Smart DC Microgrids for Mines and Cement Plants

An intelligent DC bus provides reliability as well as technical, financial and social advantages

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Technical white paper

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1 Abstract

Mines often exist in remote locations where electrical utilities can be unreliable, unstable or even non-existent. Traditionally, mines with unsuitable utility power have installed their own microgrids. These site-specific grids consist of a power source independent from the standard public electrical utility. However, the same problems that create the need for the microgrid can also hamper the microgrid's reliability and continuity: The long distance alternate fuel source must travel to get to the mine. While a remote coal mine may be fortunate enough to generate its own power using resident mined material, other mines must truck large amounts of diesel fuel over many miles of harsh road and terrain. Increasingly, sustainable power sources such as solar and wind are being integrated into mining infrastructures. To date, these alternative sources of energy don't meet the tremendous power requirements of a typical mine, nor are they very cost-efficient. This paper looks specifically at a direct current (DC) microgrid solution for mines that generates and distributes DC power directly to DC loads, avoiding the costly and energy-inefficient alternating current (AC) to DC conversion.

2 Background

2.1 A history and evolution of microgrids

Microgrids have existed since the beginning of power transmission. A microgrid is defined as small-scale power grid that can operate either independently or in conjunction with a standard utility grid.

Mines have been common use cases for microgrids, driven by the distance of a mine from the utility and/or the inability of the utility to serve the significant power demand of a mining operation. Traditionally, microgrids have been specified to mimic and produce the same power that would be available if served by a utility: medium to high voltage of AC at a frequency of 50 or 60Hz.

With the development of digital technology, the number of devices using DC power has increased exponentially. However, power transmission and delivery to facilities and homes remain predominantly AC systems. Likewise, most in-home high-power-use loads, such as appliances and HVAC systems, are built to accept AC potential. Electronic systems, on the other hand, usually require a conversion from AC to DC power. As in any conversion, losses are realized and energy is wasted. In addition, this power conversion is costly, requiring additional components and materials while negatively affecting system reliability. The avoidance of unnecessary conversions is made possible by a DC microgrid.

To better understand the significance of savings associated with optimized conversion, the following is a review of conversion technology.

3 Power conversion review

3.1 AC to DC Conversion

Ever since Westinghouse Electric Company won the “War of the Currents” with its AC technology over Edison’s DC system in the late 1800s, electrical energy has been supplied to homes and companies in the form of 50/60 cycle AC power. Most power-consuming devices at that time used AC power directly, without further conversion. Some examples include asynchronous/synchronous electric motors, lights and heaters. AC is the dominant method of transporting power, as it has several advantages over DC. Those include lower distribution costs and a simpler way of converting between voltage levels using a transformer.

With the development and evolution of modern semiconductor devices such as transistors, LEDs and microprocessors, most consumer devices – e.g., lights, computers and TVs – use DC power at their core. In the manufacturing industry, variable-frequency drives and servo systems replaced traditional fixed-speed AC motors due to their higher machine flexibility, controllability and energy efficiency. Contactor-based ladder logic was replaced by computer-operated Programmable Logic Controllers (PLC), Computer Numerical Controls (CNC) and PC-based control systems. Most factory-automation equipment today also runs on DC power.

With the increased need of DC supply power for modern devices and the continued availability of traditional AC power distribution systems, several AC/DC conversion technologies evolved. In principle, all AC/DC converters route the alternating current and associated alternating voltage into reactive impedance components such as inductors and capacitors for storage and integration. The AC power associated with the positive and negative potentials are separated, and a stable DC supply is created by filtering the output power after the separation process.

The circuits have many different forms and conversion stages dependent on the technology used, but all circuits use the same essential elements described.

3.2 AC to DC conversion topologies

Simple rectifiers use diode networks, filter capacitors and inductors to convert an AC line into a stable DC output. Negative attributes of this setup include an inadequate supply-current shape, very high ripple level and a resulting very low power factor.

Three-phase bridge rectifiers are predominant due to their advantageous technical properties: fairly low current ripple, higher power factor, simple topology and low price. Today, they are used in power supplies both small and large, as well as in AC/AC converters with a DC bus.

Active rectifiers, active front end or active infeed systems outperform passive rectifiers with the following characteristics: occurrence of harmonics in supply current is actively minimized in operation, and the intermediate circuit is charged during the whole mains period with rectified sinusoidal supply current in phase with the supply voltage. This way, the maximum active power is available through a given mains fuse and the power factor is at its maximum. Rectified voltage and current are controlled and regulated, resulting in the output being independent of the supply voltage over a wide range. This helps to overcome unstable supply voltages and power abnormalities, or it can boost the voltage for constant DC bus levels to align with global supply standards.

Some of the advantages of Active Front End technology:

- Low harmonic clean power technology that meets the requirements of IEEE 519
- Operation at unity power factor, or adjustable power factor to compensate other systems
- Voltage boost operation independent of AC supply voltage
- Stable DC voltage on systems with fluctuating voltage and frequency

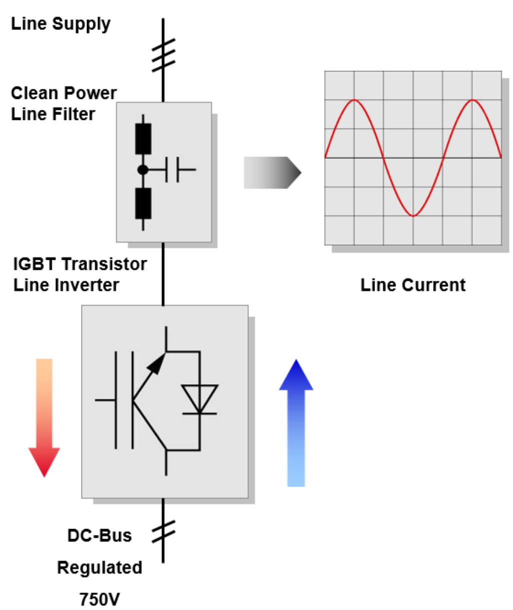


Figure 1
Active Front End Power Supply Design

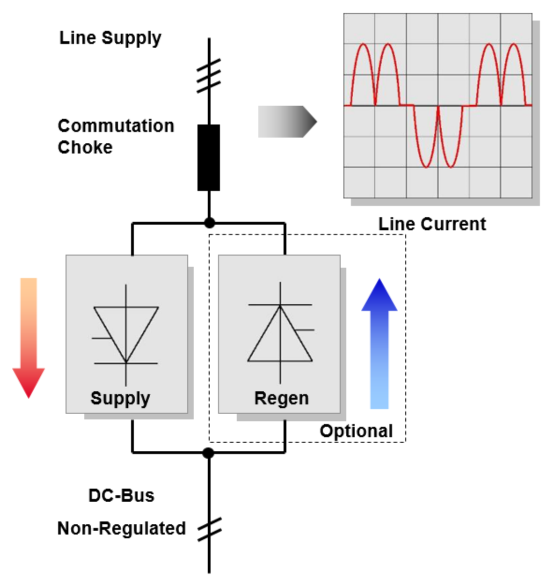
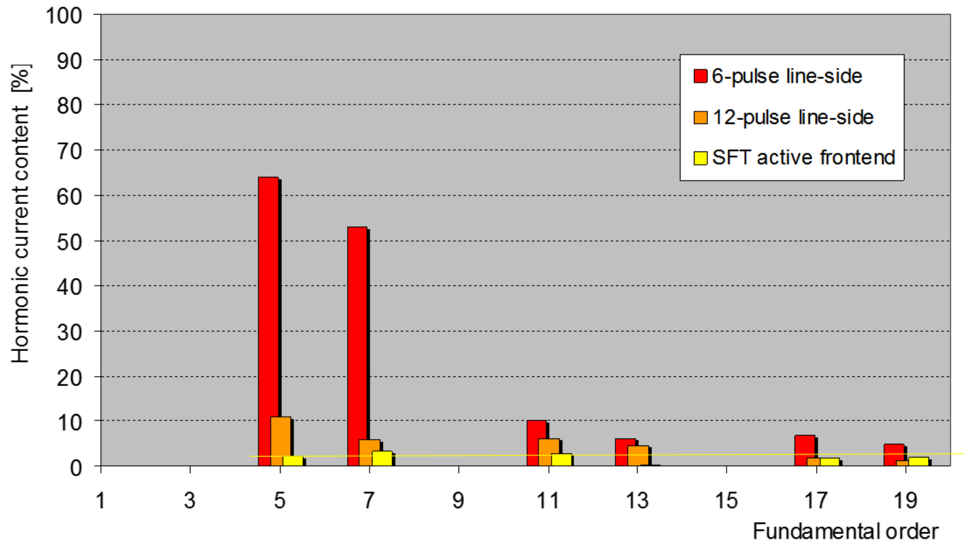


Figure 2
6-Pulse Diode/SCR Power Supply Design



Graph 1

Typical harmonic distortion diode vs. active rectification example

Line Configuration	Line Voltage	Front End	Effective DC Bus Voltage	Bus Configuration
Single Phase	120V	Diode Rectifier	170V	Floating with Line
Single Phase	230V	Diode Rectifier	320V	Floating with Line
3 Phase	400V	Diode Rectifier	540V	Floating with Line
3 Phase	400V	Active IGBT	700V (Typical min 540V)	Regulated
3 Phase	480V	Diode Rectifier	650V	Floating with Line
3 Phase	480V	Active IGBT	700V(Typical min 650V)	Regulated
3 Phase	690V	Diode Rectifier	930V	Floating with Line
3 Phase	690V	Active IGBT	1150V	Regulated

Table 1

Overview of typical AC/DC conversions

3.3 DC/DC conversion

A DC-to-DC (DC/DC) converter is used to convert a DC source from one voltage level to another level. DC/DC converters are important in applications such as electric vehicles, electrical drives and in portable devices such as cell phones and tablets, which have subcircuits operating at voltages different than the supply voltage. The main driving force for DC/DC converters is a constant demand for small, light and high-efficiency power supplies. These converters have increased use in the hybrid-automobile industry, fuel-cell automotive power systems, DC microgrids and renewable-energy applications such as solar-power generation.

Despite the fact that power-switching techniques are more difficult to implement, switching circuits have almost completely replaced linear power supplies and DC/DC conversion in a wide range of portable and stationary designs. This is because switching circuits offer better efficiency, smaller components and fewer thermal-management issues. The ideal DC/DC converter exhibits 100 percent efficiency. In practice, however, efficiencies range between 70 percent and 95 percent, depending on the complexity and cost of the circuits and the semiconductor used. One of the largest power-loss factors for DC/DC conversion is the rectifying diode. The power dissipated is simply the forward voltage drop multiplied by the current flowing through it. The reverse recovery for silicon diodes can also create loss. Switching transistors are the second largest loss-contributors in a circuit. New evolutions of semiconductor materials such as MOSFET (metal oxide semiconductor field effect transistor), GaN (gallium nitride) and SiC (silicon carbide) continue to lower conducting losses significantly in modern transistors, pushing possible conversion efficiencies up to greater than 99 percent. System power losses reduce overall efficiency and require thermal management in the form of a heat sink or fan.

As a basic functioning principle of a switching DC/DC converter, energy is periodically stored within and released from a magnetic field in an inductor or a transformer. This typically occurs within a frequency range of 300 kHz to 100 MHz. By adjusting the duty cycle of the charging voltage (ratio of the on/off times), the amount of power transferred to a load can be more easily controlled. This control can also be applied to the input current or the output current or to maintain constant power. The periodic energy flow is averaged and filtered simply by a capacitor. More advanced systems use inductor-capacitance networks to minimize harmonics and remaining ripple. Transformer-based converters can provide isolation between input and output. In general, the term *DC-to-DC converter* refers to one type of a switching converter. These circuits are the heart of switched-mode power supplies, battery chargers and DC/DC converters. The switching duty cycle, voltage regulation and current limits are controlled by specialized controller chips (ASIC – application-specific integrated circuit) or embedded microprocessors.

3.4 DC/DC conversion topologies

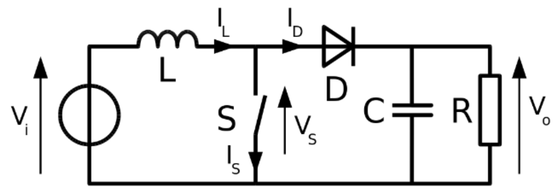


Figure 3

A **buck converter** (**step-down converter**) a DC/DC power converter that steps down voltage (while stepping up current) from its input (supply) to its output (load).

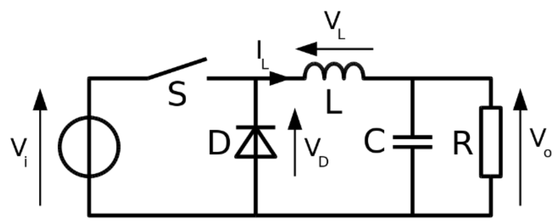


Figure 4

A **boost converter** (**step-up converter**) a DC/DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load).

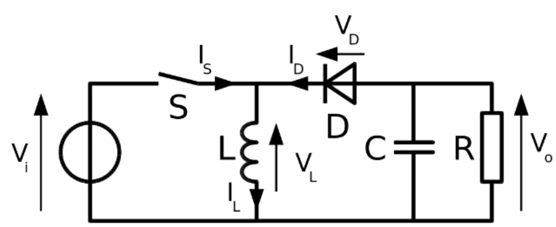


Figure 5

The **buck–boost converter** a DC/DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude.

3.5 DC recovered energy

In industrial, hybrid and electric-vehicle applications, DC/DC converters are gaining more attention due to their ability to convert recovered motion energy into different voltage levels to be used or stored by other systems including batteries, super capacitors or DC microgrids. Despite the fact that they add small additional losses, they can help increase overall system efficiency significantly by using waste energy that is otherwise lost in the process. As an example, regenerated energy from a variable frequency drive (VFD) controlled conveyor belt, crane or elevator with a typical level of 650 direct-current voltage (VDC) can be “DC/DC converted” to a voltage level of 380VDC and re-used in a DC microgrid system for LED lighting.

3.6 Common DC bus systems

Following the establishment and availability of an AC-distribution system, most production machines, motors, pumps and fans were powered by fixed-speed or expensive specialty AC or DC motors. Over time, fixed-speed direct coupled systems were replaced by variable-speed drives and servo drives due to the demand for higher productivity, flexibility and energy-efficiency. Today, with the availability of advanced low-cost switching devices like IGBT/ MOSFET transistors and new motor-control methods such as Brushless DC Drive (BLDC), consumer goods such as refrigerators and washers are driven by variable-speed drives.

A basic AC drive consists of an input stage to convert the AC power to an internal DC bus. The inverter output stage creates a three phase AC system to control the motor with various motor control technologies (i.e., V/Hz, Vector Control, or Closed Loop Servo Control, dependent on the application and level of control needed).

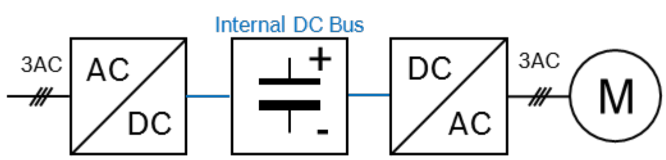


Figure 6

With the commonly used AC drive, energy can only flow from AC to DC. Motor-breaking (regenerative braking) energy has to be burned via an additional resistor module in the device. A solution to recover regenerative energy was developed over time by creating a DC bus or DC link between the individual motor inverter stages. Power is fed from the AC grid via a central AC/DC converter, commonly called the power supply or shared rectifier. Energy regenerated from one motor can now be used simultaneously by another motor demanding power (motoring). This effectively reduces the power consumed from the central power supply and AC grid.

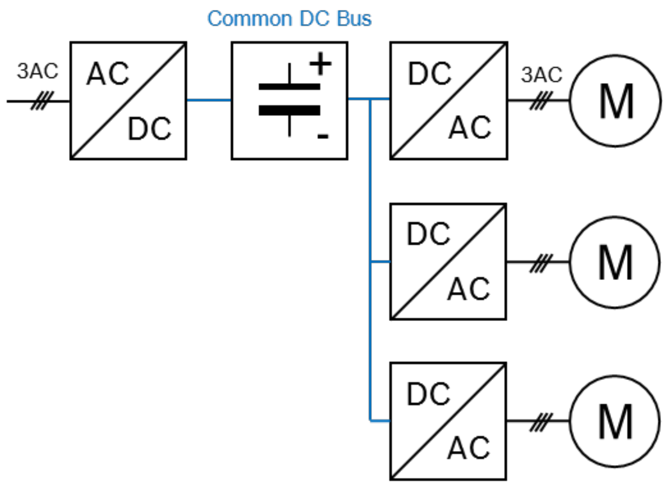


Figure 7

Common DC bus drive systems are more efficient than standalone AC/AC drives. Additionally, the line components (i.e., contactor, reactor, fuses, etc.) and rectifier can be sized based upon the maximum current draw of the system rather than the summation of the individual motors. This also results in a more-optimized and energy-efficient design as losses are realized individually in each line component and rectifier.

Some of the advantages of common DC bus:

- Optimizes the benefit of regenerative energy
- Reduces or simplifies the type of rectifier needed
- Reduces power cabling and installation time
- Reduces footprint of drive lineup
- Maximizes the drive system tolerance to incoming line disturbance
- Simplifies the number of AC/AC points to help with efficient harmonic filtering

Another advantage of a DC bus system is that the central AC/DC connection point can be equipped with a fully regenerative power supply. This can feed unused excess energy back to the main grid. A DC/DC converter could be connected to the DC bus itself to exchange energy on the DC level with other DC systems, such as a DC microgrid, DC lighting system or photovoltaic (PV) power generation.

4 DC microgrid case studies

As reported by microgridprojects.com, the use of microgrids in communities, industry and mining is well-documented. As of 2017, the number of DC microgrids stands at more than 200. The majority of these grids have been installed in leading-edge universities, research locations, government facilities and institutions. One notable exception is the Honda Motor Parts distribution facility in California, USA. [1]. The Honda system, designed and under construction by Bosch, includes a 380V DC distribution grid supplied by a rooftop photovoltaic grid, which powers LED lighting, fans, electric fork-lift chargers and energy-storage systems.

5 Power generation sources

5.1 Generation average cost of capital

Every microgrid must be powered from a source. For mines, this has traditionally been done via a generation or cogeneration generator, or turbine system. Mines with access to rail lines or natural-gas pipelines are likely to select coal or gas, as the generated cost is generally in the range of $56 to $140 per megawatt hour (MWHr) based on the 30-year average cost of capital [2]. Both solar and wind power have demonstrated a rapid reduction in cost/MWHr with comparative cost levels at $85/MWHr and $64/MWHr respectively [2]. The least cost-effective alternative – yet still one of the most used in countries with minimal infrastructure – is diesel fuel. The cost/MWHr for diesel varies dependent on market price, fuel grade and sulfur content, but it is not unusual to see a cost in the $250/MWHr range [3]. It is important to note that the surprisingly lower cost for solar (PV) and wind relative to diesel is not positively impacted by initial capital cost. Despite rapid cost decreases, solar and wind still remain more expensive to build than fossil-fuel generation. The lesser cost/MWHr value for solar and wind is a result of the nominally zero cost of fuel (sunlight and wind) over the lifecycle of the equipment.

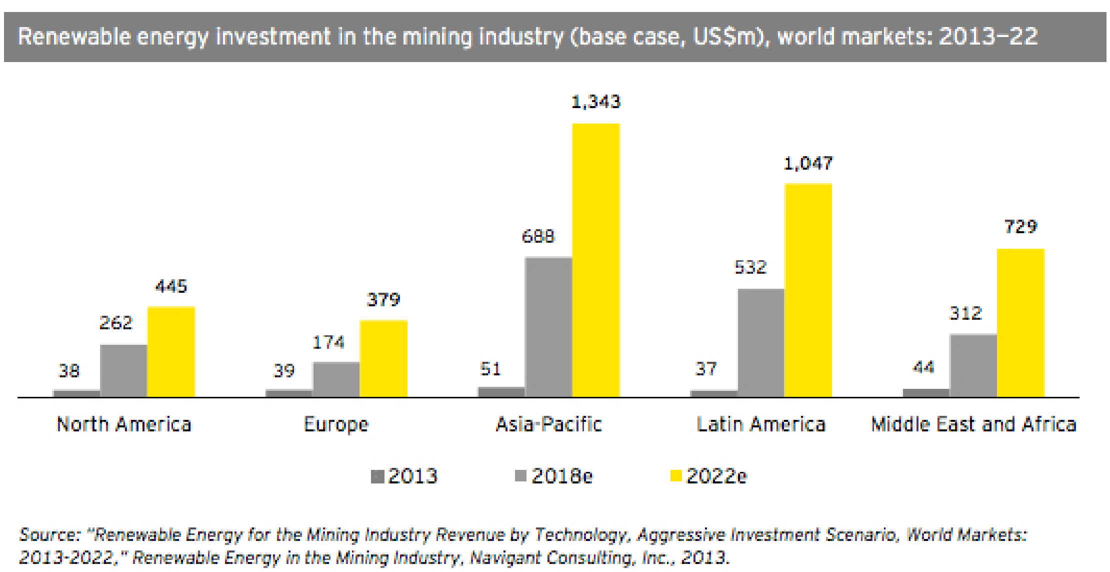
The problem with solar and wind, however, remains the stable availability of sunlight and wind. The former requires a location with minimal cloud cover over time; a desert environment meets that criteria and is also a common location for mining operations throughout the world. The bigger issue with solar is the need to store energy. The sunlight necessary for power is insufficient at night.

The same scenario exists for wind power. Terrain and geography dictate the areas most likely to experience wind speeds in a required range. Such areas do not necessarily align with mining locations. As is the case with solar, the inconsistency of wind necessitates an energy-storage system.

In spite of its high-lifecycle cost, diesel power remains a popular choice for mining microgrid generation. The reason for its popularity centers around universal availability (diesel fuel is readily available on six continents), convenience (most mines already purchase and store diesel fuel for discontinuous mining equipment) and serviceability (the same maintenance and repair personnel can service diesel engines and diesel-powered generators).

5.2 Hybrid generation systems

In a trend that echoes the automotive industry, mining operators desire reduced dependence on fossil fuels. This has promoted the development of hybrid systems that combine diesel generation with PV or wind [4]. The unique and remote nature of mines has pushed the mining industry toward the frontier of microgrid technology. Alternative considerations for microgrid power include fuel cells and the use of inactive mine shafts for hydro power or compressed-air storage [4]. Even modular, microscale nuclear plants are being considered; the future of microgrids is certainly diverse and expanding. Significant growth in sustainable-source mining microgrids is expected across all regions of the world. Growth will be more pronounced in areas with high-resource yields and relatively poor utility infrastructures, such as Asia-Pacific, Latin America, the Middle East and Africa [7].



Graph 2

Renewable Energy Investment in the Mining Industry [7].

6 DC power loads in mining

To optimize the effectiveness of a DC microgrid, we must first analyze the potential loads that exist within the operation. In terms of cost and efficiency, the DC microgrid realizes its savings by avoiding an AC/DC conversion. It is logical that the primary beneficiary loads are those that already require DC power or AC loads that can be more efficiently supplied by DC via new installation or retrofit.

The DC requirements of LED lighting and relative cost effectiveness of small, brushless DC motors has created lighting and ceiling-fan solutions that are well-served by a DC microgrid. In addition, the 380VDC distribution standard allows for less voltage drop and therefore greater wiring distances than an AC system. This makes DC microgrids well-suited for facilities that cover large ground areas.

Lighting and ambient-cooling savings offer an attractive proposition for many facilities. However, in a typical mine, these systems represent a very small portion of total electrical load. Therefore, these savings are likely to be lost or dismissed in analysis. It is important to consider the very significant number of additional systems that rely on DC power in mining facilities:

System	DC Voltage	Power Demand	Critical?
Fire/Security	24-48	Small	Yes
CCTV/POE	48	Small	Yes
Process Automation	24-48	Medium	Yes
Substation Control	130	Small	Yes
Excavators	690	Large	No
DC Voltage applied directly to VFD DC bus			
Ventilation DC Bus	700 or greater	Large	Yes (underground)
Pumps	700 or greater	Large	Yes (underground)
HVAC/Cooling-Heating	170-700	Medium	No
Process Motors	540-700 or greater	Large	No

Table 2

6.1 DC critical loads

When viewed in this format, two important facts become obvious. First, with the exception of excavators, all DC voltage levels are below the 380V standard distribution level of a DC microgrid. This allows for a more cost-effective “buck” DC/DC conversion.

Second, almost all critical loads in the mine rely on DC power. This requirement often necessitates that the mine provide separate backup systems, usually relying on batteries. Coincidently, if powered from solar and/or wind, the DC microgrid requires energy storage. This makes the value of using a centralized DC critical supply bank quite apparent as compared to using multiple backup systems or uninterruptable power supplies (UPS).

6.2 DC for discontinuous mining

Open-pit mining operations commonly use electric rope shovels (excavators) for the loading of ore into haul trucks. Most commonly, these DC machines are tethered to the nearest substation by large above-ground cables. A conceptual DC ring microgrid has been proposed that would take advantage of both PV and wind generation combined with utility AC/DC rectification, essentially a hybrid system [6]. It is important to note that such a high-power system would require advanced DC-specific overcurrent and fault protection, an important consideration in ROI analysis. Also important to analysis would be the consideration of regeneration factor: the return of useful energy back to the DC grid through the downswing of the excavator bucket and/or ropes.

7 Industry 4.0 and the DC microbus

7.1 Power line communication (PLC)

The massive growth of digital communications, including that of Industry 4.0, requires a sophisticated wiring infrastructure to carry the digital signals. The concept of superimposing a digital signal on a power line is known as power line communication (PLC). The immediate benefit of PLC is easy to understand: initial capital wiring costs are reduced or eliminated, and for utilities, the need to provide labor for local meter reading has widely been eliminated.

On a facility-wide or mine-wide basis, however, additional complications exist that prevent the widespread use of PLC for broadband and/or high-speed applications. Most power-distribution networks are AC systems, so PLC is hampered by AC-related “cyclic short term variations and abrupt long term variations” [8]. Compensating for these undesirable attributes is possible, but at the expense of additional electronics for coupling, filtering and compensation. These corrective measures are not required on a DC microbus, as the constant voltage level provides a non-variable baseline for signal imposition. It is important to remember that digital communication is fundamentally a

DC signal of on-and-off bits of data, and this signal coexists cooperatively with the DC power component.

7.2 Lighting capability

A natural progression for communications on a powerline microgrid is the control of loads connected to the microgrid. Essentially, the loads receive both power and signaling over the same two wires. While many proposed uses for PLC have already been identified [9], one of the most promising involves lighting. Lighting is a universal need for any facility, and it exists by necessity in places where personnel are located. The other beneficial attribute of lighting is that it is quite common to utilize many fixtures over a wide area to provide sufficient and uniform coverage throughout.

LED has become the preferred lighting technology for both retrofit and new installations. For AC-supplied fixtures, this requires inverters, which are commonly referred to as drivers. As previously explained, the DC microgrid eliminates the need for the fixture inverter, replacing this component with a more-reliable DC/DC converter. Because the fixture's electronics are replaced, an opportunity exists to enhance the capabilities of the fixture. Already, the Bosch DC microgrid has added addressability to the fixture, allowing for app-based control of individual or grouped lights with nearly unlimited flexibility.

7.3 Future of development

In addition to control and communication with smart devices connected to the DC microgrid as loads, new capabilities are being introduced into the Bosch DC microgrid. In a given space, smart light fixtures are capable of measuring both internal temperature (as a potential predictor of failure) and external temperature (as an indicator of HVAC operation or failure). As communications electronics become less expensive, each fixture can become a communications gateway or Ethernet hub at little additional cost. This would introduce extreme flexibility in connecting devices to ports at the fixture, such as IP cameras, air-quality sensors, data-acquisition devices, alarms, signaling systems and security devices.

8 System cost and ROI analysis

8.1 DC microgrid system architecture

As compared to existing AC-based systems, the DC microgrid is simplified due to elimination of power-converter equipment. Solar- and wind-energy storage can be directly connected to the DC bus. When there is insufficient energy available from those resources, the system can be connected to utility grid or diesel generators to provide power. The system architecture is depicted below:

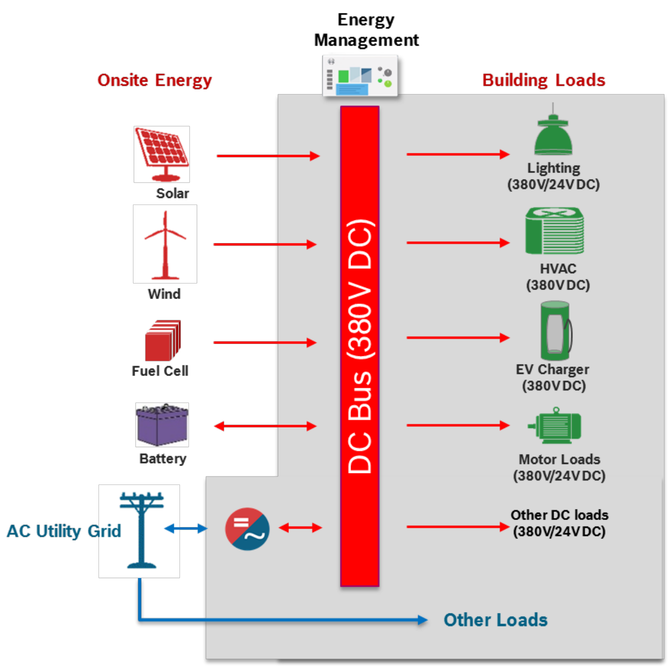


Figure 8

The Bosch-developed system architecture wherein the solar is connected to the loads directly without the use of power conversion electronics is significantly more efficient. It results in approximately 7-10 percent [10] higher utilization of solar energy.

8.2 DC vs AC overcurrent and fault protection

Because the DC system is designed to have always-connected loads such as lighting, HVAC and security systems, the likelihood of series arcs due to unplugging loads is minimized. DC+ and DC- are tied to the Earth ground through a high-ohmic resistor, providing a high-resistance mid-point grounding technique [11]. This also helps eliminate parallel arcs and ensures that the system stays operational even in the case of a single ground fault. Compared to the possibility of thousands of amperes from an AC grid, the DC microgrid is typically current-limited to a few hundred amperes: 400 amps for a DC microgrid with a solar array operating in the 600 VDC range. Depending on the business model's ROI, a very large DC microgrid is possible. For a DC microgrid of any size, DC circuit breakers must be used and differentiated from AC counterparts with internal magnetic elements to prevent an arc. An arc is more likely to occur in DC than AC overcurrent protection due to DC's lack of a zero-crossing waveform. DC circuit breakers are typically two to three times the cost of AC breakers, and this cost should be considered in the ROI analysis.

8.3 Life expectancy

Compared to the electrolytic capacitors and the power-factor correction equipment required in an AC/DC conversion, DC/DC electronics have a much longer mean time before failure. For instance, LED-lighting studies performed by the Department of Energy [10] have shown that 75 percent of LED fixture failures are due to AC/DC drivers used in these systems. Comparative studies performed on DC/DC electronics and AC/DC electronics by the Center for Advanced Life Cycle Engineering at the University of Maryland have shown that DC/DC electronics that use film capacitors can last at least twice as long as AC/DC electronics with electrolytic capacitors. This potentially results in both resources (i.e., solar and energy storage systems that have no AC/DC inverter electronics) and the loads (with no AC/DC rectifier electronics) lasting approximately twice as long as regular AC systems. They also have significantly lower operations and maintenance costs over the life of the DC system.

8.4 Model cost analysis – Utility AC/DC conversion, DC/DC conversion

For loads used in mining such as lighting, security systems and HVAC, there is a substantial investment associated with converting the utility AC power to DC power. This investment includes the AC/DC power supply equipment that must be integrated into every device. In a DC microgrid, the power-conversion equipment is eliminated and the capital costs of these devices are lowered by approximately 5 to 10 percent. As the power conversion is centralized for the central DC bus (Figure 7), there are significant infrastructure savings, operations savings and maintenance savings for the DC microgrid architecture. The operations and maintenance costs for these devices are lowered as the power-conversion equipment lasts longer when the electrolytic capacitors required for AC/DC conversion are eliminated. In the studies performed by Bosch, the total cost of ownership for these devices is reduced by up to 25 to 30 percent over the 25-year life of the system. This is due to decreased capital costs, reductions in grid electricity costs, lower equipment-replacement costs and gains in efficiency. [13]

8.5 Model cost analysis – PV+ energy storage

Since the PV system and energy-storage system connected to a DC microgrid are usually not connected to the utility grid in a mining application, the need for inverters is eliminated. This reduces the installation cost for these systems by approximately 8 to 10 percent due to the removal of inverter costs as well as other AC balance-of-system requirements. The energy-efficiency gains associated with the PV system can be increased by 2 to 3 percent if DC/DC converters are used to optimize the solar output. They can be increased by 5 to 6 percent [12] if these devices are also eliminated and the solar power is directly connected to the DC bus. In other words, the load voltage equals the PV output and DC bus voltage. Similarly, the energy-storage-system efficiency is increased by approximately 5 to 10 percent. There is no longer a requirement for the AC/DC power stage to charge the battery and a DC/AC power stage to push energy back from the battery to the AC infrastructure.

9 Benefits of DC Microgrids

9.1 Cost savings and considerations

A DC microgrid system simplifies the electrical-distribution architecture, and this simplicity also results in reliability and resiliency benefits. By eliminating or minimizing the power-conversion electronics (DC/AC for solar and energy storage and AC/DC for mining loads), the overall cost of the system can be reduced by 5 to 15 percent, as the power conversion electronics and their installation will be eliminated. As the electronics are either removed completely or replaced with DC/DC devices, the reliability of the system can be increased significantly and operations and maintenance costs for these devices can be reduced by 50 percent over the life of the system. Finally, DC loads that are directly connected to the DC generating source, such as solar and storage, are connected on a “utility independent” DC bus that is not shut down during a grid outage. It also does not need to sync back once utility grid operations resume. This flexibility provided by the DC microgrid ensures that back-up power is available without the addition of transfer switches or grid-forming inverters, which can add considerable cost to a microgrid. They can also create complexity in terms of managing the integrating and syncing required for AC microgrids. Overall, a DC microgrid system will have a payback period that is at least two to three years shorter and a significantly higher ROI when compared to an AC system.

9.2 Social perception

It is no secret that the mining industry faces continuous challenges from special interests relative to a negative perception of mining operations on the immediate environment. Mining companies work tirelessly to reduce impact on the environment and to prove themselves as positive contributors to surrounding communities. The social acceptance and positive perception of alternative, sustainable power generation is clearly an objective and benefit of the DC microgrid, and it is likely to produce positive publicity for the mining operation. More importantly, this benefit is evolving into an expectation impacting directly on a mine's "social license" to operate [7]. In areas that have stable public utility power available, a very-large-scale DC microgrid may not be presently feasible. However, consideration should be given to using the DC microgrid in areas with public access, tour routes and administrative offices as well as for the mine's critical loads.

10 Summary

When AC power was adapted as a standard for generation, transmission and distribution, it was impossible to foresee the growth of the digital age. DC power now presides, and the incandescent light bulb has even been replaced by an efficient, DC-based LED light source. In fact, all modern residences, commercial office buildings, factories and mines have a DC dependence that often goes unnoticed because of product-specific AC/DC converters. However, these converters come with a penalty of additional energy loss – minimal for a single device, but quite substantial in the entirety of a facility's numerous AC/DC appliances and machines.

Given what we know now, and considering how our electrical needs have evolved, it is advantageous to take a step back and ask how electrical distribution systems should look. The answer should be based on the present requirements of various loads, an increasing number of which are DC-based. It is at this point that a DC distribution bus becomes logical.

The further upstream a business case is analyzed, the more positive the ROI. If you can power a DC bus from a source that directly generates DC, then the cost benefit increases.

In the past, this was only practically accomplished through a rotary DC generator. As sustainable power sources have evolved and become more effective, so has the availability of DC. Due to the nature of solar and wind -- and the cyclical and interruptible nature of their fuel sources -- energy storage has become a standard requirement of sustainable energy systems. Accepting the fact that DC energy storage is the most common, cost-effective and practical solution, the reasonable approach is to distribute the DC with minimal energy loss. A relatively elevated voltage can be used either directly or with minimal and inexpensive stepdown conversion.

Initially, the capital cost of both solar and wind systems was prohibitively high. There was little practical use for these systems in the general public. Very sharp declines in the prices of both solar photovoltaic cells and wind generators have enabled systems that are cost-effective initially and cost-saving over time.

Logically, most of the pioneering work in mining microgrids has occurred in remote arctic or underdeveloped areas. The evolution of such grids, combined with an analysis of mining loads, is leading to the consideration of mine-wide DC busses or grids.

Just as the cost of PV and wind has decreased, so has the cost of DC/DC conversion. The elimination of bulky and expensive transformers and a significant decrease in the cost of semiconductor component manufacturing are the primary drivers for this conversion decrease.

This trend of increasing cost effectiveness, combined with the positive influence of social responsibility, supports a growing interest in DC microgrids. Further development in the area suggests transmission of video and data are likely near-future features on the DC microgrid, positioning the grid as a supporting infrastructure for connectivity and Industry 4.0.

11 Appendix A: About Bosch

The Bosch Group is a leading global supplier of technology and services. It employs roughly 390,000 associates worldwide (as of December 31, 2016) and generated sales of $80.9 billion in 2016.

Operating across four business sectors – Mobility Solutions, Industrial Technology, Consumer Goods, and Energy and Building Technology – Bosch is uniquely positioned to offer customers a multitude of value-add, cross-sector solutions across diverse industry applications. It leverages its expertise in sensors, software and services, as well as its own IoT cloud, to offer its customers these connected, cross-domain solutions from a single source.

Bosch is a technology leader in the mining and concrete industries, providing a comprehensive range of products and solutions to assist mine owners, planners, contractors, material handlers and mining engineering companies worldwide. Whether the project requires state-of-the-art drive and control technology, grid technology, cutting-edge security solutions or proven-tough parts and tools, Bosch offers a choice of products that are commonplace across mining and concrete sites today.

Bosch Rexroth, a leader in industrial hydraulic, electrical-drive and power-conversion technology, offers an extensive portfolio of drive, control, and conversion technology, including for mineral processing, materials handling, and minerals infrastructure and facility support. Bosch also offers an expansive portfolio of components for mining vehicles, as well as professional power tools that are optimized for reliability and long service life. Bosch Building Grid Technologies provides leading-edge DC microgrids that support sustainability, energy savings and connectivity strategies. Additionally, Bosch Security Systems offers a comprehensive suite of solutions to keep facilities safe and operating smoothly. The wide range of Bosch products and solutions for the mining industry deliver reliability, quality and durability.

The Bosch Group's strategic objective is to create solutions for a connected life and to improve quality of life worldwide with products and services that are innovative and spark enthusiasm. In short, Bosch creates technology that is "Invented for life."

Additional information is available online at cds.bosch.us.

12 Appendix B: References

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