Variable speed drives for mining power systems applications

Mining Power Systems Competency Center
White Paper No 05

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Executive summary

Variable speed drives (VSDs) are key components in modern mining installations, contributing to higher energy efficiency and greater productivity. This white paper, **WP05** describes modern VSD technologies and their performance limits. It uncovers practical aspects of using VSDs in mining applications, including benefits and constraints. Finally, it gives an overview of Schneider Electric's Altivar range of low-voltage (LV) and medium-voltage (MV) VSDs and recommendations for optimal product selection in the main hard rock mining applications.

Introduction

Installed power in hard rock mining sites range from 20 MVA to 150 MVA, which is used to feed the MV and LV electric motors that drive the machines required for mining processes. **WP01** and **WP02** explain how to optimize mining power systems to supply these motor loads.

The MV and LV motors used in mining are primarily Squirrel Cage Induction Motors (SCIM). VSD control is more costly than fixed speed control, either Direct On-Line (DOL) or Reduced Voltage Soft Starting (RVSS). However, in many applications, VSDs provide lower operating costs (OpEx) due to reduced energy consumption, increased process efficiency, and reduced asset maintenance. VSDs also contribute to capital expenditure (CapEx) reduction in switchgear, cables, and transformers by enabling lower short circuit currents due to reduced voltage drop (ΔV) during motor start-up and unity power factor (PF) at all loads. For this reason, the main criterion for using VSD is to lower the Total Cost of Ownership (TCO).

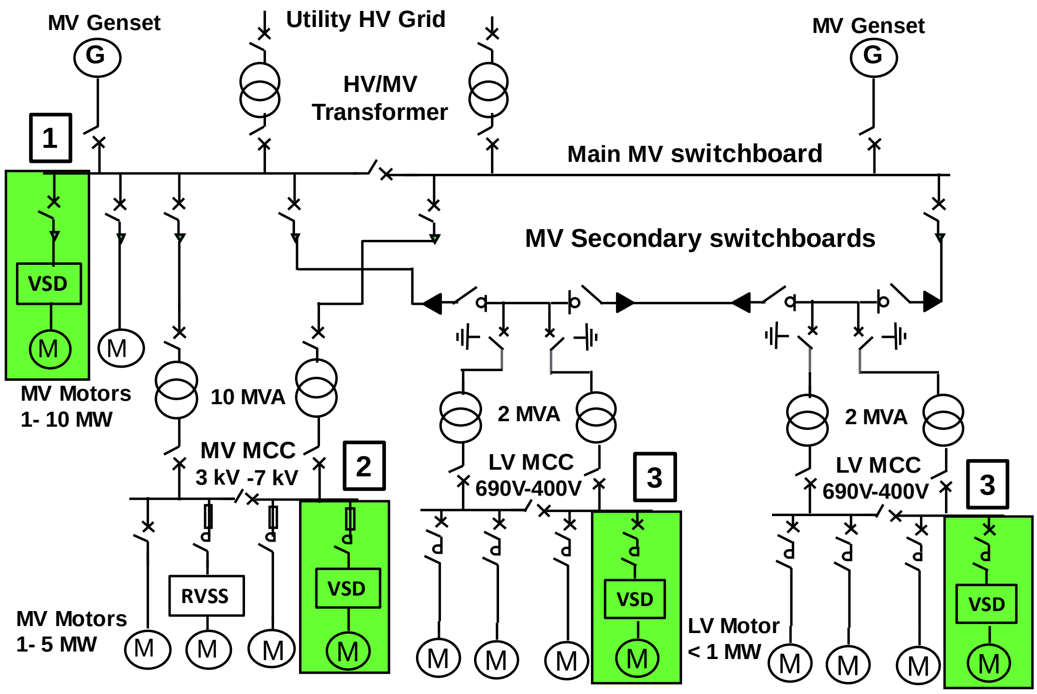
Figure 1 illustrates a typical mining power system Single Line Diagram (SLD) and the connection points for motors controlled by VSDs.

- MV motors > 5 MW are always connected to the MV main switchboard either directly, voltage below 13.8 kV or via an MV/MV transformer.
- MV motors between 0.5 MW and 5 MW are connected to an MV Motor Control Center (MCC) that supplies the motors with voltages between 4.16 kV and 6.6 kV
- LV motors with rated power between 10 kW to 2.4 MW are connected to LV MCCs that supply the motors with voltages between 400 V to 690 V.

Figure 1

Typical mining power system SLD showing LV & MV VSD connection:

1. *Main MV switchboard*
2. *MV Motor Control Center*
3. *LV Motor Control Center*



The objective of **WP05** is to help mining end users and engineering, procurement, and construction (EPCs) understand LV and MV VSD technologies and guide them in the optimized choices for each hard rock mining application, taking into account the relevant international standards (IEC or ANSI/UL).

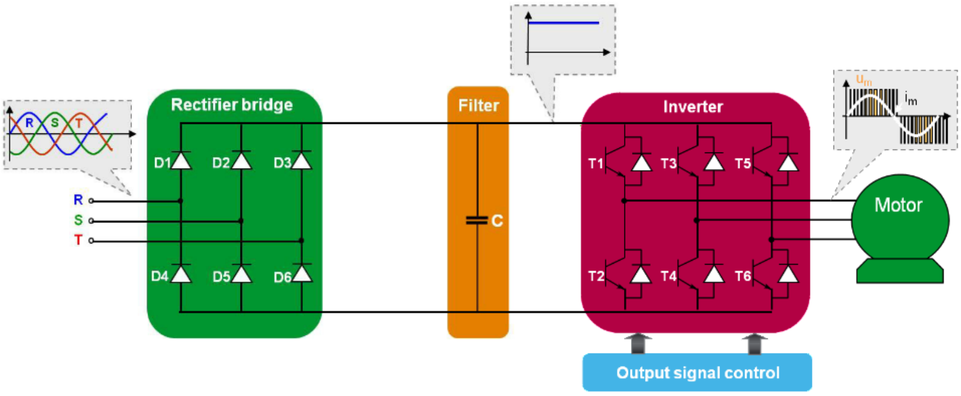
LV VSD basic topologies and performance

A VSD uses electronic power conversion to continuously adapt the voltage and frequency supplied to the SCIM to control torque (T) and speed (n) delivered to the mechanical load.

Figure 2 shows a typical LV VSD topology. It consists of a 6-pulse diode front end (DFE), a capacitor DC voltage source and Insulated Gate Bipolar Transistor (IGBT) 3-phase inverter.

Figure 2

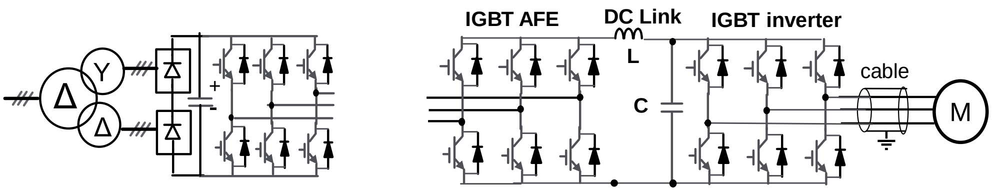
VFD Block Diagram



The inverter output voltage waveform consists of variable width pulses resulting from IGBT switching using Pulse Width Modulation (PWM). The current waveform in the motor stator winding is quasi-sinusoidal, as it is smoothed by the winding inductance. This topology, known as Voltage Source Inverter (VSI), is used in all LV VSDs available today. Its main drawback is high Total Harmonic Distortion (THD) which is detailed in **WP06**. VSDs > 200 kW often use 12-pulse DFE or Active Front End (AFE) as shown in **Figure 3**.

Figure 3

LV VSD topologies used to reduce harmonic distortion



(a) 12 pulse Diode Front End (b) Active Front End topology

LV VSDs often require additional output filters to smooth the voltage waveforms (dV/dt, peak voltage, common mode) applied to the motor, as well as input chokes to reduce the harmonics injected in the network.

MV VSD basic topologies and performances

MV VSD control motors between 0.5 MW and 15 MW. They use input transformers with multiple secondary windings for galvanic isolation of the power electronics and the required phase shifts (see **Appendix A**).

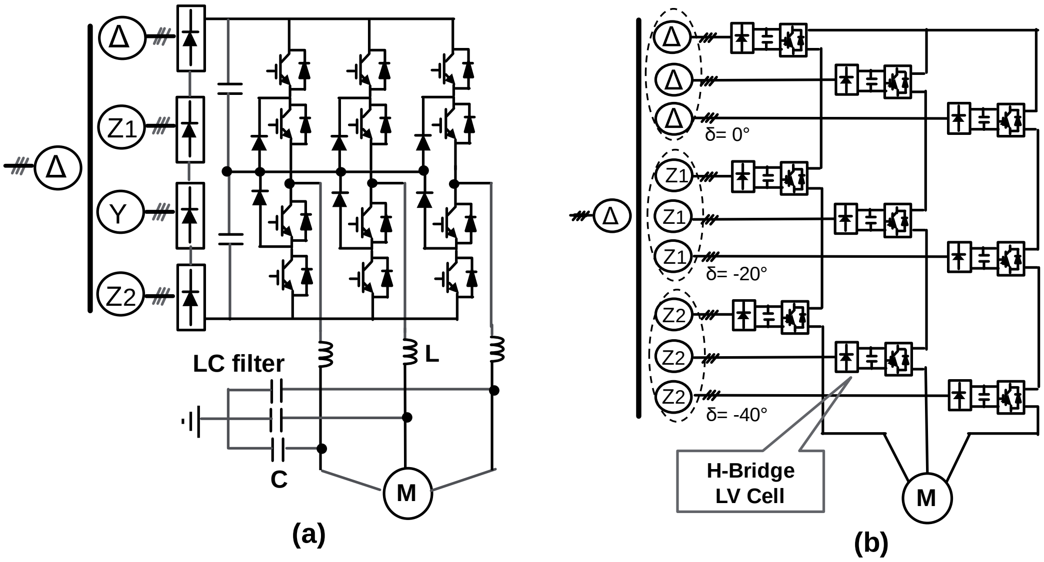
The two most common topologies are illustrated in **Figure 4.**

Figure 4

Main topologies used in MV VSD:

(a) 4.16 kV VSD using 3L -NPC VSI topology with 24 pulse DFE and LC output filter to smooth waveform

(b) 3.3 kV VSD using ML-CHB VSI topology with 3 H-Bridge LV cells per phase and input transformer with 9 secondary windings (THDi equivalent to 18 pulse DFE) which enables a multi-level output voltage

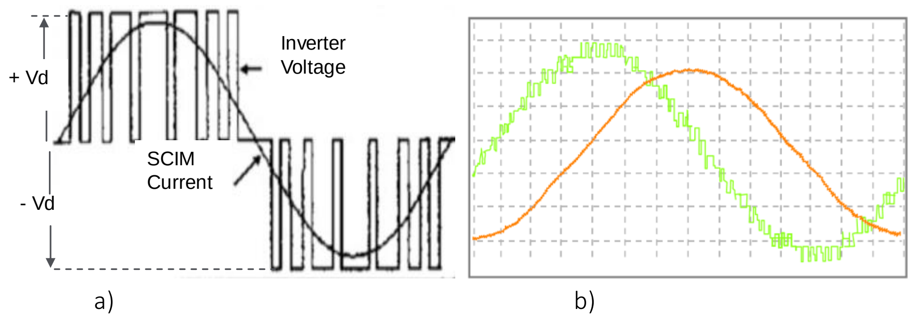


Three Level Neutral Point Clamped (3L-NPC) topology uses a multi-pulse rectifier (12, 18, or 24 pulses) and IGBT inverter module with its neutral point voltage clamped by diodes. Maximum output voltage is < 6.6 kV due to the IGBT rating, see **Figure 4 (a)**. This topology enables adding an AFE module (see **Figure 6**) required in some mining applications.

Figure 5

Example output waveforms from different technologies of VSD:

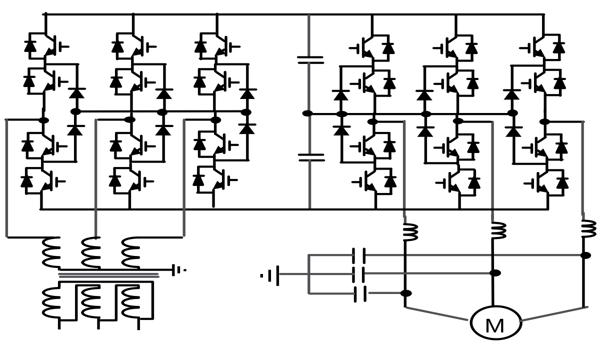
a) NPC based
b) Multi-Level Cascaded H bridge



Multi-Level Cascaded H-Bridge (ML- CHB) topology uses single-phase LV cells with 6-pulse DFE and 2-level IGBT inverter (known as H-Bridge) in series, as shown in **Figure 4(b).** This topology can reach output voltages up to 13.8 kV by adding LV cells in series (e.g., 9 cells per phase for 11 kV output). Its main advantage is high-quality input and output waveforms **(see Figure 5)**. Its main disadvantage is the lack of AFE modules required in some mining applications.

Figure 6

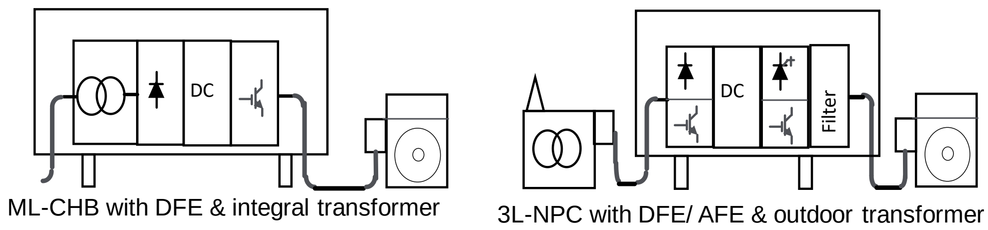
MV VSD with 3L -NPC topology and AFE



ML-CHB topology requires input transformers with a greater number of secondary windings than 3L-NPC designs, which use standard windings. This increases transformer cost and wiring complexity, making it impractical to install separately. As 90% of MV VSDs used in mining are installed in air-conditioned E-houses, their footprint and heat load have an impact on TCO. **Figure 7** shows the input transformer arrangement for ML-CHB and 3L-NPC topologies.

Figure 7

MV VSD with ML-CHB topology have integral input transformer MV VSD with 3L -NPC topology have simpler input transformer which can be installed separately



Starting current of SCIM

The current that results when the motor is connected to the power supply depends mainly on the type of starting system in use. The simplest solution is Direct On Line (DOL), which also causes the highest starting current (1a) and the highest voltage drop in the mains.

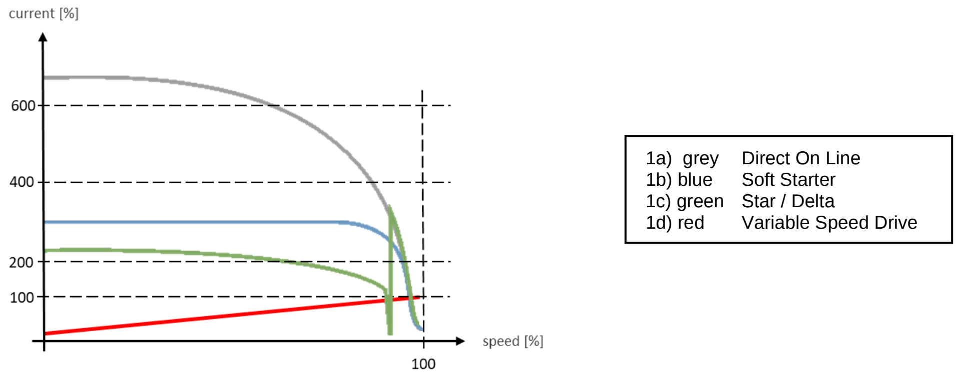
The use of star/delta starters significantly reduces the inrush current (1b) but has a high torque peak at the switchover point which can lead to mechanical problems.

Soft starters avoid such torque peaks and have similarly reduced starting currents as star/delta starters. (see **1c** in **Figure 7a)**

Frequency converters have a completely different operating behavior, as no inrush current peak occurs when using a VSD. The current on the mains side decreases with decreasing speed down to a few percent of the rated motor current. The line side current of a drive is therefore proportional to the power and not the load (torque).

Figure 7a

Motor starting current with different starting methods



Mechanical load characteristics

A rotating mechanical load is defined by a curve that plots the required torque (T) as a function of the rotational speed (n). To accelerate a rotating load up to its nominal speed, the torque delivered by the electric motor must always be higher than the one required by the load. Once the desired operating speed is reached (close to synchronous speed ns), the motor and load run at rated torque (Tr), and the system are in equilibrium.

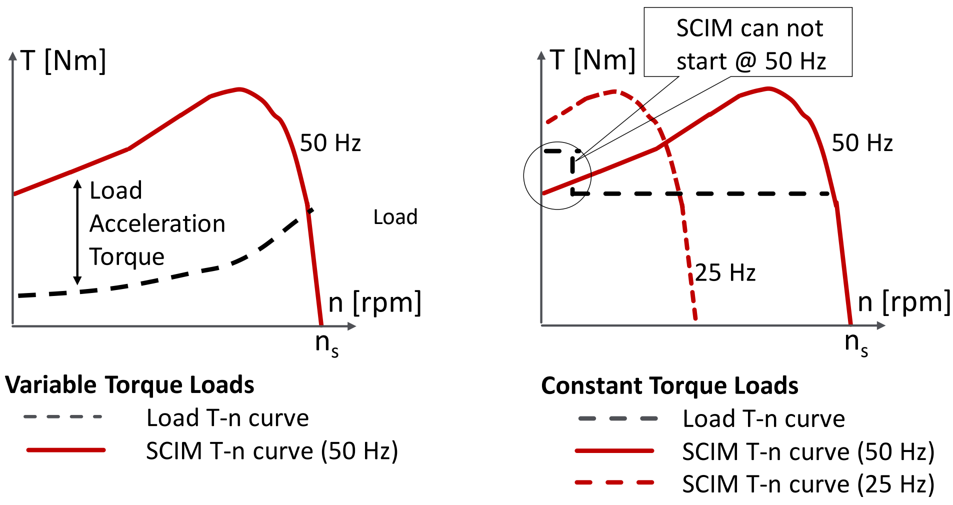


Figure 8

T-n characteristics for variable torque and constant torque loads driven by SCIM

Mechanical loads associated with each application are classified according to their T-n curve into variable torque (VT) or constant torque (CT), as shown in **Figure 8**. VT load's resistive torque increases as a function of n^2, starting with a low breakaway, initial torque (usually < 0.2 T_r). CT loads require a high breakaway torque (typically 1.3 – 1.8Tr). VSD control is well adapted to CT loads because it can provide high starting torque by lowering supply frequency. This allows for precise torque control during start/stop sequences.

Load operating modes are defined by the four quadrants diagram as shown in **Figure 9**. Loads that require regenerative breaking (Q4 operation) inject the energy generated by the SCIM working as an induction generator back into the network. Q4 operation is needed in downhill conveyors and hoists applications which require VSDs with AFE.

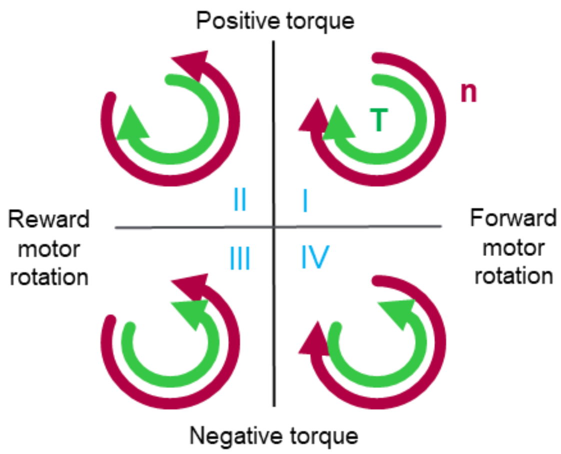


Figure 9

Load operating modes defined by the Q4 diagram

In mining applications, generally we come across Q1 and Q4 operations.

Table 1 summarizes T-n characteristics and operating modes for main mining loads:

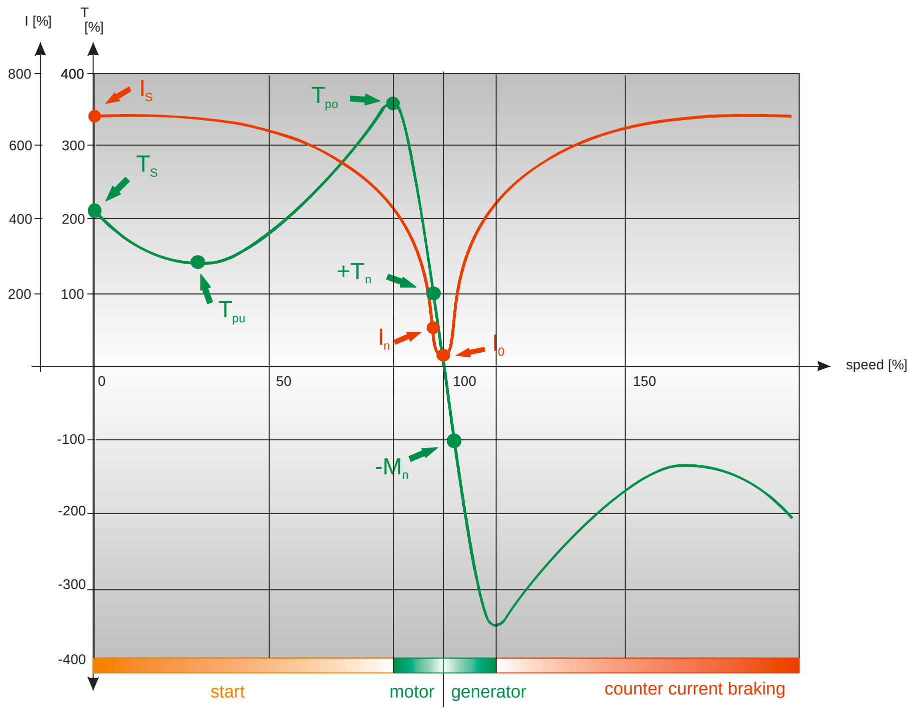
Table 1

Main mining mechanical loads classed according to their T-n characteristics curves and their operating modes

Mining Mechanical Loads	T-n Characteristic	Operating Modes
Centrifugal Pumps, Fans and Blowers	Variable Torque	Q1
Positive Displacement Pumps, Compressors, HPGR mills, Crushers Uphill Conveyors	Constant Torque	
SAG/Ball Mills,		Q1-Q2
Downhill Conveyors		Q1-Q4
Hoist and winders		

Figure 10

Magnification of Q1 and Q4 quadrants showing torque and current



Where:

T_S	- Starting Torque	I_S	- Inrush Current
T_{PU}	- Pull Up Torque	I_N	- Nominal Current
T_{PO}	- Pull Out Torque	I_0	- No Load Current
T_N	- Nominal Torque		

Selection and sizing of VSD

The selection of application-specific drives for in the mining industry must consider the following:

- Continuous load demand of the application
- Transient overload demand of the application
- Load speed range
- Load torque regarding speed control range
- Requests on speed accuracy
- Braking needs
- Energy efficiency and energy saving
- Environmental conditions
- Power supply and harmonic restrictions

The continuous load at maximum speed defines the maximum continuous power for the motor as well as the VSD. Depending on the maximum expected ambient temperature, it may be necessary to select the motor and/or VSD with a higher power rating than the continuous load.

Some applications present a higher load at startup or in certain operating situations. This can be caused by rapid acceleration/deceleration processes (e.g., hoists), load shocks (e.g., crushers), or during startup sequences (e.g., mills). These loads are typically only required for a short time and must be described in terms of the expected magnitude, duration, and frequency in order size the VSD correctly.

Frequency converters that have a dual rating can be dimensioned in 2 different variants.
1. Normal duty – this setting allows to draw a high continuous power from the VSD but reduces short-term overload. Typically, this selection is for applications that require little or no overload, such as pumps, fans, blowers, compressors, etc.

2. Heavy duty – related to a high short-term overload but where the continuous load of the VSD is reduced. This setting is used for applications such as hoists, presses, mills, shredders, crushers, and similar.

It is important to mention that the VSD provides electrical power to the motor in the form of current. The conversion to mechanical torque takes place within the motor itself. Motor data such as the number of pole pairs, cos phi, efficiency, the motor control method, and its quality have a significant influence on the torque the motor provides to the application.

In addition to ambient temperature, other influences on the required over-dimensioning of the Motor and VSD include the selected pulse frequency, the maximum output frequency, and the installation altitude.

Cooling methods and integration

Frequency converters are equipped with modern power electronic semiconductors with low losses. The overall efficiency is typically 98%. This means that 2% of the operating power is emitted as heat into the surrounding space. 2% sounds quite low, but with large power devices the heat dissipation is not insignificant. E.g. 2% of 1800kW is 36kW. To minimize the cooling requirements of the electrical rooms, there are essentially two different cooling concepts available:

2. Separate air flow systems

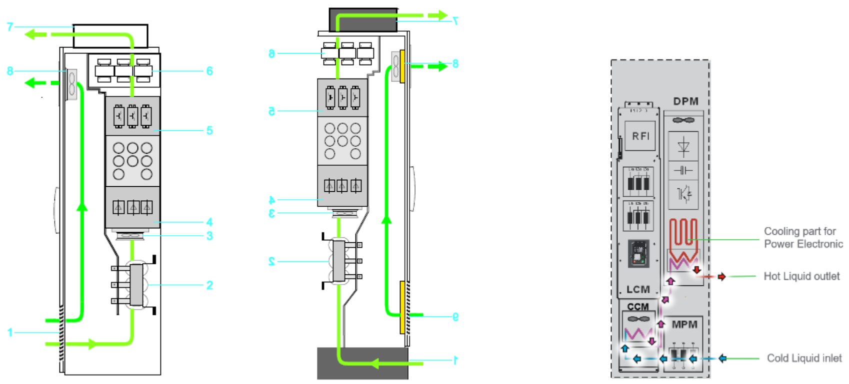
In this case, the power section airflow is supplied with unfiltered air, this air does not encounter any components sensitive to contamination. Such parts (electrical circuits, microprocessors, etc.) are supplied by a constructively separated, filtered airflow. Exhaust air can be expelled from the room via an air conduct system.

2. Liquid-cooled frequency converters

In this design, all heat losses from the VSD (semiconductors and passive elements such as chokes and filters) are removed from the VSD by a liquid-flow cooling system. The entire housing is sealed and, therefore, resistant to external influences such as dust, moisture, or even spray water. The heat-exchange is accomplished with process water or external fans outside the electrical room, depending on the situation.

Figure 11

Cooling technologies implementation



IP23

IP54 with separated air flow

IP55 with liquid cooling

Motor cables and EMC

Motor cable without shielding

The VSD's motor-side pulse width modulation (PWM) voltage (2-10kHz) causes a high-frequency leakage current to ground through the parasitic cable capacitances. A large portion of this leakage current flows back to the VSD via the star point of the transformer and its line cable. (High frequency conducted interference), as seen in **Figure 12**.

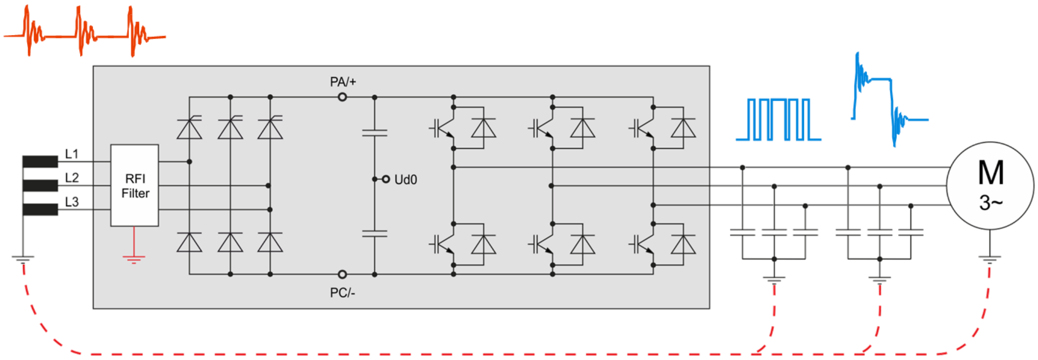


Figure 12

Leakage current path and amplitudes for unshielded motor cable

Motor cable with shielding

High-frequency (HF) leakage current flows through the motor cable shield back to the VSD where the RFI-Filter closes the loop of the HF-circuit. Only a small HF current flows back to the transformer star point, as seen in **Figure 13**.

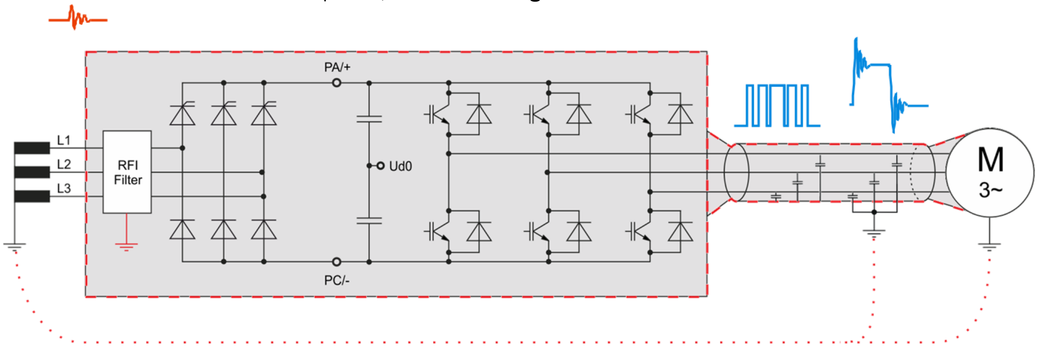


Figure 13

Leakage current path and amplitudes for shielded motor cable

Schneider Electric VSD offer overview

The Altivar ATV range of LV and MV VSDs covers all mining applications described above. It uses common tools and functionality to facilitate system integration, commissioning, and maintenance. The ATV range is compliant with IEC 61800 and ANSI/UL347 standards.

Altivar Process ATV 6xx and 9xx LV VSD range

ATV 6xx range is intended for VT and CT loads such as centrifugal pumps, fans, blowers, and compressors. It provides a dual rating functionality and includes special functions for centrifugal pumps, such as protection against cavitation, liquid leakage, burst pipes detection, and operation at maximum pump efficiency.

ATV 9xx range is intended for CT loads such as Positive Displacement (PD) pumps, crushers, belt conveyors, and hoists. It includes special functions such as high starting torque and overload capability, Master-Slave control via Ethernet, and Q4 operation with dynamic breaking and AFE.

Both ranges have a maximum rated voltage of 690 V. The air-cooled version has a maximum rated power of 1200 kW and is available in several configurations, as shown in **Figure 14**.

Liquid-cooled drives allow maximum power of up to 2400kW with high compactness.

Figure 14

Hardware configurations available Altivar Process ATV 6xx/9xx range with air cooling

Table 2 provides a capabilities summary for ATV6xx and ATV9xx air-cooled ranges

Table 2

Schneider Electric Altivar Process ATV 6xx and ATV 9xx air cooled LV VSD ranges voltage and power ratings for the different hardware configurations

ATV 6xx/9xx LV VSD			ATV 6xx Range	ATV 9xx Range	Rated Power (kW) @ Un 380 ... 480V	Rated Power (kW) @ Un 500 ... 690V
Wall Mounted Unit		IP 21	ATV 630	ATV 930	0.75 - 315	2.2 - 90 (IP 00)
Wall Mounted Unit		IP 55	ATV 650	ATV 950	0,75 - 90	---
Floor Standing Enclosure		IP 21	ATV 630	ATV 930	110 - 315	---
Floor Standing Enclosure		IP 54	ATV 650	ATV 950	110 - 315	---
MCC integration		IP20	ATV 630	ATV 930	0,75 - 90	---
CTO & ETO Drive Systems	**AC Choke**	IP 21 - IP54	ATV 660	ATV 960	110 – 800	
CTO & ETO Drive Systems	**Low Harmonic/Regenerative**	IP 21 - IP54	ATV 680	ATV 980	110 – 800	---
Modular Unit for Cabinet Integration	**AC Choke**	IP00 (module) IP 21 - IP54 (Enclosure)	ATV 6A0	ATV 9A0	110 - 1000	110 - 1200
Modular Unit for Cabinet Integration	**Low Harmonic/ Regenerative**	IP00 (module) IP 21 - IP54 (Enclosure)	ATV 6B0	ATV 9B0	110 - 1000	110 - 1200
Modular Unit for Cabinet Integration	**Liquid Cooled**	IP00 (module) IP 21 - IP66 (Enclosure)	ATV 6L0	ATV 9L0	132 - 1800	200 - 2600

Altivar Process ATV 6000 MV VSD range

ATV 6000 MV VSD shown in Figure 15 has maximum ratings of 13.8 kV and 20 MW. It uses Multi Level-CHB topology, which gives THDi < 5%. ATV 6000 is used with VT loads (centrifugal pumps, fans, and blowers) as well as CT loads (grinding mills, uphill conveyors) operating in Q1 and Q3 modes.

Figure 15

Schneider Electric Altivar Process ATV 6000 air-cooled MV VSD range specification summary

Output Voltage	2.4 kV, 3.3 kV, 4.16 kV, 6.0 kV, 6.6 kV, 10 kV, 11 kV, 13.8 kV
Rated Power	0.2 - 20 MW (Air Cooled)
Output Frequency	0.1 to 120 Hz
Input Transformer	Dry type with phase-shifting Integrated in the cabinet
Rectifier (50/60Hz)	18/24/30/36/48/54/66 pulse DFE according to voltage
Inverter	Multi-level VSI CHB with LV IGBT
Maximum dV/dt	2 kV/µs (no filter necessary)
Cabinet Protection	IP31, with Optional IP41 and IP42
Control Modes	Vector with/without encoder, Energy saving
Efficiency	Inverter efficiency is 98.5 %. Drive efficiency including input transformer is 96 % to 96.5%.
MV motor types	SCIM and SM with DC excitation control
Applications	Quadratic torque (pumps, fans), Constant torque (conveyor, HPGR mill)
Communications	Modbus TCP, EtherNet/IP, Modbus serial, CANopen, EtherCAT, PROFINET, PROFIBUS DP V1, DeviceNet

Altivar Process ATV 1260 MV VSD range

ATV 1260 MV VSD, shown in **Figure 16,** has maximum ratings limited to 4.16 kV and 4.8 MW. Its 3L-NPC topology allows 12, 18, or 24 pulse DFE or AFE to achieve different THDi levels. ATV 1260 is adapted to CT loads with Q4 operating modes like hoist or downhill conveyors. MV input transformer can be installed outdoors.

Figure 16

Schneider Electric Altivar Process ATV 1260 air-cooled MV VSD range specification summary

Output Voltage	3.3 kV and 4.16 kV
Max. Rated Power	4.8 MW (air cooled), 12 MW (water cooled)
Output Frequency	0-100 Hz
Input Transformer	Integrated or separate
Rectifier (50/60Hz)	18/24 pulse DFE or 3 level AFE with IGBT
Inverter	3 Level VSI NPC with 6.5kV IGBT
Output filter	Sinewave LC filter limiting dV/dt to 50kV/µs
Cabinet Protection	IP31, with optional IP42
Control Modes	V/Hz, Vector with/without encoder
Efficiency	98 % @In and 97% @ 0.5In
MV motor types	SCIM and SM with DC excitation control
Applications	Quadratic torque (pumps, fans), Constant torque (conveyor, grinding mill), 2Q and 4Q
Communications	Ethernet, Modbus TCP, Profibus, DeviceNet

Conclusion

LV and MV VSDs are key components of mining power systems. Although they require additional CapEx compared to fixed-speed motor control, they deliver lower TCO due to their ability to reduce electricity bills, improve process efficiency, extend asset life, reduce maintenance, and minimize unplanned outages.

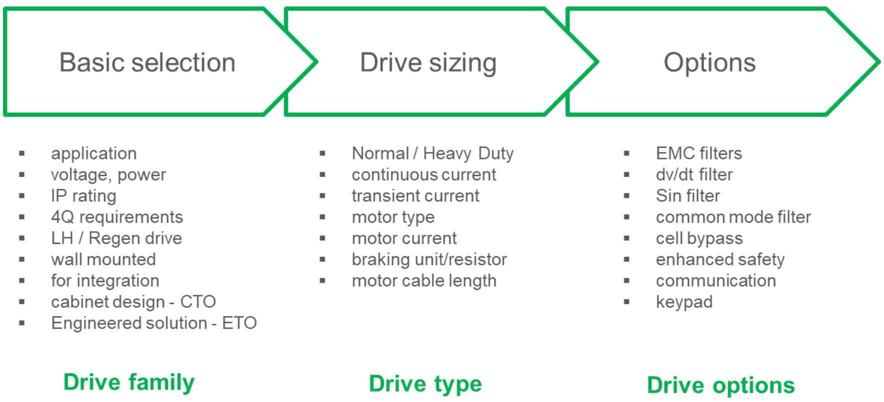
VSDs allow starts of large motors with high starting torque and minimal ΔV which enables CapEx savings by reducing transformer-rated power and cable size. VSDs enable SCIM operation at unity PF, eliminating PF correction capacitor banks. The inherent harmonic distortion caused by diode rectifiers can be mitigated by correctly selecting VSD topologies in combination with other solutions adapted to each power system, as explained in **WP06**.

Schneider Electric has invested heavily in its Altivar Process LV and MV VSD range, incorporating the latest technologies, including hardware, digital connectivity, and asset management.

Mining end users and EPCs can benefit from the full range of Schneider Electric MV and LV electrical distribution and industrial automation offers, including access to a team of mining power system experts during the project conceptual design phase.

Characteristic	**Variable Speed Drive (VSD)**
Inrush current on motor	~ 0.4* - 1.5 x I_{nom}
Inrush current on mains	~ 0.1 x I_{nom}
Voltage drop	Minimal Impact
Harmonic distortion	~ 40% THDi with 6 pulse DFE ~ 5 -15% with filter < 5% with AFE
Cos phi (full load)	0,99
Reactive current	~1% at nominal load ~1% at start
PF correction	not necessary

* according to load



About the authors

Delcho Penkov graduated from the Technical University of Sofia, Bulgaria, in 2002 with a degree in engineering. In 2006, he obtained his Ph.D. in electrical engineering from the Institut National Polytechnique in Grenoble, France. He started his career at Schneider Electric as a technical expert for transient analysis and simulation. He currently leads the Motor Management Competency Center for high-power motor applications. He has authored and co-authored several papers and patents for motor application-oriented equipment. He is a member of the IEEE.

Reinhard Kapeller started his career in 1989 at VEE, a joint venture between Austrian Elin and German Voith Group active in industrial drives technology. His first responsibility was projecting and commissioning CSI inverters up to 800kW, sold in a brand labeled ATV42 by Telemecanique. On the digital generation of drives he worked on customer front-end functionalities which led to a new operating structure called Matrix, the unique market feature for the next 15 years on MX and ATV62/68 drives. 1997 VEE got renamed to EEL - Elin EBG Electronic. During this time, his responsibility was customer training on drives, applications, and field bus communications. 2001 the drive range MXeco/ATV61/ ATV71 was developed where he led the functional extension, documentation, and testing of application-oriented functions. In 2006 Schneider Electric acquired EEL and Reinhard Kapeller took over the GHD responsibility Level 3 for Drive Systems, and 2013 the Drive Systems marketing lead for ATV660 – ATV980 drive range.
Since 2016 he has been manager of the Drive training department with training centers in France and Vienna.

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Appendix A

MV VSD Input Transformer Characteristics

MV VSD Input transformer has four main functions:

1- Adapts MV network voltage to rectifier withstand level

- MV network voltages: 3.3 KV, 4.16 KV, 6.6 KV, 11 KV, 13.8 KV
- Typical rectifier voltage withstand $\simeq$ 1.5 KV

2- Provides galvanic isolation from the MV network

- Better protection of power electronic modules and MV motors

3- Limits short circuit current to power electronic modules

- Transformer short circuit impedance Zt (%) is an important VSD design parameter

4- Reduces harmonics injected in the MV network

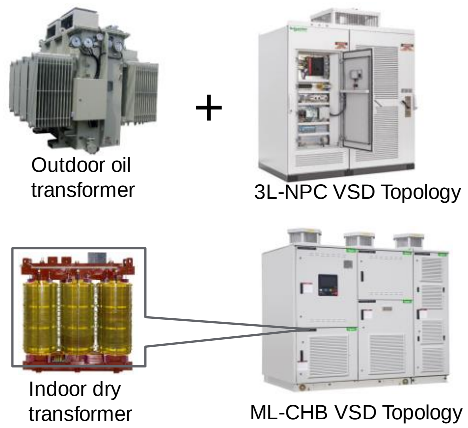
- Harmonic cancellation by secondary winding phase shift

MV VSD Input Transformer has the following special design challenges:

- Higher heat losses caused by harmonics can damage insulation
- Multi-winding design needs a large number of connections
- High insulation levels are needed to withstand the high dV/dt caused by IGBT switching
- Electrostatic shield between windings is needed to minimize EMC

MV VSD input transformer can be external or integrated in the VSD enclosure. An external transformer is feasible in 3L-NPC topology (few connections) but not easy in ML-CHB designs due to the large number of secondary wires. Integrated transformers are dry type with forced cooling. They represent up to 50% of VSD cost and 70% of its size and weight. External transformers are usually liquid-filled units suitable for outdoor installation.

Designers can choose between Y or Δ primary windings connections. The secondary windings connections can be a combination of Y, Δ, and zigzag (Z_1 and Z_2) to give the required phase shift (δ) as shown in **Figure A1.**



Winding connection type		
Name	**Diagram**	**Symbol**
Star		Y
Delta		Δ
Zigzag 1		Z1
Zigzag 2		Z2

Figure A1

MV VSD input transformer types and winding connections

Appendix B

Motor Load Sharing using VSDs

Certain applications require two or more mechanically linked motors to drive the same load. To be effective, the total load must be shared by all motors in proportion to their rated power. The mining applications that require load sharing between two or more drives are:

- Dual pinion SAG/Ball Mills: two identical MV SCIM or LSSM must equally share the load to turn the mill drum
- High-Pressure Grinding Rolls (HPGR): two identical LV or MV motors must equally share the load while ensuring that both rolls rotate at the same speed
- Overland belt conveyors: several LV or MV SCIM handle the load of driving the pulleys, maintain the correct belt tension and avoid slippage

VSDs enable accurate load management or load sharing between motors using three main control techniques:

1. Droop control
2. Torque Leader/Follower
3. Speed Leader/Follower

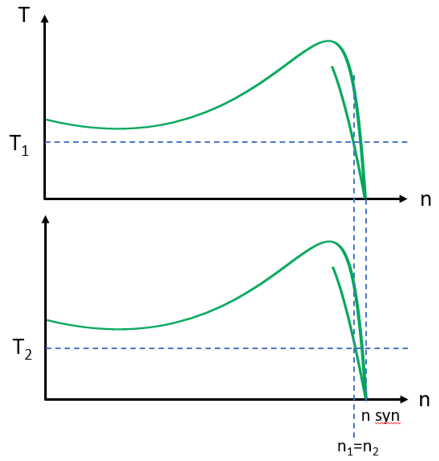
Load-sharing control must consider the type of mechanical coupling between motors and load. Soft couplings, such as a belt conveyor or rack and pinion in SAG/ball mills, cannot ensure that both motors run at the same speed. However, motors coupled by a solid link, as used in conveyors with twin-drive pulleys and HPGR mills, are forced to run at the same speed.

In Droop Control Mode all VSDs share the target speed setting. The Droop Function (set in % speed) controls motor slip by varying output frequency as a function of load current (as shown in **Figure B1**). Droop setting (%) allows loading allocation according to motor power.

Droop is the simplest technique as it does not require any drive-to-drive communication but is the least accurate. Precision depends on the VSD control algorithm, motor characteristics, and type of mechanical load.

Figure B1

VSDs operating in droop control mode to achieve equal load share varies slightly the drive speed accordance to the motor load. It requires the same no load speed on all relevant motors.



It is used in applications with solid mechanical couplings, such as a belt conveyor with twin drive pulleys. Each motor is linked via a gearbox on both sides of the pulley and ensures the same speed for both motors, even if the diameter of the drum might become smaller due to wear.

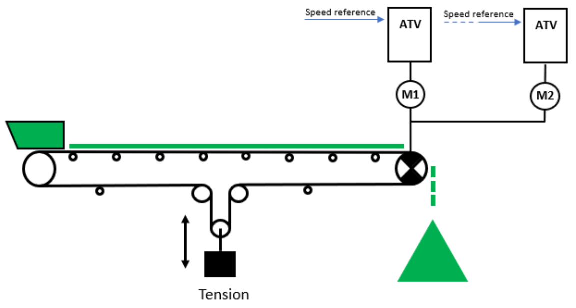


Figure B2

Conveyor belt with twin drives on its head side.
Load sharing ensured by droop control on both solid couped motors

The Leader/Follower Torque Mode load sharing scheme requires configuring one VSD as "Leader" set in "Speed Regulator" mode and the other VSDs as "Followers" set in "Torque Follower" mode. Torque Follower schemes can be used in applications where motors are flexible, or rigid coupled with each other. Next to the torque reference, Slave drives also require a speed limit reference, typically identical to the speed setpoint of the Master. As long as the speed remains within a defined window (**see Figure B3**), the drive reacts as torque follower. Should the speed be lower or higher than the defined speed limit, the drive switches to speed limit mode to prevent overspeeding or stalling of the motor.

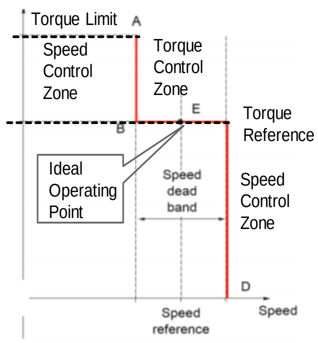
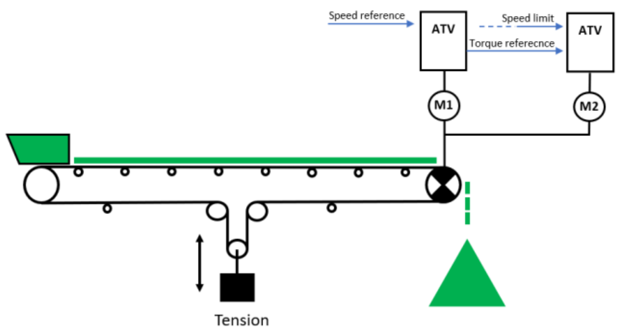


Figure B3

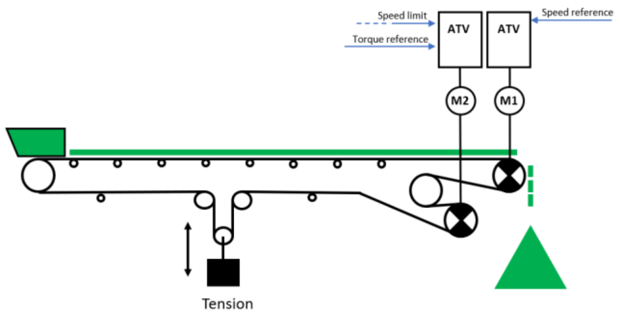
Torque follower load sharing applied to rigid a) and flexible b) mechanic links

The Master/Slave Speed Follower is used in torque sharing applications where two or more motors have their shafts directly coupled together, such as hoists, winders, and twin motor pulley drives. Its continuous automatic compensation provides higher stability to long overland conveyors, minimizing risk of belt oscillations. The system is also well adapted for PLC control using Ethernet peer-to-peer communications, as there is a need to exchange real-time data between drives and the PLC.

The Master VSD receives the desired speed setting and sends its torque reading to the Slaves that use it as their torque setting, as illustrated in Figure B4. Signal transmission between VSDs can be hardwired or via serial communication link.
The control can be done by a PLC using peer-to-peer communication link. In this case, the PLC sends the speed reference to the Master VSD and reads the torque magnitude. The torque reference and speed limit is then broadcasted to all slaves, adjusting their speed to reach the desired torque. Because the coupling is not rigid and drum diameters may differ, each motor may be running at a slightly different speed.
Depending on the VSD used, Master/Slave communication can also be a part of VSD function.



a)



b)

Figure B4

Torque follower load sharing applied to rigid a) and flexible b) mechanic coupling

Motors with different nominal power can share load proportionally by programming the PLC to scale the torque signal according to the motor drive capacity. For example, a 100 kW mechanical load could be jointly powered by 100 kW and 75 kW motors both running at 86% of rated power. This is a common arrangement found in overland conveyors.

Belt conveyors with actively-driven head and tail motors as illustrated in **Figure B5** don't use a classic load sharing principle, as the load on both sides of the belt is not equal. The head drive must apply torque to overcome the belt friction caused by the load, the tail drive only moves the empty return strand. For such architectures the tail drive can be operated on Slave principle, but with a constant torque setting and narrow speed limits in order to tolerate different shaft speeds due to worn drums.

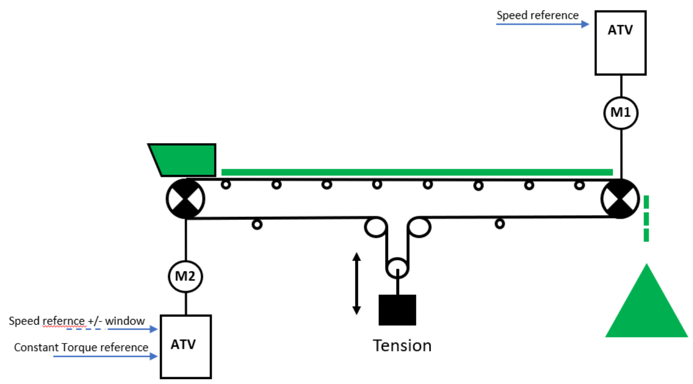


Figure B5

Conveyor with driven head and tail drive

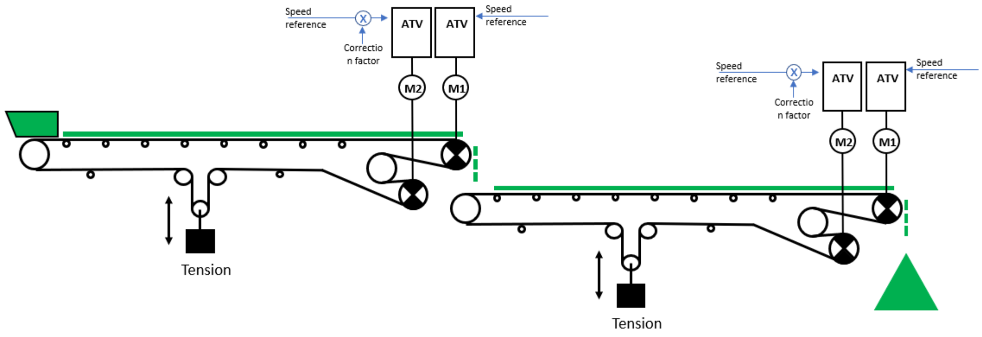
Long belt conveyors can be controlled using the following architectures:

- Multiple driven head drives (see **Figure B3b**)
- Cascaded conveyors (see **Figure B6a**)
- Belts with booster drives (see **Figure B5b**)

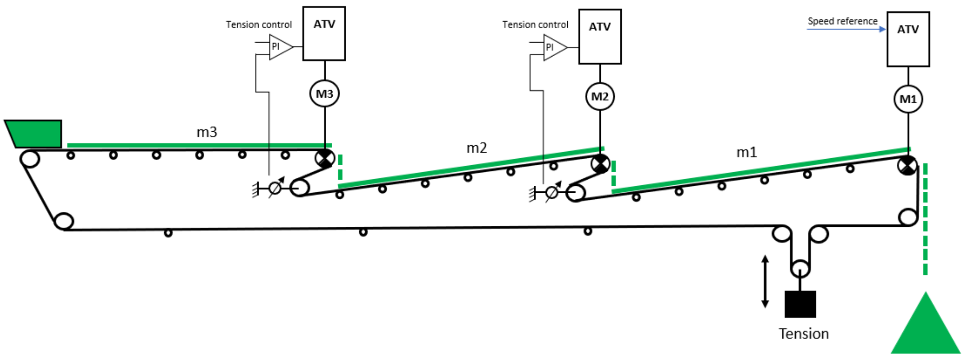
Figure B6

Cascaded conveyors (6a) easy architecture for large and robust overland conveyors

Conveyor with booster stations (6b) typical for long belts in narrow environment e.g. mining or tunneling



6a)



6b)

Conveyors with driven booster stations can be equipped with tension sensors and PI controllers to enable tension control for each section, without the need for a fast drive or for PLC communication.

Glossary

3L-NPC	Three Level Neutral Point Clamped
AFE	Active Front End
ANSI	American national Standards Association
CapEx	Capital Expenditure
CT	Constant Torque
DFE	Diode Front End
dV/dt	Delta voltage/Delta time
DOL	Direct On Line
HPGR	High Pressure Grinding Rolls
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers (USA)
IGBT	Insulated Gate Bipolar Transistor
LRS	Liquid Resistor Starter
LSSM	Low Speed Synchronous Motor
LV	Low Voltage (Un < 1 kV)
MCC	Motor Control Center
ML-CHB	Multi-Level cascaded H Bridge
MV	Medium Voltage (1 kV < Un < 52 kV)
OpEx	Operational Expenditure
PD	Positive Displacement
PF	Power Factor
PWM	Pulse Width Modulation
RVSS	Reduced Voltage Soft Starter
SABC	Comminution process using **SA**G mill, **B**all mill and primary **C**rusher
SAG	Semi-Autogenous
SCIM	Squirrel Cage Induction Motor
SLD	Single Line Diagram
UL	Underwriters Laboratory
TCO	Total Cost of Ownership (CapEx + OpEx)
VOD	Ventilation on Demand
VSD	Variable Speed Drive
VSI	Voltage Source Inverter
VT	Variable Torque
WRIM	Wound Rotor Induction Motor
Zt (%)	Transformer short circuit impedance measured in %

Resources

Electrical installation guide Schneider Electric
www.electrical-installation.org

Solving the MV vs LV dilemma when optimizing Motor Management cost

Mining Power Systems Competency Center- Recommended Power System Design for Mid-size Iron Ore Mines- IEC Standard

Mining Power Systems Competency Center- White Paper 04 - Recommended Power System Design for High Altitude Lithium Mines-IEC Standard

Mining Power Systems Competency Center- White Paper 01 - Network Architecture for optimized mining power systems

Mining Power Systems Competency Center- White Paper 02- HV/MV transformer specification for optimized mining power systems

Mining Power Systems Competency Center- White Paper 03 – MV switchgear for mining power systems applications- IEC vs ANSI

Mining Power Systems Competency Center- White Paper 04 - LV Motor Control Center in mining applications – IEC vs ANSI/NEMA

Mining Power Systems Competency Center- White Paper 06-Power factor Correction and harmonic mitigation in mining power systems

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