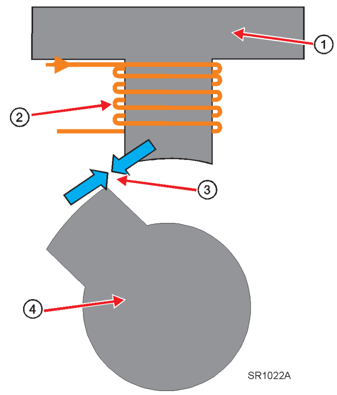
Figure 3: Sample SR motor

	
Rotor	**Stator**

Torque Production

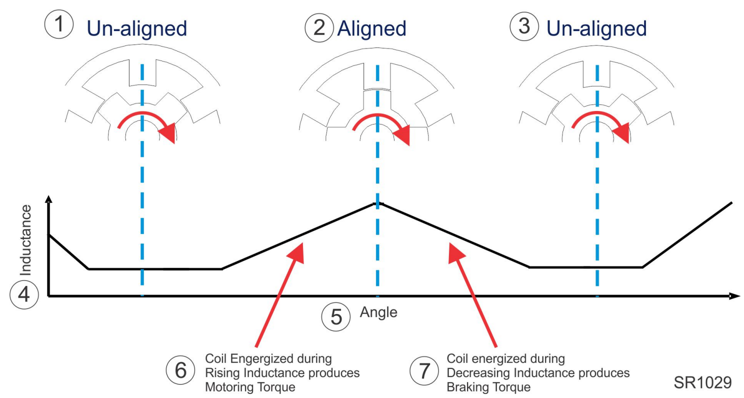
As a stator pole winding is energized, a magnetic force is generated and the rotor pole is forced into alignment with that stator pole.

Figure 4: Basic torque production



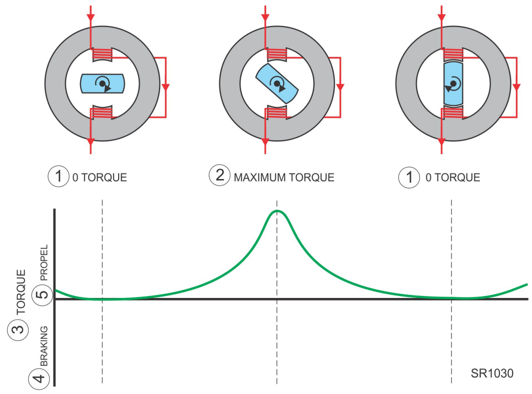
1. Stator
2. Coil
3. Magnetic attraction
4. Rotor

Figure 5: Inductance vs. Rotor position



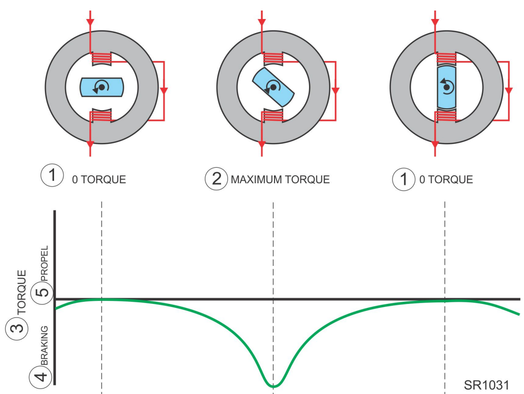
1) Un-aligned, **2)** Aligned, **3)** Un-aligned, **4)** Inductance, **5)** Angle, **6)** Coil energized during rising inductance produces motoring torque **7)** Coil energizing decreasing inductance produces braking torque

Figure 6: Propel torque vs rotor position



1. 0 Torque
2. Maximum torque
3. Torque
4. Braking
5. Propel

Figure 7: Braking torque vs rotor position



1. 0 Torque
2. Maximum torque
3. Torque
4. Braking
5. Propel

Figure 8: Maximum torque position – point on rotor pole close to point on stator

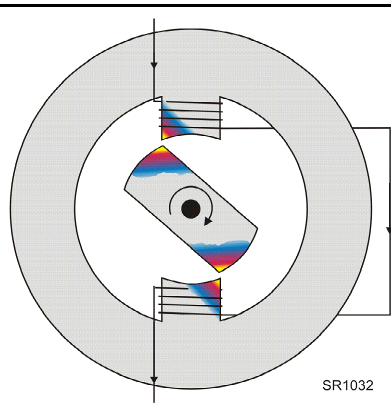
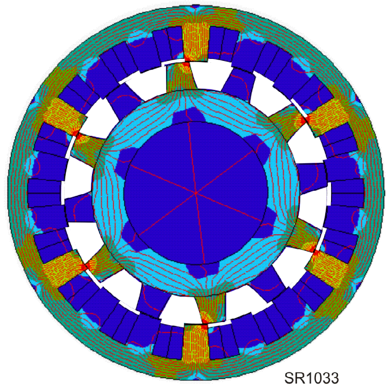


Figure 9: Maximum torque position – multi pole motor 18/12

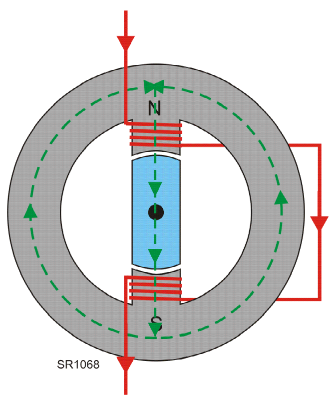


An SR motor can also be operated in braking as an electrical generator.

Exact opposite of motoring operation

Braking torque is produced when rotor and stator poles are being "pulled apart" by the rotating inertia of the rotor – when inductance is falling.

Figure 10: Flux flow in basic SR motor



N = North, S = South

The coils are wound so that one is N and one is S. Flux will flow from N to S across the rotor when the rotor is aligned with the poles. The flux returns via the one piece lamination structure of the stator.

This Page Intentionally Left Blank

Motor Rotation Sequence

Figure 11: Motor rotation and IGBT switch sequence (propel)

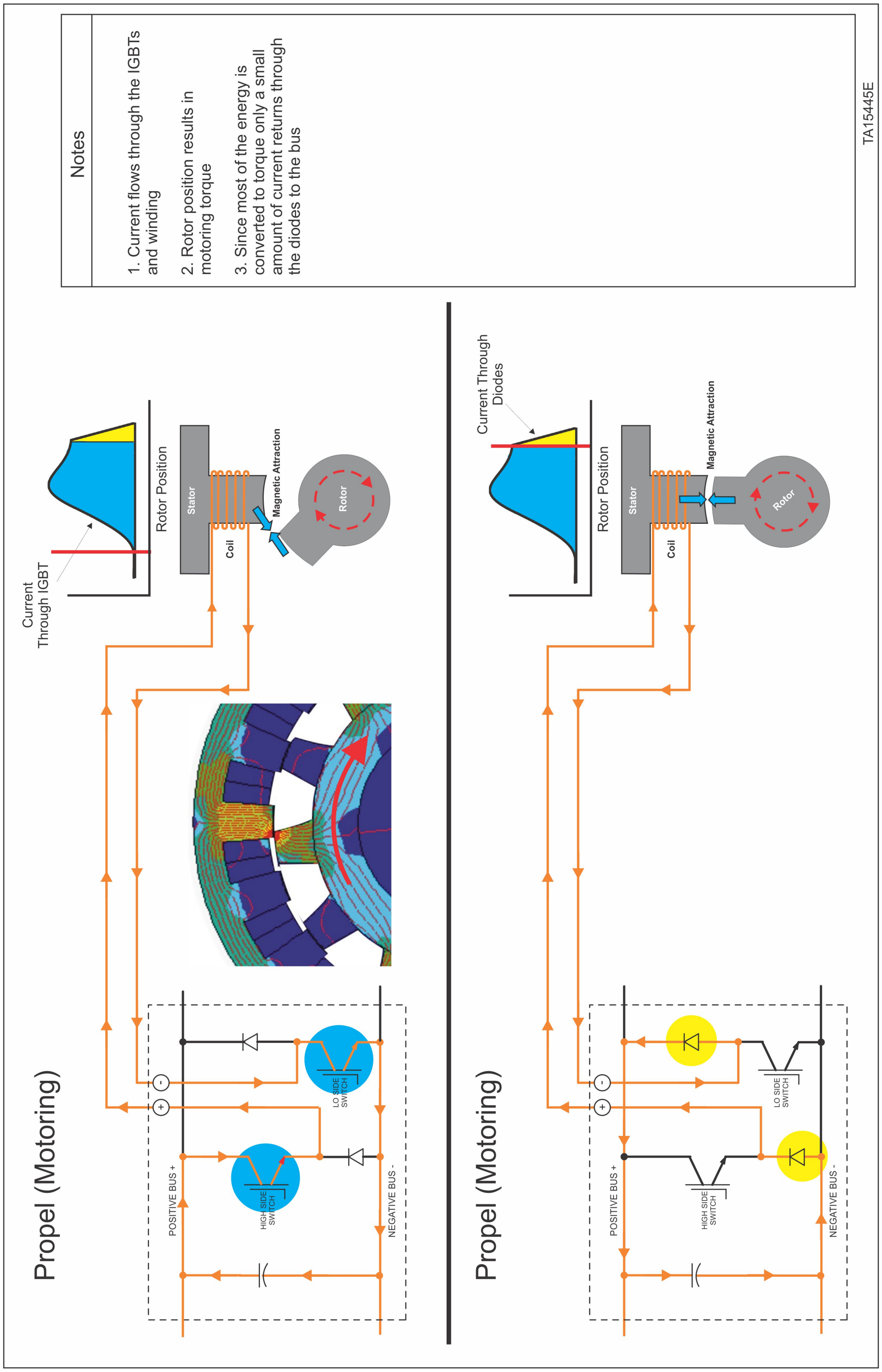
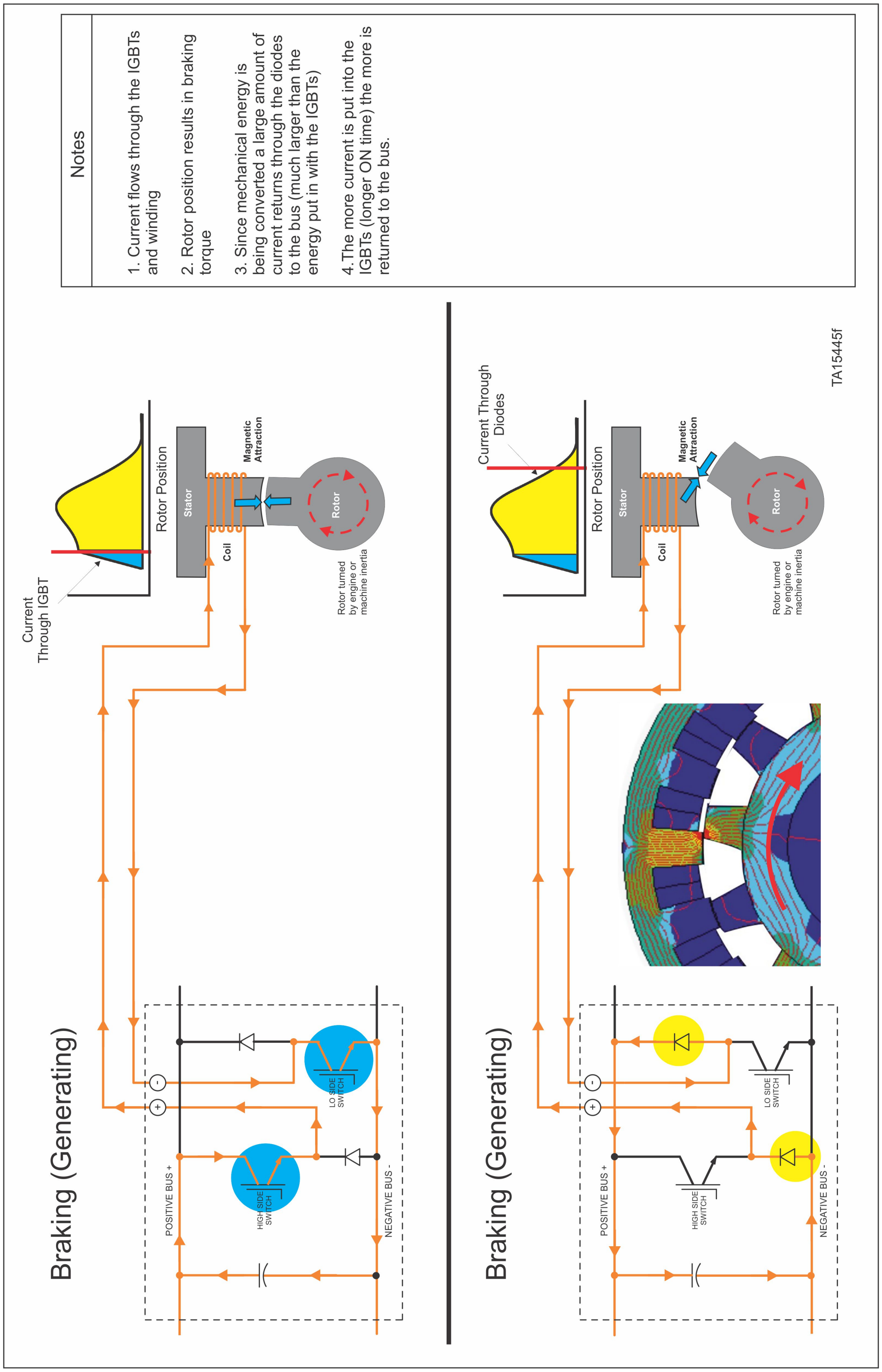
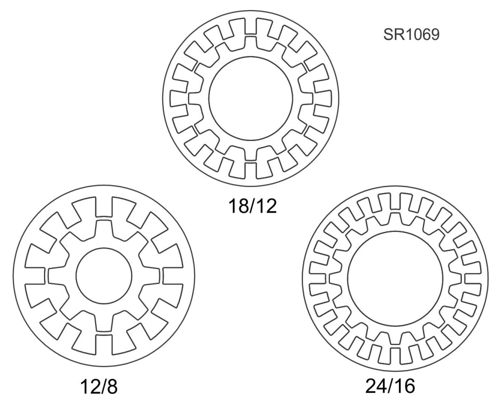


Figure 12: Motor rotation and IGBT switch sequence (braking)



Motor Designs

Figure 13: Basic SR pole configurations



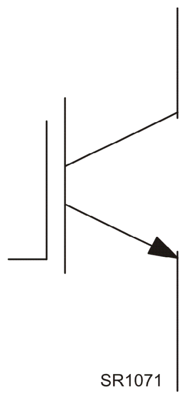
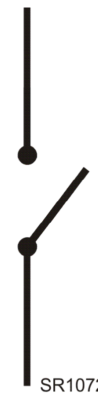
A wide number of SR motor designs are possible depending on the requirements of the application. A small sample of the various combinations of rotors and stators that can be used as is shown in the drawing above. In all cases (except for the simple 1 coil group design) the stator will have a greater number of poles than the rotor.

This Page Intentionally Left Blank

IGBT Switches

The current to the stator coils is controlled by using IGBTs. The IGBT transistor has two states – ON or OFF – like a switch. The IGBT switches **cannot** be operated partially on or partially off or they will be severely damaged (nearly immediate failure).

Figure 14: IGBT switches

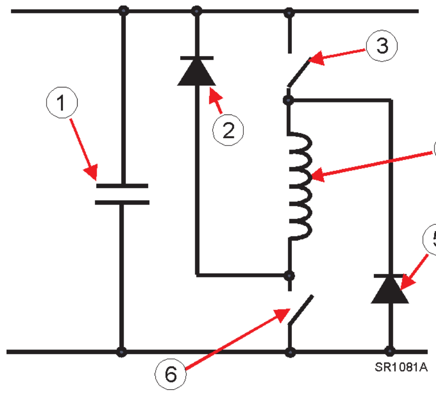
	
IGBT Schematic	**IGBT Simple Schematic**

An individual IGBT is capable of about 75A. Many small IGBT's are used in parallel in order to get the rated capacity of the IGBT module.

Figure 15: IGBT module package (600A shown)

The coils in the SR motor are controlled with two IGBT modules. One switch is used as a HIGH SIDE IGBT switch connected between the + bus and one side of the SR motor coil. One switch is used as a LOW SIDE IGBT switch connected between the – bus and the opposite side of the SR motor coil. The converter also consists of diodes for freewheeling and discharging energy in the coils and bus capacitors for storing energy on the DC bus.

Figure 16: IGBT Schematic



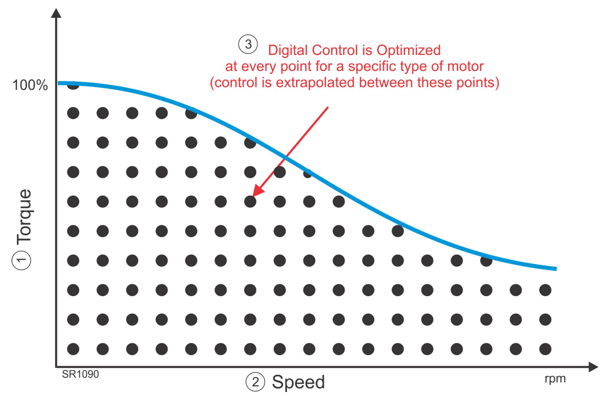
1. Bus capacitor
2. Diode
3. High side IGBT switch
4. Motor stator coil
5. Diode
6. Low side IGBT switch

Rotation is achieved with the sequential energizing of stator poles. The rotor will follow this sequence, trying to align with the energized stator pole. However, as alignment is almost achieved, that pole turns off and the next pole comes on. The switched-reluctance motor makes these torques continuous by turning on the next pole before the previous one is turned off. This consecutive switching of the stator pole currents ensures the poles on the rotor are continually being attracted by the magnetic field created by the stator winding current. The torque is achieved by creating flux, which is a function of the current through the winding and the characteristics of the iron

Current Control

The best method for torque and speed is determined by the characterization of the SR motor. Characterization is the initial testing of a motor over its entire torque and speed range. The control is optimized at each point. This is referred to as the characterization curve for a motor. This is based on the physical motor type. It has to be redone whenever there is a change to the electrical characteristics of the motor (lam material, lam pole shape, coil type, coil turns, etc. This information is then programmed into the SR code that is loaded into the SR control board.

Figure 17: Example of typical characterization chart



1. Torgue
2. Speed
3. Digital control is optimized at every point for a specific type of motor (control is extrapolated bewteen these points)

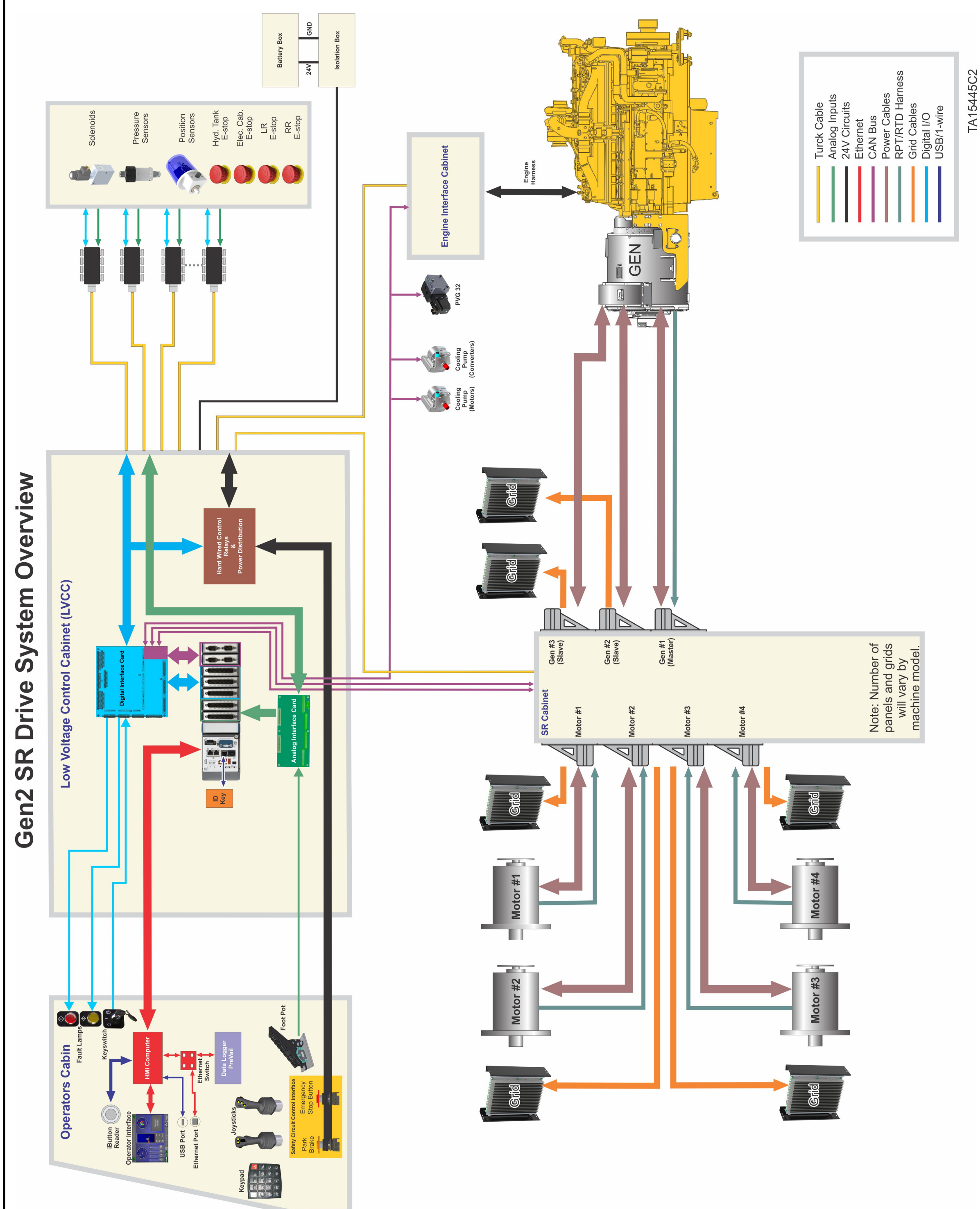
This Page Intentionally Left Blank

SR Circuits

Figure 18: Power flow

- All drives report bus voltage over the CAN bus.
- All drives should have the same voltage since they are all connected to a common bus.
- Both positive and negative buses are fused.
- If a drive has less voltage, it has a blown fuse.
- When a converter is powered (24V ignition), it will charge the bus to 15V.
- The isolation monitor works at 15V as well and much of the diagnosis of a hard ground fault can be done with the engine off.
- During braking, the generator does all it can to prevent the bus voltage from rising.
- Bus voltage varies with vehicle speed.
- The IGBT modules are cooled by a dedicated liquid cooling circuit.
- The capacitors are convection cooled.
- There is no ‘hill hold’ switch. Releasing the foot pedal causes the drive system to increase gain near zero speed (with zero pedal input).
- Propel is disabled when service brakes are applied beyond a set threshold.
- There are no drive faults that are Red Alarms.
- All drive faults are Yellow Warning, identified in detail by a PM alert message.
- Some drive faults, such as the generator, take away propel.

Figure 19: LINCS II control system overview



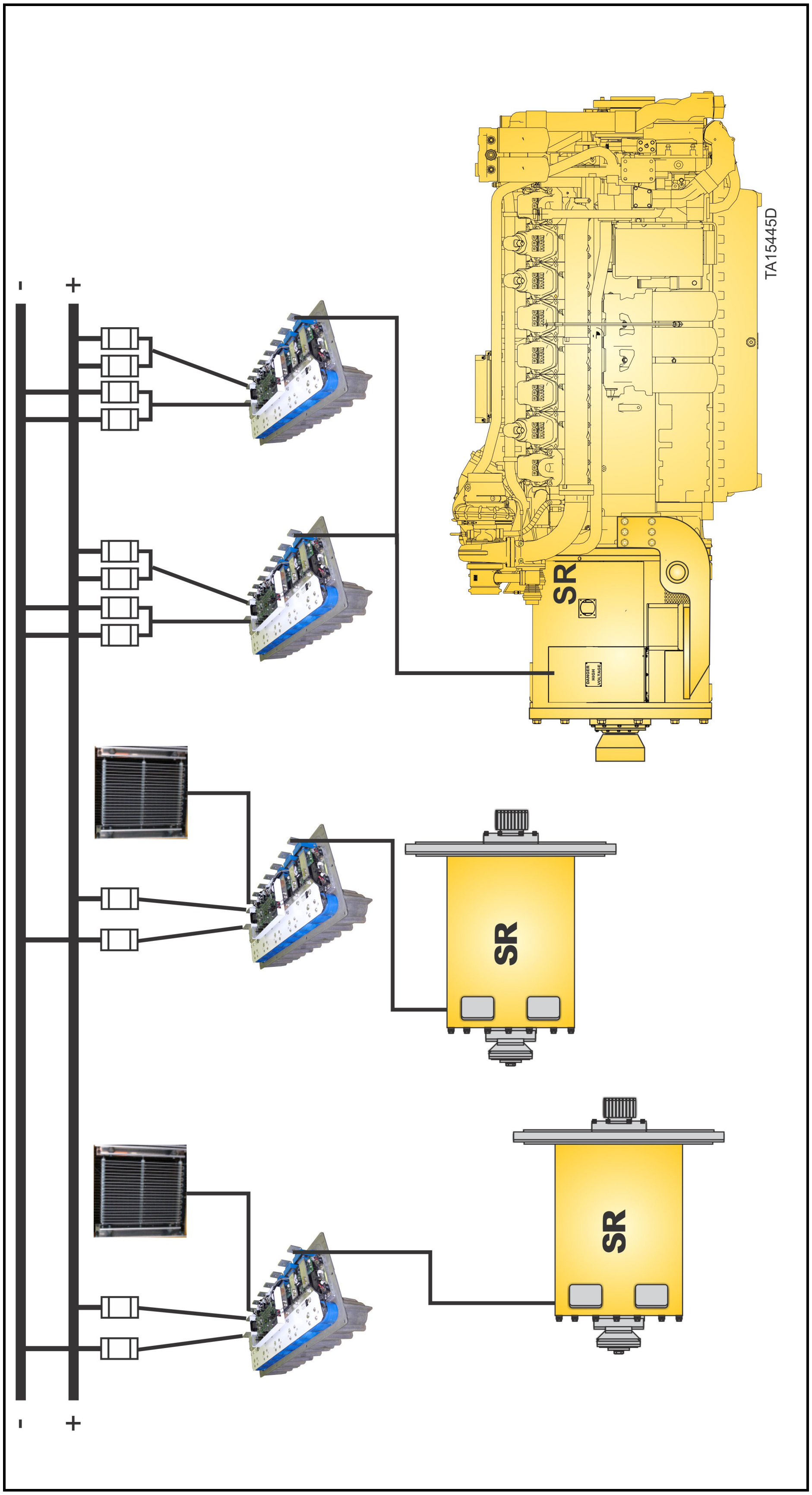


Figure 20: Drive system overview

This Page Intentionally Left Blank

Komatsu Mining Corp.

https:\\mining.komatsu