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Power-Agnostic Approach for Surface Drill Rigs

Technology Shifts, Maturity, and Roadmap Impact on Performance, Design, and Operation

Master's thesis in Sustainable Electric Power Engineering and Electromobility

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Abstract

The mining industry's transition towards low-carbon operations requires electrification strategies that remain reliable under weak grids, variable renewable output, and highly dynamic drilling loads. This thesis proposes and evaluates a power-agnostic electrical architecture for surface drill rigs that enables operation across AC grids, DC microgrids, and hybrid renewable-storage systems without major system redesign. The work develops a conceptual multi-source architecture, assesses technology maturity through TRL mapping, and outlines a road-map for the evolution of converters, batteries, and control systems that can be substituted or upgraded without redesigning the system between the grid interface and the motor.

The study proceeds in two parts. The first decomposes the rig power supply into its functional subsystems and assesses each against technology readiness and S-curve maturity, producing evolution matrices for cables, transformers, filters, rectifiers, grid-forming converters, DC-DC converters, batteries and inverters. A cross-impact analysis then examines how those subsystems constrain one another, and three candidate architectures are derived from the matrices. The second part evaluates the selected architecture, a grid-forming converter with a common DC bus and DC-link battery storage, in time-domain simulation over four supply scenarios spanning short-circuit ratios from 20 to 2 and four disturbance families.

The technology assessment finds the constituent hardware mature and the integration immature: active front ends and medium-voltage converters sit at readiness levels 8 to 9, while the supervisory and analytics layers that would make an architecture genuinely source-agnostic remain at 5 to 7. The simulations show that DC-link storage decouples the rig from the supply almost completely. A load variation of 290.5 kW across the drilling cycle reaches the point of common coupling as 0.13 kW on the stiffest connection, and the machine side registers no measurable response to any grid disturbance applied. As the connection weakens, more of the load variation reaches the grid, rising to 2.2 % of it on the weakest supply. The converter also meets its active-power droop once the frequency has settled, although the power swings well beyond the droop value while the frequency is still changing. The main limitation lies in the converter current. Three of the sixteen disturbance cases took it above the 1.50 pu rating. In the 60° phase jumps the current rose faster than the virtual-impedance current limit could act, reaching 1.97 pu on the stiffest supply, so a higher converter rating or a different current-limiting method is needed. In the zero-voltage sag on the weakest supply, the converter took 2.2 s to regain synchronism, because the angle correction applied after fault ride-through has no output limit. Overall, the architecture can keep a drill rig running across a wide range of grid strengths, provided the grid-side converter is rated and controlled for the disturbances. Based on these results, the thesis recommends limiting the output of the angle correction and selecting the converter rating or current-limiting method with phase steps in mind. It further proposes simulating a full working shift to size the storage by energy, using a switching converter model to assess harmonics and semiconductor losses, quantifying total cost of ownership and CO₂ emissions, and checking the technology assessment for design evolution and implementation strategies to support OEMs in advancing sustainable, future-ready drilling systems.

Keywords: Power-agnostic, Surface drill rigs, Technology evolution matrix, TRL mapping, Grid-forming converter, Virtual synchronous machine, Battery energy storage, Weak grids.

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List of Acronyms

The following is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating current
AFE	Active front end
AI	Artificial intelligence
BESS	Battery energy storage system
BMS	Battery management system
CAN	Controller area network
DC	Direct current
DOL	Direct-on-line
EMF	Electromotive force
EMS	Energy management system
EMT	Electromagnetic transient
ESS	Energy storage system
EV	Electric vehicle
GaN	Gallium nitride
GFL	Grid-following converter
GFM	Grid-forming converter
HES	Hybrid energy storage
HV	High voltage
HVDC	High-voltage direct current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-gate bipolar transistor
IGCT	Integrated gate-commutated thyristor
IMD	Insulation monitoring device
IP	Ingress protection
ISO	International Organization for Standardization
LCL	Inductor-capacitor-inductor filter
LFP	Lithium iron phosphate

LV	Low voltage
MV	Medium voltage
MVDC	Medium-voltage direct current
NMC	Nickel manganese cobalt oxide
OEM	Original equipment manufacturer
PCC	Point of common coupling
PF	Power factor
PI	Proportional-integral controller
PLL	Phase-locked loop
PMSM	Permanent magnet synchronous motor
PWM	Pulse-width modulation
RMS	Root mean square
RoCoF	Rate of change of frequency
SCADA	Supervisory control and data acquisition
SCR	Short-circuit ratio
SiC	Silicon carbide
SoC	State of charge
SST	Solid-state transformer
TCO	Total cost of ownership
TRIZ	Theory of inventive problem solving
TRL	Technology readiness level
VFD	Variable frequency drive
VSM	Virtual synchronous machine

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Per-unit bases

S_b	Base apparent power, 645.9 kVA
V_{LL}	Base line-to-line voltage, 6.6 kV
Z_b	Base impedance, 67.44 Ω
f_b	Base frequency, 50 Hz
T_b	Base torque, 4112 N·m

Network and supply

SCR	Short-circuit ratio at the point of common coupling
k_{cap}	Substation capacity factor
V_{src}	Source voltage magnitude behind the network impedance
V_{pcc}	Voltage magnitude at the point of common coupling
X_{src}	Source reactance
X_s	Total series reactance between source and converter
R_{eff}	Effective series resistance referred to the filter current
θ	Grid phase step angle

Converter and control

P_{conv}	Active power at the converter terminals
Q_{conv}	Reactive power at the converter terminals
P_{ref}	Active power reference

E	Internal electromotive force behind the virtual impedance
E_{emf}	Internal EMF magnitude
E_{ref}	Voltage reference of the PCC-voltage controller
E_{min}, E_{max}	Lower and upper bounds on the internal EMF
v_{err}	Error signal of the PCC-voltage controller
δ	Load angle between the internal EMF and the grid voltage
ω_c	Internal frequency of the virtual synchronous machine
i_f	Filter current magnitude
i_{fq}	Quadrature-axis component of the filter current
$i_{f,0}$	Pre-disturbance standing filter current
Δi	Current increment produced by a supply phase step
X_f	Coupling filter reactance
X_v	Virtual reactance
R_v	Virtual resistance
X_c	Converter-side reactance, $X_v + X_f$
I_{lim}	Current-limiter engagement threshold
I_{max}	Converter current rating
K_f	Active-power frequency droop gain
$K_{d,vc}$	Reactive-current droop coefficient of the voltage controller
$K_{i,vc}$	Integral gain of the voltage controller
H	Virtual inertia constant
Δf	Frequency deviation from nominal

Machine, DC link and storage

V_{dc}	DC-link voltage
C_{dc}	DC-link capacitance
P_{batt}	Battery active power, positive when discharging
P_{mot}	Active power at the motor terminals
Q_{mot}	Reactive power at the motor terminals
T_e	Electromagnetic torque
T_L	Load torque
n_r	Rotor speed
s	Slip

J	Moment of inertia of the machine and load
-----	---

Grid interface and simulation

P_{grid}	Active power at the point of supply
Q_{grid}	Reactive power at the point of supply
Q_{pcc}	Reactive power at the point of common coupling
T_s	Controller sample time
t	Simulation time

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1

Introduction

1.1 Background

The mining industry contributes significantly to CO₂ emissions due to its dependence on fossil fuels and diesel engines. The electrification of mobile mining equipment opens the door to de-carbonization. It also helps the sector in terms of reliability, efficiency, and improves maintenance by reducing variability, eliminating site-specific electrical modifications, and standardizing the system components. Electrification in mining refers to the use of electricity to drive mining equipment for clean and efficient use of energy sources. If low-carbon sources are used, they can significantly assist in de-carbonization, along with more efficient energy conversion compared to combustion systems. Furthermore, electrification makes the path to renewable integration flexible to help the target of net-zero carbon emissions [1]. However, it comes with several challenges, such as mining locations that are often remote with the absence or connection to weak grid conditions. The dynamic load variations of mining activities, especially drilling and hauling, make a stable power-supply operation a challenge. For example, large industrial motors in drills and haulage hoists draw inrush currents several times their rated operational current during start-up. These sudden, massive current draws cause transient voltage drops ($I \cdot Z$ drops) across the network impedance, disrupting nearby sensitive electronic equipment. Cyclic high-peak loading from shovels and drag-lines disrupts the real power balance (P), forcing generators to rapidly accelerate or decelerate and causing system frequency variations. Heavy inductive loads from under-loaded induction motors consume large amounts of reactive power (Q), reducing system efficiency and destabilizing voltage control.

Simultaneous charging of vehicles can overload the distribution line or destabilize local renewable connections. Renewable integration (solar, wind, hydro) requires special attention due to its variable nature. These conditions, such as weak-grid operation, simultaneous charging peaks, variable renewable output, and large load transients, motivate a power-supply architecture that is not tied to a single source type. A power-agnostic architecture specifies individual components (converters, transformers, filters, storage) so the system can operate under AC grids, DC microgrids, or hybrid renewable-storage supplies without major redesign.

1.2 State of the Art

1.2.1 Grid infrastructure in open-pit mines

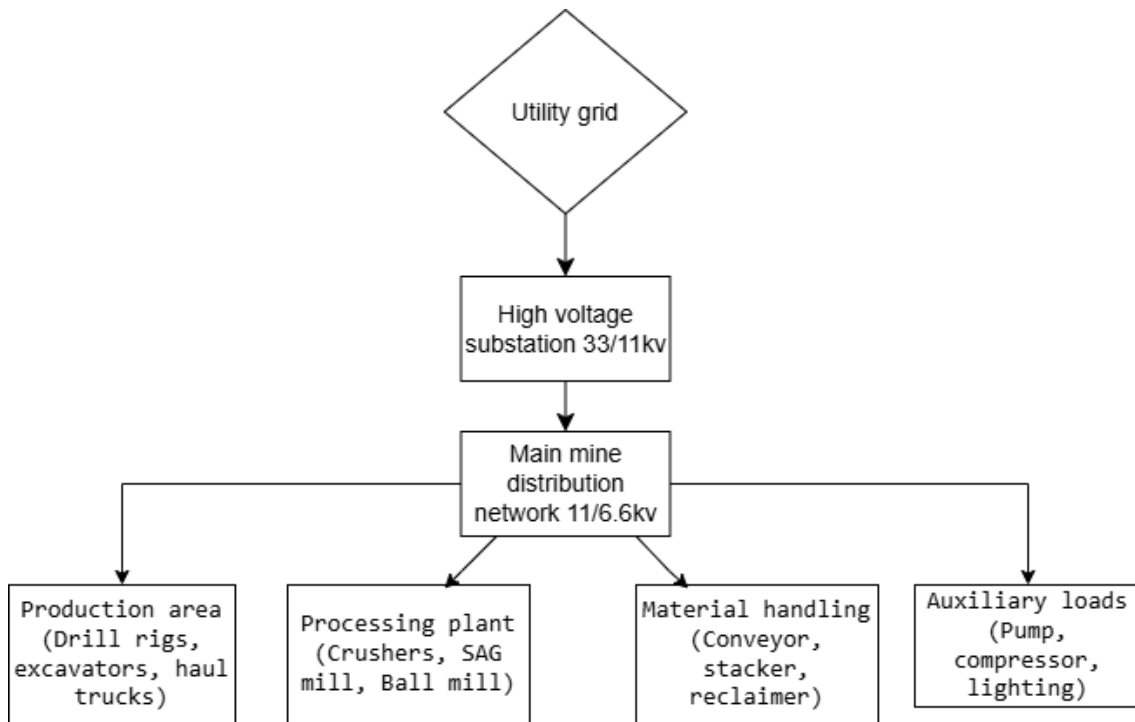


Figure 1.1: Conceptual architecture of an open pit mine.

The electrical infrastructure of an open-pit mine has evolved progressively, as shown in Figure 1.1, to meet the increasing energy demand of modern operations. Traditionally, the network can be segmented into three parts: a high-voltage substation, medium-voltage (MV) distribution feeding production machinery such as drilling units, loading shovels, crushers, and conveyor drives, and a low-voltage (LV) system supplying lighting, control circuits, ventilation, and pumps. LV is for auxiliaries, not drills/shovels [2]. On-site renewables and grid-forming power-electronic interfaces: the structure of these networks is currently being re-evaluated to support new operating modes while preserving reliability and power quality by simultaneously integrating battery-electric vehicles.

The components of open-pit mines and their main function with typical characteristics are summarized in Table 1.1. In open-pit mines, power distribution relies on overhead lines, mobile substations, and flexible feeder arrangements that can be repositioned as the pit expands [3]. An open-pit mine includes drilling, blasting, loading, hauling, and mineral processing. The fragmentation of rocks is collected from blasting and drilling and is loaded by shovels onto hauling trucks. These transportation systems transport the rocks to the mineral processing plant, where grinding, crushing, and refining processes extract valuable minerals [4]. Each of these operations has a high power demand, especially for the loading and transport of materials.

Table 1.1: Key components and characteristics of a typical open-pit mine electrical network.

Component	Primary Function	Typical Characteristics
Utility Grid / External Supply	Provides primary electrical energy to the mine	High power capacity, stable voltage source, typically operating at 33-132 kV.
High-Voltage (HV) Substation	Steps down transmission voltage and interfaces with the mine	Performs voltage transformation, switching, protection, and grid interconnection.
Medium-Voltage (MV) Distribution	Distributes power across different mine zones	Typically operates at 6.6-33 kV with radial or ring feeder configurations over long distances.
Low-Voltage (LV) Distribution	Supplies individual machines and auxiliary loads	Provides 400-690 V supply for motors, pumps, compressors, lighting, and auxiliary equipment.
Production Equipment	Performs drilling, loading, hauling, and crushing operations	Characterized by high-power cyclic loads with frequent startup and transient conditions.
Processing Plant	Carries out mineral size reduction and separation	Contains large motor-driven equipment such as crushers, mills, flotation units, and pumps operating continuously.
Auxiliary Systems	Supports overall mine operation	Includes ventilation, lighting, water treatment, dewatering systems, and compressed air systems.
Power Electronic Interfaces	Provides power conversion and motor control	Includes rectifiers, Active Front Ends (AFE), Variable Frequency Drives (VFD), and bidirectional converters for improved controllability and efficiency.
Energy Storage Systems (ESS)	Buffers energy and supports peak demand	Battery-based systems integrated through DC/DC converters or DC buses for peak shaving, backup power, and renewable energy integration.

Electric drills and shovels require high peak power while in operation. On the other hand, conveyor, grinding, and crusher mills operate continuously in a comparative steady-state mode. Auxiliary loads like lighting and de-watering pump, also add to total power consumption, necessitating a dynamic and flexible power distribution network [5]. The mobility of the load distribution is what most distinguishes open-pit electrical infrastructure from comparable industrial networks. As the pit advances,

mobile substations are repositioned and trailing cables move with shovels and drills [4, 5]. This physical reality produces the long feeder lengths and elevated source impedance that characterize the open-pit network and that motivate the weak-grid analysis presented in the subsection 1.3.3. Three power-distribution topologies are commonly used: radial, ring, and mesh are selected based on energy demand, mine size, fault-tolerance level, and economics of the infrastructure[5]. In typical practice, radial feeders are favoured for small or temporary loads because of their low cost, ring feeders are used where single-contingency (N-1) resilience is required, and meshed feeders are reserved for the most critical high-power operations. Reported substation ratings span roughly 5-20 MVA for radial schemes up to 60 MVA or more for meshed designs, at incoming voltages of 33-132 kV and equipment voltages of about 1.1-6.6 kV (Table 1.1).

1.2.2 Electrical machines and drives in open-pit mines

Mining demands a wide range of electrical machinery, with drilling and excavation alone accounting for approximately 25% of total mine power consumption and grinding operations contributing roughly a further 40% [4, 5]. Drill rigs and shovels typically use squirrel-cage or double-cage induction motors, whose minimal maintenance and rugged construction suit the dusty and abrasive environment of an open-pit mine [6, 8]. For medium-voltage ratings, these motors have historically been energised direct on line (DOL), that is, connected directly to the supply, which is the simplest and lowest-cost connection method but produces the largest electrical disturbance. An induction motor behaves close to a short circuit during start-up, drawing inrush currents which are five to six times higher than its rated value. The largest part of this inrush is reactive, depressing the bus voltage and producing sags that propagate to neighbouring equipment on the same feeder [6, 8]. Drill rigs and shovels exhibit a cyclic load profile in which the instantaneous power demand can climb higher than average level; for drillers these peaks coincide with the start-up, and for shovels with the loading cycle [6]. Modern drives allow regeneration of the shovel-cycle energy, but inrush remains a dominant power-quality concern whenever multiple induction machines are energised on the same feeder. To mitigate these effects, three drive configurations are in current industrial use [6]. DOL connection offers no inrush mitigation and a relatively low power factor of 0.8 - 0.85, but introduces no harmonic distortion and is the cheapest option. Inverter drives with diode (passive) front ends limit starting current and improve power factor to roughly 0.95 but inject characteristic harmonics into the supply, requiring filtering at the PCC. Inverter drives with active front ends (AFE) limit starting current, regulate the power factor, and keep the supply current near-sinusoidal with a total harmonic distortion of around 5% [6]. The AFE topology additionally offers four-quadrant operation, enabling regenerative energy recovery and, with appropriate control, dynamic reactive-power support properties that make it the natural front-end candidate for a power-agnostic architecture. A further architectural option, central to the present thesis, is a battery energy storage system (BESS) integration on the DC link of the AFE drive. With bidirectional DC - DC conversion between the BESS and the DC bus, the rig becomes a dispatchable resource: capable of

riding through voltage sags using stored energy, of peak shaving the inrush current seen by the upstream feeder, and when the AFE is operated in GFM mode by providing voltage and frequency support. The combined AFE-with-BESS arrangement is what enables true interoperability between AC, DC, and hybrid supply modes without architectural changes to the rig.

1.3 Challenges

The global mining industry is rapidly transitioning toward electrified operations to achieve decarbonization targets, improve energy efficiency, and enhance worker safety. Diesel-powered surface drill rigs are increasingly being replaced by electric alternatives, eliminating direct carbon emissions while introducing new challenges for the electrical power system. Unlike conventional industrial loads, surface drill rigs exhibit high starting currents, rapid load variations, regenerative operation, and strong interactions with the mine distribution network.

- High inrush current during motor starting, which depresses the local bus voltage (Section 1.3.1);
- Rapid, cyclic load variations that stress the DC link and converters (Section 1.3.2);
- Converter interaction under weak-grid conditions, where control loops can become poorly damped (Section 1.3.3); and
- Limited dynamic reactive-power support and slow voltage recovery (Section 1.3.4).

Open-pit mining grids differ significantly from conventional utility grids due to their remote locations, weak grid connections (low Short Circuit Ratio, SCR), long medium-voltage feeders, and simultaneous operation of multiple large induction motors. Weak grids are characterized by increased sensitivity of the PCC voltage to reactive power variations and high source impedance [6]. These characteristics make power quality and system stability major concerns during mine electrification.

The key technical challenges are summarized below.

1.3.1 Voltage Sag During Motor Starting

Surface drill rigs typically employ large induction motors with ratings ranging from several hundred kilowatts to megawatts. During Direct-On-Line (DOL) starting, these motors draw high inrush currents, resulting in severe voltage sag at the PCC [7].

The voltage drop is approximated using Equation (1.1):

$$\Delta V \approx I_{\text{start}} Z_{\text{th}} \quad (1.1)$$

where I_{start} is the motor starting current and Z_{th} is the equivalent Thevenin impedance of the feeder.

- High inrush current caused by DOL motor starting
- Larger voltage sag under weak-grid (low SCR) conditions

- Simultaneous operation of multiple drill rigs exceeding acceptable voltage limits
- Production interruptions and instability of connected equipment such as shovels, crushers, and mills
- Potential non-compliance with voltage sag standards (e.g., SEMI F47)

1.3.2 Dynamic and Cyclic Load Behavior

Modern electrified drill rigs operate with highly dynamic and cyclic load profiles. Improvements in automation have increased drilling accuracy, penetration rates, and reduced cycle times, but have also introduced significant load variability.

The DC-link voltage dynamics are governed by Equation (1.2):

$$C_{dc} \frac{dV_{dc}}{dt} = \frac{P_{in} - P_{out}}{V_{dc}} \quad (1.2)$$

where C_{dc} is the capacitance of DC-link, P_{in} is the grid output power, and P_{out} is the motor power demand.

Rapid torque changes produce temporary power imbalance, resulting in DC-link voltage oscillations and increased converter stress. The key challenges regarding dynamic and cyclic load behavior include:

- Frequent torque steps and rapid power fluctuations
- Increased peak-to-average power ratio
- DC-link voltage oscillations caused by power mismatch
- Higher thermal cycling of converters and transformers
- Increased frequency of grid disturbances in autonomous drilling fleets

1.3.3 Converter Interaction in Weak Grids

Modern drill rigs increasingly employ PFE, AFE, and battery-supported DC-link architectures. While these technologies improve controllability and efficiency, they also introduce converter interaction issues under weak-grid conditions.

Converter control loops become sensitive to PLL dynamics and low SCR conditions, where converters may exhibit negative impedance characteristics and poor damping, potentially amplifying oscillations [8]. The key challenges regarding converter interaction in weak grids include:

- PLL sensitivity under weak-grid operation
- Control-loop interaction between multiple converters
- Oscillation amplification due to negative impedance behavior
- Renewable sources and battery system's integration within AC/DC architectures

1.3.4 Reactive Power Management

Reactive power compensation and voltage control in conventional mining systems are typically achieved using fixed capacitor banks, transformer tap changers, or

oversized transformers. Although these solutions improve steady-state voltage levels, they provide limited dynamic support during rapid load changes. The key challenges regarding reactive power management include:

- Slow voltage recovery following motor starting
- Limited dynamic reactive power compensation
- Risk of resonance due to capacitor overcompensation
- Reduced voltage stability during simultaneous operation of large machines
- Fleet electrification becoming constrained by grid capability

The challenges discussed above demonstrate that conventional power supply architectures are becoming increasingly inadequate for future electrified surface drill rigs. Traditional systems were designed around a fixed AC supply, passive front-end rectifiers, and relatively predictable load profiles. However, the ongoing transition toward battery-electric equipment, renewable energy integration, converter-dominated networks, and autonomous mining operations requires a more flexible approach to power system design.

Rather than relying on a single predefined power source, future drill rigs are expected to operate under multiple supply configurations, including:

- conventional AC utility grids,
- DC microgrids,
- battery energy storage systems,
- renewable generation,
- hybrid power plants, and
- mobile charging infrastructure.

This transition creates new opportunities for system integrators. Instead of designing machine-specific power interfaces, future platforms can adopt a power architecture where the internal powertrain remains independent of the external energy source. Such an approach enables the same drill rig platform to be deployed across different mine sites while accommodating evolving grid conditions and emerging energy technologies. There is therefore a need for a power-supply architecture capable of operating under different supply configurations (AC or DC), enabled by appropriate component- and system-level design.

Electrification incorporates the use of electrical energy instead of diesel-based systems, for example, electric motors, drives, and power electronics, which allow precise torque and speed control with continuous operation. It creates the ability to shift to electrified systems and interoperability, which means the ability of different machines, charging systems, software, and power grids to connect, communicate, and work together seamlessly, regardless of the manufacturer or brand.

This thesis evaluates the surface drill rig's power-supply system architectural framework, using comparative simulations and technology evolution to quantify effects on efficiency, stability, cost, and environmental performance over time.

1.4 Aim

This thesis aims to evaluate a power-agnostic electrical architecture for surface drilling rig power supply systems, with defined voltage and power level specifica-

tions, and to determine the impact of the proposed architecture on system performance, and mine operation relative to conventional baselines. The objective is to identify a power-supply structure in which individual components such as converters, transformers, filters, energy storage can be substituted or upgraded without requiring redesign of the architecture from the grid interface to the motor.

The technology shift studied is the transition from a diesel-hydraulic baseline rig to a battery electric rig with a grid-forming AFE drive, on-board BESS on the DC link, and the ability to operate from an AC grid, a DC microgrid, or a hybrid renewable-storage system. The work assesses how the maturity of the underlying technologies like power converters, batteries, drives, charging interfaces, and supervisory control that affects system efficiency, design constraints, and operational flexibility. Business and sustainability value are quantified through total cost of ownership and lifecycle CO₂ emissions.

The following questions are formulated to guide the achievement of the research aim: How do power-supply architectures differ in their ability to support the dynamic power demands of a surface drill rig? How does the choice of electrical architecture, components, and their development roadmap affect energy efficiency and regenerative-energy recovery? How does the architecture choice influence machine design, converter sizing, cooling requirements, and cable sizing? How does the surface drill rig's power-supply system affect mine operation in terms of grid loading, stability, flexibility, and uptime?

1.5 Scope

The scope of the study includes the system-level evaluation of a power-agnostic electrical architecture for a surface drilling rig power supply system. The modeling boundary extends from the upstream grid Thevenin equivalent through the substation transformer, MV feeder, on-rig transformer, AFE drive, DC link with on-board BESS, and motor inverter to the induction-motor terminals. Modeling and simulation is done in MATLAB R2025b with Simulink and Simscape Electrical. Renewable generation and external storage are represented as aggregated models at the relevant bus rather than at the device level. The scenario matrix spans short-circuit ratios from approximately 2 to 20 (short-circuit power at PCC of about 1.0-12.9 MVA), feeder lengths of 1–5 km, and an 800 kVA Dyn11 isolation transformer feeding an approximately 0.5 MW-class, 6.6 kV double-cage induction motor.

The performance assessment compares the proposed architecture against a DOL baseline across a scenario matrix that varies short-circuit ratio, feeder length, grid loading, and substation capacity, and reports voltage sag depth and duration, reactive-power dynamics, ride-through capability, and stability margins. A technology-maturity assessment of the principal subsystems like converters, batteries, drives, charging interfaces, and supervisory control, is also performed, mapped to the readiness-level scale defined by ISO 16290 [25].

1.6 Limitations

Control-strategy evaluation is limited to motor-starting and transient scenarios, assessed at the control-loop level under representative grid conditions; detailed time-domain implementation of supervisory control across multiple rigs and EMT switching detail are excluded. The harmonic analysis at the AFE supply is performed at the level of compliance margin against IEEE Std 519 [14] rather than as a detailed filter-design exercise. Cybersecurity, grid code compliance for individual jurisdictions, and on-site auxiliary systems (ventilation, drilling fluids, mechanical handling) are not addressed.

1.7 Thesis structure

It is divided into six chapters, each describing a distinguished part of the research. **Chapter 1** describes the research background, the challenges that might arise, justifies the purpose of the work, and research scopes.

Chapter 2 provides the theoretical base for the study. It takes inspiration from the open-pit mine's architecture and creates the context of a power supply architecture by discussing converter control strategies, motor starting techniques, DC-link, energy storage systems, and transformers.

Chapter 3 includes the methodology that integrates the proposed technology evolution roadmap to analyze different power supply architectures in the future. It also discusses the component evolution matrix, selection criteria, and different power supply architectures.

Chapter 4 discusses the simulation model and use cases for studying Direct-on-line (DOL) and Virtual synchronous machine (VSM) architectural approaches. The performance of the systems will be evaluated based on power quality, voltage stability, component utilization, and system flexibility.

Discusses the obtained results and the study that influenced them. The advantages, limitations, trade-offs, and opportunities with respect to the power supply architectures will be discussed in terms of surface drill rigs.

Chapter 5 concludes the study by summarizing the findings and contributions. Finally, recommendations for future studies have been provided.

2

Theory

This chapter is going to focus on the key electrical components of existing drill rigs. The objective is to prepare the foundation of the components that will be used to trace the requirements in the mining context. The main components considered are the transformer, rectifier, LCL filter, inverter, battery system, and cable reel.

2.1 Electric surface drill rigs

The mining industry is undergoing structural electrification to reduce diesel dependence and increase operational efficiency. Surface mining is based on diesel-powered drill rigs, shovels, and haul trucks, which have a large carbon footprint throughout their operational life. Electrification enables a lower carbon footprint, higher efficiency, and improved controllability due to the power electronic interface. Modern drill platforms can reduce the drilling cycle time while increasing the penetration rate, thereby increasing the frequency of electrical load transients. These developments indicate that the power supply architecture for surface drill rigs is an important factor to consider. Open-pit mines are usually located in remote areas and are often supplied by high-impedance medium-voltage feeders and weak transmission connections to the main grid. Grid strength is commonly quantified using SCR, as shown in Equation (2.1), defined as:

$$SCR = \frac{S_{SC}}{S_{rated}} \quad (2.1)$$

where S_{SC} is the short-circuit apparent power at PCC and S_{rated} is rated apparent power of the connected load. Alternatively, Equation (2.2) can be used as:

$$SCR = \frac{V_{PCC}^2}{Z_{th} \cdot S_{rated}} \quad (2.2)$$

where Z_{th} is the Thevenin equivalent of the grid impedance. Low SCR (<3) (weak grid) shows load change sensitivity to grid voltage, voltage oscillation, and voltage sag.

2.2 Transformer systems

Transformers are a critical node in the power supply connection, which facilitates voltage transformation, galvanic isolation, and impedance matching [9]. In mobile

drill rigs, this system steps down MV feeder voltages (6 kV to 22 kV) to 690-1000 V needed to power variable speed drives (VSD), active front end (AFE), and auxiliary systems [10]. In surface mining, an extended distribution network and frequent relocation of mobile platforms and substations make the grid impedance profile highly dynamic.

2.2.1 Impedance dynamics and weak grid interaction

In weak grids defined by low SCR (< 3), transformer leakage impedance (Z) directly regulates voltage stability and short-circuit current availability[11]. High leakage reactance can limit fault current but creates penalties in voltage regulation during transient, which is a high current phenomenon that occurs during direct-on-line (DOL) start of an induction motor or cyclic peak loading of drilling actuators[10]. This impedance exacerbates voltage sag propagation across the distribution bus.

2.2.2 Line frequency transformers-industry benchmark and limitations

Line frequency transformer technology became a benchmark for the industry due to its high thermal overhead capabilities, structural simplicity, and high reliability under mechanical shock, vibration, and ambient dust [12]. However, they require more space, and certain types of rigs do not have more space. Moreover, passive LFTs cannot manage power quality degradation, for example, harmonic current injection from non-linear converter loads or reactive power imbalances [13].

2.2.3 Emerging topologies-power electronic interface

To overcome the constraint of LFT, hybrid and solid-state transformers are taking place as a solution.

- Hybrid transformer: It defines a standard magnetic core with a fractional-rated power electronic converter at its auxiliary or tertiary winding[12, 14]. This technology allows dynamic voltage regulation, active series compensation, and reactive power injection (Q) without compromising the overload robustness of the magnetic core [12]. The power rating of the integrated converter (S_{conv}) in Equation (2.3) is typically limited to a fraction of the total system (S_{sys}), governed by the maximum required voltage injection or reactive power regulation margin (ΔV).

$$S_{\text{conv}} \approx S_{\text{sys}} \cdot \left(\frac{\Delta V_{\text{max}}}{V_{\text{nominal}}} \right) \quad (2.3)$$

By having a fraction of power going through the converter (typically 10-20 % of total transformer MVA capacity), it reduces semiconductor conduction and switching losses and maintains a higher full-load efficiency profile compared to multi-stage SST.

- SST: It refers to a fully power electronic interface with AC-DC, DC-DC isolation, and DC-AC stages. The high-frequency power electronics typically

utilize Silicon Carbide (SiC) or Gallium Nitride (GaN) wide-bandgap (WBG) devices[13, 15]. A solid-state transformer replaces the conventional low-frequency transformer with a high-frequency isolated DC-link architecture following the relation demonstrated in Equation (2.4).

$$E = 4.44fN\Phi_{max} \quad (2.4)$$

where E is the RMS induced voltage, f is the electrical frequency in Hz, N is the number of turns, and Φ_{max} is the maximum magnetic flux in Wb. It shows the inverse relationship between the transformer and frequency. Operating in the kHz range drastically reduces core volume and weight [13]. A typical SST consists of an MV rectifier, a high-frequency inverter, a DC-DC isolation stage, and a low-frequency inverter. It provides decoupled active-reactive power control, active harmonic filtering, an integrated DC bus for energy storage integration, sub-millisecond fault isolation[12, 15].

2.2.4 Environmental and space constraints

Mining environment subject transformer insulation to cyclic thermal loading, high ambient humidity, and conductive dust accumulation, resulting in dielectric degradation [9, 10]. This mechanical stress is compounded by the high penetration of the converter-based load. High-frequency switching harmonics (1 kHz to 20 kHz) from VSDs cause increased core loss due to skin and proximity effect, causing a localized hotspot [15]. Consequently, robust thermal management and precise magnetic derating factors for insulation safety are a must. To mitigate the thermal effect, water-glycol closed-loop cooling method is also a requirement instead of forced air cooling to have elevated heat transfer coefficient within a compact and mobile enclosure.

2.3 Energy Storage Systems

BESS in the mining industry is transitioning from a passive auxiliary power source to an integrated energy management system. As the mining industry is increasingly considering converter integration, battery systems are becoming unavoidable to stabilize transient behavior, increase operational reliability, and system flexibility. It can be utilized to stabilize DC-link voltage, mitigate voltage sag, reduce peak grid loading, and support converter operation during rapid load variation of the drilling cycle.

2.3.1 Li-ion technology

Among all the possible alternatives, Li-ion batteries are dominant in the heavy-duty electric application market because of their balance between energy density, response capability, efficiency, and lifetime performance[16].

- Lithium-iron-phosphate: It is widely used in mining for its high thermal stability, safety, and cycle life under repetitive operation. Sandvik has also intro-

duced a couple of machines for underground mining, as well as one load-haul-dump machine LH518B and one articulated dump truck Z50. The batteries in Sandvik machines are based on a lithium ferrophosphate compound (LiFePO_4 - LFP) [17]. Comparatively lower thermal runaway risk and more robust operating characteristics make it suitable for mining conditions involving dust exposure, vibration, and cyclic load. However, LFP chemistry demonstrates lower energy density than other chemistries, which results in larger volume and higher weight for equivalent stored energy capacity[18].

- Nickel-manganese-cobaltthe : To overcome the energy density issue of LFP, NMC is taking place in electric vehicle industry. NMC has significantly higher energy density with reduced volume and weight, while achieving a cycle life that of LFP. Nevertheless, it comes with higher thermal sensitivity, which requires better battery management for cooling, critical for harsh mining environment. Thus, the selection between LFP and NMC often comes with energy density, reliability, durability, and system complexity[19].

2.3.2 Hybrid energy storage systems

From a standalone technology, HES systems combine supercapacitors with batteries for applications that have a highly dynamic torque profile. In this case, the battery supplies long-duration power, and the supercapacitors mitigate fast transient power fluctuations and high torque impluses while motor starting, rapid drilling operation, or converter disturbance. Such system can reduce battery stress, cycle life, and enhance transient voltage support. This hybrid configuration is suitable for mining application where repetitive high-power load cycling can impose severe stress. LFP provides higher specific energy but lower power. On the other hand, supercapacitors provide lower specific energy but high specific power. A hybrid configuration meets a balance where both energy and power take part through optimal converter sizing[20].

2.3.3 Semi solid state and solid-state batteries

Semi solid-state and solid-state Li technologies aim to provide higher energy density, thermal stability, and operational safety.

- Semi solid-state batteries: Semi solid-state batteries consist of partially solid electrolyte that reduces flammability risk and increases thermal tolerance while maintaining improved energy density compared to LFP. These technologies are viewed as a shift from liquid electrolyte to solid electrolyte while maintaining higher pack-level energy density[21].
- Solid-state batteries: Shifting from liquid electrolyte to fully solid electrolyte (polymer, ceramic) refers to a direction of higher volumetric energy density and reduced cooling requirement. Although the solution is more research-centric, it is a promising solution for mining applications due to its safety margin with a compact high-energy storage design[22].

2.3.4 Battery management systems

Apart from electrochemical configurations, these technologies increasingly rely on battery management systems (BMS), software integration for monitoring platforms, and communication interfaces. Contemporary ESS architecture includes state-of-charge estimation, thermal management, fault diagnosis, and predictive safety to ensure reliability under harsh environments.

2.4 Induction Motor

The three-phase induction motor is used widely in industrial applications because of its simplicity and robustness[23]. The speed in Equation (2.5):

$$n_s = \frac{120f}{p} \quad (2.5)$$

where n_s is the synchronous speed in rpm, f is the grid frequency in hertz, and p is the number motor poles. When the rotating magnetic flux comes in contact with the rotor winding conductors, an EMF is induced in the rotor winding[24].

Rotor windings are shorted. Thus, Current flows in the rotor windings. The current tries to oppose the induced EMF. The EMF will be interfered with if the magnetic field and rotor speed are the same. In such a situation, there will be no torque [25]. It is always important that the rotor speed is lower than synchronous speed. The difference is called slip and is defined in Equation (2.6) as:

$$s = \frac{n_s - n_r}{n_s} \quad (2.6)$$

where n_r is the rated speed of the motor in rpm.

For motor parameter estimation, a simple equivalent circuit of the motor is used shown in Figure 2.1.

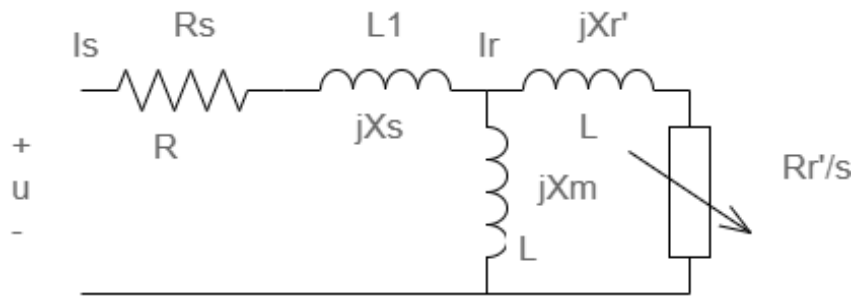


Figure 2.1: Motor's equivalent circuit.

From the circuit, the following parameters can be identified:

- u : stator voltage
- I_s : stator current
- R_s : stator resistance
- X_s : stator leakage reactance
- I_m : magnetizing current

- X_m : magnetizing reactance
- X_r' : rotor leakage reactance
- R_r'/s : rotor resistance
- I_r : rotor current

The equivalent resistance is calculated with Equation (2.7):

$$R_{eq} = R_s + R_r' \quad (2.7)$$

To get the equivalent reactance, the starting current and equivalent resistor have been used. The equivalent reactance is found using Equation (2.8) as follows:

$$X_{eq} = \sqrt{\left(\frac{V_{ph}}{I_{st}}\right)^2 - R_{eq}^2} \quad (2.8)$$

where V_{ph} is the phase voltage. Besides this, it follows the NEMA rating A values for the reactance shown in Equation (2.9):

$$X_s = X_r' = \frac{X_{eq}}{2} \quad (2.9)$$

However, the magnetizing current in Equation (2.10) is unknown, which is approximately 25-50% due to the air gap[24].

$$I_m = 0.3I \quad (2.10)$$

The magnetizing reactance is obtained from Equation (2.11):

$$X_m = \frac{V_{ph}}{I_m} \quad (2.11)$$

Equation (2.12) is used to determine electromagnetic torque from mechanical power and rotor speed:

$$T_e = \frac{P_{out}}{\omega_m} \quad (2.12)$$

2.5 Motor starting and drive technologies

System efficiency, reliability, and robustness depend on the method of motor starting. For surface drill rigs, large induction motors are used in harsh environments under repetitive load cycles and weak grid conditions. As a result, the choice of motor starting highly influences starting current magnitude, voltage sag severity, and energy efficiency.

The technology of the starter method has evolved significantly from simple fixed-speed direct switching to highly controllable converter-based drive systems. This process has been driven by increasing demand for energy efficiency and enhanced compatibility with weak grids. Direct-on-line methods are still widely adopted due to their simplicity and robustness, whereas variable-frequency drives are preferred when dynamic grid interaction is required.

2.5.1 Direct-on-line (DOL) starter

It is the conventional and widely used starter. In the DOL system, the induction motor is directly connected to the supply through electromechanical switches such as contactors and protection relays. It allows the application of full supply voltage during startup, which is highly reliable.

The simplicity of DOL lies in its ruggedness, low cost, and minimal control complexity. Due to the absence of power electronic switching devices, DOL requires straightforward maintenance, which is also an advantage in the harsh mining environment. However, it comes with the disadvantage of no precise speed control.

Due to minimal controllability, the starter operates with full supply voltage and high inrush motor current. In weak mining grids, this current can cause severe voltage sag, prolonged acceleration period, and mechanical and thermal shock to the connected equipment. Moreover, due to a lack of controllability, it operates in fixed-speed mode, which reduces system flexibility. As a result, although being a mature technology, DOL is not preferred in dynamic load demand conditions[26].

2.5.2 Soft-starter

Soft-starters are intermediately introduced to reduce the mechanical and thermal stress caused by DOL. Typically controlled by thyristor, soft-starters gradually increase the applied voltage to prevent the starting torque shock. The current is limited in proportion to that of voltage, while the torque reduces with its square. So that starter can hold upto three or four times rated current for a six to eight for a DOL connection. An IGBT-controlled soft starter can reduce the starting loss up to 50%[28].

Compared to DOL, a soft-starter provides improved reliability during start-up. This characteristic makes it suitable for mining, where repetitive startup cycles occur while being connected to weak feeders. In addition, a soft-starter maintains comparatively lower system complexity and cost compared to a fully converter-controlled system.

Despite the improvement, the soft-starter operates the motor at essentially a fixed speed after the startup condition. Consequently, they provide minimal system flexibility and minimal energy optimization capability. While a soft-starter comes with the solution for transient behavior, it does not address the issue of operating a motor at a fixed speed[27].

2.5.3 Variable frequency drive

It is an advanced technology in motor control for highly dynamic operations like the mining industry. Unlike DOL and soft-starters, VFDs use a converter and PWM to control voltage and frequency continuously. This allows precise torque and speed control over a wide operating range.

The ability of VFD for controlled acceleration and deceleration reduces both inrush current surge and voltage sag, and controlled speed throughout the operation, which reduces mechanical stress for the whole operation. It provides the grid's reactive power support whenever required with the help of power electronics. It reduces

energy consumption and increases equipment lifespan. Furthermore, it aligns the load demand and torque provided.

Modern VFDs integrate a communication interface, fault diagnostic and programmable control. Nevertheless, VFD control comes with switching harmonics, control complexity, and cooling requirements. Increased use of power electronic devices requires increased thermal management [29].

2.6 Power electronic interfaces

Power electronic interfaces have become fundamental to improve power quality through controllability and establish a strong connection of the drill rig with the grid network. For surface drill rigs, this interface is responsible for converting and conditioning. The increasing penetration of converters has increased operational flexibility but also come up with challenges such as harmonics, thermal management, and converter stability [30].

The interface can accommodate both passive rectification and bidirectional flow. Conventional passive rectification is widely adopted because of simplicity and robustness, whereas active bidirectional control enables dynamic voltage support, regenerative capability and power quality improvement.

2.6.1 Passive rectifier

Passive rectification is the most used AC-DC conversion in today's mining industry. Typically controlled by diode or thyristor, these systems take alternating current from the grid and supply DC power to the drive system or the DC-link. Owing to their simple structure, passive rectifiers are preferred in the mining industry for their robustness and low-cost operation [31].

Diode rectifiers allow unidirectional power flow and require no active switching control, making the design simpler. Thyristor-controlled rectifiers extend the feature by providing limited output voltage regulation through phase angle control. However, passive rectifiers typically demonstrate poor power factor characteristics and significant harmonic distortion within the supply network. In weak grid conditions, these harmonic currents and reactive power demand can increase transformer stress. Furthermore, passive conventional rectifiers have limited controllability over active and reactive power.

2.6.2 Active front end (AFE)

Active front-end converters allow bidirectional power flow, making the system more flexible to control. Unlike passive rectifier, it has self commutated switching device, typically IGBT, combined with PWM to control power flow (active and reactive) with the grid [32].

One of the primary advantages of AFE is to reduce harmonic distortion significantly and maintain a nearly unity factor. Moreover, AFE supports bidirectional power flow, enabling regenerative braking and energy feedback into the supply network.

This makes it suitable for mining drill operation due to the dynamic load profile, regenerative operation, and weak-grid interaction.

In weak grid conditions, AFE can also contribute to voltage stability through reactive power injection and absorption. This functionality can improve transient voltage behavior and enhance compatibility between the high-power drive system and low short-circuit ratio network. Furthermore, modern AFE can integrate digital control, fault diagnostic capability, and communication with energy supervisory platform.

Despite the advantages, AFE comes with increased complexity of control, higher switching losses, cooling requirements, and greater dependence on software. The use of a high frequency switching device requires filtering and consideration of electromagnetic compatibility due to harmonics.

2.6.3 Grid following converter (GFL)

GFL is the most used converter control strategy in modern industry application. In GFL configuration, the converter follows the grid voltage angle through a PLL for synchronization. This approach relies on external grid frequency and voltage reference to control active and reactive power[33].

Grid-following converters are highly effective in strong grids from where stable voltage and frequency reference can be achieved. However, reference from grids with low SCR and high impedances can be highly sensitive to voltage instability and harmonic distortion. The increased penetration of converters has demonstrated the limitation of pure GFL control.

2.6.4 Grid forming converter (GFM)

GFM control has emerged to meet the limitations of GFL. GFM will respond nearly immediately to changes in the external system and attempt to maintain control during challenging network conditions to maintain grid stability. The voltage phasor is controlled to maintain synchronism with other devices while regulating the active and reactive power appropriately to support the grid. Immediately after a disturbance (0-5 cycles), the internal voltage phasor magnitude and angle remain unchanged and the output current is determined by the network impedance. The angle is set by the active-power synchronization loop as compared to a phase-locked loop, which is what distinguishes this control from the grid-following case. The injected power is regulated only within the transient time frame (tens of cycles) to strictly control the power being injected into the network. This allows the converter to maintain system stability through voltage regulation during transient or inertia emulation [34].

The increasing interest in grid-forming technology is driven by the penetration of ESS and converter-based industrial loads in modern power systems. GFM allows isolation during operation with weak distribution feeder when grid-following synchronization may become insufficient. Nevertheless, it comes with the challenge of increased system complexity and advanced protection requirements.

2.6.4.1 Droop Control

The P-f droop control demonstrates the frequency deviation to the measured real power deviation according to:

$$\omega = \omega_0 - \frac{\omega_0}{K_f} \cdot (P_{\text{meas_filtered}} - P_{\text{ref}}) \quad (2.13)$$

When P_{meas} equals P_{ref} the angular frequency becomes $\omega = \omega_0 = 2\pi \cdot 50$ rad/s. If the converter delivers more power than P_{ref} , the frequency decreases below the nominal value. In a grid-connected scenario, this reduces the power angle and consequently decreases the transmitted power flow. This behavior is analogous to the self-regulating droop characteristic of a synchronous machine.

The voltage magnitude is produced by an integral controller acting on the error between the reference and the measured PCC voltage, with a droop on the measured reactive current, as in Equation (2.14). Its output is bounded between a minimum and a maximum internal EMF.

$$V_{\text{mag}} = \int K_{i,vc} (E_{\text{ref}} + K_{d,vc} i_{q,\text{meas}} - V_{\text{pcc}}) dt \quad (2.14)$$

The converter acts as a voltage source of magnitude V_{mag} behind an impedance, in the same way a synchronous machine sits behind its own reactance. That impedance is a virtual admittance of reactance X_v and resistance R_{eff} inside the controller, so the converter draws the current based on the impedance when the internal voltage and the PCC voltage differ. The dq frame rotates with the angle produced by the active-power loop and the internal voltage lies on the d-axis, so the d-axis is driven by V_{mag} against the d-component of the PCC voltage and the q-axis only by its q-component. The resulting currents are the references handed to the inner loop, as in Equation (2.15):

$$i_{d,\text{ref}} + j i_{q,\text{ref}} = \frac{V_{\text{mag}} - V_{\text{pcc}}}{R_{\text{eff}} + jX_v} \quad (2.15)$$

When the filter current passes a threshold, the resistance of that impedance is raised in proportion to the excess, as in Equation (2.16). The larger drop across the impedance pulls the current back while the converter goes on behaving as a voltage source.

$$R_{\text{eff}} = R_v + K_{r,\text{lim}} \max(0, |i_f| - I_{\text{lim}}) \quad (2.16)$$

A proportional controller on each axis then drives the converter-side current to these references. Its output is applied to the converter, where decoupling and feedforward terms are included, as given in Equations (2.17) and (2.18):

$$V_{d,\text{cmd}} = K_{p,\text{cc}} (i_{d,\text{ref}} - i_{d,\text{meas}}) - X_f i_{q,\text{meas}} + V_{d,\text{pcc}} \quad (2.17)$$

$$V_{q,\text{cmd}} = K_{p,\text{cc}} (i_{q,\text{ref}} - i_{q,\text{meas}}) + X_f i_{d,\text{meas}} + V_{q,\text{pcc}} \quad (2.18)$$

The decoupling terms compensate for the cross-coupling between the d- and q-axes induced by the filter inductance in a rotating reference frame. The feedforward

terms shift the operating point so that the controller is not required to generate the entire voltage drop across X_f from zero.

2.6.4.2 Virtual Synchronous Machine (VSM) Control

A VSM, also known as a synchronverter or a virtual synchronous generator, is a grid interfaced converter control strategy. Integration of VSM at the grid-interfaced active end tries to face challenges regarding power quality and dynamic loading. In open-pit mines, networks are built based on long overhead cables with high impedance and low short-circuit ratios. DOL connection for air compressors, hydraulic pumps, or the massive cyclic torque pulsations of the rotary head and percussion hammer draw intense transient reactive power. In a weak feeder, it can cause deep voltage sags, which can result in cascading system shutdown [45].

From the passive converter or conventional active grid following control, the shift to VSM allows drill rigs to be an asset instead of a destabilizing load. Instead of following a phase-locked loop (PLL), which can lose synchronization even for a small voltage drop, VSM mimics a synchronous generator. Whenever a drill rig encounters rock variation or starts a large induction motor, VSM provides a virtual inertia, the virtual inertia slows the frequency excursion that follows. The drive itself is fed from the DC bus rather than from the supply, so a sag at the point of connection is absorbed by the battery instead of reaching the machine which allows the drill rig to match voltage sag ride-through compliance, for example, the SEMI F47 standard[45].

Mathematical description:

To replicate the characteristic of a synchronous alternator, VSM implements the swing equation, Equation (2.19). The virtual rotor speed (ω_m) is governed by virtual mechanical power (P_m), supplied by the DC-link battery, and the electrical output power (P_e) is injected into the drill rig's front-end converter:

$$J \omega_0 \frac{d\omega_m}{dt} = P_m - P_e - D \omega_0 (\omega_m - \omega_0) \quad (2.19)$$

where:

- J is the virtual inertia ($\text{kg} \cdot \text{m}^2$), which determines the amount of virtual kinetic energy available to resist rapid frequency variation (df/dt).
- ω_0 is the synchronous grid angular frequency (rad/s).
- D is the virtual damping coefficient ($\text{N} \cdot \text{m} \cdot \text{s}/\text{rad}$), which prevents power oscillations during heavy cyclic drilling load and assists power stabilization.

The virtual rotor phase angle (θ) is obtained in Equation (2.20) by integrating virtual rotor speed over time:

$$\frac{d\theta}{dt} = \omega_m \quad (2.20)$$

where θ is virtual rotor angle (rad) and ω_m is the virtual rotor speed (rad/s). The calculated phase angle works as the internal voltage reference of the converter, enabling it to have its own voltage magnitude and frequency. This process mimics the rotor dynamics of a synchronous generator and gives support for inertia and fre-

quency. This phase angle directly commands the PWM of the converter. It ensures the converter works as a voltage source[45].

Along with frequency support, VSM works as the compensator for reactive power transients due to, for example, flushing air compressors. The virtual excitation EMF is set by a single voltage loop, in which a droop on the measured reactive current shifts the voltage reference before the error is integrated, as in Equation (2.21).

$$E = \int K_{i,vc} (E_{\text{ref}} + K_{d,vc} i_q - V_{\text{pcc}}) dt \quad (2.21)$$

where $K_{d,vc}$ is the reactive-current droop gain, $K_{i,vc}$ the integral gain and V_{pcc} the voltage measured at the PCC, with the output bounded between a minimum and a maximum EMF. If a localized voltage sag appears in the feeder, E rises and the AFE injects reactive power into the grid, which stabilizes the voltage profile and prevents an unexpected trip due to undervoltage.

2.7 Control and monitoring system

Control and monitoring systems have become increasingly important because of the increased penetration of PE interfaces and digital subsystems. Initially, the control system was limited to basic electromechanical switching and local machine protection. However, now software-assisted real-time monitoring and intelligent predictive control is more demanded, which is suitable for modern drill rigs. For example, Sandvik Intelligent Control System Architecture (SICA), demonstrates how modern drill rigs leverage high-speed digital fieldbuses (e.g., Ethernet, CAN-bus, Profibus) to stream continuous performance data directly to centralized Human-Machine Interfaces (HMIs) [46].

2.7.1 Conventional control system

Traditional systems mostly rely on electromechanical switches and relay protection for motor starting protection and operational sequencing. These systems were adopted due to robustness and simplicity for basic operational control with limited dynamic adjustment. In DOL system, motor starting operation takes place through contactor-based switching with overload and short-circuit protection integrated through relay protection or circuit breaker. While this system is highly adopted in harsh mining environment, it offers limited controllability in changing operational condition.

Digital control platforms offer real-time control of voltage, current, power flow, speed, and torque. It allows increased process optimization, reduced mechanical stress, and system-level coordination.

2.7.2 Smart monitoring system

Smart monitoring systems offer flexible maintenance planning and system reliability. This monitoring system uses distribution sensors and communication interfaces to continuously track electrical, thermal, and mechanical conditions. Parameters like

voltage, current, state-of-charge, temperature, vibration, and insulation condition can be obtained to identify abnormal behavior and predict unexpected failure[35]. In mining industry, smart monitoring can be invaluable due to harsh operating conditions. Continuous monitoring can have early fault detection and effective maintenance planning, which reduces operational downtime.

2.7.3 Software integration and digital control

Software integration in monitoring system enables digitally integrated electromechanical platform. Modern battery management system (BMS) and drive control system highly rely on software for fault handling, synchronization, and communication. Advanced software integration enables co-handling of multiple subsystems, including energy storage system, converters, and control platform.

Industrial communication protocol such as CAN, Modbus, Ethernet/IP, and IEC 61850 increasingly support interoperability between equipment and enable real-time data exchange. Moreover, some advanced features also include adaptive control, energy optimization, and operational logging[36].

Despite the advantages, the additional software introduces system complexity, cybersecurity issues, and communication reliability concern. Thus, modern industry needs better verification procedure through the softwares integrated.

2.7.4 Predictive and intelligent control

Modern industry is showing interest in intelligent control through artificial intelligence integration, which enables automation and predictive operation. Predictive models take sensor data, machine learning algorithm, and operation analytics to estimate component health and predict faults before they occur. This enables condition-based monitoring rather than fixed maintenance intervals[37].

In addition to maintenance application, predictive control is widely used for converter coordination and energy management under varying load condition. Intelligent control system can dynamically adjust load distribution to increase system stability. Such systems are highly relevant for weak-grid conditions where operational conditions may vary rapidly and converter interaction can strongly influence voltage stability and power quality. Sandvik has RMS (remote monitoring service) to read and analyze machine health status and recommend actions to the customer before problems arise [46].

2.8 Auxiliary and protection system

Auxiliary and protection systems are responsible for equipment reliability and safe operation through thermal stability. As the mining industry is going towards electrification through converters, supporting infrastructure like filters, cooling system, DC-link components, insulation coordination, and protection mechanisms has significantly increased. These systems operate in parallel with primary power conversion and drive systems to ensure stability and safety during both stable and transient condition.

2.8.1 Filters

Power electronic converters produce switching harmonics and high frequency noise into power system due to PWM operation. In mining system harmonic distortion may affect transformer, motor, communication system, and sensitive control electronics. Consequently, filters are mostly incorporated to reduce harmonic content, improve power quality, and reduce electromagnetic interference.

Passive filters with inductors, capacitors, and resistive damping network are often used due to their simplicity and reliability. Active filters, however, inject compensating currents into the system for dynamic harmonic compensation. These systems are increasingly popular for dynamic load profile-based operation[38].

2.8.2 DC-link capacitors

DC-link capacitors are an important element of converter-based power system and AFE architectures. Positioned between rectifier and inverter system, it helps to stabilize DC voltage, reduce ripple, and temporarily store energy during transients. In weak grid condition, these capacitors help to maintain converter stability during voltage disturbances and rapid load changes.

The performance and reliability of DC-link capacitors strongly influence converter lifespan. High ripple current, elevated operating temperature and frequent load cycling can accelerate capacitor degradation over time. Therefore, thermal management and capacitor sizing are crucial for mining context. Film capacitors and electrolytic capacitors are mostly used depending on voltage level, switching frequency, and durability requirement[39].

2.8.3 Cooling and thermal system requirement

Cooling and thermal management are critical because of the heat generation from converters, transformers, and energy storage systems. High power semiconductor switching devices, for example, IGBT or SiC-based converters, have switching losses and conduction losses which require effective cooling system that helps to maintain safe operating temperature.

Air cooling was adopted in the industry because of its ease of maintenance and simplicity. However, liquid cooling (water-glycol) is a requirement for mining industry due to high power and high-density applications, and also for its compactness. In battery systems, thermal management is an additional requirement to maintain cell balance, prevent thermal runaway, and preserve battery lifetime[40].

2.8.4 Protection systems

Protection systems are the safeguarding systems of converters, transformers, batteries, and motors from faults, overloads, insulation failure, short circuits, and over-voltage. In conventional mining systems, protection was primarily based on electromechanical relays and circuit breakers. Modern electrified systems increasingly utilize digital protection relays, intelligent fault monitoring, and coordinated converter protection strategies.

Converter-dominated systems require faster and more selective protection schemes due to the rapid switching behavior and reduced fault current contribution of power electronic devices. Protection systems commonly include overcurrent protection, differential protection, DC fault protection, insulation monitoring, arc-flash protection, and thermal protection mechanisms. Battery systems additionally require specialized protection against overcharging, deep discharge, thermal runaway, and internal short circuits.

The integration of digital communication and monitoring platforms further enables coordinated protection strategies across multiple subsystems, improving fault detection speed and operational reliability.

2.8.5 IP Protection and Environmental Considerations

Table 2.1 shows the degree of protection, commonly specified using the Ingress Protection (IP) rating defined by IEC 60529, where the first digit indicates protection against solid particles (e.g., dust) and the second digit indicates protection against water ingress. Typical mining equipment uses IP54 for protection against limited dust ingress and water splashes, IP65 for dust-tight enclosure protected against water jets, and IP67 for equipment capable of withstanding temporary immersion in water.

Table 2.1: Typical Ingress Protection (IP) ratings used in mining electrical equipment.

IP Rating	Protection Against Solids	Protection Against Water	Typical Mining Application
IP54	Limited dust ingress (dust protected)	Water splashes from any direction	Indoor electrical cabinets, control panels
IP65	Completely dust-tight	Water jets from any direction	Motors, converters, junction boxes
IP67	Completely dust-tight	Temporary immersion in water (up to 1 m for 30 min)	Battery packs, outdoor electrical enclosures
IP68	Completely dust-tight	Continuous immersion (manufacturer specified)	Sealed sensors, critical electronics, harsh environments

Mining environments impose severe operational conditions, including dust, moisture, vibration, shock loading, and temperature variation. Therefore, auxiliary and protection systems must satisfy demanding enclosure and environmental protection requirements. In electrified mining systems, high Ingress Protection (IP) ratings are often necessary to ensure reliable operation of converters, battery enclosures, sensors, and control electronics.

Higher IP-rated enclosures improve resistance to dust and water ingress but may also increase cooling challenges and maintenance complexity. Consequently, system designers must balance environmental protection, thermal performance, accessibility, and serviceability when developing electrified mining equipment. Rugged enclosure designs and industrial-grade components are therefore commonly utilized in mining applications to ensure long-term reliability under harsh operating conditions.

2.9 Technology Readiness Level (TRL)

The technology readiness level (TRL) in Table 2.2 is a standardized framework originally developed by NASA and later widely adopted by the European Union, research organizations, technology developers, and industrial sectors to assess the maturity of technology from basic research to full commercial deployment [41]. It is used to assess the readiness of an emerging technology throughout its development lifecycle before large-scale implementation. Rather than assessing only technical performance, TRL indicates the confidence that a technology can operate reliably under progressively realistic operating conditions.

For industrial applications, TRL works as a decision-making tool by reducing technical and financial risk associated with the introduction of a new technology. Product developers can use TRL assessments to determine whether a technology is sufficiently mature for prototype development, pilot testing, or commercial deployment. It also facilitates communication between researchers, manufacturers, and stakeholders by providing a standardized measure of technology maturity. Consequently, TRL supports investment decisions, product planning, technology roadmaps, and the prioritization of development activities.

In the mining industry, where equipment must operate reliably under harsh environmental conditions with high availability requirements, adopting immature technologies may lead to increased operational risk, maintenance costs, and production downtime. Therefore, evaluating component maturity using the TRL framework enables a systematic comparison between conventional and emerging technologies while balancing innovation with industrial readiness.

In this thesis, TRL is used as one of the evaluation criteria within the technology evolution matrix to assess the maturity, as shown in Table 2.2, of key components of the power system, including transformers, rectifiers, DC-DC converters, batteries, protection systems, and control strategy. The TRL framework complements the technical comparison by indicating the likelihood of successful industrial applications. Technologies with higher TRL indicate the state of commercial deployment readiness, and lower TRL indicates opportunities for product development through research, validation, and demonstration.

2.9.1 TRIZ S-curve

The TRIZ S-curve in Table 2.3 indicates how the technology matures throughout its lifecycle. It shows that the technology evolution follows an S-curve, which demonstrates how a product or technology development is slow initially, followed by rapid

Table 2.2: Technology Readiness Levels (TRL)

TRL	Meaning
1	Basic principles is observed
2	Technology concept is formulated
3	Experimental proven concept
4	Technology is validated in laboratory
5	Technology is validated in a relevant environment
6	Technology is demonstrated in a relevant environment
7	System prototype is demonstrated in a relevant operational environment
8	System is complete and qualified
9	System is proven in operational environment and ready for commercial usage

development after that, and before reaching the maturity level with leads to saturation. Unlike TRL, which demonstrates the readiness of the technology, TRIZ demonstrates development potential. Therefore, these two methods complement each other by indicating maturity and future innovation [42].

Table 2.3: Stages of technology evolution based on the TRIZ S-curve.

Stage	Description
Infant	Initial concept development with limited performance and high uncertainty.
Growth	Rapid technological improvement driven by innovation and increasing industrial adoption.
Maturity	Technology becomes commercially established with incremental performance improvements.
Decline	Performance improvements diminish as physical and economic limits are approached, encouraging the emergence of new technologies.

3

Methods

3.1 Research Methodology Overview

The chapter includes a systematic framework for technology evolution to evaluate different power supply systems for surface drill rigs and a simulation framework to identify the requirements and challenges of electric surface drill rigs.

3.2 Technology Assessment Methodology

The methodology involves a complete power supply system and its interaction within mining networks. The framework involves system decomposition, technology readiness assessment, technology evolution analysis, and cross-impact analysis to identify future promising solutions.

The overall methodology is shown in Figure 3.1.

System architecture definition

The process starts by defining the power supply system architecture of electric surface drill rigs through single-line diagrams.

System architecture decomposition

It identifies the major subsystems within the system and sets the boundaries for further analysis to be conducted. The boundary conditions are defined on the basis of the objective of evaluating the power supply architecture. Consequently, the analysis includes all components directly involved in electrical power conversion, transmission, storage, control, and utilisation, such as transformers, power electronic converters, electric machines, and energy storage systems. Components related to the mechanical drilling structure, hydraulic actuators, structural frames, and operational control outside the electrical power supply are excluded, as they do not directly influence the electrical architecture under investigation. This boundary definition ensures that the study remains focused on the electrical power system while capturing all subsystems that significantly affect system performance. It is decomposed into separate functional blocks. Examples include transformer systems, motor drive systems, battery storage systems, power electronic interfaces, control and monitoring systems, and auxiliary systems. This decomposition enables individual evaluation of each component along with its interaction with the overall system. For each subsystem, its primary function, operating principle, and contribution to the power supply have been evaluated. This process explains the functional requirements for different alternative technologies.

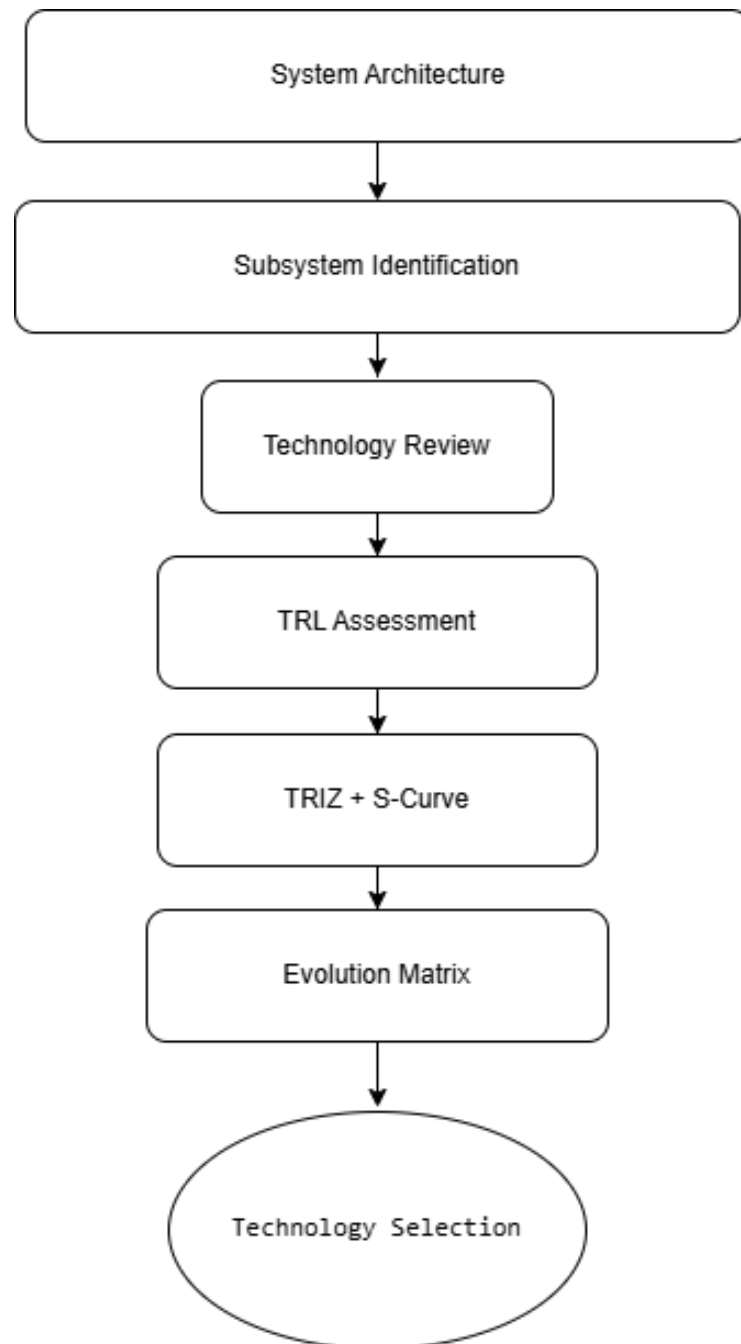


Figure 3.1: Technology evolution methodology flowchart

Technology Readiness Assessment (TRL)

Each technology is assessed based on the TRL framework. TRL describes the level of technology based on its validation stage, commercial deployment, and operational readiness. The TRL analysis focuses on the following questions:

- Is the technology experimentally validated?
- Is the technology currently deployed in industrial applications?
- Can the technology be implemented using commercially available solutions [43]

Technology Evolution Assessment

TRL alone cannot determine the future potential of technologies. Thus, the methodology includes technology S-curve analysis along with TRL to indicate the future.

The S-curve analysis revolves around:

- Is the technology still improving?
- Did the technology reach its limit?
- Is it time to replace the technology with alternative solutions [42]?

Evaluation criteria

A set of evaluation criteria has been decided for competing technologies. The criteria include technical performance, controllability, reliability, implementation complexity, scalability, and cost implications.

Each technology is qualitatively assessed on the basis of these criteria to understand its future potential for electric surface drill rig power systems. For off-road EV component studies, technology and Functionality, Design / Dimensions and Performance, IP Rating, and Interface reliability are selected in general. Based on components, criteria are modified according to influence, for example, materials for cables, cooling for the transformer, software for grid-forming control, energy density, and ratings for battery storage. These criteria are appropriate because off-road EVs depend not only on performance but also on ruggedness, integration, and digital control.

Evolution matrix

The analysis has been presented in a matrix format in which successive technologies are evaluated. Instead of focusing on a single component, the matrix illustrates how different subsystems have evolved from conventional practices to strong emerging solutions. The evolution matrix is the foundation for identifying possible power supply architectures.

This study enables the identification of appropriate combinations of technologies from the technology evolution matrix in the technology selection step and increases the flexibility of power supply systems.

3.3 Simulation Methodology

The methodology involves evaluating the current power supply system and proposing future systems based on its interaction within mining networks. The framework encompasses the existing DOL model, the proposed grid-forming model, controller design, simulation cases, and performance indicators to identify promising future solutions.

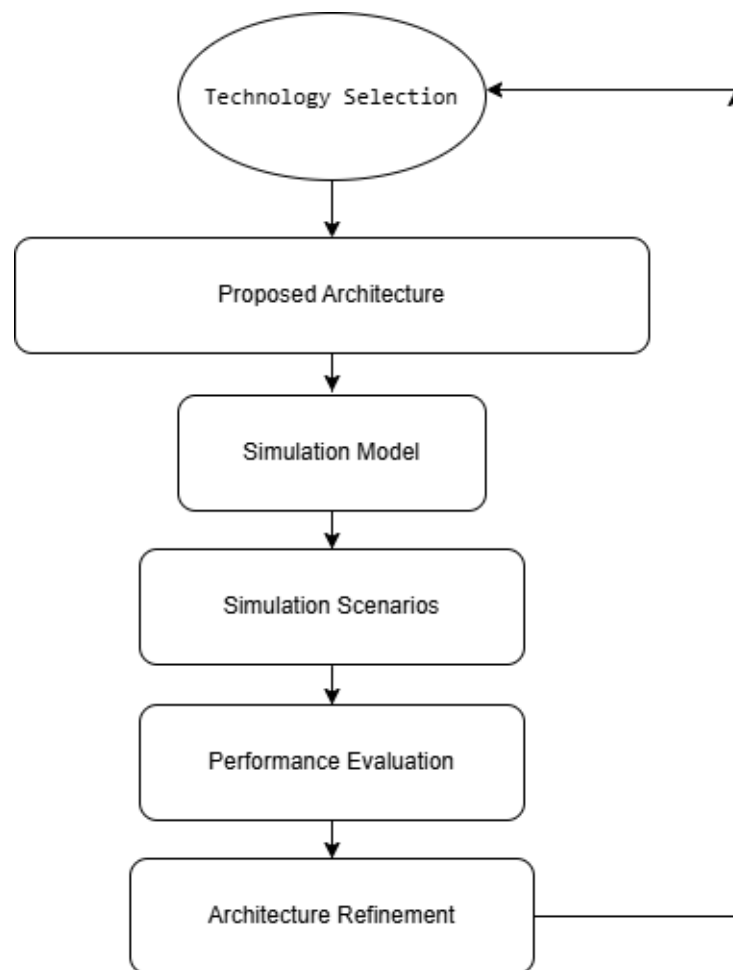


Figure 3.2: Simulation methodology flowchart

The overall methodology is shown in Figure 3.2, which focuses on the power supply architecture for surface drill rigs.

Transition from existing model through technology selection

The study first evaluates the existing DOL power supply system for a 500 kW induction motor for driving both the hydraulic and compressor loads of drill rigs. The supply starts from a direct grid connection (3-phase, 50 Hz), with cable and switchgear in between. A shunt capacitor bank is added at the motor end for reactive power support and to improve PF. At the start of the induction motor, high inrush current is drawn, which results in a voltage sag. This architecture works as a baseline to analyze the need of voltage support in the supply system for mining loads.

Proposed architecture

Identify the main challenges within the current system and establish the requirements for further analysis to be conducted. After evaluating current and emerging technologies, GFM control has been proposed to evaluate the changed performance. Evaluation criteria include active power monitoring, torque steps assessment, voltage sag response, weak grid response, frequency deviation, and impact on other components. This process enables individual evaluation of each component along with its interaction with the overall system. For each subsystem, its primary function, operating principle, and contribution to the power supply have been evaluated. This process explains the functional requirements of other components.

Simulation model

This step includes developing a detailed simulation model and identifying an appropriate grid-forming controller for the system. The model includes power system components, power electronic interfaces, battery energy storage, and a grid interface. The appropriate parameter types and control algorithms for components have been selected to represent similar operating conditions and dynamic behavior.

Simulation scenarios

A series of different operating scenarios have been implemented to demonstrate the behavior of the selected architecture. These conditions are based on a real mining environment, for example, load variation, motor starting, weak-grid conditions, and voltage sag. The test case scenarios enable a systematic assessment of the system's robustness.

Performance evaluation and cross-impact analysis

Finally, the methodology considers predefined standards and compares the results. Moreover, different subsystems and their cross-impact analysis with other subsystems are also considered [44]. The introduction of a new subsystem into a power supply can affect the requirements, feasibility, and performance of other subsystems. For example, introducing active front-end converters reduces reactive power but increases control complexity.

The circular flowchart leads to architecture refinement from the evolution matrix based on the performance evaluation and starts again from the technology selection step. It results in a continuous development process.

4

Results

Results will be discussed in two parts. The resulting technology evolution direction by following the methodology in Chapter 3, will be discussed first. After that, different architectures will be discussed by combining different technologies chosen from the matrix, from which two power supply methods are selected and simulated for simulation result discussion.

4.1 Technology evolution roadmap

4.1.1 Evolution of motor starting method

Table 4.1: Technology evolution of motor starting methods for mining applications.

Criteria	DOL Starter	Soft Starter	VFD (Variable Frequency Drive)
Technology	Direct-on-line switching	Thyristor-based voltage control	PWM inverter-based control (TRL 8–9)
S-Curve Stage	Saturation	Maturity	Growth–Maturity

Table 4.1 shows that the evolution of motor starting technologies reflects the increasing demand for improved power quality, operational flexibility, and energy efficiency in industrial applications. Direct-On-Line (DOL) starters represent the most mature and widely adopted. They produce high inrush currents and significant voltage dips during motor startup. Soft starters address these limitations by slowly increasing the applied voltage using thyristor-based control, thereby reducing mechanical and electrical stresses. The most advanced solution is the Variable Frequency Drive (VFD), which employs PWM inverter technology to control both voltage and frequency. VFDs provide superior starting performance, precise speed control, reduced energy consumption, and improved grid interaction, making them the preferred technology for modern electrified mining equipment despite their higher complexity and investment cost.

4.1.2 System architecture definition of DOL model

Figure 4.1 illustrates the DOL power supply system for a kW-range induction motor for driving both the hydraulic and compressor load of drill rigs. The supply starts from a direct grid connection (6.6 kV, 3-phase, 50 Hz), with switchgear in between,

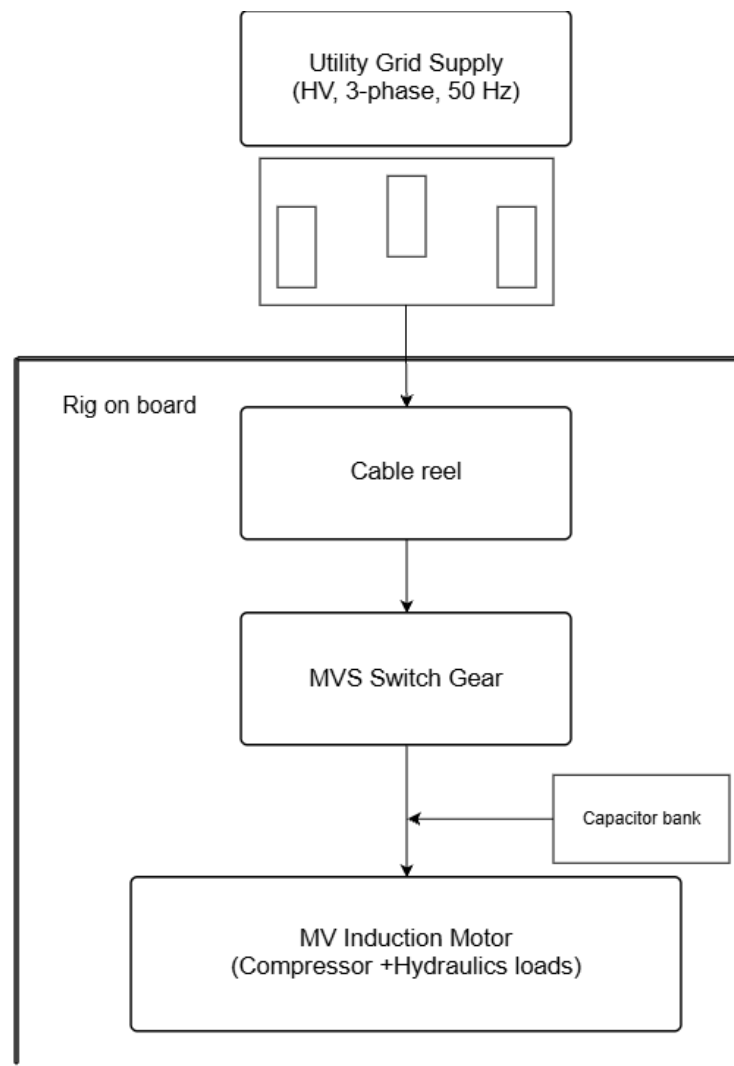


Figure 4.1: DOL power supply

with or sometimes without a transformer. A shunt capacitor bank is added at the motor end for reactive power support. During the start of the induction motor, high inrush current is drawn, which results in a voltage sag. This architecture works as a baseline to analyze different alternatives for voltage and frequency support.

4.1.3 Technology evolution of trailing cable

The evolution of trailing cable technology is summarized in Table 4.2 and has been driven by increasing power demand, equipment mobility, and reliability requirements in mining operations. Early trailing cables primarily employed conventional copper conductors with basic rubber insulation and simple plug-and-socket interfaces designed for fixed voltage and power levels. As mining equipment became larger and electric, cable designs evolved to incorporate improved insulation systems, enhanced mechanical protection, and higher current-carrying capacity to withstand harsh operating conditions [47]. Material developments have focused on enhancing flexibility, abrasion resistance, thermal performance, and service life while maintaining acceptable weight for mobile applications. More recently, advances in connector and interface technology have enabled faster connection and disconnection, improved safety features, condition monitoring capabilities, and support for higher voltage levels. High-flex, low-resistance copper cables, which match mining requirements, for example, low loss for more efficient grid interaction, are currently used in open pit mines [48]. Aluminum hybrid/ lightweight high-strength cables have been demonstrated in heavy mobile equipment, offering improved maneuverability, which aligns with the surface drill rig's operation [49]. It also has simultaneous transmission of data via fibre-optic cable, CAN bus, and Cat7 Ethernet. This evolution reflects the industry's transition toward more electric, automated, and power-intensive mining equipment, where cable systems must provide not only power transmission but also increased reliability, maintainability, and flexibility. Technical documentation for the PROTON(IQ) and similar high-end reeling cables (like those from Nexans or Cavotec) often lists "customizable communication interfaces". They also provide unique Gateway modules [50].

Table 4.2: Evolution matrix for trailing cable technologies.

Criteria	Conventional Rubber-Insulated Copper	Reinforced Heavy-Duty Mining Cable	High-Flex Resistance Copper	Aluminum Hybrid / Lightweight	Smart Trailing Cable
Technology	• Copper conductor • Rubber/EPR insulation • TRL 9 • Standard mining solution	• Reinforced insulation • Abrasion-resistant sheath • Steel/textile armor • TRL 9	• Fine-strand copper • Low-resistance design • Reduced voltage drop • TRL 8-9	• Aluminum/composite conductor • Lightweight architecture • Lower cable weight • TRL 6-7	• Embedded fiber/sensors • Temperature & strain monitoring • Fault detection • TRL 5-6
Design / Dimensions	• Heavy construction • Large cross-section • High bending stiffness	• Extra armor layers • Thick outer sheath • Increased weight	• Fine-strand design • High flexibility • Slightly larger conductor	• Lower density • Larger conductor area • Reduced overall weight	• Integrated sensing fibers • Slightly larger diameter • Smart cable architecture
Material	• Tinned copper • EPR insulation • PCP/CSP outer sheath	• Nylon/polyamide braid • Steel/copper armor • TPU outer jacket	• Ultra-fine copper strands • Optimized core layout • High reeling flexibility	• AAAC conductor • High strength-to-weight ratio • Up to 70% lighter	• Optical fibers • Embedded pilot wire • Real-time sensing
Interface	• Standard MV connectors • 1.1-11 kV • Minimal monitoring	• Standard MV interface • 3.3-35 kV • Armored terminations	• Standard mining connectors • 0.6/1-30 kV • Stress-controlled terminations	• Aluminum-compatible lugs • Corrosion protection • Up to 35 kV	• Power + communication interface • Optical sensing • SCADA connectivity
IP Rating	IP54 to IP55	IP55 to IP65	IP55 to IP65	IP55 to IP65	IP65 (sealed sensors)

4.1.4 Technology evolution of transformer

The evolution of transformer technology is summarized in Table 4.3 and has been driven by voltage requirements, improved thermal performance, reduced footprint, and enhanced grid integration capabilities. Conventional oil-filled transformers have long dominated industrial applications because of their high reliability, robustness, and suitability for high-power operation. Over time, improvements in core materials, winding design, and insulation systems have reduced losses and increased operational efficiency. The introduction of dry-type and cast-resin transformers improved safety and reduced maintenance requirements, particularly in harsh or enclosed environments[51]. Line Interphase Transformer (LIT) integrated with liquid-assisted cooling and multipulse converter interface for harmonic reduction and improved converter compatibility in high-power industrial systems[52]. More recently, hybrid transformer concepts have emerged, combining conventional magnetic components with power-electronic modules to provide voltage regulation and power quality support. ABB and the Enel group have piloted a 250 kVA Hybrid Distribution Transformer, which has been validated in a real distribution grid environment[53][54].

The latest stage of evolution is represented by Solid-State Transformers (SSTs), which integrate high-frequency power electronics to enable bidirectional flow of power, compact design, and direct interfacing with DC and AC systems. High power SSTs are still in piloting or prototype phase, categorized as greater than or equal to 1 MW power and MV level application. HITACHI-ABB developed two SSTs (15 kV AC/0.75 kV DC), especially designed for railway applications (1.2 MW). In 2014, ABB PETT 1.2 MVA demonstrated 1.75 kHz switching frequency, and in 2016, ABB PETT 1.2, 1.2 MW project demonstrated 10 kHz switching frequency. Siemens has developed a similar prototype with higher power in 2004, which was a 2 MW and 2.5 kHz SST. The project of HEART in 2019, developed a research prototype of 1 MVA and 20 kHz SST connection between 10 kV AC (DC link at 10.2 kV), and 0.4 kV AC nodes (DC link at 0.7 kV) in a hybrid grid. Recently, in 2020, TBEA Xinjiang Sunoasis had a pilot deployment of a 1 MW, 20 kHz SST for DC grid integration between 10 kVAC/ 0.4-0.8 kVDC. Thus, the observed range is between 1 and 20 kHz. However, it is mostly between 1-5 kHz during the initial phase of industrial research. The application of SiC-based SST can raise it to 20 kHz [55].

This progression reflects the industry's transition from passive power-transfer devices to intelligent, actively controlled grid-interface solutions capable of supporting the future electric power supply for mining systems. The progression also includes a cooling method that is considered for space-limited applications. Thus, the cooling method has transferred from conventional cooling to liquid-assisted cooling, and potential future solutions include experimental dry-type transformer architecture using a submerged coil or encapsulated winding arrangement combined with active cooling concepts for high thermal-density compact transformer platforms.

Table 4.3: Evolution matrix for transformer technologies.

Criteria	Direct-Cooled Cast Resin	Line Interphase	Hybrid Electronic Transformer	High-Frequency Solid State	Submerged-Coil "Dry" Prototype
Technology	• Cast-resin dry-type • direct cooling channels into winding/core eliminates oil tanks • TRL 7-8	• liquid-assisted cooling • multipulse converter interface for harmonic reduction • TRL 7-8	• LF transformer combined with power electronics interface • TRL 7	• Isolated DC-converter modules • High power density • TRL 4	• Encapsulated winding • Active cooling for high thermal-density compact • TRL 4
Design / Dimensions	• Reduced footprint • Suitable for on-board integration	• Integrated transformer + converter with cooling system • More compact than conventional	• transformer + AFE • Sw freq of PE: 5-10 kHz • More than 20 kHz will cause large heat sink	• Smaller magnetics • Sw frequency 1-5 kHz • Can be 10-20 kHz for SiC-based modules	• Reduced insulation spacing
Cooling	• Direct air or liquid cooling through thermal channels • Improved thermal transfer compared to passive dry transformers	• Water/glycol cooling due to thermal density and converter losses	• Dry: liquid cooled resin • PE: Liquid Cooled Plates • Both: Water to Air or Water exchanger	• Water-glycol flows through channels directly beneath SiC chips	• Liquid immersion cooling due to high thermal density.
Interface	• Similar to conventional LF transformers with simpler integration • Compatible with modular switchgear	• Strong coupling with converter systems • Supports AFE and PE-assisted architectures	• PE enabled voltage control, Q power support, and DC integration	• Isolated DC buses connected through modular converter units • Communication with central controller	• Compact electrical systems with close coupling to PE converters
IP Rating	IP55-IP65	IP55-IP65	IP66	IP65-IP67	IP65

4.1.5 Technology evolution of filter

The evolution of filter technology is summarized in Table 4.4 and has been driven by increasingly stringent power quality requirements and the growing use of power electronic converters in industrial systems. Early solutions primarily relied on passive CL and LC-tuned filters, which provided cost-effective harmonic mitigation but were limited by fixed compensation characteristics and sensitivity to system parameter variations[56]. CL filters are common in low-switching-frequency rectifier and inverter applications before the widespread adoption of LCL architectures with grid-side and converter-side inductors. LCL with passive or active damping can be found embedded in ABB ACS880 / ACS6000 drives and Siemens SINAMICS drives[57]. As converter-based loads became more prevalent, hybrid filter configurations emerged to combine the simplicity of passive components with the adaptability of active compensation. The development of Active Harmonic Filters (AHFs) introduced dynamic harmonic mitigation, enabling real-time compensation across varying operating conditions and improving overall power quality. If AHF is combined with AFE, standalone AHFs are often more efficient at partial loads because they are only sized for 20-30 % of the load. In a combined AFE, 100% of the power passes through the high-speed switching electronics, which can increase heat losses by 2-3%. The combined version (AFE) is much smaller because it eliminates the need for a separate filter cabinet and a massive transformer-secondary side inductor. If a combined line converter fails, the drive is dead. If a standalone AHF fails, the drive keeps running[58]. Moreover, grid converters for photovoltaic and wind power systems have demonstrated lab validation of digitally controlled LCL with adaptive tuning. It adapts to grid conditions (SCR variation) and LCL network filters switching harmonics. With integration with control systems, it relies on sensors and control algorithms for active damping. Performance improves, but dependency on control system and electronics increases sensitivity to noise, faults, and harsh conditions (dust, EMI). Software actively stabilizes the filter using real-time measurements (current/voltage). Control algorithms (e.g., active damping, resonance suppression) are essential for operation. The filter's performance and stability strongly depend on controller accuracy and response. It offers improved performance under varying grid conditions, but increased dependency on control systems reduces robustness and reliability in harsh mining environments[59]. This evolution reflects the transition from passive filtering approaches toward intelligent and actively controlled grid-interface solutions capable of supporting modern electric and converter-dominated mining systems.

Table 4.4: Evolution matrix for filter technologies.

Criteria	CL filter	Basic L / LC Filter	Standard LCL Filter	Damped / Optimized LCL Filter	Active Harmonic Filter / Hybrid
Technology	- line reactor combined with shunt capacitance - harmonic and current smoothing - TRL 9	- Simple passive inductive or LC filter - TRL 9	- LCL filter with grid-side + converter-side inductors - TRL 9	- LCL with passive/active damping - TRL 8-9	- Power-electronic-based harmonic compensation - TRL 8-9
Design / Dimensions	- lower efficiency at higher sw freq - Physically larger than modern LCL filters	- Simple - bulky	Optimized inductance-capacitance structure	Additional damping components	- Converter-based system - no passive limitation
Reliability	- simple passive construction and absence of active control - Low maintenance - Thermal aging and vibration-related stress	- No control or switching elements - Highly robust against dust, temperature variation, and vibration - Minimal failure modes	- Passive structure integrated inside AFE systems - No moving parts - High robustness	- Resistors or active damping circuits - Introduces minor losses - Slight increase in complexity	- System with switching devices, sensors, and controllers - Higher component count and thermal stress - Requires maintenance
Interface	- Between converter & grid - Integration with rectifiers, & VFD - Limited interaction with control	Passive grid connection	Integrated with AFE interface	Improved stability with converter	- Sized for 20-30% of load - No filter cabinet & secondary-side L if combined with AFE
IP Rating	IP55(if container)–IP65 inside	IP55(if container)–IP65 inside	IP55(if container)–IP65 inside	IP55(if container)–IP65 inside	IP55(if container)–IP65 inside

4.1.6 Technology evolution of rectifier

The evolution of rectifier technology is summarized in Table 4.5 and has been largely driven by the increasing demand for improved power quality, higher efficiency, and greater controllability in industrial power systems. Early rectifier solutions relied on passive diode-based topologies, such as six-pulse and twelve-pulse rectifiers, which offered high reliability and low cost but suffered from poor power factor and significant harmonic distortion. Six-pulse diode rectifiers are fully mature and widely deployed[60]. Twelve-pulse rectifiers, for example, ABB ACS1000, are operational at cement mills, conveyors, and crushers (315 kW up to several MW)[61]. The introduction of thyristor-based controlled rectifiers enabled adjustable output voltage and improved process control; however, harmonic generation and reactive power consumption remained important challenges. For example, Komatsu Mining rope shovels use ABB DCS800 for 500 kW to several MW applications[62]. As power electronic technology advanced, Active Front-End (AFE) rectifiers emerged as a key development, providing near-unity PF, lower harmonic distortion, and bidirectional power flow capability. An example of an IGBT-based active front end is ABB ACS880[63]. More recently, the adoption of semiconductor devices, for example, IGBTs, IGCTs, and SiC-based switches have further improved efficiency, switching performance, and power density. ETH Zürich Power Electronic Systems Laboratory has prototyped a multi-hundred-kW level SiC-based Active Front End[64]. This evolution reflects the transition from passive energy conversion toward intelligent and actively controlled grid interfaces capable of supporting regenerative operation, energy storage integration, and advanced grid-support functions in modern electric mining systems.

Table 4.5: Evolution matrix for rectifier technologies.

Criteria	Diode Rectifier (6-Pulse)	12-Pulse Rectifier	Thyristor Controlled Rectifier	IGBT-based Active Front End (AFE)	SiC-based Active Front End
Technology	- Uncontrolled diode bridge - Supplying DC link - TRL 9	- Phase-shifted dual six-pulse rectifier - Use transformer phase displacement to reduce harmonic - TRL 9	- Phase-controlled DC voltage through firing-angle control - TRL 9	- PWM-controlled bidirectional - Regulate grid current, unity PF, regeneration, and V support - TRL 9	- Wide-bandgap - Higher sw freq, lower sw losses, and improved efficiency - TRL 4
Design / Dimensions	- Compact and simple topology - Large DC-link capacitors and passive filters	- Requires multi-winding phase-shift transformer - Additional rectifier bridges - Increases footprint, weight, and space	- Large heat sinks and harmonic filters required - Bulky cabinet	- Requires LCL filter, I sensors, gate drivers - Bulky cabinet	- Requires LCL filter, I sensors, gate drivers - Bulky cabinet
Reliability	Minimal control electronics	- Improves harmonic - Adds transformer complexity - Adds failure points	- Thyristor stress - Poor power factor	- Controls grid current - Mitigates voltage disturbances	- High device stress - Improved thermal performance and efficiency
Interface	- Direct connection to supply - No synchronization required	- Phase-shift transformer interface - Coordinated bridge configuration	PLL or timing circuitry	- PLL - Integration with LCL and DC-link control	- Same as IGBT AFE but high sw freq - Faster control response
IP Rating	IP65	IP65	IP65	IP65	IP65

4.1.7 Technology evolution of GFM

The evolution of converter control strategies is summarized in Table 4.6 and has progressed from conventional grid-following (GFL) operation toward grid-forming (GFM) control in response to the increasing penetration of converters and the reduction of system inertia. Traditional GFL relies on strong external voltage source and phase-locked loop synchronization, making it suitable for stable power systems but less effective in weak-grid conditions. As electrification and renewable integration increased, advanced control algorithms were developed to improve dynamic performance, fault response, and system stability. Grid-forming technology represents the latest stage of this evolution, enabling converters to actively establish and regulate V and f rather than simply following existing grid. Droop control is currently testing the limits of droop stability in 100% renewable-fed remote sites [65]. In addition to supporting black-start capability and islanded operation, GFM converters can provide inertia, fast response, and enhanced voltage support. Siemens Gamesa upgraded a 102 MW wind farm with VSM grid-forming software[66]. Advanced microgrid field tests are planned or underway (2024-2025) to test dVOC's ability to handle "black starts" and extreme transients in subgrids[67]. This evolution reflects the transition from passive grid-dependent converters toward intelligent power electronic systems capable of actively contributing to system stability and resilience in future power-agnostic mining architectures.

Table 4.6: Evolution matrix for GFM technologies.

Criteria	GFM – Droop Control	GFM – VSM (Virtual Synchronous Machine)	GFM – dVOC (dispatchable virtual oscillator control)
Technology	- Power mismatch is proportional to frequency deviation, inertialess - Voltage source converter - TRL 7–8	- Converter with synchronous machine emulation - Swing equation, inertia - TRL 7–8	- Local measurements with adjustable droop - Converter with oscillator-based / matching control - TRL 5–6
Design / Dimensions	- Droop Gains usually set to 3%–5% [72] - LPF typically set between 2 Hz and 10 Hz [73]	- Inertia Constant usually dimensioned between 2 to 10 seconds [72] - Can be 6–10 s in mining context as RoCoF is common [74] - Damping Factor tuned (0.707), needs DC link capacitor	- dVOC responds faster is V ampl gain, synchronization gain higher - larger power module due to higher current - dimension based on geographic coordinate
Reliability	Grid dependency is low (can operate in weak grid)	- Grid dependency is very low (strong grid support) - Better transient behavior	- Independent (self-synchronizing system) - Fast and adaptive
Interface	- Self-synchronized - One PLL for initial synchronization before closing the breaker	- swing equation handles synchronization - PLL kept for monitoring or smooth reconnection to the main grid	- No PLL required - Instant synchronization by feeding I measurement into the virtual oscillator's differential equation
Software	- Real-time control for P–f and Q–V droop - Moderate computational demand	- Solving swing equation, inertia, damping in real time - Precise tuning	- Nonlinear control - Signal processing and high-speed control

4.1.8 Technology evolution of DC-DC converter

The evolution of the DC-DC converter technology has been driven by the growing demand for efficient power conversion, voltage adaptation, and integration of ESS in modern electrical networks. Early converter designs were based on simple non-isolated topologies, such as buck and boost converters, which provided effective voltage regulation but offered limited flexibility and functionality. Direct connections with no DC-DC converters were widely used in conventional industrial VFD systems [68]. As power levels and system complexity increased, isolated converter topologies were developed to improve safety, voltage matching, and system integration. EV power electronics and industrial battery systems initiated using unidirectional DC-DC converter [69]. More recently, bidirectional converter architectures such as the Dual Active Bridge (DAB) have the ability to support energy storage integration, regenerative operation, and power flow control in both directions. It is widely used in battery-supported industrial power systems and microgrids [70]. Improvements in semiconductor devices and control techniques have further improved converter efficiency, power density, and dynamic performance. For example, multi-port DC-DC converter has been demonstrated in hybrid energy storage research and pilot systems such as HES in the Electric Bus - Shanghai Project [71]. Table 4.7 highlights some examples of high-frequency DC-DC industrial applications.

Table 4.7: Examples of high-frequency transformer (HFT)-based DC-DC converters and their switching frequencies[55].

Project Name	Power	Switching Frequency	Application
DTU/Vestas Wind DC-DC Converter	400 kW	20–25 kHz	Wind turbine DC grid
ONR Shipboard MVDC Converter	380 kW	10–15 kHz	Naval MVDC systems
CRRC Traction DC-DC Converter	600 kW	8–12 kHz	Railway traction
ABB HVDC Breaker DC-DC Module	500 kW	15–20 kHz	HVDC protection

This evolution in Table 4.8 reflects the transition from basic voltage conversion devices toward highly controllable and flexible power electronic interfaces capable of supporting future DC-based mining systems.

Table 4.8: Evolution matrix for DC-DC converter technologies.

Criteria	Passive DC Link (No DC-DC) – Historical	Unidirectional DC-DC Converter	Bidirectional DC-DC Converter (Current Mining Integration)	Multi-Port DC-DC Converter	Modular High-Frequency DC-DC (Next Gen)
Technology	- Battery (if present) or rectifier output is connected directly to the inverter through DC link capacitors - TRL 9	- Step-down DC-DC - Regulating battery discharge into the DC bus - TRL 9	- Two-way power flow between battery storage and DC link for energy buffering and grid support - TRL 8–9	- Simultaneous integration of multiple energy sources (battery, supercapacitor, renewable inputs) into a shared DC bus - TRL 6–7	- High-frequency isolated DC-DC modules - High power density - TRL 5–6
Design / Dimensions	DC link capacitor bank for energy buffering	- DC link capacitor for energy buffering - Minimal power electronics	Dual switching bridges, inductors, and thermal management system required	Dual switching bridges, inductors, and thermal management system required	- Compact by high-frequency - smaller magnetics but requires liquid cooling and insulation - sw freq 1-5 kHz, upto 20 kHz for SiC
Reliability	- Simple passive topology - Minimal control electronic	- Mature converter topology - Reliable switching control	- Improves system-level reliability by stabilizing DC bus - Reduced stress on grid supply	- Increases system flexibility - Adds converter complexity.	- High performance but emerging technology - Higher switching stress.
Interface	- Between rectifier output and inverter bus - Through DC link capacitor	- Between BESS and DC bus - Communicates with system controller	- Between BESS and DC bus via controlled converter - communication with EMS	- Multiple energy sources to common DC bus - EMS manages power flow	Isolated buses through modular units and communication with controller
IP Rating	IP54–IP55 (cabinet)	IP54–IP55	IP55–IP65(industrial)	IP55–IP65	IP65–IP67 (sealed)

4.1.9 Technology evolution of Battery

The evolution of battery energy storage technologies is summarized in Table 4.9 and has been driven by the increasing demand for energy density, improved safety, longer life, and enhanced system flexibility. Early battery systems, such as lead-acid technologies, provided a reliable and cost-effective solution but were limited by low energy density, relatively short cycle life, and significant maintenance requirements. Advances in electrochemical materials led to the widespread adoption of lithium-ion technologies, offering substantial improvements in energy density, efficiency, charging performance, and operational lifetime. More recently, battery development has focused on improving safety, reducing dependence on critical materials, and optimizing performance for high-power applications through chemistries such as LFP. NMC chemistry provides increased energy density and longer operational range in electric industrial vehicles [75]. A hybrid ESS combining a lithium-ion battery for ESS and a supercapacitor for high-power transient support has been demonstrated in the project SITRAS HES system developed by Siemens for the Madrid Metro [76].

The NIO 150 kWh pack utilizes a semi-solid electrolyte that replaces traditional liquid components with a "solid-liquid hybrid" material, enhancing safety and energy density. It achieves a pack-level density of 260 Wh/kg by packing ultra-dense 360 Wh/kg cells (developed by WeLion) into the same physical footprint as a standard 100 kWh battery [77]. Toyota solid-state battery development programs developed a prototype system for demonstration in laboratory and pilot environments [78]. Furthermore, lithium-metal battery systems using lithium-metal anodes, enabling ultra-high theoretical energy density, are currently under active research and early prototype development by MIT's lithium-metal battery research. It has theoretically extremely high energy density (>400 Wh/kg) per cell, which reduces pack volume but requires advanced safety packaging, liquid cooling or immersion cooling systems, and enhanced BMS to control dendrite growth and thermal stability [79].

In parallel, the integration of advanced battery management systems and power electronic interfaces has enabled batteries to provide not only energy storage but also grid-support services such as peak shaving, voltage regulation, and frequency support. This evolution reflects the transition from standalone energy storage devices toward intelligent and actively managed energy assets capable of supporting future electric mining systems.

Table 4.9: Evolution matrix for battery technologies.

Criteria	LFP (Current)	High-Energy Lithium-Ion	Hybrid Battery + Supercapacitor	Semi Solid-State	Solid-State Lithium
Technology	- Lithium iron phosphate battery packs with modular architecture - Integrated battery management system (BMS) - TRL 9	- Higher energy density - Longer operational range - TRL 9	- Lithium-ion battery energy storage - Supercapacitor for high-power transient support - TRL 6-7	- Replaces traditional liquid with a "solid-liquid hybrid" - Enhanced safety and energy density - TRL 6-7	- Lithium batteries using solid electrolyte - Improve safety and energy density - TRL 5-6
Energy density	120-160 Wh/kg per cell	200-250 Wh/kg per cell	40-100 Wh/kg per cell	360 Wh/kg at the cell level and 260 Wh/kg at the pack level	300-450 Wh/kg
Rating	3.2 V per cell 1C-3C	3.7V per cell 0.5C-2C	- Variable voltage 10C - 100C (Pulse)	3.6-3.7V 1C-2C	3.7 V+ per cell 1C - 3C
Interface	- Integrated through DC-DC converter and BMS - Voltage and current monitoring	- To monitor DC-link through high-current connectors - BMS communicates with controller for SOC and thermal monitoring - Overcharge, over-discharge, and thermal runaway prevention.	- Connecting battery and supercapacitor modules to DC bus - Energy management system (EMS) controls power distribution - Current limiting and fault isolation between storage units	- Mechanical: liquid cooling ports - A standardized latching mechanism in approximately 3 minutes.	- Modified BMS algorithms for solid electrolyte characteristics - Communication for cell monitoring and fault diagnostics - Overcurrent and temperature monitoring.
IP Rating	IP54-IP65(pack enclosure, liquid cooled)	IP54-IP65(pack enclosure, liquid cooled)	IP54-IP65(requires thermal protection)	IP67	IP55-IP65 (integrated enclosure)

4.1.10 Technology evolution of Inverter

The evolution of inverter technology is summarized in Table 4.10 and has been driven by the need for higher efficiency, improved power quality, increased power density, and greater operational flexibility. Early inverter systems were primarily based on conventional two-level Voltage Source Inverters (VSIs), which provided reliable AC power conversion but were limited by switching losses and output waveform quality at higher power levels. Advances in semiconductor technology enabled the development of multilevel converters, such as NPC and Modular Multilevel Converters (MMCs), which reduced harmonic distortion, lowered voltage stress, and improved efficiency in medium- and high-voltage applications. More recently, the adoption of advanced semiconductor materials, including Silicon Carbide (SiC), has enabled increased switching frequency, lower losses, and increased power density. Mitsubishi has demonstrated SiC power modules for high-power motor drives and railway traction systems, often in the MW class. The company commercialized a traction inverter using 3.3 kV full-SiC modules for railcars in 2013 [80]. Silicon carbide (SiC) power modules that use direct liquid cooling to improve thermal management and increase current density in high-power converters and meet the liquid-cooling requirements from a mining perspective. CISOID SiC Intelligent Power Modules Product Page outline 3-phase 1200V platforms featuring a pin-fin AlSiC baseplate designed specifically for direct liquid cooling [81].

In parallel, inverter control strategies have evolved to support bidirectional power flow, reactive power compensation, and grid-support functionalities. Bidirectional PWM active front-end (AFE) replacing diode front-end, enabling controlled grid current, regenerative operation, unity power factor, and improved system efficiency in high-power industrial drives. It is currently commercially deployed in industrial VFD systems, for example, pumps, compressors, mills, conveyors, and traction systems such as ABB BORDLINE [82].

BORDLINE converter provides the following functions:

- AC to DC conversion - three phase
- DC to AC conversion
- Braking chopper
- Auxiliary converter
- Battery charger
- Multi Vehicle Bus (MVB) interface

AI-enabled Predictive Maintenance VFDs Inverters are integrating AI/ML algorithms for predictive maintenance, fault detection, and remaining useful life estimation of drive components. ABB Ability Condition Monitoring for Drives is part of the Digital Powertrain, which provides fact-based insights [83].

Digital twin models representing physical drive systems combined with cloud analytics to enable performance monitoring and predictive diagnostics are currently on pilot deployment in manufacturing plants and industrial process facilities, for example, Siemens Digital Twin. Siemens has developed Drive Train Analytics that uses Siemens Mindsphere to send data. Customers have access to the analysis tools in the observatory [84]. This progression reflects the transition from basic power conversion units toward highly controllable and intelligent power electronic interfaces capable of meeting the requirements of future electric surface drill rigs.

Table 4.10: Evolution matrix for inverter technologies.

Criteria	SiC Modules (Wide Bandgap) Technology	Active Front End (AFE) Drives Technology	AI enabled Predictive Maintenance VFDs Inverters	Liquid-Cooled SiC Modules Inverter Technology	Digital Twin & Fleet Analytics Integration
Technology	- Replacing conventional IGBTs - Higher switching frequency and improved efficiency - TRL 7–8	- Bidirectional PWM - Controlled grid current, regenerative operation, unity PF - TRL 9	- Predictive maintenance, fault detection - Remaining useful life estimation - TRL 6–7	- Improve thermal management - Increase current density - TRL 7–8	- Cloud analytics to enable performance monitoring, predictive diagnostics, and operational optimization - TRL 5–6
Design / Dimensions	- Reduced inverter cabinet volume and passive filter size - Smaller heat sinks are possible compared with IGBT drives	LCL filters, current sensors, and control hardware, increasing cabinet size and integration complexity compared with diode front-end drives.	Additional sensors and monitoring modules are integrated into existing cabinets without significant increase in footprint.	- Higher current density and compact inverter design - Liquid cooling circuits - Increasing system complexity	No direct impact on hardware dimensions
Power and voltage range	2.475 MVA 3.3-6.5 kV	30 MW to 85 MW 2.3 kV to 13.8 kV	- Up to 36 MW - Up to 13.8 kV	1 MW to 10 MW+ 3.3-6.5 kV	N/A
Interface	- Standard MV connectors 1.1-11 kV - Minimal monitoring	- Standard MV interface 3.3-35 kV - Armored terminations	- Standard mining connectors 0.6/1-30 kV - Stress-controlled terminations	- Aluminum-compatible lugs - Corrosion protection - Up to 35 kV	- Power + communication interface - Optical sensing - SCADA connectivity
IP Rating	IP54 to IP55	IP55 to IP65	IP55 to IP65	IP55 to IP65	IP65 (sealed sensors)

4.1.11 Cross-impact analysis

The cross-impact analysis highlights the strong interdependencies between the battery system, inverter, and cable infrastructure within an electric mining powertrain. The battery determines the available energy capacity, which directly influences the inverter operating range and power delivery capability. In turn, inverter power demand and dynamic torque requirements affect battery current levels, cycling behavior, and thermal stress. Cable characteristics also play a significant role, as cable resistance and length contribute to power losses and voltage drops, reducing the effective utilization of the battery system.

The interaction between the inverter and cable reel is particularly important. Higher switching frequencies, especially in PWM-based and SiC-based inverters, can improve power quality and reduce filter requirements but may increase cable losses, insulation stress, and thermal loading. Consequently, cable sizing, cooling requirements, efficiency, and mobility must be evaluated together rather than independently. Furthermore, increasing the DC-bus voltage reduces current, lowering cable losses and enabling higher power transfer. For high-power mining applications, elevated DC-link voltages may require the adoption of high-voltage semiconductor technologies such as IGCTs, which offer superior voltage handling capability and reliability compared to conventional IGBT-based solutions. Therefore, the selection of battery voltage, inverter technology, semiconductor devices, and cable infrastructure must be performed as an integrated system-level optimization to achieve the desired balance between efficiency, power capability, reliability, and operational flexibility.

4.2 Different architectures from the evolution matrix

The evolution matrices presented in the previous sections demonstrate that the development of individual power electronic components has enabled a wide range of electrical power architectures for high-power industrial applications. Advances in semiconductor devices, energy storage systems, converters, transformers, digital control, and communication technologies have progressively shifted power systems from conventional AC-fed topologies toward hybrid AC/DC and fully DC-based architectures. Each architecture offers advantages of efficiency, flexibility, controllability, and integration with renewable sources and BESS.

For surface drill rigs, selecting an appropriate architecture is essential to ensure interoperability with different power sources while maintaining reliable operation under varying grid conditions. The following sections present representative architectures identified from the evolution matrix, highlighting their operating principles, advantages, limitations, and suitability for future electric surface mining applications.

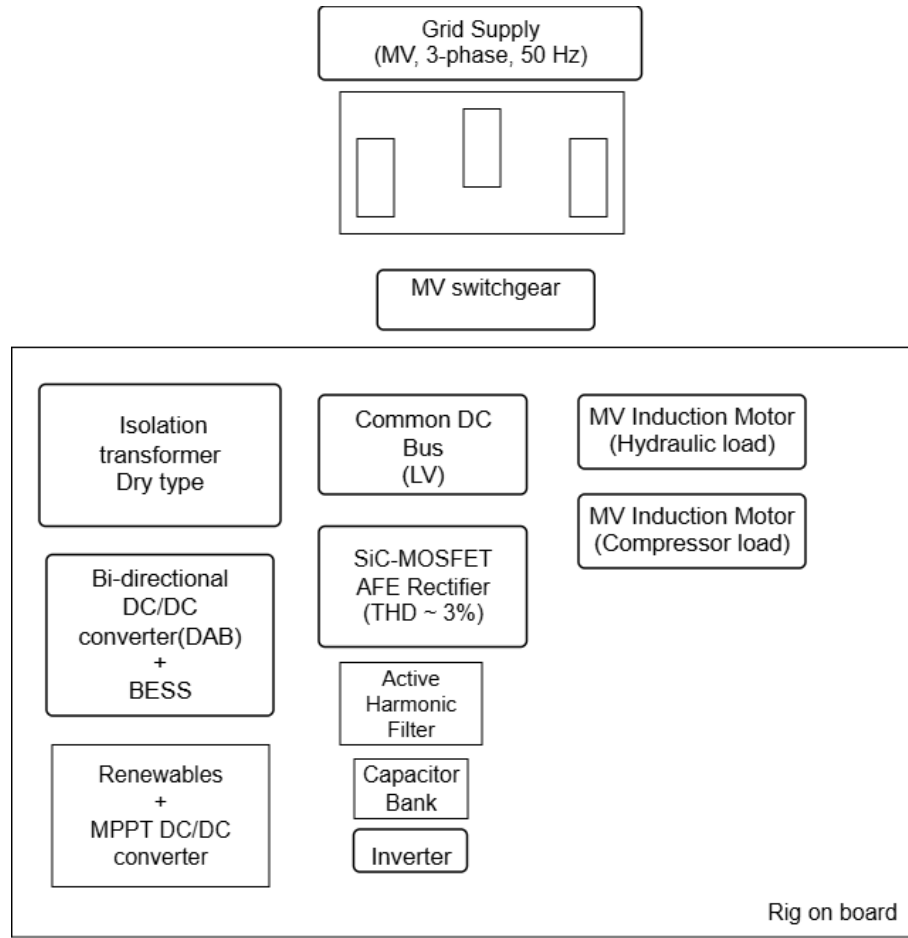


Figure 4.2: Megawatt-scale common DC bus with SiC AFE rectifier

Figure 4.2 presents a megawatt-scale motor power supply architecture based on a common DC bus. The architecture is intended for rigs supplied at medium voltage, with the conversion equipment mounted on board and only the grid connection, the disconnect and the switchgear remaining on the supply side. Rectification is provided by a SiC-MOSFET active front end, which gives bidirectional capability and a total harmonic distortion of approximately 3 per cent, and additional power quality support is provided by an active harmonic filter together with a capacitor bank. A dry-type isolation transformer is used in preference to an oil-filled unit because of the fire protection and containment requirements that oil introduces on mobile equipment. Energy storage is provided by a battery system with a bidirectional dual active bridge converter on the DC side, and provision is also made for a renewable source through an MPPT converter, so that locally generated power can be used without an additional AC conversion stage. The compressor and hydraulic loads are driven by inverter-fed induction machines. This architecture enables efficient energy management, regenerative braking, and seamless integration of energy storage, making it suitable for future surface drill rigs.

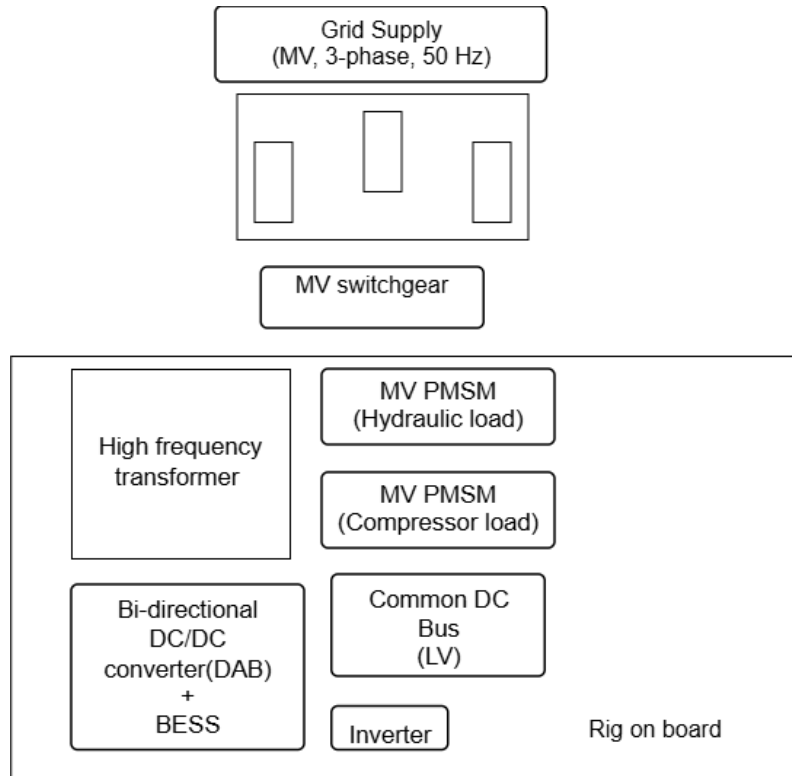


Figure 4.3: Kilowatt-scale common DC bus with passive front-end

Figure 4.3 presents a kilowatt-scale architecture in which the line-frequency transformer and the separate rectifier are replaced by a single high-frequency stage that provides both galvanic isolation and the AC-to-DC conversion. This reduces the mass and the volume of the installation, which is relevant for mobile equipment, and it also reduces the number of stages that require cooling and maintenance. The compressor and hydraulic loads are driven by permanent magnet synchronous machines, and energy storage is again provided by a battery system with a bidirectional dual active bridge converter. The main limitation of this architecture is the maturity of the high-frequency stage. As shown in Table 4.3, high-frequency solid-state transformers are assessed at TRL 4, compared with TRL 7 to 8 for cast-resin designs, and the switching frequencies reported for megawatt-class demonstrators range from 1 to 20 kHz without an established industrial practice. This architecture is therefore considered a future alternative solution.

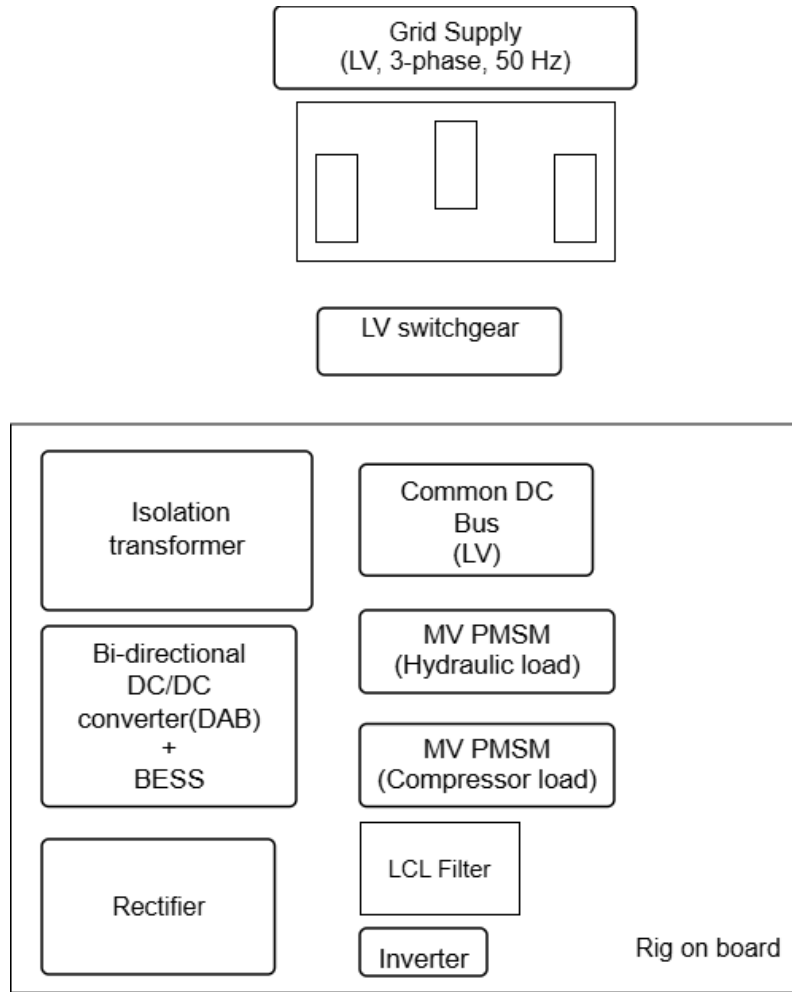


Figure 4.4: Kilowatt-scale common DC bus with AC/DC front-end and LCL filter

Figure 4.4 presents a kilowatt-scale architecture supplied at low voltage, in which the DC bus is established using an isolation transformer, an LCL filter and a rectifier. All three are mature components; Tables 4.4 and 4.5 assess them at TRL 9. The harmonic mitigation that is performed actively by the front end in Figure 4.2 is provided here by the LCL filter, which is less costly and well established, although the compensation is fixed at the design stage. As in the previous architecture, the compressor and hydraulic loads are driven by permanent magnet synchronous machines and energy storage is provided by a battery system with a bidirectional dual active bridge converter. The main disadvantage is the line-frequency transformer, which reintroduces the mass and volume that the high-frequency architecture is intended to avoid. This architecture provides improved power quality, efficient energy conversion, and flexible integration of battery storage for future industrial applications.

4.3 Simulation

The architecture selected based on the evolution matrix in Section 4.2 is a grid-forming model with a common DC bus and DC-link storage. The configuration is given first, followed by the results grouped by the behavior each set of cases was designed to test.

4.3.1 Simulation configuration

The model is built in MATLAB R2025b using Simulink and Simscape Electrical with an average-model converter representation. Switching behavior is not simulated, so the results describe control and power-flow dynamics rather than switching harmonic content.

All per-unit quantities use a common base taken from the machine rating: $S_b = 645.9$ kVA, $V_{LL} = 6.6$ kV, $f = 50$ Hz. The derived bases are $Z_b = 67.44$ Ω , peak phase voltage 5388.9 V, peak phase current 79.9 A, and torque 4112 N · m.

The converter is evaluated over a matrix of four supply scenarios and four disturbance families, giving sixteen simulation cases in total. Table 4.11 defines them. Every case uses the same duty cycle, the same converter parameters and the same solver settings. The only difference between any two cases is the supply scenario, the disturbance, or both.

Table 4.11: Simulation matrix. Each disturbance is applied one second into the drilling phase for the scenarios A to D with varying grid strength, at 7.0 s, once the operating point has settled.

Disturbance	A	B	C	D
None (duty cycle only)	✓	✓	✓	✓
Frequency ramp, -2.0 Hz/s for 0.5 s	✓	✓	✓	✓
Voltage sag to 0.5 pu for 200 ms	✓	✓	✓	✓
Voltage sag to 0.0 pu for 200 ms	✓	–	–	✓
Phase step of 60° , permanent	✓	–	–	✓

The severe sag and the phase step are applied to scenarios A and D only, as those two influence the range of supply strength. However, scenarios B and C do not have much impact on the supply strength.

The solver is variable-step `ode23t` with a relative tolerance of 10^{-3} . Only the converter control is discrete, at a sample time of 200 μ s. All logged signals are recorded on a fixed 0.1 ms grid independent of the control sample time, so every engagement time is resolved to 0.1 ms and the cases compare directly.

4.3.2 Duty-cycle operation

4.3.2.1 The Rig Duty Cycle

A surface blast-hole rig does not draw constant power. It works through a repeating sequence of operations, and the electrical demand of each one is different. The

simulation represents that sequence as a torque profile applied to a single induction machine, which stands in for the aggregate rig load of both the hydraulics and the air compressor.

Once loaded, the rig moves through four phases. *Idling* is when the rig is energized, and both the compressor and hydraulics are running, so the motor draws 40% of what drilling torque demands and is the lowest load of the cycle. It is not a no-load condition. *Drilling* is the working phase, the longest and the heaviest, and it occupies 13 of the 21 seconds simulated. During the *rod change* phase, the drill rod is extended or withdrawn, and the load falls back to near the idling phase level. *Tramming* moves the rig between holes at an intermediate load. Between phases, the torque is ramped rather than stepped, so that the machine can represent a real rig.

The machine is started separately from this cycle. The shaft is unloaded, and an open-loop V/f ramp brings it to nominal frequency at 2.5 s with no mechanical load, and the duty cycle begins when the load engages at 3.0 s. Everything before that point is a starting transient and is excluded from the averages reported here.

Table 4.12 defines the cycle and gives the measured result for scenario A, which has the stiffest supply ($SCR = 20$) and does not include any grid disturbances. The intervals are used for every steady-state value quoted in the rest of Section 4.3.

Table 4.12: Operating cycle and measured steady state, scenario A. The torque values below are referred to the 4112 N·m torque base. All powers are per unit on 645.9 kVA.

Phase	Interval [s]	T_e [pu]	P_{mot} [pu]	P_{grid} [pu]	P_{batt} [pu]
Idling	3.0–5.0	0.2805	0.2876	0.7106	−0.3881
Drilling	6.0–19.0	0.7154	0.7374	0.7107	+0.0685
Rod change	19.5–21.5	0.2946	0.3019	0.7105	−0.3627
Tramming	22.0–24.0	0.4910	0.5034	0.7107	−0.1676

The DC-link power balances in every phase: converter power plus battery power equals motor power, and at the drilling phase this reads $0.6689 + 0.0685 = 0.7374$ pu against a measured motor power of 0.7374 pu.

4.3.2.2 Peak shaving

The P_{mot} and P_{grid} columns of Table 4.12 is verified against Figure 4.5. The motor power moves by 0.4498 pu between idle and drilling, which is 290.5 kW. The grid import moves by 0.0002 pu, which is 0.13 kW. The converter passes only 0.044 % of the load variation to the point of supply and the battery absorbs the rest.

Figure 4.5 shows the same result as a time record. The upper panel is the duty cycle itself. The lower panel is the power profile.

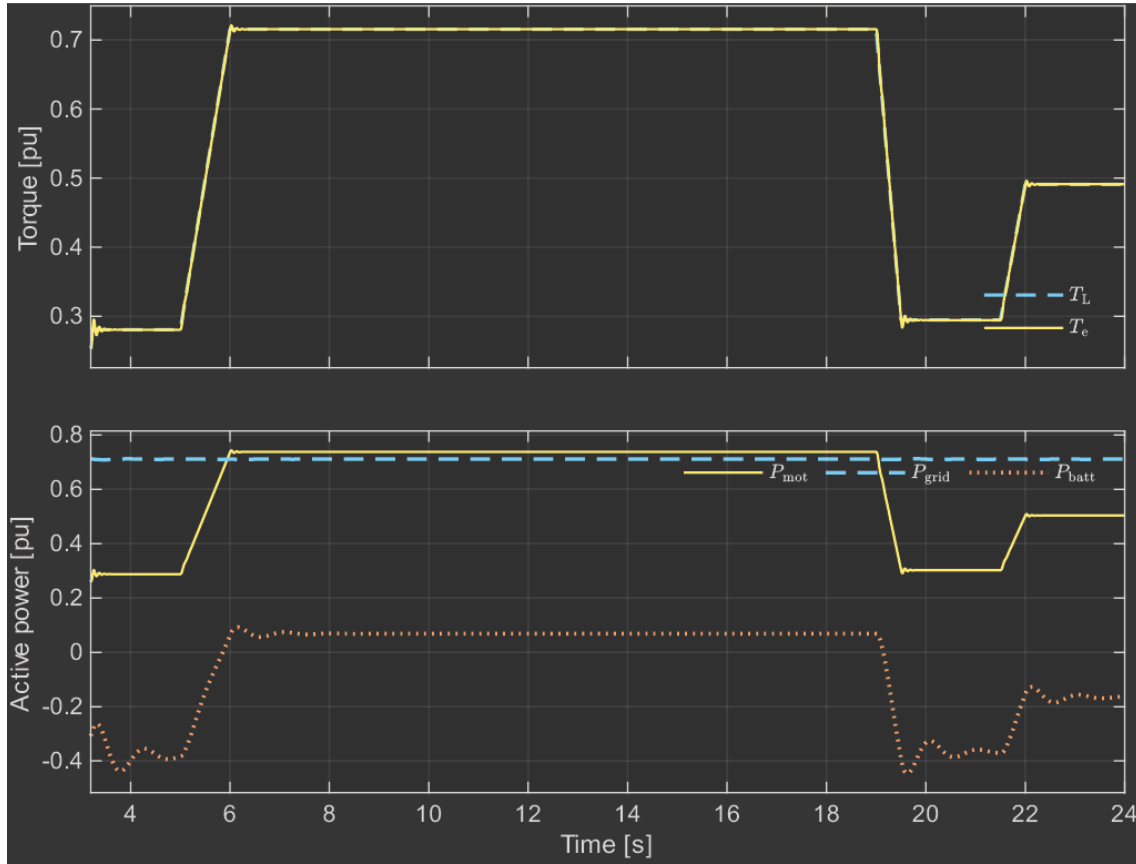


Figure 4.5: Duty-cycle operation, scenario A. Upper panel: load torque T_L and electromagnetic torque T_e . Lower panel: motor, grid and battery active power. The record starts at 3.2 s, once the V/f starting transient has decayed.

The battery signature follows from the same table. In three of the four phases, the converter imports more than the machine consumes and the surplus charges the DC link, which is why P_{batt} is negative for idle, rod change, and tramming. Only during drilling the machine demand exceeds the demand, so the battery discharges during this time.

4.3.3 Sensitivity to grid strength

The measurement is taken at the converter terminals, where P_{conv} is 0.6689 pu or 432.0 kW, within 1.8 % of the set point. The active-power reference is -440 kW. The negative sign indicated the import from the grid. The grid import is a different quantity: averaged over the cycle it is 459.0 kW, which is 19.0 kW higher, because the network losses between the source and the converter terminals lie outside the control loop.

4.3.3.1 Scope of the comparison

Scenarios A, B and C differ in one parameter. The short-circuit ratio falls from 20 to 6 to 3 while the feeder length, source voltage, load factor and substation capacity factor stay at their nominal values, so any difference between these three runs is

attributable to source impedance. Scenario D is not a fourth point on that sweep, as Table 4.13 shows.

Table 4.13: Scenario definitions from the parameter file. The source reactance is computed from the short-circuit ratio and the capacity factor at an X/R ratio of 10. The feeder and the isolation transformer act as additional series elements.

Parameter	A	B	C	D
Short-circuit ratio	20	6	3	2
Capacity factor	1.00	1.00	1.00	0.80
Effective short-circuit ratio	20	6	3	1.6
X_{src} [pu]	0.0498	0.1658	0.3317	0.6219
Feeder length [km]	3	3	3	5
Source voltage [pu]	0.98	0.98	0.98	0.94
Mechanical load factor	0.90	0.90	0.90	1.10

Scenario D changes five parameters at once, and the load change is visible directly in the measurements. The mechanical load factor in Table 4.13 is a multiplier on the shaft power of each phase of the rig duty cycle, applied before the power is converted to a torque, so it describes how hard the rig is being worked rather than how heavily the machine is loaded against its rating. It is 0.90 for scenarios A, B and C and 1.10 for scenario D, which represents a drilling duty heavier than nominal. Even in scenario D the drilling torque is 0.8744 pu, so the machine remains within its rating. D's torque should therefore be $1.10/0.90 = 1.2222$ times that of the other three in every phase of the cycle. Drilling torque is 0.8744 pu in D as compared to 0.7154 pu in A, resulting in a ratio of 1.2223. Across all four phases the measured ratios lie between 1.2220 and 1.2225. Scenario D is therefore reported as a combined worst case and is excluded from any statement about grid strength alone.

Figure 4.6 shows the modeled system and the point at which each logged quantity is taken. The converter regulates power at its own terminals while the supply measurement is taken before the feeder and the transformer, and the network in between carries a loss that grows as the connection weakens.

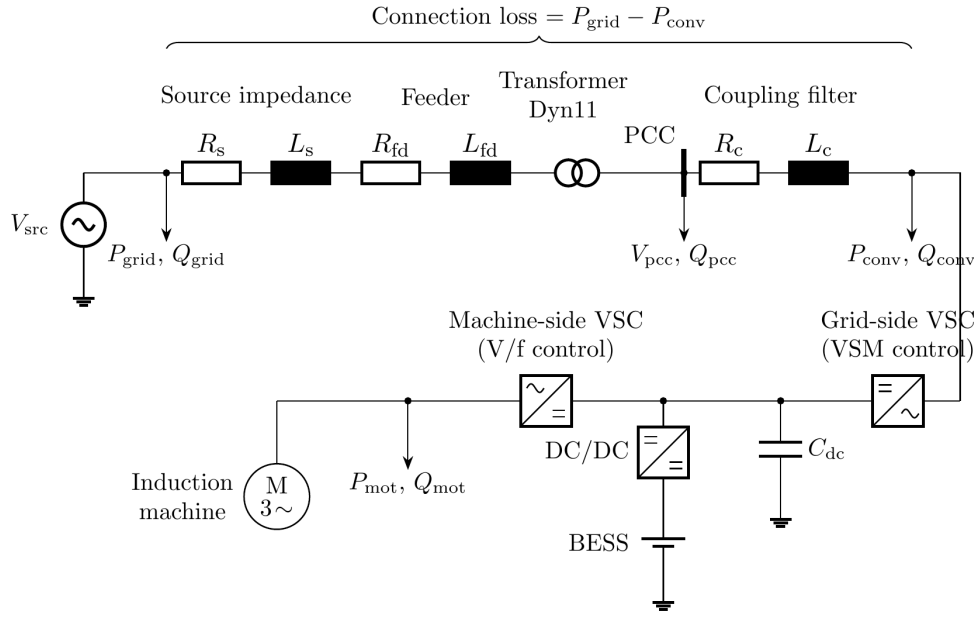


Figure 4.6: Single-line diagram of the modeled system, showing where each quantity in Table 4.14 is measured. The connection loss reported there is the difference between the active power at the source and that at the converter terminals, so it covers the source impedance, the feeder, the transformer and the coupling filter.

Table 4.14: Drilling-window steady state. Loss is measured between the source and the converter terminals, marked in Figure 4.6.

Quantity	A	B	C	D
V_{pcc} [pu]	0.9350	0.9222	0.9059	0.8509
P_{grid} [pu]	0.7107	0.7199	0.7346	0.7984
P_{conv} [pu]	0.6689	0.6686	0.6679	0.6633
P_{mot} [pu]	0.7374	0.7374	0.7374	0.9057
Loss [kW]	27.0	33.1	43.1	87.3
Q_{conv} [pu]	-0.0375	-0.0901	-0.1577	-0.3878
i_f [pu]	0.7288	0.7397	0.7600	0.8798
δ [deg]	-27.79	-28.75	-29.91	-33.45
E_{emf} [pu]	0.8098	0.8309	0.8592	0.9640

Figure 4.7 presents the first four rows of Table 4.14 graphically. The upper panel makes the central point: the converter power is flat across the four scenarios while the PCC voltage falls and the grid import rises. The gap between the two power traces is the connection loss, plotted below.

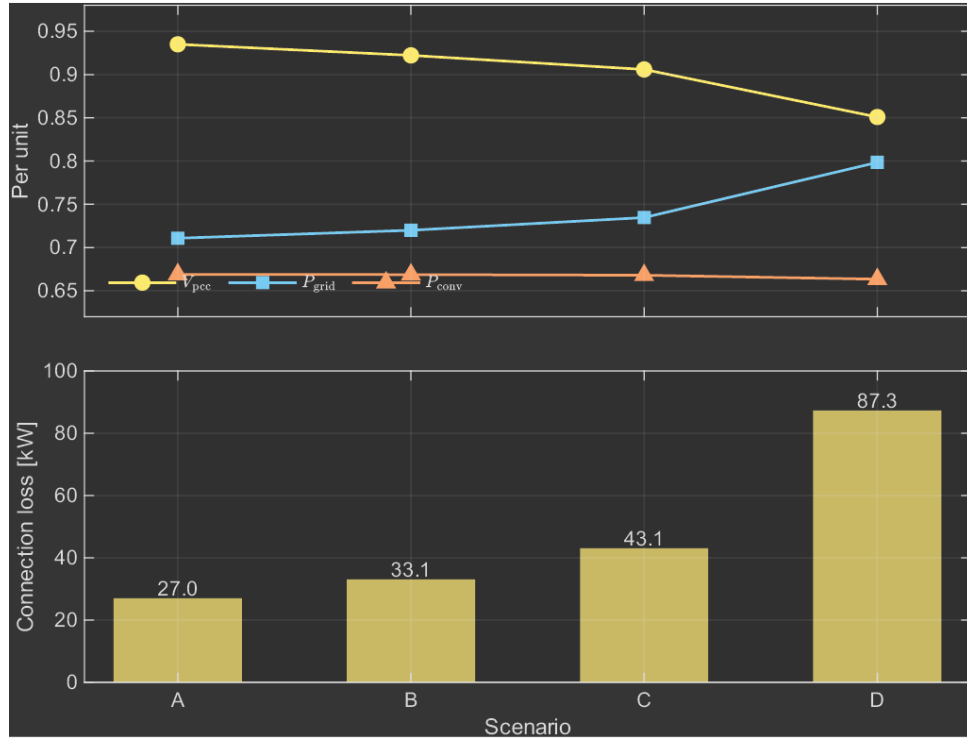


Figure 4.7: Steady state across the four scenarios during drilling. Upper panel: PCC voltage, grid import and converter power. Lower panel: the connection loss, which is the difference between the two power traces above.

4.3.3.2 Voltage at the point of common coupling

The PCC voltage settles at 0.9350 pu on the stiffest supply and falls to 0.9059 pu at a short-circuit ratio of 3. The voltage error integrated by the AFE voltage controller is given by Equation (4.1),

$$v_{err} = E_{ref} + K_{d,vc} i_{fq} - V_{pcc}, \quad (4.1)$$

where $K_{d,vc} = 0.20$ pu is the reactive-current droop coefficient. The integrator output is bounded so that the internal EMF lies between 0.50 and 1.20 pu. Across the four undisturbed runs, the EMF settles between 0.8098 and 0.9640 pu, as shown in Table 4.14, which are within the limits. For the runs with grid disturbances, the integrator reaches its limits. The voltage loop settles, and it is given by Equation (4.2),

$$V_{pcc} = E_{ref} + K_{d,vc} i_{fq}. \quad (4.2)$$

This applies to the settled operating point. During a transient, the integrator input is not zero. Under the 60° phase step on the weak supply, the EMF reaches 1.20 pu within 1.6 ms of the step, as shown in Section 4.3.6. As long as it sits there, the loop is open, and Equation (4.2) gives the voltage at the point of common coupling. Since the measured voltage is below the reference in every scenario, Equation (4.2) requires $i_{fq} < 0$, which is consistent with the converter reactive power in Table 4.14. The spread from 0.9350 to 0.8509 pu is the droop characteristic operating as designed and not a steady-state error. The distinction matters for specification:

raising E_{ref} shifts the whole characteristic, whereas reducing $K_{\text{d,vc}}$ flattens it at the cost of reactive-power sharing.

4.3.3.3 Losses and converter power

Between scenarios A and D, P_{conv} falls by only 3.6 kW (from 432.0 to 428.4 kW, 0.84 %), whereas P_{grid} rises by 56.6 kW (from 459.0 to 515.7 kW, 12.3 %). The two differ because they are measured at different points: P_{grid} is measured at the source and so includes the network loss between the source and the converter terminals. That loss grows from 27.0 to 87.3 kW as the current increases and the feeder is lengthened to 5 km in scenario D. Over scenarios A to C, where only the short-circuit ratio changes, the corresponding changes are 0.65 kW in P_{conv} and 15.4 kW in P_{grid} .

The active-power controller regulates P_{ref} at the PCC: it computes power from the PCC voltage and the filter current, so P_{pcc} is held at 0.6812 pu (440 kW) in all four scenarios. P_{conv} is measured on the converter side of the coupling filter, so its small drop is the resistive loss of that filter as the filter current rises from 0.73 to 0.88 pu. Any verification of a droop or set-point law therefore has to be carried out close to the converter; evaluated at the grid, the same control law depends on supply strength. Section 4.3.4 quantifies that error.

4.3.3.4 Effect on peak shaving

Table 4.15 repeats the duty-cycle measurement for all four scenarios. The mean values are taken after the load is applied at 3.0 s. The motor swing is the difference between the highest and lowest phase-mean motor power, which is the drilling and idling phases. Across the A to C sweep the share of it that reaches the grid grows from 0.044 to 0.356 %, while the grid-side swing itself rises from 0.13 to 1.03 kW against a motor swing of 290.5 kW. Scenario D carries the higher load factor, so its 7.82 kW is measured against a motor swing of 358.1 kW instead of 290.5 kW.

Table 4.15: Peak shaving over the operating cycle, computed from phase means.

Quantity	A	B	C	D
P_{mot} variation [kW]	290.5	290.5	290.5	358.1
P_{grid} variation [kW]	0.13	0.26	1.03	7.82
Transmitted variation [%]	0.044	0.089	0.356	2.18
Cycle-mean P_{grid} [kW]	459.0	465.0	474.4	515.6
Excess over set point [kW]	19.0	25.0	34.4	75.6

Figure 4.8 overlays the four scenarios as time records. The PCC voltage traces are separated by scenario and stay flat within each one, so the operating point instead of the duty cycle setting the voltage.

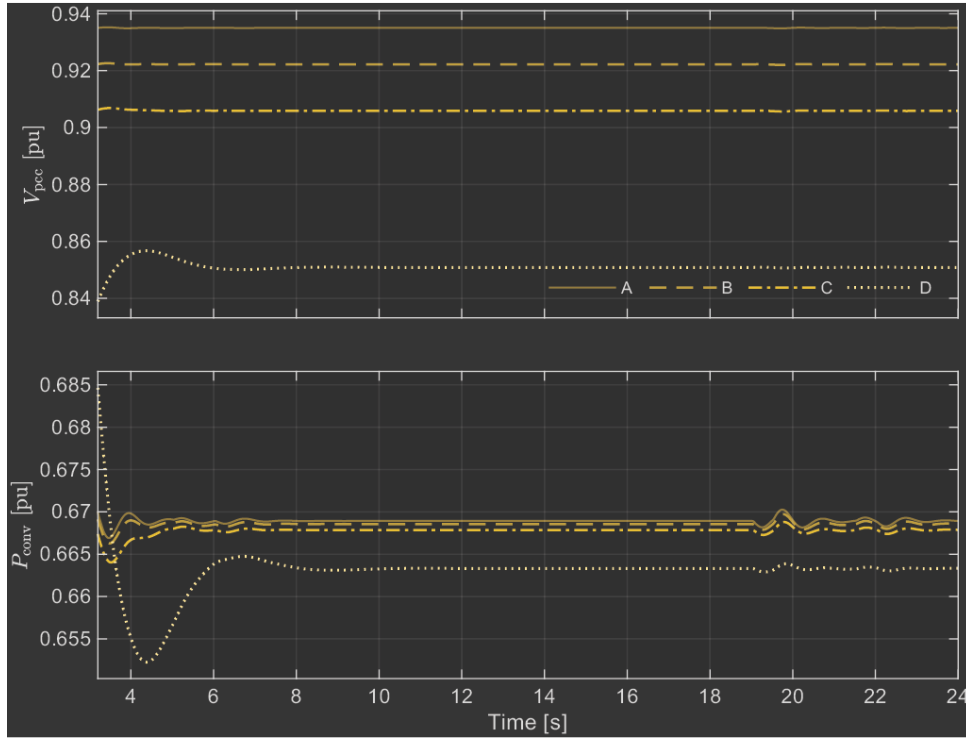


Figure 4.8: PCC voltage and converter active power for scenarios A to D under the undisturbed duty cycle. Scenarios A, B and C differ only in short-circuit ratio; scenario D additionally carries a longer feeder, a reduced source voltage, a higher load factor and a lower capacity factor.

The small disturbance visible in both panels shortly after 19.5 s is the load stepping down from drilling to the rod change, which is the largest change in the cycle. The converter reference is not changed across that step, so the battery absorbs it through the DC link, and what appears in the converter power is the DC-link voltage recovering. The excursion peaks about 0.001 pu above the settled level, under 1 kW against an operating point of 432 kW.

The rig is commanded to draw 440 kW, and Table 4.15 shows the reading of 459.0 kW on the stiffest supply and 515.6 kW on the weakest. The difference is the network loss.

4.3.4 Frequency ramp response

The four scenarios apply a frequency ramp of 2.0 Hz/s to the source over a 0.5 s window, from 50 to 49 Hz, and hold the final frequency for the rest of the run. The active-power droop gain is set to $K_f = 10$ pu/pu, a 10 % droop characteristic. The converter re-synchronizes to the new supply frequency in every case, and its own internal frequency ω_c settles at 49.0 Hz, which is 0.980 pu. The commanded power is therefore $10 \times 0.020 = 0.200$ pu for all the cases. Any difference between them comes from the supply, and the Table 4.16 shows whether the droop law holds independently of connection strength.

Table 4.16: Droop gain evaluated at the grid and converter. The power increment is taken between the undisturbed run and the corresponding frequency run at the drilling state, with $\Delta f = 1$ Hz, or 0.020 pu, throughout.

Quantity	A	B	C	D
P_{conv} undisturbed, 50 Hz [pu]	0.6689	0.6686	0.6679	0.6633
P_{conv} at 49.0 Hz [pu]	0.4753	0.4752	0.4751	0.4739
K_f at converter [pu/pu]	9.68	9.67	9.64	9.47
P_{grid} undisturbed, 50 Hz [pu]	0.7107	0.7199	0.7346	0.7984
P_{grid} at 49.0 Hz [pu]	0.4954	0.4995	0.5057	0.5289
K_f at grid meter [pu/pu]	10.77	11.02	11.45	13.48

At the converter terminals, the measured droop gain, $K_f = \Delta P_{\text{conv}}/\Delta\omega$, lies between 9.47 and 9.68, which is 3.2 to 5.3 % below the commanded 10, and varies by 2.2 % as the short-circuit ratio falls from 20 to 2. Evaluated with the grid-side power instead, $\Delta P_{\text{grid}}/\Delta\omega$, the same gain rises from 10.77 to 13.48, so at the grid meter the droop appears to depend on connection strength.

The significant change is because of the loss term from Section 4.3.3. Losses scale with the square of the filter current, so when the converter reduces its import, the loss falls with it, and these losses are also considered for the droop response. The Droop must be assessed at the converter terminals.

The gains above describe where the converter settles, as shown in Figure 4.9. The same ramp is applied in all four scenarios, from 50 to 49 Hz between 7.0 and 7.5 s. So a single trace covers the source, and the four scenarios that differ are the converters' own. Each internal frequency falls more slowly than the source at first, which is the virtual inertia of $H = 2$ s resisting the change, then overshoots to 48.88 Hz in scenario A and 48.83 Hz in D before recovering to 49.0 Hz. Converter power swings with it, leaving 0.669 pu and reaching -0.307 pu on A, so the rig briefly delivers about 198 kW into a supply whose frequency is falling. The swing is roughly five times the 0.200 pu increment the droop law commands and settles in 2.5 to 4.0 s. A weaker supply softens it: the peak falls to -0.235 pu on D and arrives 0.18 s later, since the larger series reactance couples the virtual rotor to the grid less stiffly. The excursion crosses zero in every scenario, so the converter and the DC link have to carry reverse flow of about 0.31 pu for as long as it lasts. The droop law is therefore met at the settled point while the path to it is lightly damped, and the two have to be specified separately.

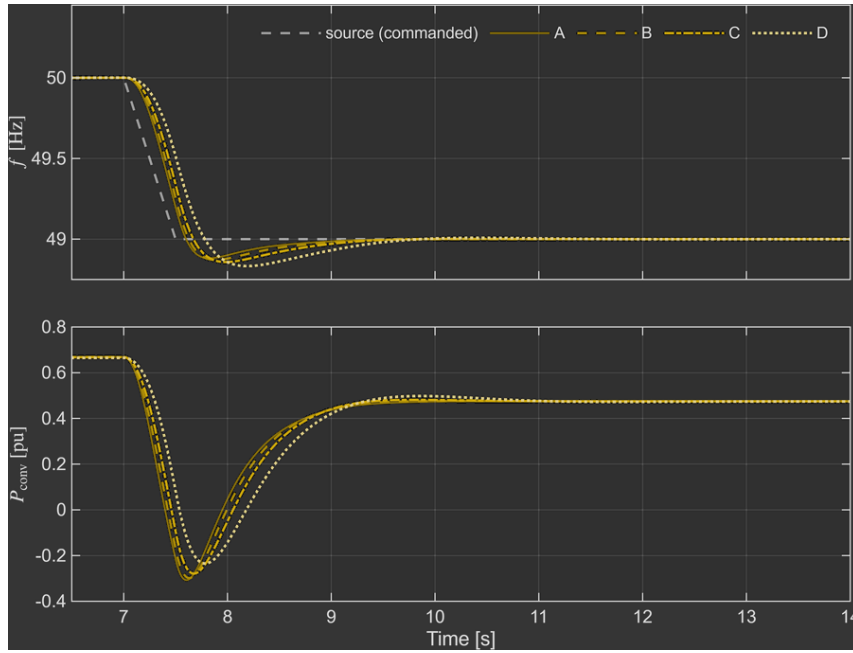


Figure 4.9: Response to the frequency ramp. Upper panel: the commanded source frequency, which is the same in all four scenarios, together with the internal frequency each converter reaches. Lower panel: converter active power. The ramp runs from 7.0 to 7.5 s, and the final frequency is held thereafter.

The converter control includes two limiting functions that act only during large disturbances. They are part of the control and keep the converter operating through an event, unlike protection, such as the gate-driver de-saturation detector discussed in Section 4.3.7.1, which trips it. The first is the current limiter. Once the filter current exceeds 1.20 pu, it adds virtual resistance in proportion to the overcurrent, which pulls the current back. The second is the fault ride-through (FRT) mode. The converter enters it when the measured PCC voltage collapses and leaves it when the voltage recovers. While it is active, the active-power synchronization loop is frozen and the angle-restoring path is disconnected, so the virtual rotor is not driven by a power measurement taken at a collapsed voltage. Neither function engages during the frequency ramp in any scenario.

4.3.5 Voltage ride-through

The four scenarios are now tested by applying a balanced three-phase sag of 200 ms at the source, one second into the drilling phase. Two depths are used: a retained voltage of 0.5 pu, and a sag to 0.0 pu at the source as shown in Table 4.17. Both protection functions are reported as the time for which each is active, resolved to the 0.1 ms logging interval.

Table 4.17: Voltage ride-through. Engagement is the time for which each function is active, resolved to the 0.1 ms logging interval. Peak quantities were taken only for the zero-voltage cases.

Scenario	Retained [pu]	Limiter [ms]	FRT mode [ms]	i_f peak [pu]	$ \delta $ peak [deg]
A	0.5	148.0	139.6	—	—
B	0.5	45.6	35.4	—	—
C	0.5	9.6	0.0	—	—
D	0.5	6.4	2.4	—	—
A	0.0	205.4	196.0	1.4106	123.97
D	0.0	390.2	300.4	1.5624	161.85

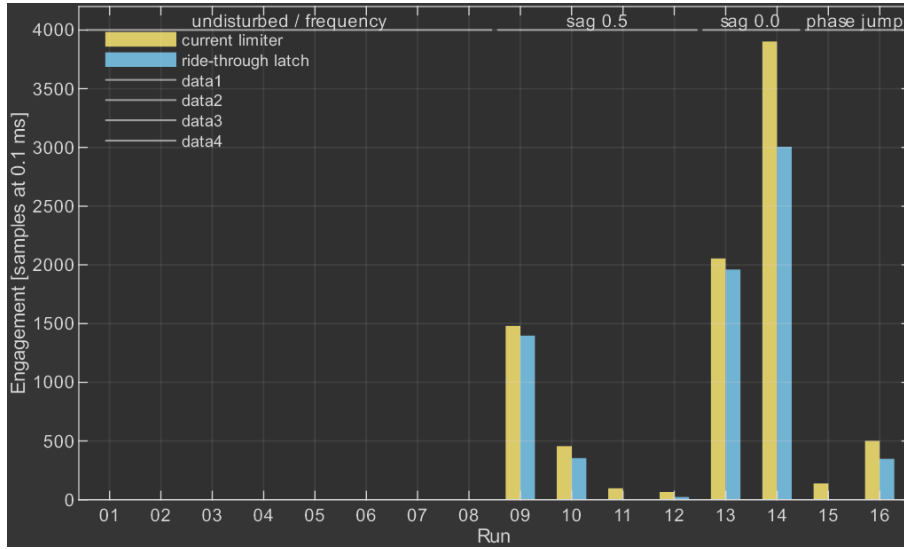


Figure 4.10: Current-limiter and FRT-mode engagement across the sixteen simulation cases, resolved to 0.1 ms. The undisturbed and frequency-ramp cases show no engagement at all. Under the moderate sag, the stiffest supply is the most severely affected. At zero retained voltage, the ordering reverses.

Scenario A holds the current limiter active for 148.0 ms against 6.4 ms for scenario D, and the ordering across the four scenarios is similar in short-circuit ratio. The mechanism is the series impedance. A depressed source behind a large reactance is partly isolated from the coupling point, so the weaker the connection, the more it shields the converter from a disturbance originating at the source. The two branches meet at the coupling point, so $(E - V_{pcc})/jX_c = (V_{pcc} - V_{src})/jX_s$ when no other current is injected there and the V_{pcc} gives the voltage-divider relation.

$$V_{pcc} \approx \frac{E/X_c + V_{src}/X_s}{1/X_c + 1/X_s}. \quad (4.3)$$

With a converter-side reactance $X_c = X_v + X_f = 0.60$ pu and the pre-fault internal EMF, it predicts a retained PCC voltage of 0.131 pu for scenario A in the zero-

voltage sag, against a steady state of approximately 0.13 pu in the simulation, seen in the upper panel of Figure 4.11.

Figure 4.11 records the two zero-voltage cases. During the sag the shielding is visible directly: the weak supply holds 0.64 pu at the coupling point while the stiff one is driven to the steady-state Equation (4.3), and the filter currents move in the opposite way. What separates the cases is the recovery. Scenario A is back at its operating point within a cycle of the source returning; scenario D swings between 0.25 and 1.25 pu for 2.2 s first, for a reason Section 4.3.7 attributes to the control rather than to the connection. Converter power follows the swing from below zero to just over 2 pu, while motor power holds at 0.906 pu throughout, so none of it reaches the drive.

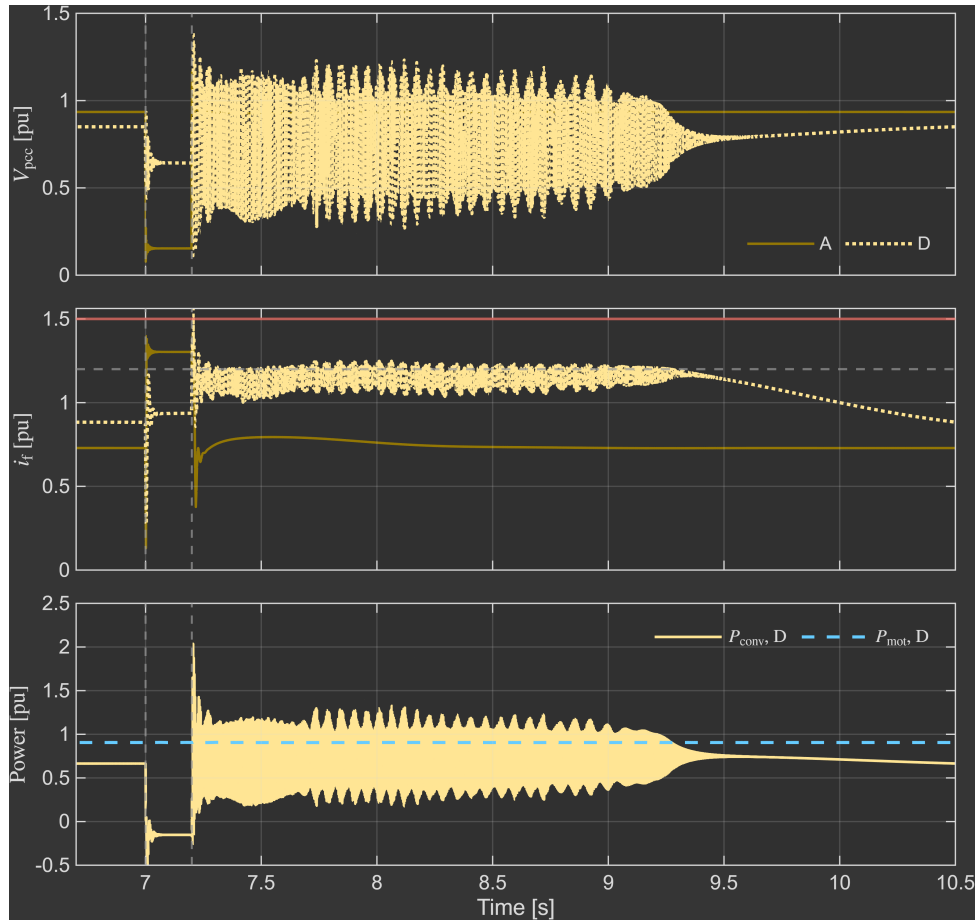


Figure 4.11: Sag of the source voltage to zero for 200 ms from 7.0 s, on the stiffest and the weakest supply. Upper: PCC voltage. Middle: filter current against the 1.20 pu limiter threshold and the 1.50 pu converter rating. Lower: converter and motor active power for scenario D. The dashed vertical lines mark the start and the end of the sag.

At zero retained voltage the ordering reverses and scenario D becomes the more severe case, holding the limiter active for 390.2 ms against 205.4 ms for scenario A. This is true, since the higher load factor of scenario D leaves less converter headroom. The rest comes from the control rather than the connection: the limiter

stays active for 89.8 ms after the converter leaves FRT mode, against at most 15.4 ms in every other case simulated. In FRT mode the synchronization loop is held at nominal frequency, so nothing restrains the load angle and it drifts beyond the $\pm 70^\circ$ boundary. When FRT mode ends, the angle correction is reconnected in a single control step at a load angle of about 98° . That correction is proportional to the excess angle and has no output limit, so it commands the virtual rotor to 74.25 Hz and keeps the current above the limiter threshold while the converter re-synchronizes. This is not integrator windup. Both controller integrators have anti-windup: the active-power integrator is clamped to ± 0.20 pu and frozen in FRT mode, and the PCC-voltage integrator is limited so that the EMF stays between 0.50 and 1.20 pu. The inner current controller is proportional and has no integrator. Section 4.3.7 gives the sequence in detail.

4.3.6 Grid phase jump

A permanent 60° phase step is applied to the source in scenarios A and D, one second into drilling. Due to this the converter has a new operating point means the converter has re-synchronized to a new grid angle. Both runs recover exactly. Table 4.18 gives the peak quantities.

Table 4.18: Grid phase jump of 60° . Results were taken for peak values only.

Quantity	A	D
Short-circuit ratio	20	2
Pre-event i_f [pu]	0.7288	0.8829
Peak i_f [pu]	1.9712	1.6936
as % of $I_{\max}$	131.4	112.9
Peak $ \delta $ [deg]	97.26	173.27
Peak E_{emf} [pu]	1.0635	1.2000 (bounded)
ω_c range [pu]	0.9939–1.2362	0.9148–1.3465
Equivalent frequency [Hz]	49.70–61.81	45.74–67.33
Minimum V_{pcc} [pu]	not logged	0.0137
Limiter engagement [ms]	13.8	50.2
FRT mode active [ms]	0.0	34.8

4.3.6.1 Event sequence

The logged diagnostics resolve the first 25 ms of the event. Table 4.19 gives the order in which the internal actions occur, which is not the order the control structure was designed around. Figure 4.12 shows the same event as a time record.

The voltage controller reaches its bound 3.2 ms before the current limiter engages and 7.0 ms before the current peaks following the Equation (4.1). The phase step collapses the measured PCC voltage, so the integrator input approaches E_{ref} , and with an integral gain of 377 the output reaches its upper bound in well under a millisecond. The controller commands the largest available internal EMF into a collapsing terminal voltage, which raises the current. The limiter is then required to contain within the boundary values. The two loops act in opposition during the first

Table 4.19: Event sequence. The phase step is applied at 7.0000 s.

Time [s]	Elapsed [ms]	Event
7.0000	0.0	60° phase step applied
7.0016	1.6	E_{emf} reaches the 1.20 pu bound
7.0048	4.8	current limiter engages and FRT mode activated
7.0086	8.6	peak filter current, 1.6936 pu
7.0138	13.8	peak load angle, 173.27°
7.0216	21.6	minimum PCC voltage, 0.0137 pu
7.2347	234.7	last sample with limiter or FRT mode active

few milliseconds of a phase jump, and the voltage loop acts first. Scenario A does not show this, since its EMF peaks at 1.0635 pu, well inside the bound. Figure 4.12 shows the event as a time record.

4.3.6.2 Current limiting performance

The limiter does not clamp the current directly. It raises an effective series resistance through the virtual admittance path, which reduces the current by changing the impedance at the converter. It is then applied through the control loop, so it inherits the bandwidth of that loop, and it cannot influence a current change that is complete before the loop has responded.

A phase step is exactly such a change. The driving voltage across the series path is the difference between the converter EMF and the source, $E\angle\delta_0 - V_{\text{src}}$ before the step and $E\angle\delta_0 - V_{\text{src}}e^{j\theta}$ immediately after it, since the source magnitude is unchanged and the converter EMF is an integrator state in both angle and magnitude that cannot move within the step. Subtracting the two cancels the EMF, and the operating point with it, leaving $V_{\text{src}}(1 - e^{j\theta})$ and it is of length V_{src} separated by θ , so its magnitude is $2V_{\text{src}}\sin(\theta/2)$, and dividing by the series reactance gives

$$\Delta i \approx \frac{2V_{\text{src}}\sin(\theta/2)}{X_c + X_s}. \quad (4.4)$$

Taking $X_c = 0.60$ pu, and a source-side reactance of 0.116 pu for scenario A and 0.692 pu for scenario D, using Equation (4.4) gives us 2.0975 and 1.6104 pu for these scenarios. The measured peaks are 1.9712 and 1.6936 pu, so this shows that there is an overestimation by 6.4 % on the stiff supply and underestimation by 4.9 % on the weak one. The peak is set by the size of the step and by the series reactance, both of which are fixed before the control can act, so it cannot be brought down by changing the 1.20 pu limiter threshold.

The times in Table 4.19 shows the same result. The current reaches its peak 8.6 ms after the step, while the limiter first engages at 4.8 ms, so the limiter is active for less than four milliseconds before the peak is reached. Under four milliseconds is not long enough for the added virtual resistance to build a voltage drop that changes the current.

$$X_c + X_s \geq \frac{2V_{\text{src}}\sin(\theta/2)}{I_{\text{max}} - i_{f,0}} = \frac{0.98}{0.7712} = 1.271 \text{ pu}, \quad (4.5)$$

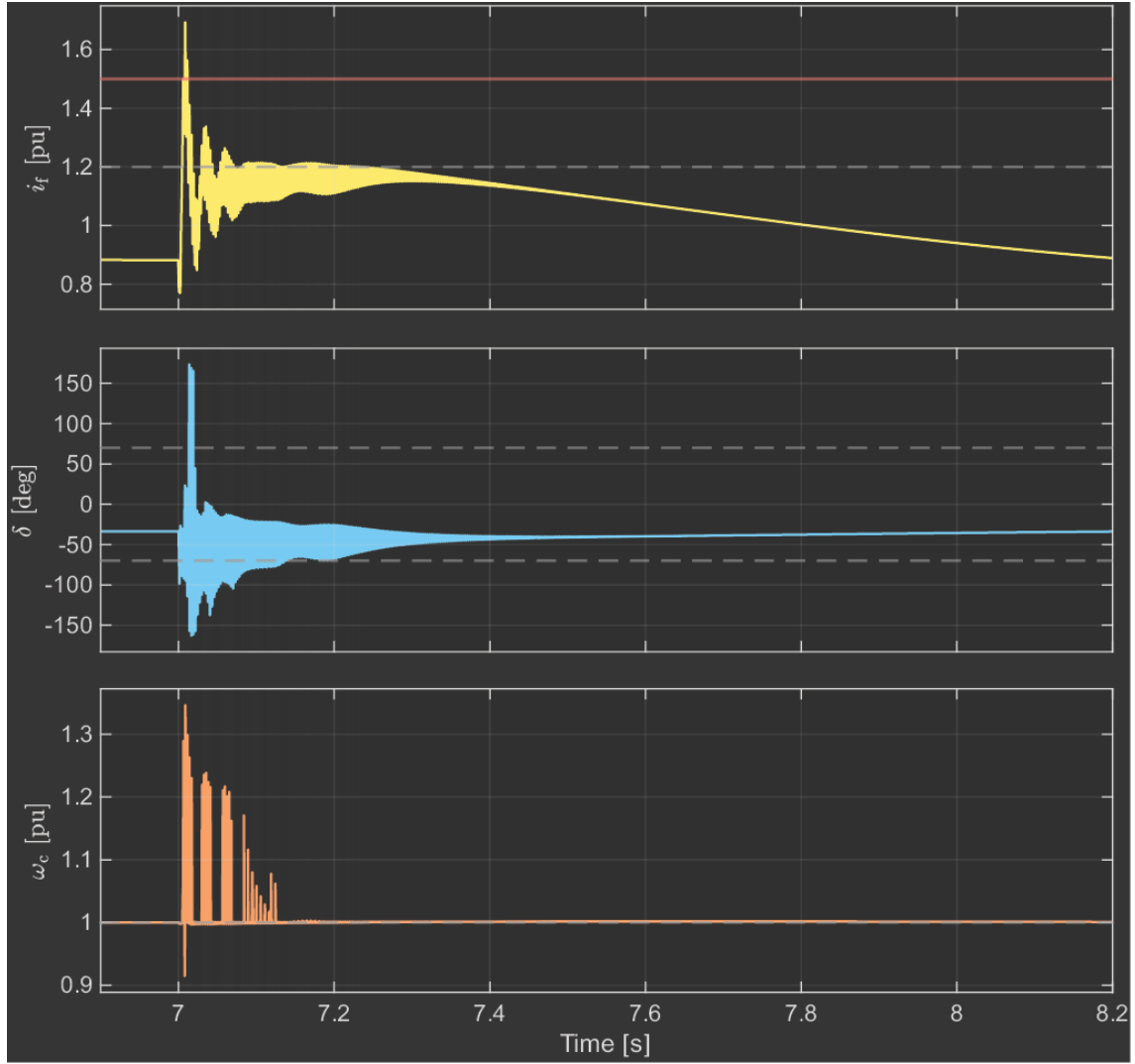


Figure 4.12: Scenario D under a 60° grid phase jump applied at 7.0 s. Upper: filter current with the 1.20 pu limiter threshold and the 1.50 pu converter rating. Middle: load angle with the $\pm 70^\circ$ boundaries. Lower: internal frequency. Shaded intervals mark the periods in FRT mode. The converter enters and leaves FRT mode between 7.0048 and 7.2347 s, holding for 34.8 ms in total, and on each interval the power synchronization loop is frozen and the angle restoring path disconnected.

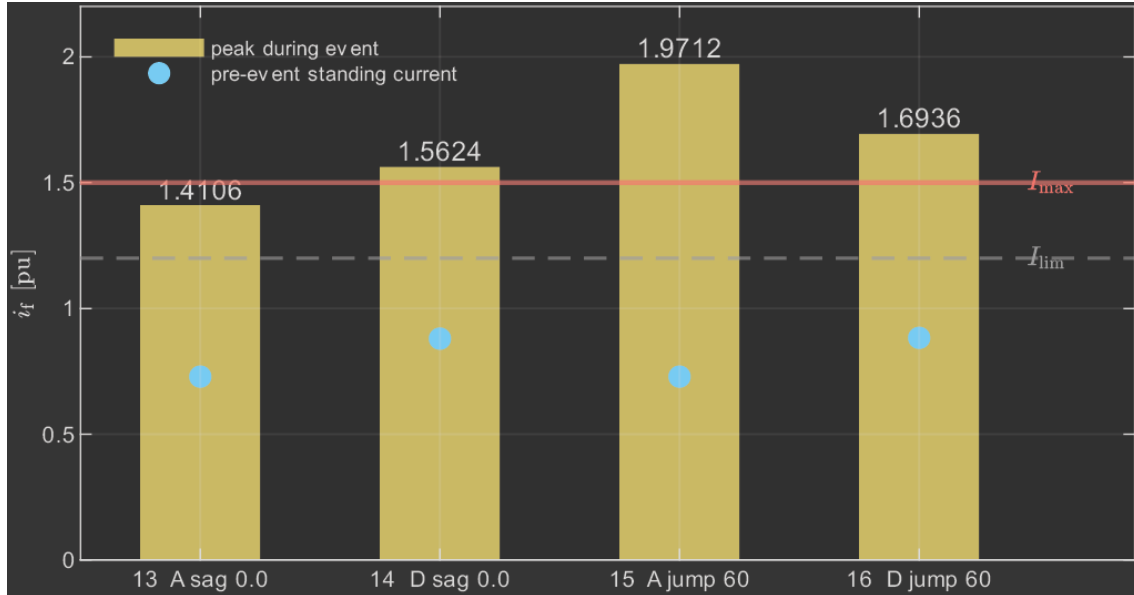
The consequence is a sizing constraint rather than a tuning one. Requiring the peak to stay inside the converter rating on the stiff supply gives the sizing condition of Equation (4.5), against the 0.716 pu present in the model. Since X_s is a property of the connection and X_f is fixed by the filter design, the whole increase falls on the virtual reactance, which would have to rise from 0.50 to at least 1.055 pu

4.3.7 Converter rating and limit engagement

The converter exceeds its 1.50 pu current rating in three of the sixteen cases, listed in Table 4.20. Figure 4.13 shows them against the rating and the limiter threshold, together with the standing current for each event.

Table 4.20: Runs exceeding the converter current rating.

Disturbance	Peak [pu]	% of rating	Time above rating
D, 60° jump	1.6936	112.9	2.00 ms
D, sag to 0.0 pu	1.5624	104.2	not measured
A, 60° jump	1.9712	131.4	not measured

**Figure 4.13:** Peak filter current for the four instrumented disturbance runs, against the 1.20 pu limiter threshold and the 1.50 pu converter rating. Markers show the pre-event standing current.

4.3.7.1 Scenario D with 60° jump

This case spends 2.00 ms above the rating within a 234.7 ms disturbance window. Whether that counts as a failure depends on which limit is reached first, the device's or its protection's. The device is not at risk, since one sized for this duty does not use up its thermal capability in two milliseconds at 112.9 % of rating. The gate driver has a de-saturation detector, which watches the voltage across the transistor while it conducts and turns it off when that voltage shows the current has left its normal range. The detector is blanked for only a few microseconds after turn-on, so it would see the whole 2.00 ms and trip. The converter would not be harmed in this case. The result is a protection setting that would take the rig offline without damaging the components.

4.3.7.2 Scenario D with 0.0 pu sag

The $\pm 70^\circ$ boundaries drawn in the middle panel of Figure 4.12 mark where the controller begins acting on the angle. The controller adds a frequency correction in proportion to how far the angle has moved beyond the limit, at one per unit of frequency for every radian of excess, so that the virtual rotor is pulled back before it slips a pole. The correction has no output limit and grows with the angle without

bound. The integrator summed with it is held to ± 0.20 pu, which leaves the total unbounded.

While the converter is in ride-through the correction is held at zero, and it returns in a single control step once ride-through ends. In this run that moment came at a load angle of about 98° , which is 0.49 rad beyond the limit, so a correction of 0.49 pu was applied in a single control step. The internal frequency reached 1.4850 pu, or 74.25 Hz, and synchronism took 2.2 s to recover. The same event appears in Figure 4.10 as the gap between the two bars for this case, with the current limiter still active 89.8 ms after ride-through ends against at most 15.4 ms in all the other cases.

4.3.7.3 Scenario A with 60° jump

The peak current of a phase jump is established before the limiter can act, as shown in Equation (4.4). Scenario A peaks at 1.9712 pu, 131.4 % of rating, and no change to any controller gain brings that down. The available remedies are a larger virtual reactance, a higher converter rating, or a restriction on the phase step on the connection is required to withstand.

4.3.7.4 Sizing the virtual reactance

The two disturbance families place opposite demands on the virtual reactance. Equation (4.5) requires at least 2.1 times the present value to keep the phase-jump current inside the rating, and that constraint is measured. Section 4.3.4 shows the swing growing smaller and slower as the total series reactance rises, which would point the same way, but the reactance that varies across those four scenarios belongs to the supply and not to the converter. A sweep of X_v itself would settle whether the two requirements agree or conflict.

4.3.7.5 Ride-through response

The converter enters ride-through on a voltage measurement alone. The 60° phase jump on scenario D is not a fault, since the source keeps its magnitude and only its angle moves, yet it drove the PCC voltage to 0.0137 pu and put the converter into ride-through for 34.8 ms. Freezing the power loop and disconnecting the angle path are therefore reachable by disturbances in which nothing has failed, and the condition for entering ride-through should be reconsidered on that basis.

4.3.8 Decoupling of the drive from the supply

The machine side does not see any of the disturbances. Rotor speed, electromagnetic torque and load torque are identical for the runs that does not have any grid disturbances and for the runs that have grid disturbances, across eight distinct grid events. The DC link and the open-loop V/f stage decouple the drive from the supply completely, which is the isolation property the architecture was selected for in Section 4.2.

4.3.9 Model verification

The model verification involved five checks that were carried out before the results were interpreted. Each compares a measured quantity against a value that follows independently from the model parameters, so agreement is evidence that the per-unit bases, the measurement points and the load model are correct.

The measured electromagnetic torque equals the commanded mechanical power divided by rated speed, referred to the torque base, to four decimal places in all four duty-cycle phases. This confirms the torque base and the load timeline.

The reactive power absorbed between the converter terminals and the coupling point equals $i_f^2 X_f$ to within 5×10^{-5} pu on every supply scenario, which confirms the filter reactance and the two power measurement points across the converter terminals.

The DC-link balance $P_{\text{conv}} + P_{\text{batt}} = P_{\text{mot}}$ holds to four decimal places at the drilling phase in all four scenarios. Three independently logged quantities agree, which is the strongest single indication that the power measurements can be relied on.

During the open-loop V/f ramp the unloaded machine accelerates at 0.50304 pu/s with a mean electromagnetic torque of 0.18622 pu. The modeled inertia gives an accelerating torque of 0.184 pu, leaving 0.0022 pu due to friction and windage.

The ratio of slip to torque is 0.007564, 0.007982, 0.007575 and 0.007735 across the four duty-cycle phases, a spread of 5.5 % about the mean. The machine stays in the linear region of its torque-slip characteristic throughout the cycle, and the drilling phase is the least linear of the four, as expected at the highest torque.

These checks establish internal consistency. They do not establish that the model represents a physical rig, which would require measurements from hardware. No such validation was performed, and none of the results in this section should be read as validated against a real installation.

4.3.10 Limitations of the simulation study

The converter is represented by an average model, so switching behavior is not simulated. The results describe control and power-flow dynamics. Harmonic content, filter design against switching frequency, and semiconductor loss fall outside what this model can support.

Each simulation covers a single operating cycle of 21 s. The battery state-of-charge balance over repeated cycles is therefore not established. Whether the storage returns to its starting state of charge across a working shift cannot be answered from these runs, and the storage is consequently sized here against peak power instead of the energy throughput.

Scenario D varies five parameters at once, as Table 4.13 sets out, and is reported as a combined worst case rather than as a point on the grid-strength sweep. Differences between scenario D and the other three cannot be attributed to supply strength alone. The clean comparison is the A to C sweep, where only the short-circuit ratio changes.

The duty cycle is a representative four-phase profile. It reproduces the power levels and the ordering of rig operations, but not the variability of real drilling, where formation changes and operator intervention produce load transitions that the modeled ramps do not capture.

5

Conclusion

This thesis aims to establish whether a single electrical architecture can serve a surface drill rig across the range of supplies from a stiff utility connection to a weak remote network. The work approached this question in two parts: A technology assessment decomposed the power supply into functional subsystems, mapped each according to readiness and maturity, and derived different architectures from the result. A simulation study then took the selected architecture and measured how it behaved under different mining conditions.

5.1 The technology assessment

Decomposing the power supply and building an evolution matrix for each subsystem produced a consistent picture in nine subsystems. The individual hardware is mature. Active front ends are commercially deployed at medium voltage, silicon carbide devices and liquid-cooled modules are at readiness levels 7 to 8, and battery technology suitable for the duty are in production. What is not mature is the layer above them. Predictive maintenance sits at readiness level 6 to 7, and digital twin and fleet analytics at 5 to 6. The obstacle to a power-agnostic rig is therefore not the power hardware but the supervisory control and data infrastructure that would allow a rig to recognize and adapt to whatever source it is connected to.

Cross-impact analysis showed why the subsystems cannot be selected independently. The battery voltage sets the operating range of the inverter, the inverter switching frequency drives cable losses and insulation stress, and the cable resistance limits the usable fraction of the stored energy. Raising the DC bus voltage reduces current and cable loss, but pushes the semiconductor choice towards higher-voltage devices. Thus a component substitution or choice is local, replacing an inverter, for instance, will propagate into cable sizing and cooling. So, a genuinely power-agnostic design has to be specified with these dependencies fixed rather than the components.

Three architectures were derived from the matrices, all built on a common DC bus. The bus is what makes the architecture source-agnostic in principle, since it admits an AC grid, a DC microgrid, a renewable source, or storage through the appropriate converter without altering anything downstream of it. The architecture selected for a detailed evaluation combines a grid-forming converter at the supply interface with DC-link battery storage.

5.2 Simulation findings

The storage decouples the rig from the grid Over the operating cycle the mean motor power varies by 290.5 kW between idling and drilling. This difference between the highest and lowest phase-mean motor power is referred to as the motor swing. On the stiffest supply the grid draw varies by only 0.13 kW over the same four phases, which is 0.044 % of the motor swing. The converter holds its 440 kW reference and the battery supplies the difference through the DC link, charging during idling, rod change and tramping and discharging during drilling. As the connection weakens, a larger share of the motor swing reaches the grid; in the weakest case studied the grid draw varies by 7.82 kW, which is 2.18 % of a motor swing of 358.1 kW. In the other direction, none of the grid disturbances simulated reached the machine: rotor speed and electromagnetic torque were identical with and without them. The machine-side converter is supplied only from the DC link, whose voltage the battery converter regulates, so a grid event changes the power the grid-side converter delivers but not the voltage the drive receives. This holds only while the grid-side converter stays connected. In three of the disturbance cases its current exceeded the rating (Section 4.3.7), and a de-saturation trip would then take the rig offline. The ability to ride through grid events is therefore set by the rating and protection of the grid-side converter, not by the drive.

Response to the disturbances Three categories of disturbances were applied: a frequency ramp, voltage sags of two depths, and a permanent phase step. None of them reached the machine, so the rig continued working through every event, and both phase-step runs returned exactly to their operating point after the grid angle had permanently changed. The motor did not see these disturbances, it was the converter that saw these disturbances. Under a 200 ms voltage sag to 0.5 pu, the strongest supply was the most affected, with its current limiter active for 148.0 ms against 6.4 ms on the weakest. Since the sag is applied at the source, behind the supply impedance, the supply and converter reactances form a voltage divider at the PCC. With a small supply reactance the PCC voltage follows the source voltage tightly, so the whole voltage drop appears across the converter reactance and drives the current above the limit. With a large supply reactance, the converter's own current through it keeps the PCC voltage higher. With the voltage sag to zero the ordering reversed, and the limiter was active for 390.2 ms on the weakest supply against 205.4 ms on the strongest. The weak supply still held a higher PCC voltage during the sag, holding the PCC at 0.64 pu against 0.13 pu, but two other effects outweighed it. Scenario D starts with less current headroom, since its higher load factor puts the pre-event current at 0.88 pu against 0.73 pu, and after the sag its unlimited angle correction kept the limiter active for a further 89.8 ms while the converter re-synchronized (Section 4.3.7). The reversal is therefore not an effect of grid strength alone. In the phase angle step response, the strongest supply drew the highest peak current, 1.9712 pu against 1.6936 pu in a weak supply. No single supply is therefore the worst case, since which one is the hardest depends on the disturbance and on the quantity being measured.

The frequency ramp did not engage either limiting function, the current limiter or

FRT mode, both of which are implemented in the controller. The droop gives a steady-state relation: once the supply has settled 1 Hz lower, the converter should import 0.200 pu less, and that is met at the settled point. During the ramp itself the active power is set by the swing dynamics of the VSM rather than by the droop. The converter's internal angle and frequency come from an emulated swing equation with an inertia of $H = 2$ s, so they follow the supply only gradually. Over the 0.5 s ramp the source falls 90° behind a phase turning at nominal frequency, the angle between the converter and the source opens up, and the active power follows that angle. On the strongest supply the converter power went from 0.669 pu import to 0.307 pu export, a change of about 0.98 pu, or five times the 0.200 pu the droop calls for. The internal frequency then dropped below the supply, overshooting to 48.88 Hz, before settling at 49.0 Hz after 2.5 to 4.0 s. For that time the converter exported about 198 kW, which the DC link had to supply together with the motor load. On the weakest supply the larger series reactance couples the converter less stiffly to the source, and the export peak falls to 0.235 pu.

Limits on the converter current Three of the sixteen cases went above the 1.50 pu rating, by 4.2, 12.9 and 31.4 %. Two of them are the phase angle steps. The 500 Hz current controller tracks its reference quickly, but the reference comes from the virtual admittance and has no hard limit at $I_{\max}$. Current limiting is instead done through the virtual impedance: once the current passes 1.20 pu, the virtual resistance is raised in proportion to the overcurrent, as in Equation (2.16). That threshold was crossed 4.8 ms after the step (Table 4.19), which is too late for the peak at 8.6 ms. Equation (4.4) matches the measured peaks to within 6.4 %, so the peak is set by the step and the series reactance, including the virtual reactance, and holding it at the rating would need a hard limit on the current reference.

The third case is the zero-voltage sag on the weakest supply, in which the current went 4.2 % above the rating. While the converter is in ride-through, the correction that pulls the load angle back is held at zero, and when ride-through ends it is applied in a single step. Nothing limits its output, so here it drove the virtual rotor to 74.25 Hz, and the converter took 2.2 s to regain synchronism.

The two causes need different solutions. The angle correction applied beyond $\pm 70^\circ$ needs an output limit, like the ± 0.20 pu clamp on the active-power integrator, which is a change to the control. The phase-step peaks are contained only by a converter rating of at least 1.97 pu, about 1.3 times the present rating. A hard current-reference limit or a virtual reactance of about 2.1 times the present value would also reduce them, but neither was simulated, and each has a cost: the first makes the converter act as a current source while it is active, and the second reduces the power it can transfer at a given EMF.

5.3 Findings against the research questions

How the supply architectures differ in handling a varying rig demand

The technology evolution analysis places direct-on-line starting at the saturation end of its S-curve, and the variable-frequency drive in the growth-to-maturity level.

A direct connection cannot separate the rig from the supply, so every change in drilling load appears at the feeder. Whereas the architectures shown in Section 4.2 can separate the rig from the supply through a shared DC bus with storage, using a bidirectional DC-DC converter at TRL 8-9 and an LFP battery at TRL 9.

The simulation shows the results of one such architecture with a grid-forming converter along with a DC-link with a battery energy storage. Motor demand varies significantly between idling and drilling phases, whereas grid power remains nearly constant across all tested connections, with only a slight reduction under weaker grid conditions. None of the applied disturbances reached the motor, and the measured figures are given in Section 4.3. For a real rig, this means the connection no longer has to follow the drilling cycle, which is what allows a rig to stay online. This makes the drill rig functional even on a long feeder with a weak grid supply with disturbances.

Recovery of braking energy The evolution matrix represents the choice of components that can improve system integration. The trailing-cable matrix shows the industry moving to high-flex, low-resistance copper, chosen for low loss, with lighter Aluminium hybrids, which are still at initial development level. The rectifier matrix puts the active front end in TRL 9 with a near-unity power factor and a two-way power flow, which makes recovery possible. Efficiency at a mine site is therefore set by the connection and by DC bus voltage, which the cross-impact analysis in Section 4.2 links directly to cable loss. The common DC bus makes regeneration possible, and the duty cycle measurements show the storage absorbing and returning energy on every phase transition, but the recovered energy over repeated cycles was not quantified.

The simulation shows where the loss occurs. As the connection weakens, the losses in the feeder and the transformer grow by several times, while the power measured at the converter terminals remains almost unchanged. So, the same drilling work costs more energy at the point of supply on a weak grid compared to a stiff grid. Efficiency at a mine site is therefore set by the losses in the network rather than by the converter, and shortening the feeder or raising the DC bus voltage gives a larger return than improving converter efficiency. The duty-cycle runs also show the battery absorbing and returning energy at every change of phase, which confirms that the architecture allows recovery, but each run covers a single cycle and the energy recovered over a full shift was not measured. The storage is therefore sized here against peak power rather than against energy.

Rating and sizing of the main components Component ratings in this architecture are set in two different ways, and the study reaches them by two different routes. The filter matrix sets the share of load an active harmonic filter carries, the inverter and rectifier matrices demonstrate the relation between higher switching frequency and a higher current density. The cross-impact analysis follows those choices through to cable current, insulation stress and thermal loading. Between them, they decide the ratings of the filter, the cable and the cooling system, and they do so from the technology survey rather than from any simulation run.

The transient ratings come from the simulation, which is different from the regular

duty cycle. When a sudden grid angle change takes place, the filter current reaches its peak before the control can respond, so raising the virtual impedance does not hold it down, and on the strongest connection that peak went above the converter rating. The converter therefore has to be rated for what a grid event produces, or given a larger virtual reactance, and Section 4.3.6 gives the value the measurements imply. The protection settings carry as much weight as the device rating, since one case stayed above the rating long enough for a gate-driver protection to operate, although the semiconductor itself would not have been damaged.

The continuous ratings therefore follow from the technology chosen and the transient ratings from the connection the rig is attached to, and a rig specification has to carry both.

Effect on mine operation Section 1.4 defines the objective as a power-supply structure in which individual components such as converters, transformers, and energy storage can be substituted or upgraded without redesigning the architecture between the grid interface and the motor.

The proposed architecture is a power-agnostic or source-agnostic architecture. The common DC bus and the grid-forming converter help to build this architecture. It enables the rig to maintain operation under very weak-grid conditions, during grid disturbances, and even in the event of complete voltage collapse. The simulation supports this claim, showing that the grid-forming converter maintains the rig at its commanded operating point across a tenfold range of short-circuit ratios and restores the operating point following each applied disturbance.

The architecture is only conditionally agnostic to component substitution, and this qualification comes from the study's own cross-impact analysis. For example, battery voltage sets the inverter operating range, inverter switching frequency drives cable loss and insulation stress, and DC bus voltage couples to both cable sizing and semiconductor selection. The component substitution is local in these architectures, with dependencies on other components when cross-impact is identified between two. Replacing an IGBT-based inverter with a higher-switching-frequency Sic MOSFET inverter improves power quality and reduces passive filter size. However, the higher switching frequency and steeper voltage gradients increase cable losses, insulation stress, and thermal loading, potentially requiring a different trailing cable design. A power-agnostic design defines the electrical interfaces and coupling parameters between subsystems, instead of prescribing fixed component technologies. Parameters such as DC-bus voltage, power rating, voltage class, communication interfaces, and protection coordination remain constant, allowing components, including transformers, batteries, inverters, and converters, to evolve independently as long as they satisfy the specified interface requirements. This enables technology substitution without requiring a whole redesign of the overall power supply architecture.

5.4 Future work

Quantify total cost of ownership and CO₂ emissions. Section 1.4 states that business and sustainability value are quantified through total cost of ownership and

CO₂ emissions. That analysis is not present. The measured connection losses give a defensible starting point, since the difference between the stiffest and weakest supply is about 60 kW of continuous loss, which converts to an energy cost once operating hours are assumed.

Extend the duty cycle to a measured shift. The used load profile is a representative four-phase cycle of 21 seconds. Running the architecture against a recorded rig duty cycle over a full shift which could go usually for about 6-8 hours would establish the battery state-of-charge balance across repeated cycles, which a single-cycle simulation cannot answer, and would allow the storage to be sized against measured energy throughput rather than against a peak.

Resolve switching behavior. An average-value converter is modeled; thus, harmonic content is outside the present results. If harmonics are included for the switching model, semiconductor loss can be estimated.

Strengthen the technology assessment against industry ambition. The evolution matrices were compiled from published literature and supplier material. Validating them against manufacturer roadmaps and revisiting the readiness levels assigned to the supervisory and analytics layers would keep integration continuous and reliable.

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