ANALOG DEVICES

Motor Drives

The fascinating world of electronic motor control

VISIT ANALOG.COM/INTELLIGENT-MOTION

FOREWORD

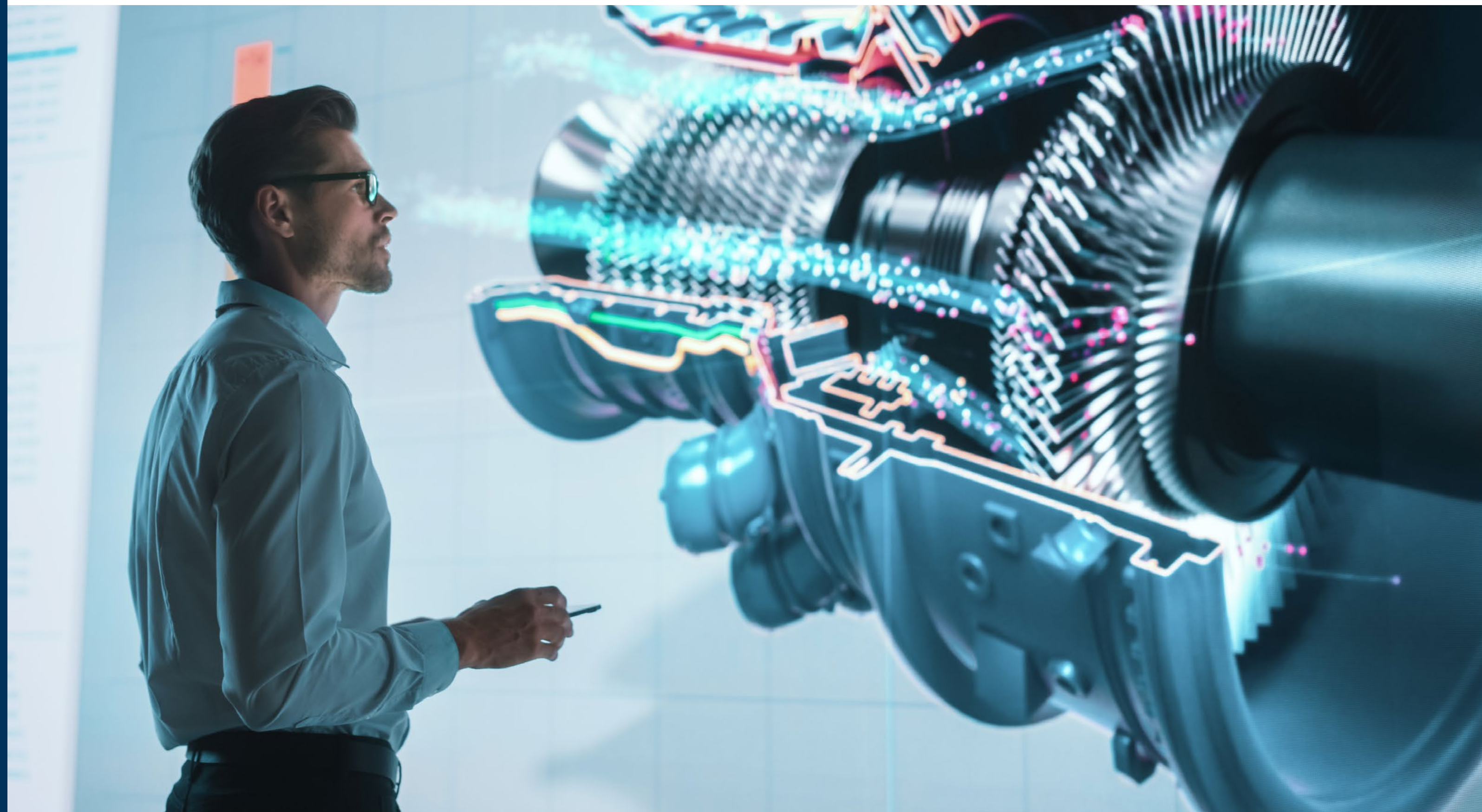
BY DARA O'SULLIVAN, DIRECTOR OF SYSTEM APPLICATIONS SMART MACHINES & ROBOTICS, INDUSTRIAL AUTOMATION, ANALOG DEVICES INC.

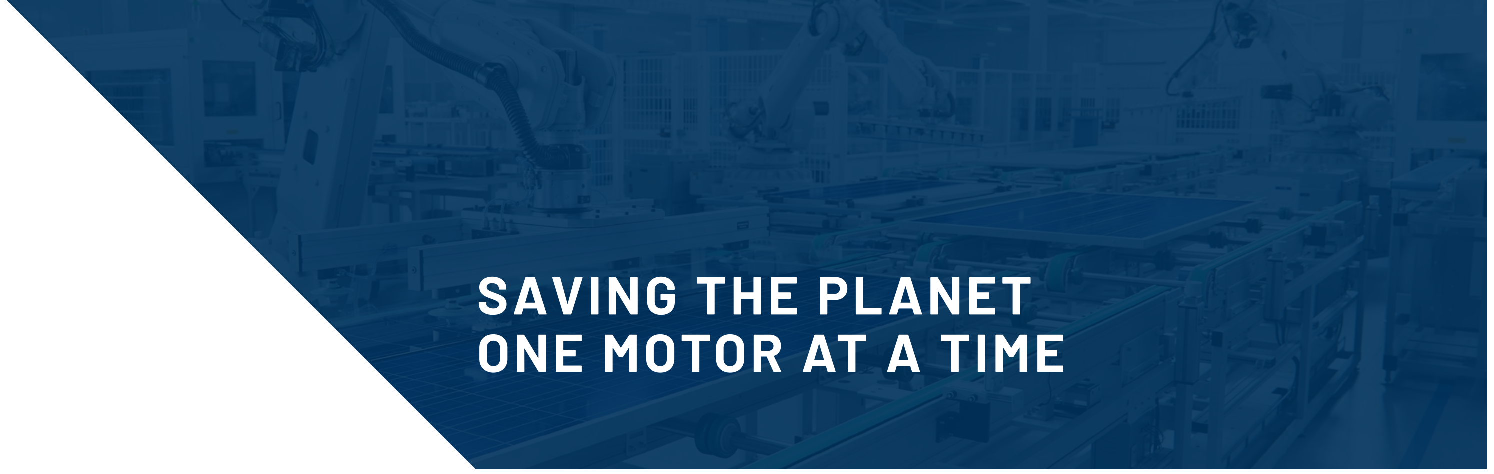
Industry consumes 30% of global electricity and within industry, electric motors make up approximately 70% of power consumption. Motors are used across industrial applications to drive pumps, fans, compressed air systems, material handling, processing systems, and more. It is estimated that if all deployed motor driven systems were operated at maximum efficiency, it would reduce global electricity demand by 10% and remove 2490 Mt of CO2 emission in 2030.

Intelligent motion control combines precision feedback, advanced sensing, high performance control, and seamless connectivity to deliver deterministic motion solutions that enable highly flexible and efficient manufacturing. Motion control solutions in industrial applications have evolved from basic on/off fixed speed motors to complex multi-axis servo-drive solutions. This transformation has been driven by the increasing complexity of automation required to deliver higher levels of performance and autonomy in smart manufacturing.

This eBook aims to provide a holistic overview of motor drives. It starts with an overview of industrial automation trends that have been driving the evolution of motion control and progresses to examine motor control architectures and explore the constituent blocks – including input stage, power supplies, inverter stage, main controller, feedback loops and connectivity considerations.

CONTENTS





SAVING THE PLANET ONE MOTOR AT A TIME

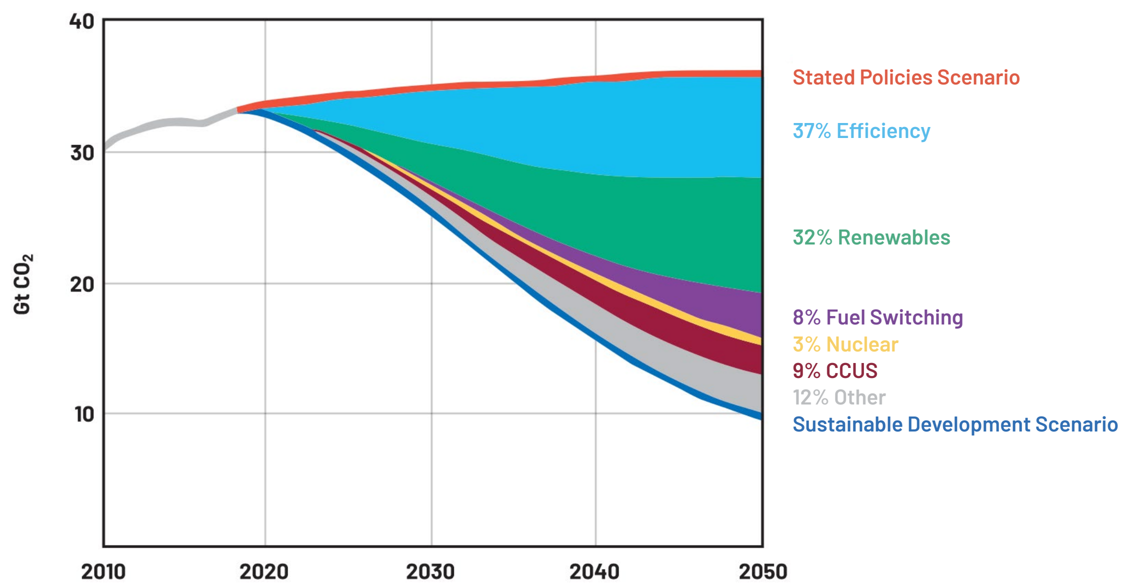
The material covered throughout these chapters will look at motor drives from many different angles - from architectures to power management, from connectivity to cybersecurity, and much more in between. We are starting from the top down and this first chapter looks at how making motors more energy efficient can play a significant role in reducing the harmful emissions which are contributing to climate change.

The Paris Agreement in 2015 set out a plan to limit global warming to 1.5°C by 2050. Meeting the 1.5°C target in 2050 requires an approximately 70% reduction in CO_2 emissions from 2018 levels. The current trajectory of global warming has the potential to cause major economic, societal, and environmental disruptions. The world has already warmed by 1.1°C and experts say that it is likely to breach 1.5°C in the 2030s.

Figure 1 outlines a path to the 1.5°C target by reducing CO_2 emissions to under 10 Gt CO_2, as covered in World Energy Outlook 2019 [1]. In that report, the International Energy Agency (IEA) looks at two scenarios for the trajectory of global emissions. The first is the Stated Policies Scenario, which estimates emissions based on publicly announced government policies. The second is the Sustainable Development Scenario, which looks at additional paths to mitigating emissions. The largest opportunity to reduce CO_2 emissions as part of the IEA's Sustainable Development Scenario is gains in energy efficiency, accounting for 37% of the Sustainable Development Scenario's reductions when compared to the Stated Policies scenario. With 25% of CO_2 emissions coming from industry in 2022 [2], accelerating industrial energy efficiency investments will be an important part of the path to net zero emissions in 2050.

> The world has already warmed by 1.1°C and experts say that it is likely to breach 1.5°C in the 2030s.

Figure 1: *Path to CO_2 emissions reductions* [1]



WHY INDUSTRIAL MOTORS MATTER

The global electricity supply in 2022 was 28,642 terawatt-hours, contributing 13.2 Gt of carbon emissions [3]. Industry consumes an estimated 30% of global electricity and within industry, electric motors make up approximately 70% of electricity consumption [1]. Clearly, the efficiency of these components is a potentially critical contribution to the efficiency savings identified in *Figure 1*. The most basic and lowest efficiency motion solutions are based on direct AC grid-connected 3-phase motors that use switchgear to provide on/off control and basic protection. These motion solutions run at a relatively fixed speed, independent of any load variation. Adjustments in output variables (such as fluid flow in pumps and fans) are implemented with mechanical controls such as throttles, dampers, and valves, whereas significant speed changes are implemented with gears.

Deploying Sustainable Motion Solutions Reduces Total Global Energy by 10%

450 Mu	52 Mu/Y	30%	96%
Installed Motors	New Installations	of Total Energy Used by Industry	of Industrial Energy Used by Motors

Figure 2: *The part played by Industrial Motors in global energy usage*

The addition of a rectifier, DC bus, and a 3-phase inverter stage, as illustrated in *Figure 3* (b) creates an inverter with variable frequency and a variable voltage output that is applied to the motor to enable variable speed control. This inverter driven motor significantly reduces system energy consumption by running the motor at the optimum speed for the load and application. Examples include higher efficiency pumps and fans. When added to the existing motor of a pump, fan, or compressor, an inverter can potentially reduce power consumption between 25% and 60%, depending on the motor and application [4,5]. For higher performance motion control applications, a variable speed drive (VSD) *Figure 3* (c) enables accurate torque, velocity, and position control.

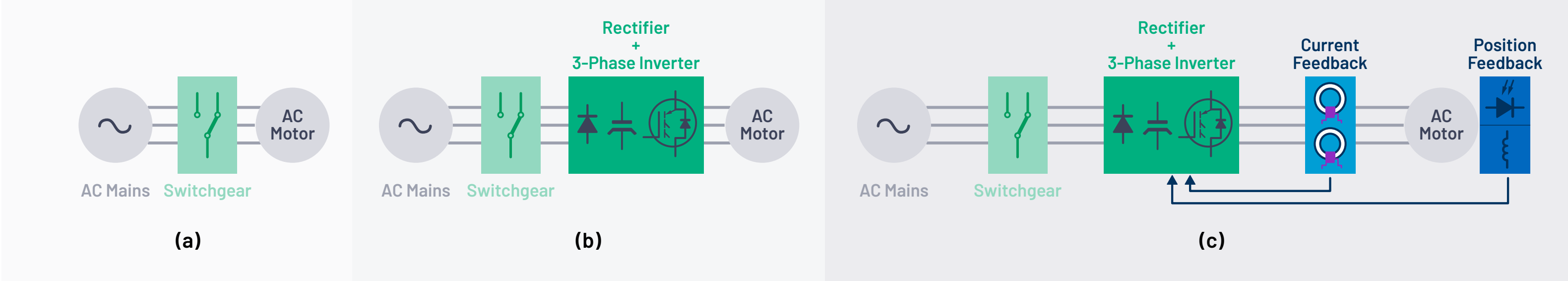


Figure 3: *(a) Grid-connected AC motor (b) Inverter fed motor (c) Variable speed motor drive*

It is estimated that only about 1-in-6 of all deployed motors in the industry are inverter driven or connected to a VSD [6]. By moving more deployed motion assets from grid-connected motors to inverter-driven or VSDs, it is possible to significantly reduce the energy consumption and CO_2.These reductions in energy consumption would enable more sustainable manufacturing with reduced CO_2 emissions. It has been estimated that if all deployed motor driven systems were operated at maximum efficiency, it would reduce global electricity demand by 10% and remove 2490 Mt of CO_2 emission in 2030 [7].

MOTOR EFFICIENCY STANDARDS

To accelerate the deployment of higher efficiency motor driven systems, the International Electrotechnical Commission (IEC) has contributed to the definition of energy efficient electric motor standards. This includes the IEC 60034-2-1 test standard for electric motors and the IEC 60034-30-1 classification scheme comprised of four levels of motor efficiency (IE1 through IE4), with the IE5 level due to be introduced in the future. The higher-level standards can be achieved either through more efficient motor design or through the addition of an inverter or VSD to a standard motor design. As the efficiency classes become more stringent, meeting them by improved motor design alone is becoming more and more challenging, and costly. Alongside the additional benefits provided by variable speed control in the application, the case for VSD-attach to most industrial motors is becoming more compelling.

The next chapter will highlight the other trends in industrial automation – apart from energy efficiency – that have been driving the evolution of motion control away from simpler grid-connected machines to highly controllable multi-axis VSD-based systems.

REFERENCES

[1] World Energy Outlook 2019. International Energy Agency, 2019.

[2] World Energy Outlook 2022, International Energy Agency.

[3] Electricity Market Report 2023. International Energy Agency, February 2023.

[4] Achieving the Paris Agreement: The vital role of high-efficiency motors and drives in reducing energy consumption. ABB, 2021.

[5] Applications of variable speed drive (VSD) in electrical motors energy savings. R. Saidur, S. Mekhilef, M.B. Ali, A. Safari, H.A. Mohammed, Renewable and Sustainable Energy Reviews, Jan 2012.

[6] U.S. Industrial and Commercial Motor System Market Assessment Report, Volume 1. Lawrence Berkeley National Laboratory, January 2021

[7] Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems. International Energy Agency 2011

MOTOR CONTROL FOR THE 4TH INDUSTRIAL REVOLUTION

This chapter looks at how motor control architectures and functions are evolving to meet the requirements of Industry 4.0 – from simple grid-connected motors to complex multi-axis servo drive solutions.

This evolution has been accelerated by the increasing complexity of automation needed to deliver the higher levels of productivity, flexibility, and autonomy required by the rapid digitalization of consumption, supply chains, and smart manufacturing [1]. The demand for agile production and greater access to production data have both contributed to the increasing complexity of motor control systems.

> The demand for agile production and greater access to production data have both contributed to the increasing complexity of motor control systems.

AGILE PRODUCTION

As industries are adapting to keep up with consumer demand and changing buyer behaviors, agile production, based on reconfigurable production lines, is required to deliver more customization and faster turn-around times. Consumer demand is driving a shift away from low-mix, high-volume manufacturing toward high-mix, low-volume manufacturing, which demands greater flexibility on the factory floor. Complex, repetitive, and often dangerous tasks can now be performed by industrial and collaborative robots, leading to higher throughput and increased productivity. This shift in production patterns has resulted in a higher demand for more complex, customizable, autonomous, and intelligent automation hardware, at the heart of which are motor control systems. For example, systems such as conveyors and handling machines are required to be smarter, have more axes of motion, and be highly configurable.

ACCESS TO PRODUCTION DATA

Global spending on digital transformation will reach $6.8 trillion globally by 2023 [2]. Variable speed drives can provide access to machinery data in the form of voltages, currents, position, temperature, power, and energy consumption combined with external sensors for monitoring vibration, and other process variables. With a converged information technology/operating technology (IT/OT) Ethernet network motor and machine data and associated insights are now more accessible and can be analyzed by powerful cloud computing and Artificial Intelligence (AI) to optimize manufacturing flows and monitor the current state of health of the assets across the entire installation. This optimization of manufacturing flows will further reduce energy consumption in smart manufacturing.

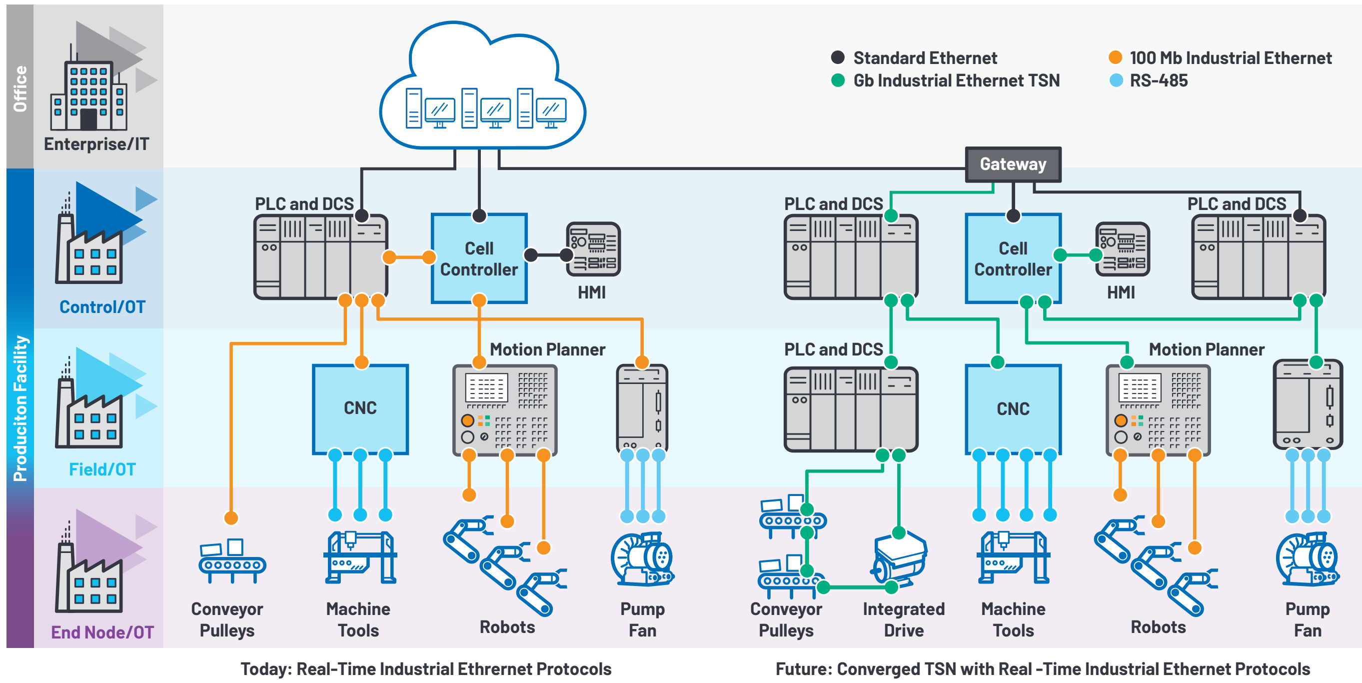


Figure 1: *Digital transformation enabled by seamless industrial Ethernet connectivity.*

To deliver this, motion control systems are moving towards a converged connectivity scenario, where legacy, mixed industrial Ethernet communication protocols are being gradually displaced by Time-Sensitive Networking (TSN) - based systems, standardized around the IEEE802.1 network standards [3], as illustrated in *Figure 1*. This will enable time-synchronized data from end equipment to be available across all areas of the network in real-time.

A SPECTRUM OF MOTOR CONTROL SOLUTIONS

Ultimately, modern production systems will include a mix of simpler and more complex motor control systems, as those highlighted in *Figure 2*, with the grid-connected and simple inverter drives being replaced more and more by interconnected, sensor-integrated, synchronized systems. Each of these "flavors" of motor control is described briefly here, along with the applications served by them.

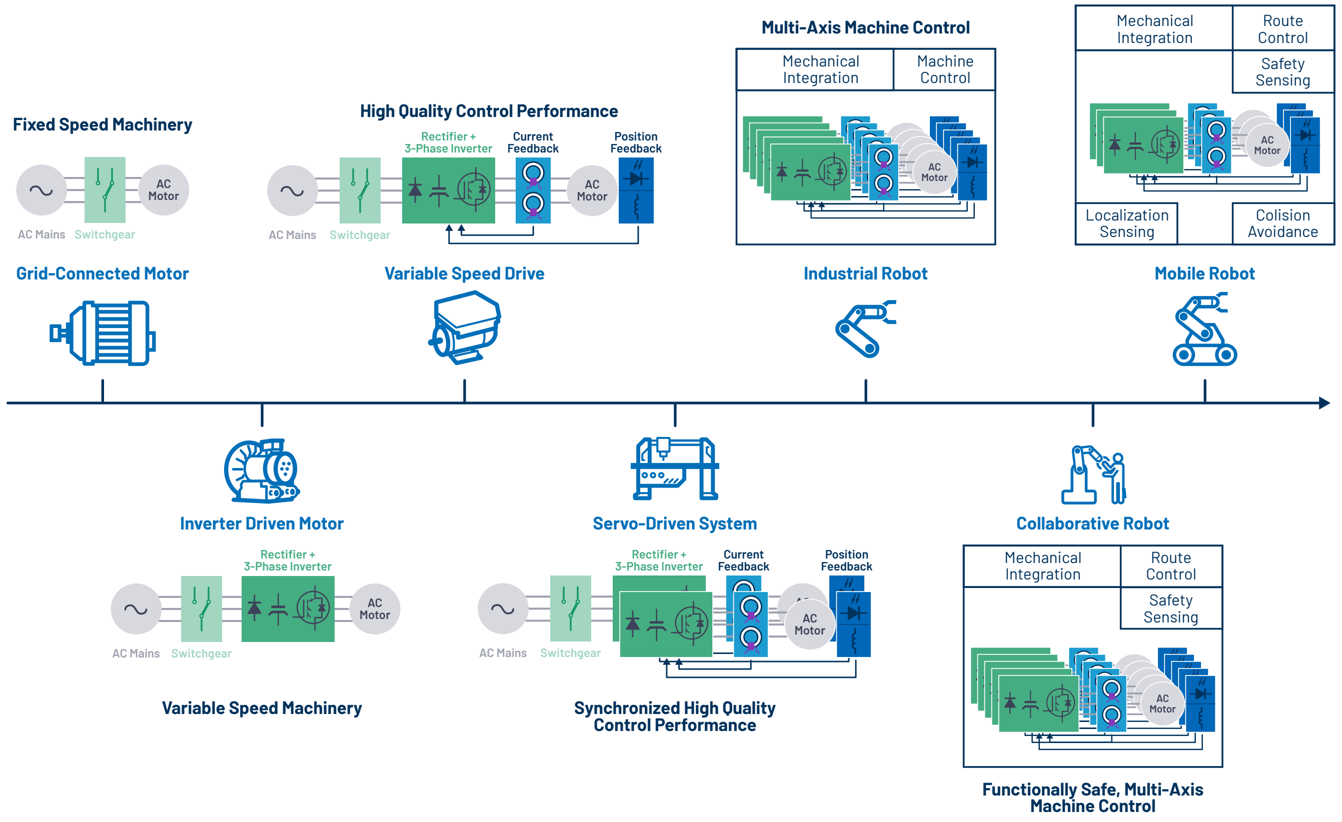


Figure 2: *The range of motor control solutions used in modern automation*

Grid-Connected Motor: These basic motion solutions run at a relatively fixed speed. True constant-speed applications are fairly limited in industry, but these will continue to be used in situations where motor operation is very intermittent, and the cost of a VSD is not justified (e.g. low power, intermittently used blowers, pumps, valves, actuators).

Inverter Driven Motor: The addition of a simple open-loop inverter to the motor control enables significant reductions in energy consumption by running the motor at the optimum speed for the load and application. Pumps, fans, blowers, and more crude control systems, such as platform movers are typical applications.

Variable Speed Drive: For higher-performance motion control applications, a variable speed drive (VSD) enables accurate torque, velocity, and position control. To achieve this, current and position measurements are added to the basic open-loop inverter drive. Conveyors, winding, printing, and extrusion machinery are typical examples of applications needing VSDs.

Servo-Driven System: Synchronized, multi-axis servo-driven systems are used in more complex motion applications. Machine tools and CNC machines require synchronization of multiple axes, with extremely accurate position feedback. Precision machining and additive manufacturing are key applications that utilize multi-axis servo drives.

Industrial Robot/Collaborative Robot/Mobile Robots: Industrial robots require multi-axis servo drives combined with mechanical integration and advanced machine control algorithms to achieve complex 3D spatial positioning. Collaborative robots (cobots) build on industrial robotic solutions by adding power and force limiting (PFL) and safety sensing to deliver functionally safe, multi-axis machine control where an operator can work safely alongside the cobot. Mobile robots add localization sensing and collision avoidance. The applications served by robotics systems are growing, from traditional automotive manufacturing to handling, palletizing, pick-and-place, packing, and logistics.

In the next chapter we will begin to look into the architecture of the motor drive itself and start breaking it down into its subsystems and components.

REFERENCES

[1] The Fourth Industrial Revolution: what it means and how to respond | World Economic Forum (weforum.org)

[2] Shawn Fitzgerald, Daniel-Zoe Jimenez, Serge Findling, Yorikiharu Yorifuji, Megha Kumar, Lianfeng Wu, Giulia Carosella, Sandra Ng, Robert Parker, Philip Carter, and Meredith Whalen. "IDC FutureScape: Worldwide Digital Transformation 2021 Predictions." IDC, October 2020.

[3] https://1.ieee802.org/

VARIABLE SPEED DRIVE 101

This chapter is focused on the basic working of the variable speed drive - a critical component in enabling precise and accurate motor control in applications such as conveyors, winding, printing, extrusion machinery, and many other industrial applications. It is estimated that only between 20% and 30% of all deployed motors in the industry are inverter-driven or connected to a variable-speed drive. If each motor is driven in the most efficient way possible - that is with proper load matching and with an appropriate motor drive, it will have the potential to reduce global energy usage by up to 10%.

> A variable speed drive (VSD) helps in optimizing energy consumption, increasing productivity, extending equipment lifetime, and enhancing the overall efficiency of motor-driven systems.

A variable speed drive (VSD) controls the speed and torque of an AC motor by converting fixed frequency and voltage input to a variable frequency and voltage output to achieve precise control of motor speed and torque. It helps in optimizing energy consumption, increasing productivity, extending equipment lifetime, and enhancing the overall efficiency of motor-driven systems. Motor drives are primarily located between the AC grid and the motor. They take their main power source from the AC grid and convert the AC supply voltage to DC using a rectifier and a capacitive filter. The filter capacitor bank helps to reduce the AC ripple on the DC bus. After smoothing, the DC voltage is applied to the inverter stage.

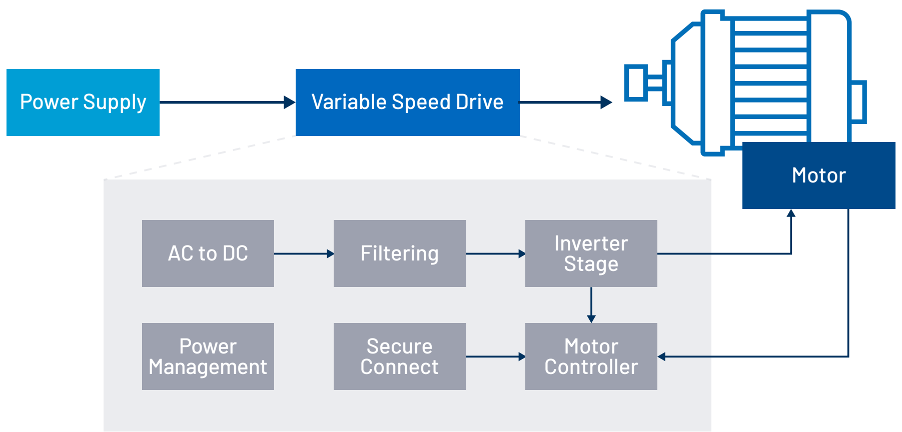


Figure 1: *Block diagram*

The inverter stage is the most important in the variable speed drive as it converts the DC input into a variable-frequency output. It consists of power transistors, isolated gate drivers, voltage and current feedback circuits, as well as other protection and monitoring circuits. The power transistors convert the high voltage DC bus to variable frequency, variable voltage three-phase AC output for the motor. In the inverter stage, gate drivers turn on and off the power transistors using pulse-width modulation (PWM) signals from the motor controller to vary the AC output (voltage and frequency) required by the motor, depending on its load. The gate drivers efficiently turn on and off the power transistors and regulate the output voltage and frequency while also protecting them from any fault conditions.

The voltage and current sense circuitry plays a crucial role in measuring the current and voltage in the motor and feeding these values back to the current control loop. The motor current is a direct function of the motor torque and the bandwidth of the current control loop determines the overall torque response of the variable speed system. Precise and robust measurement is important to ensure maximum torque per ampere of current and optimize motor efficiency. This in turn saves energy and enhances sustainability.

The inverter is directly connected to the motor itself. In many systems, the motor will have an encoder device attached to it, that measures the position of the motor rotor and feeds this back to the motor controller. The motor controller is the processing unit that takes input from the encoder, the inverter, and any external connectivity interfaces, and transmits output-optimized pulse width modulation signals back to the inverter to run the motor efficiently. The choice of the processor depends on the application and compute power requirement, it can be a microcontroller, an FPGA, a high-performance microprocessor, or a combination of these. The secure connect block is where the user and network interface interact with the motor drive. Connectivity and security are becoming critical elements of the motor drive to enable communication with the outside world. Since motor drives operate in harsh noisy environments for reliable operation, it is essential to design connectivity solutions with added noise immunity and robustness. With increased connectivity comes the need for added security at the device level. Manufacturers have to protect production assets from malware attacks, and untrusted commands to ensure secure boot and trusted execution, ensuring secure communication across the network.

GETTING PLUGGED IN: THE AC INPUT STAGE OF A VARIABLE SPEED DRIVE

The previous chapter gave a snapshot overview of the different elements that make up a variable speed drive (VSD). The block diagram is expanded in more detail in ***Figure 1*** below, where the different parts of the drive as well as the various external interfaces to the motor, encoder, and external networks are shown, as well as the power and data flows between the different elements.

Every drive architecture is slightly different, particularly in terms of how electrical isolation between the high voltage zone and the Safety Extra Low Voltage (SELV) zone is managed, but the architecture shown in *Figure 1* is quite common.

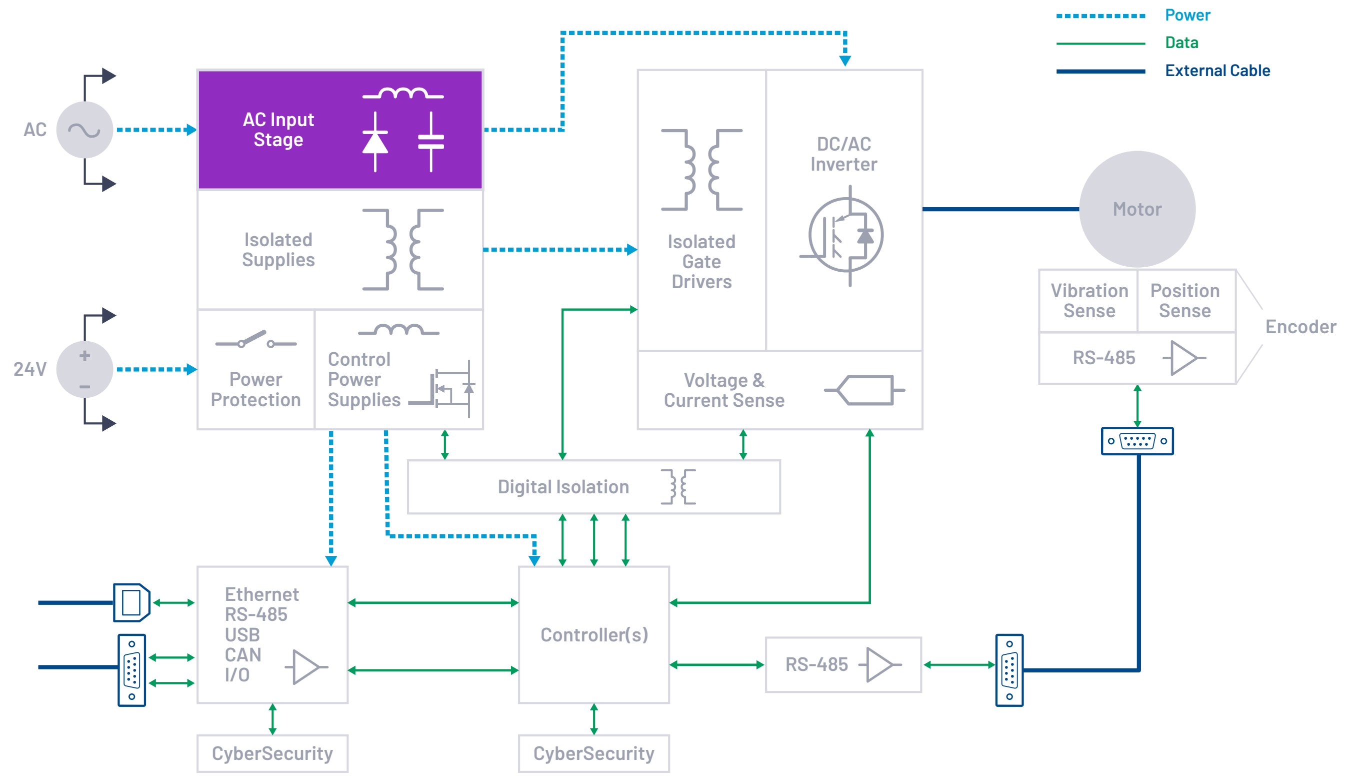


Figure 1: *Detailed Variable Speed Drive Architecture*

The block under more detailed consideration in this chapter is the AC input stage. As shown in *Figure 1*, the AC input stage is the main power path from the AC grid supply to the DC/AC inverter stage. This chapter discusses the different functions performed by this block, namely:

- AC/DC Conversion
- EMI Filtering
- Inrush Protection
- Transient Protection

The AC input stage is the main power path from the AC grid supply to the DC/AC inverter stage

AC/DC CONVERSION

The main purpose of the rectifier is to convert the mains AC input (1-phase or 3-phase) to a DC bus supply which acts as the input to the DC/AC inverter stage. This is generally achieved through a six-diode bridge rectifier, followed by a large electrolytic capacitor bank across the DC bus, which provides smoothing for the rectified AC signal, and renders it more DC-like, effectively acting as a large low-pass filter. The amount of "ripple" present on the DC bus is directly proportional to the size of the DC bus capacitor bank, which must also be sized to provide holdup of the drive during short AC mains dropout events. Some variable speed drives implement fully controlled AC/DC converters, that use power switches rather than power diodes – these allow for full control of the input AC current, to manage low-frequency harmonics. However, these are much more expensive and are not required in the majority of applications.

EMI FILTERING

The AC/DC rectifier stage is also important in that it helps ensure that he drive complies with conducted EMI regulations such as EN61000-3-2, which is published by the International Electrotechnical Commission (IEC). The DC/AC inverter is a switching converter with many fast transient voltages and currents which result in significant differential and common mode high-frequency currents through parasitic inductances and capacitances, and these must be prevented from polluting the AC network and impacting other equipment. Input EMI filtering is typically implemented using a mix of differential and common mode chokes, and a mix of high-frequency bypass capacitors between the AC lines (known as X-capacitors) and between the AC lines and earth (known as Y-capacitors). These components present a high series impedance to high-frequency currents and a low impedance to earth for these high-frequency currents.

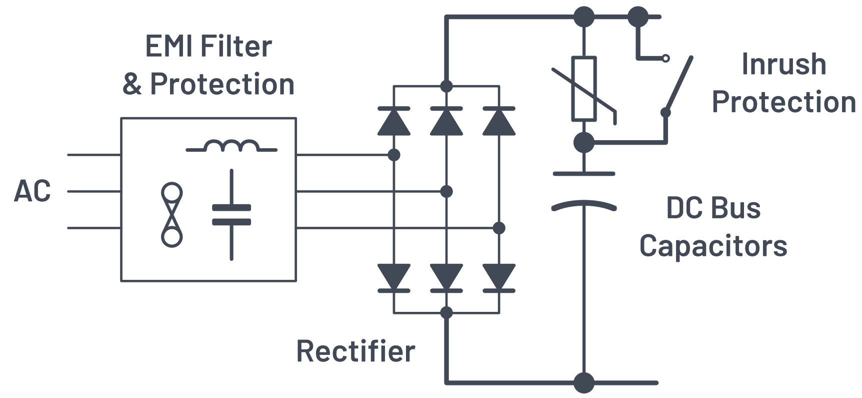


Figure 2: *Input Stage Circuits*

INRUSH PROTECTION

Inrush protection is another important function carried out by the input AC/DC stage. On startup, the DC bus capacitor bank is completely discharged, and the charging current from the AC line voltage to the DC bus is limited only by the resistive impedance of the EMI filter chokes and bridge diodes.

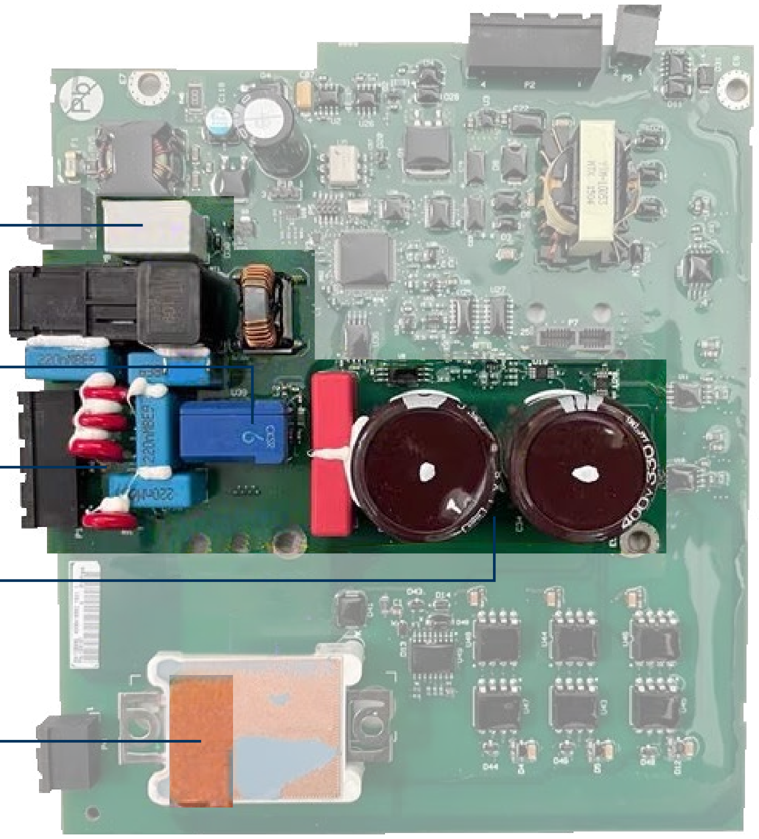
Without some additional current limiting, a very high transient charging current will flow from the AC line to the DC bus capacitor bank, and this can result in overload in the filter components and/or the rectifier diodes. To counteract this, a series thermistor is sometimes inserted in the charging path – this has high resistance when it is cold, and this limits the charging current to a reasonable level. Once it heats up, the resistance reduces dramatically, limiting the power losses. The one issue with this style of inrush protection is related to multiple restarts in close proximity – in this case, the thermistor will not have cooled down enough in between restarts and damaging over-currents can occur. A better solution is to use a standard current limiting resistor, with a relay or solid-state switch in parallel, that can be turned on once the inrush period is over, as illustrated in *Figure 2*.

TRANSIENT PROTECTION

Last, but not least, transient voltage protection is a critical function performed by the input AC/DC stage. Transient voltage spikes and surges can be present on the AC grid for many different reasons, and these have the capacity to permanently damage a motor drive. In order to counteract this, components such as Transient Voltage Suppressors (TVS) diodes or Metal Oxide Varistors (MOV) are generally inserted in parallel with the AC line phases. These act to clamp any voltage spikes and absorb the energy associated with them, and in so doing protect the rest of the electronics.

These various elements of the AC input stage are shown in *Figure 3* inside a Rockwell motor drive. Even though they are relatively simple components, electronically speaking, they take up a large area within a motor drive and have a large impact on the overall reliability, protection, and lifetime of the drive.

***Figure 3:** AC Input Stage Elements in a Variable Speed Drive*



It is estimated that only **20–30%** of all deployed motors in the industry are inverter-driven or connected to a variable speed drive.

POWERING YOUR DRIVE – IT'S MORE THAN JUST PLUGGING IT IN

The last chapter addressed the AC input stage of the motor drive. This is primarily an AC-DC power conversion stage where the AC input power is converted to a DC level that provides the input to the main three-phase inverter. Several other power domains are required in the drive apart from the high-voltage inverter power domain. Managing these power domains, providing the appropriate ground referencing and isolation, and protecting them from external transients is a critical task of the variable speed drive designer.

This chapter examines the topic of power management in a variable speed drive and looks at some of the requirements that exist in the different power domains. In the last chapter, we introduced a typical architecture diagram, shown here again in *Figure 1*. The section of the drive under consideration is highlighted.

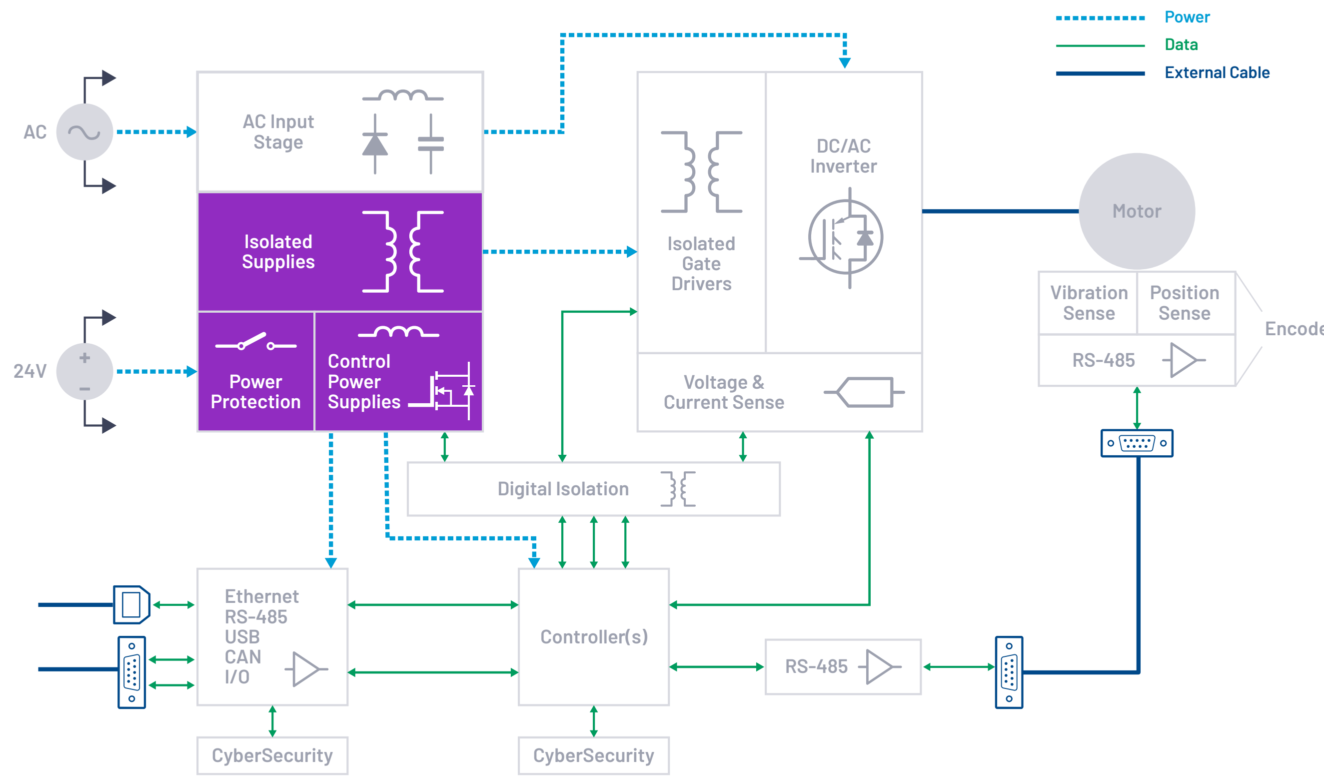


Figure 1: *Detailed Variable Speed Drive Architecture*

Firstly, let's identify the main power supplies within a variable speed drive. These are:

- Main control power
- Inverter-isolated power supplies (Gate driver and motor phase current sense)
- Multiple low-voltage control power rails

Managing power domains and protecting them from external transients is a critical task of the variable speed drive designer.

Each of these power supplies carries out a unique function and has certain requirements associated with it.

MAIN CONTROL POWER

The main control power supply is usually a 24V DC bus (although it can sometimes be a 12V bus). This power supply has several functions. It acts as the intermediate DC voltage from which the low-voltage rails are distributed. It can also be used to directly supply the power for any cooling fans that may be needed within the drive housing or for other higher voltage loads such as motor brakes, as illustrated in *Figure 2*.

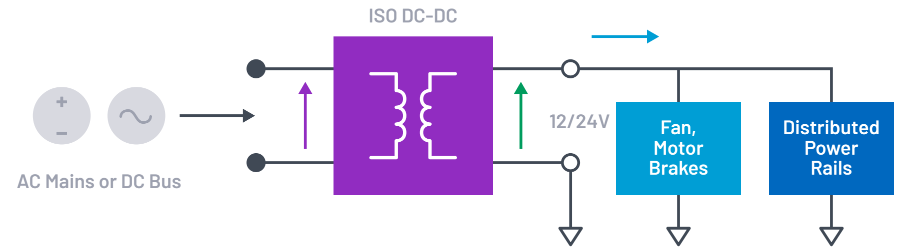


Figure 2: *Main Control Supply*

This is mostly derived from the main high-voltage DC bus via an isolated DC-DC converter. In some cases, it can be derived directly from one of the AC input phases. In both of these cases, a flyback converter is a popular choice of power topology. Flybacks are not the nicest power converters to work with! They are quite noisy, and it can be challenging to provide tight control of the output voltage. However, they have some major plusses associated with them in their simplicity (one transistor, one magnetic component) and low cost. In the context of variable speed drives, which can be highly competitive in terms of cost, and which are already huge noise generators, the disadvantages of flyback converters are mostly outweighed by their advantages. An example is shown in *Figure 3* of a solution from Analog Devices which has the advantage of providing good control of the output voltage without requiring an optocoupler to provide output voltage feedback to the controller, a "no-opto flyback". In higher power variable speed drives, a flyback may not be suitable and in this case, half-bridge or full-bridge isolated topologies are generally chosen (e.g. LLC converter).

INVERTER ISOLATED POWER SUPPLIES

Isolated power supplies are needed for each of the gate driver units, which are responsible for controlling the inverter power switches. The requirement is typically three 12-20V supply rails (sometimes with a negative rail also), referenced to the three motor phase switching nodes and one low side supply referenced to DC bus negative rail. The "grounds" for these power supplies are not tied to safety earth, or even to a quiet ground reference, and are rapidly moving over hundreds of volts in the case of the gate driver supplies – hence the need for isolation. Overall this usually translates into four isolated DC-DC converters, normally from the intermediate DC bus to the gate driver supply.

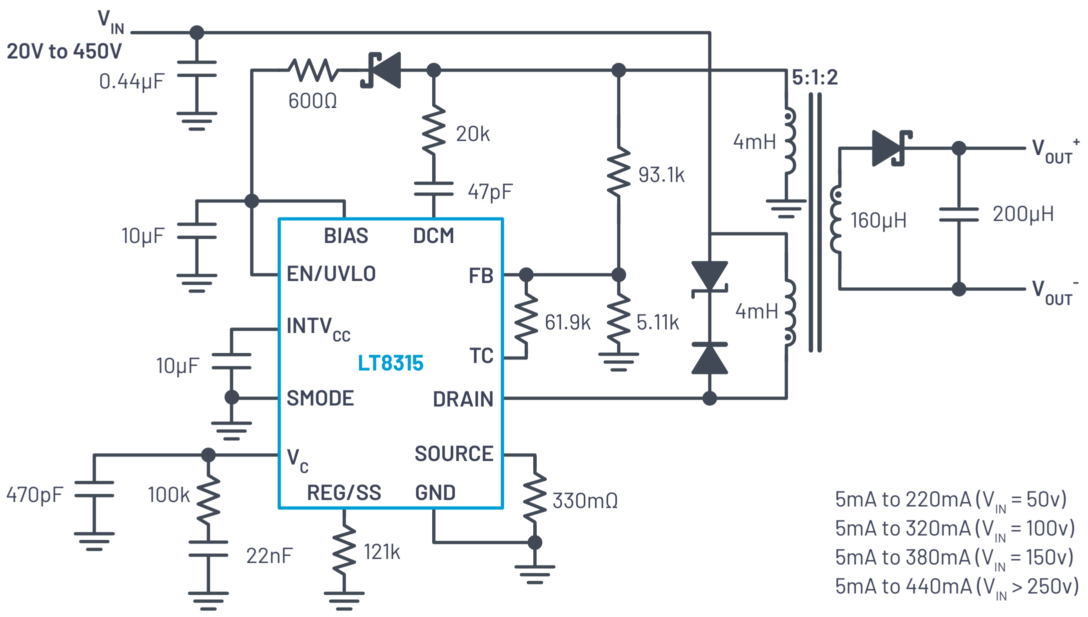


Figure 3: *No-Opto Flyback Converter Example*

These isolated voltage rails are designed to provide the switching voltage levels for the power transistors used in the VSD – whether they are power MOSFETs, IGBTs, or SiC/GaN devices. Any current sensors connected in the motor phases, will also generally require isolated supply voltages – these are often derived directly from the gate driver supplies using an LDO (low dropout) regulator as shown in *Figure 4*.

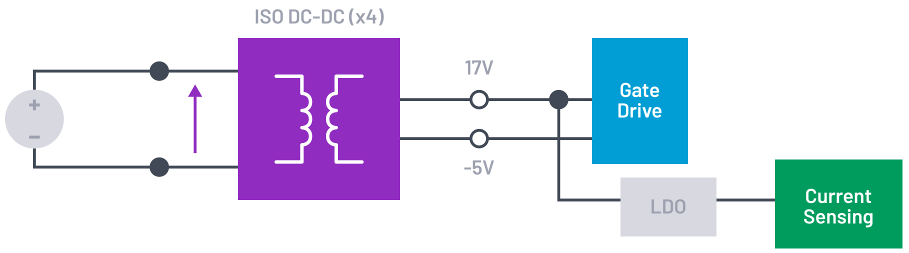


Figure 4: *Inverter-isolated Supplies*

Once again, multi-output flybacks can be a solution for these supplies, although these tend to have quite complex and bulky transformer designs due to the need for so many outputs.

CONTROL POWER PROTECTION

Protection of the main control power supply (usually 24V) from transients and anomaly conditions is extremely important within a VSD. The reason for this is that there are generally two paths for this supply rail. The first path as described earlier in which the 24V control power supply is derived from the AC mains, or high voltage DC bus via an isolated power conversion stage.However, this 24V rail can also usually be supplied directly from an auxiliary power input connected to the VSD.

Most automation environments distribute 24V supplies around the control cabinets for a range of control equipment, and the VSD usually taps into this supply. This auxiliary 24V input is usually diode OR'ed with the converter-derived 24V supply, to ensure that only one supply source is active at a time. The advantage of having this available is that even if the AC mains drops out or trips, usually the auxiliary 24V supply will keep running, meaning the VSD's control electronics can stay energized, resulting in the capability to quickly restart the VSD and not lose any context information. The disadvantage is that the VSD power supplies are now exposed to all of the voltage transients existing on the factory-wide 24V supply system – these can occur through switching loads that excite voltage ringing on distribution cables, lightning events that propagate through the system, electrostatic discharge from nearby electric fields or human contact, as well as electromagnetic interference picked up on cables. Hence the need for solid protection on this auxiliary supply input.

The VSD functional safety standard IEC 61800-5-2 Annex A (Section B.3.2) shows a recommended Power Supply (PS) and Voltage Monitor (VM) subsystem for such a 24V DC rail. It consists of protection against a variety of common faults such as reverse polarity, overcurrent, and voltage transients.

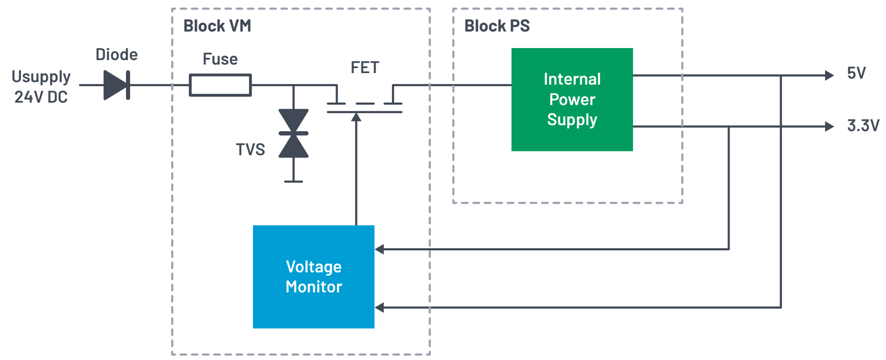


Figure 5: *Recommended auxiliary supply protection per IEC 61800-5-2*

As the transients involved can vary in energy level and duration, designing a discrete circuit can be time-consuming and prone to error, and may have poor long-term reliability. Integrated solutions such as Analog Devices Surge Stopper family integrate all of the IEC 61800 requirements, including input reverse polarity detection and protection, overcurrent, short circuit and inrush current detection and protection, and high voltage transient disconnect.

Figure 6 depicts the use of surge stopper solutions from Analog Devices as a potential implementation of IEC61800-5-2 protection recommendations. Components such as the LT4363 or the integrated MOSFET variant LTC4381 can provide robust and reliable protection solutions for the main control power supply.

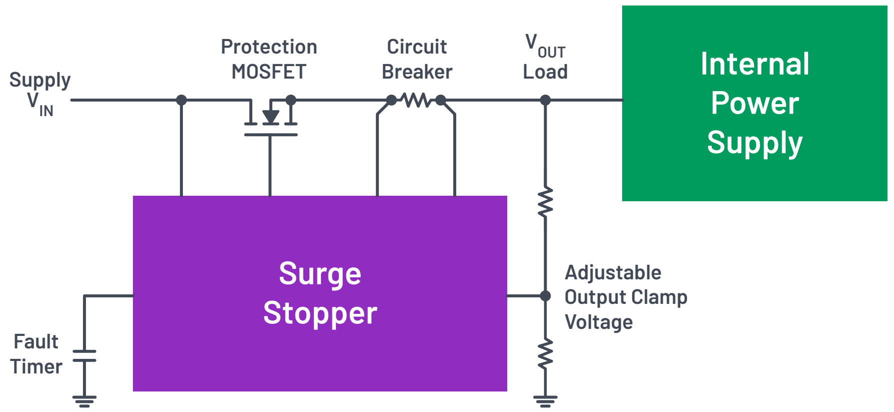


Figure 6: *Analog Devices' Surge Stopper implementation of IEC 61800-5-2*

LOW VOLTAGE POINT-OF-LOAD (POL) POWER

Downstream of the main control power supply sit the low voltage (<12V) power rails. These are by and large the point-of-load (POL) supplies that directly power the main controller devices (CPU, FPGA), other digital components (memory, transceivers, interfaces) analog circuitry (ADC, DAC, op amps, etc), and I/O devices and terminals. The specific design of these power architectures is unique to each VSD, and it is difficult to speak in generalizations, but the typical approaches to these power supplies are illustrated in *Figure 7* and *Figure 8*. In *Figure 7*, single-stage switching regulators are utilized for some key low voltage rails, with downstream low-dropout (LDO) regulator being added for noise-sensitive analog rails or very low current rails at lower voltage levels.

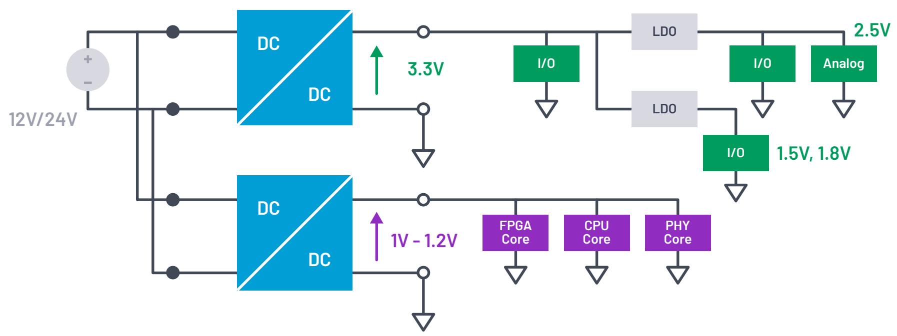


Figure 7: *Single-stage switcher approach*

In *Figure 8*, a single intermediate rail is generated (in this case 5V) and this is further stepped down to individual rails as needed by the POL devices. Also shown here, is the potential need for startup sequencing or tracking of supply rails, which can be important in the complex multi-controller systems used in many VSDs.

POL power supply architecture design is complex and involves many tradeoffs related to overall efficiency, cost, space, and noise. Tools such as LTpowerCAD, LTpowerPlanner, and LTSPICE, from Analog Devices can significantly ease the design challenge.

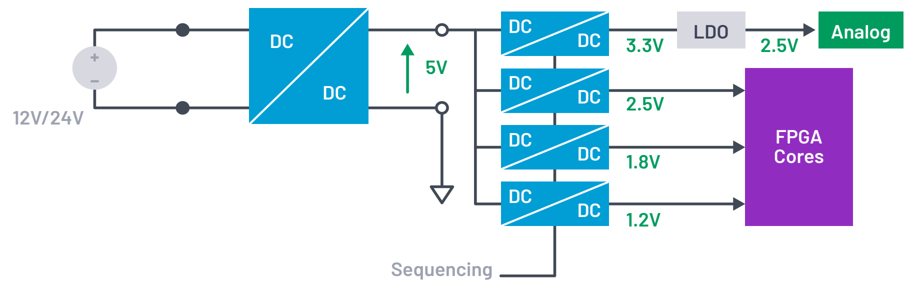
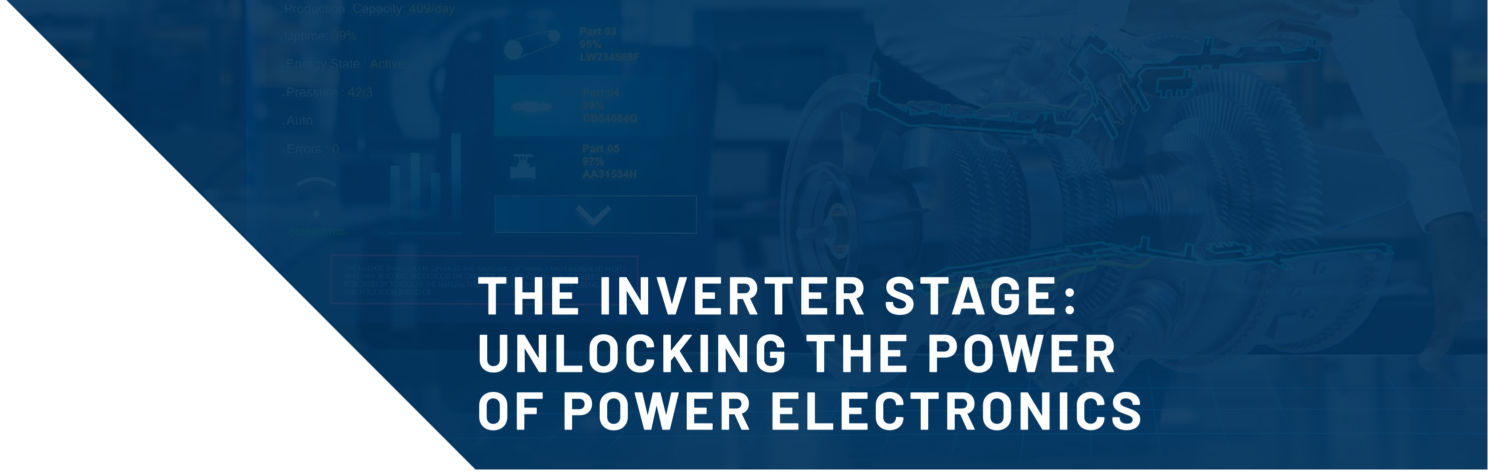


Figure 8: *Multi-stage switcher approach*

SUMMARY

The power supplies within a variable-speed drive fulfill different functions that are fundamental to the overall operation of the drive. Isolation for reasons of electrical safety, and galvanic separation of voltage reference levels is an important factor in many of these power supplies.

This chapter addressed the requirements and circuits needed within a variable speed drive to provide the main control power supply and the power supplies for the inverter electronics - namely gate drivers and current sense circuits. It underlined the importance of protection circuits and touched on the challenges relating to POL low voltage supply design.



THE INVERTER STAGE: UNLOCKING THE POWER OF POWER ELECTRONICS

The inverter stage is the "muscle" of the drive – a power electronics block that provides the regulated, conditioned power directly to the motor, driving it in the manner required by the end application, providing the amperes needed for torque production, the voltage needed for speed and magnetic flux regulation, and the frequency and phase relationships required for control of the speed and torque in the most efficient manner.

In the previous chapter, we covered the power supply functions within the variable speed drive (VSD). In this chapter, we move into the heart of the drive – the inverter stage. This is highlighted in *Figure 1*.

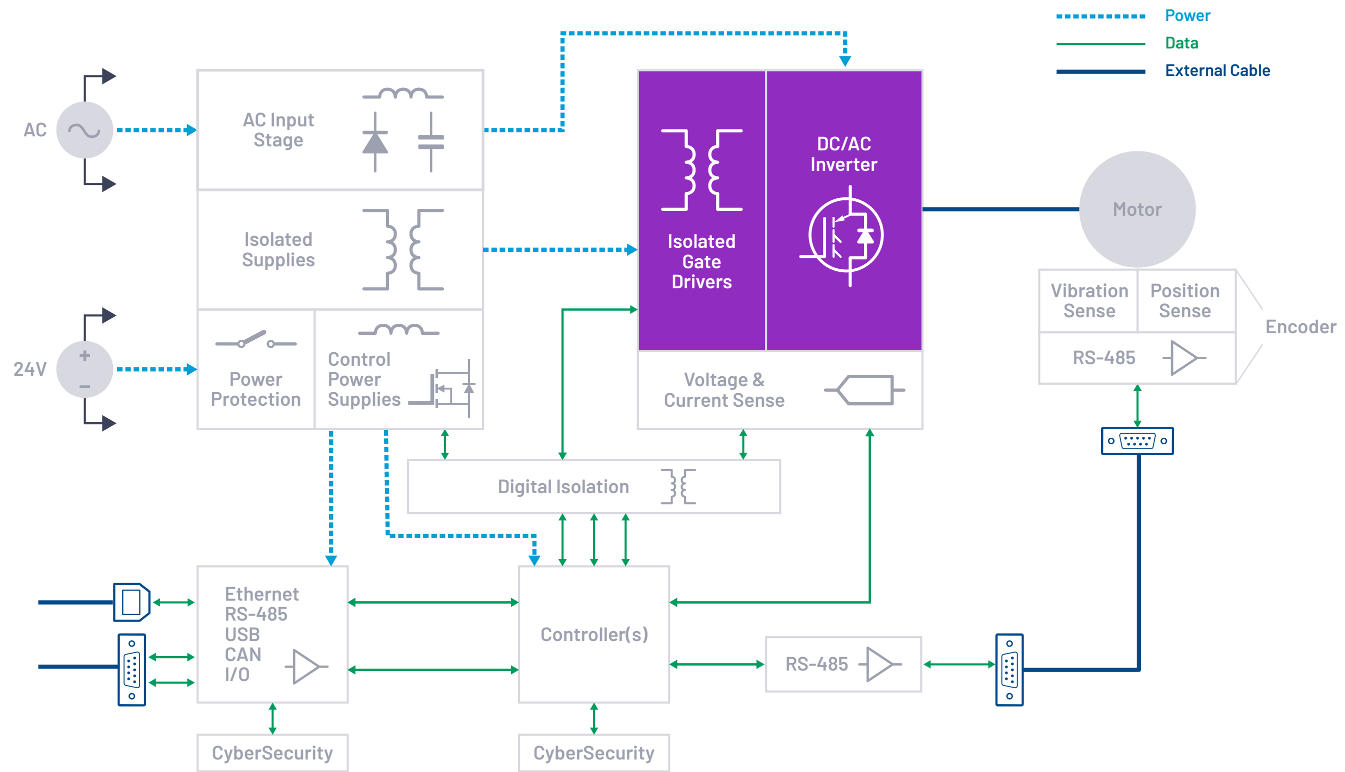


Figure 1: *Detailed Variable Speed Drive Architecture*

The inverter stage fundamentally has two sets of inputs and one set of outputs. The main power input is the DC bus (discussed in the previous chapter on the input stage). The main power outputs are the three-phase lines to the motor. The main control inputs are the gate signals to each of the switching power transistors in each leg of the inverter. There are various flavors of an inverter with different numbers of phases, and different power electronics topologies (multi-level, matrix, etc) but the vast majority of inverters on the market are three-phase, two-level inverters as shown in *Figure 2*.

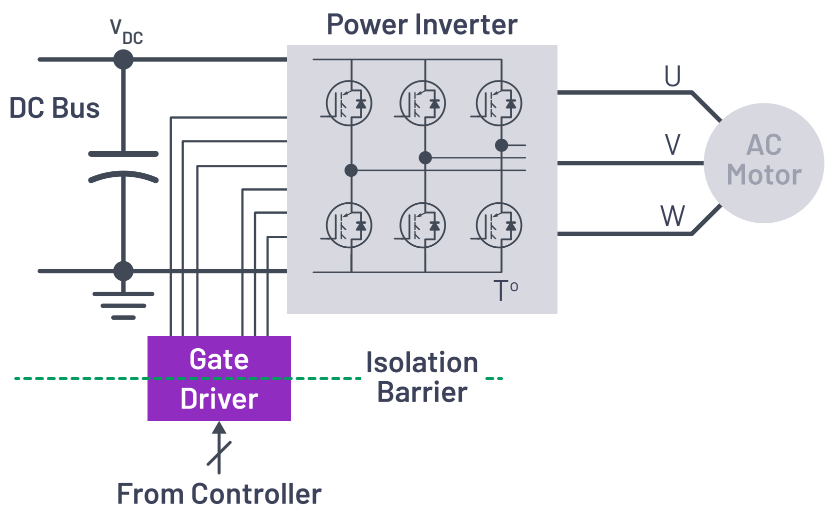


Figure 2: *Inverter Stage Driving Three-Phase Motor Power Transistors*

The power transistors in each leg of the inverter are power-switching devices that turn fully on or fully off at a high frequency (usually in the range of 5-20kHz) and a controlled duty cycle or modulation index. They act as quasi-ideal switches that modulate the voltage applied at each motor phase winding and re-create a waveform with low-frequency components (typically sinusoidal) related to the motor velocity (typically in the range DC-1kHz) and instantaneous position and an averaged voltage amplitude related to the motor velocity and rated magnetic flux. This is illustrated in Figure 3. The output inverter phase-to-negative voltage is a pulse width modulated square wave switching between the DC bus voltage and zero. The inherent inductance of the motor windings will filter this signal to result in a motor current at the required low-frequency phase, frequency, and amplitude, with some undesirable switching frequency ripple present.

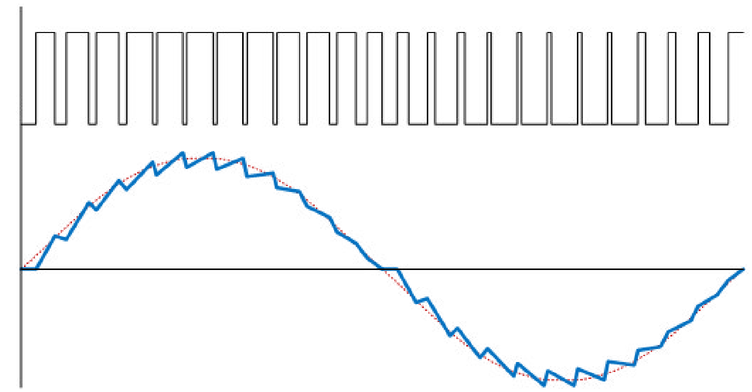


Figure 3: *Inverter phase output voltage and current*

The power transistors and associated thermal management (heat sinks, fans) are usually amongst the most expensive components in a VSD and also tend to take up the most space, especially at higher power levels. Power losses in the transistors come from the fact that they are not ideal switches, have a small voltage drop across them when conducting current, and also have non-zero turn-on and turn-off switching times when high voltage and high current within the switch overlap for short periods resulting in switching losses. Historically MOSFETs and IGBTs have dominated the power transistor market, but in recent years, there has been a trend to look to wider band-gap SiC and GaN-based power transistors. These can offer lower switching losses, which can allow for higher switching frequencies or more efficient inverters at the same switching frequency.

The incentive for VSD designers to move to SiC and GaN is not quite as compelling as in other application spaces, where moving to higher switching frequencies allows for smaller filters. In VSDs, the filter is the motor winding, so in many applications, a higher switching frequency does not give a huge advantage.

> The power inverter is the heart of the VSD and manages the currents and voltages applied to the motor.

GATE DRIVERS

Gate drivers are responsible for converting the logic level signals from the motor controller to signals that have the voltage amplitude and current drive capable of fully controlling the power transistors, and for ensuring that those drive signals are correctly referenced, as illustrated in *Figure 4*.

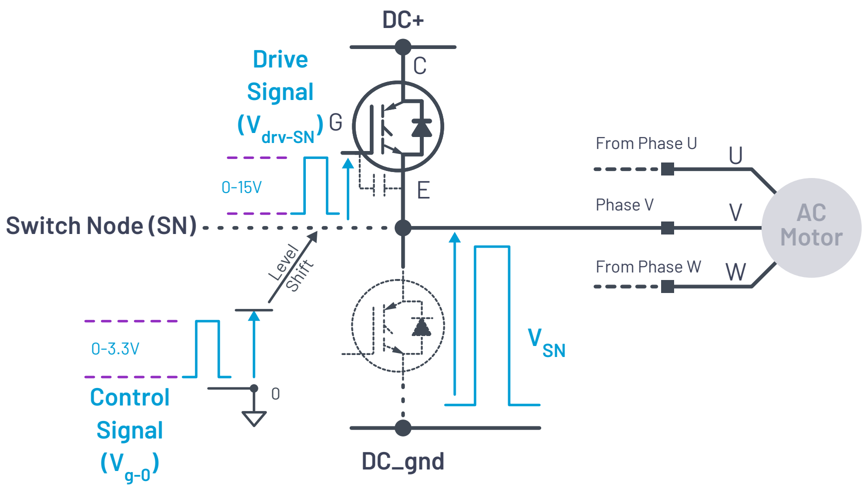


Figure 4: *Switching function of a gate driver*

Other functions provided by the gate drivers can be:

- Power transistor protectio (e.g. desaturation detection in inverter/motor short-circuit conditions)
- Managed switching of the power transistor (e.g. application of different slew rates to the gate drive signal to manage EMI in certain conditions)
- Galvanic and safety isolation of the motor controller from the inverter stage
- Reporting of fault conditions in the inverter and power transistors

So gate drivers can be very complex devices with full communication interfaces (e.g. ADuM4177), or quite simple devices with only driving functionality (e.g. MAX22700). Whatever features are included in the gate driver, robustness to transients (expressed in specifications such as Common Mode Transient Immunity – CMTI) is an important feature as these devices live in a very noisy domain in the inverter, and need to be able to sit between the quiet, low voltage environment of the motor controller, and the high voltage, high current, noisy domain of the power transistors.

SUMMARY

The power inverter is the heart of the VSD and manages the currents and voltages applied to the motor. Safe, robust, efficient switching of the power transistors within the power inverter is an important function of the gate drivers within a VSD. The next chapter will consider some of the signals that are measured within the inverter stage to accurately control its operation.

REV UP YOUR MOTOR CONTROL WITH CURRENT SENSING

The previous chapter highlighted how the control of the inverter is thus critical to the whole operation of the drive. For any closed loop control system we generally need a set point (e.g. the desired operating point) and a measured variable (known as feedback) to compare it with, in order that the control loop can respond to any difference between these. In drives, the key measured variables are typically motor current, and motor position. Other variables such as DC bus voltage are helpful to the operation of the control loop.

In this chapter, we will examine the current feedback and the DC bus voltage measurement as these occur within the inverter stage described in the last chapter, as highlighted again in our architecture diagram below.

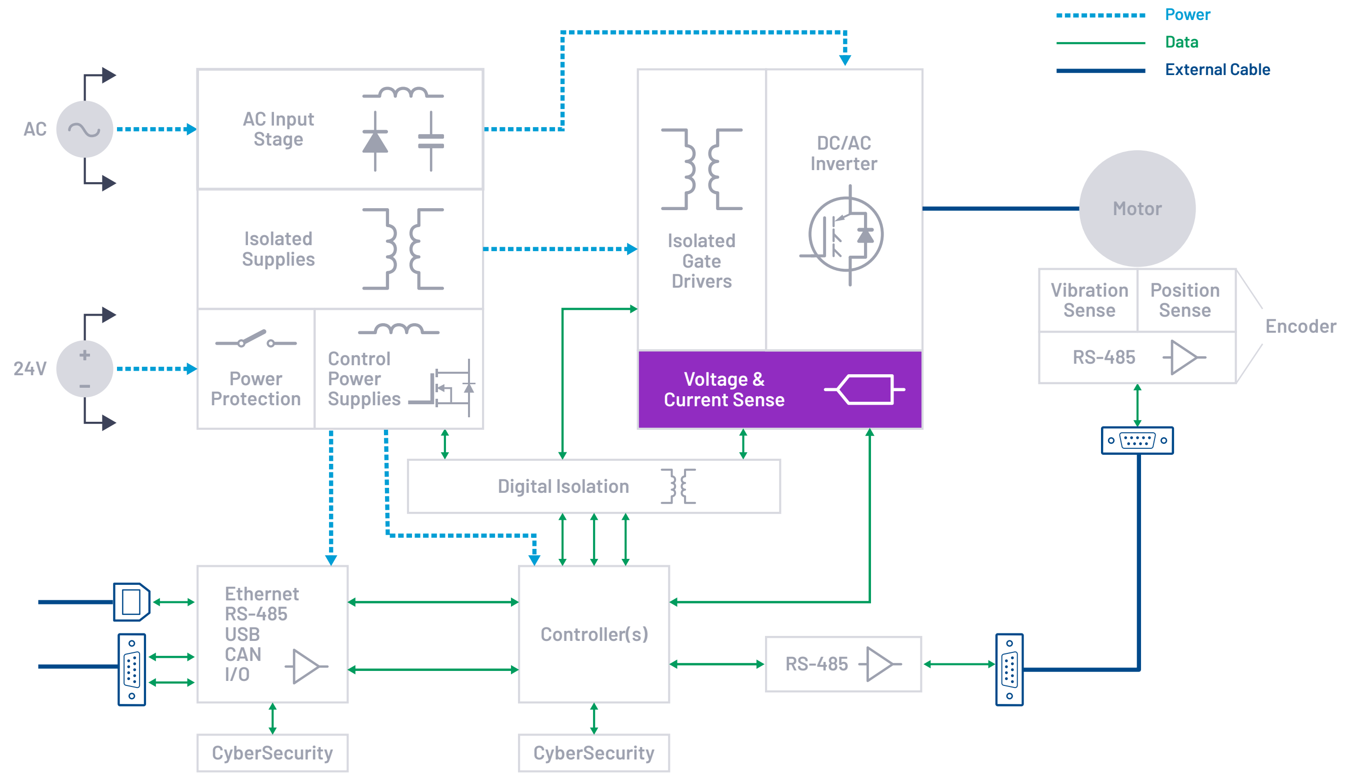


Figure 1: *Servo Drive Architecture Diagram*

> In drives, the key measured variables are typically motor current, and motor position.

What is important in the current feedback path is that the measurement is synchronized with the PWM cycle in order that no high frequency switching current ripple is introduced into the feedback path. This requires precise timing of the current sampling in order that it is sampled at the midpoint of the waveform. At this point in the waveform, the instantaneous current is equal to the PWM cycle average, and the measurement will not include any of the PWM switching ripple current. This is illustrated in *Figure 2* in a simplified fashion – where the sampling point on the phase current waveform is shown, along with its relative alignment to the PWM high-side switching waveform, and the switching period Tsw. The PWM_SYNC pulse indicates the point at which sampling of the current must be triggered in this scenario (this can also be understood as the center-point of the digital filter in the case where sigma-delta ADC type sampling is used which is not a single-point sample, see [1])

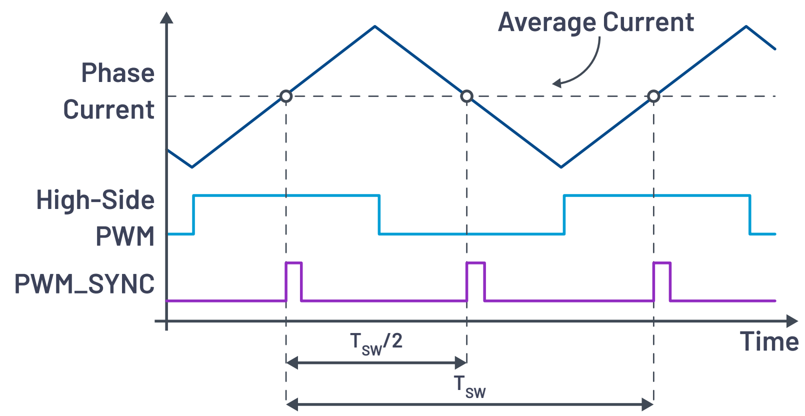


Figure 2: *Motor current mid-point sampling*

Simultaneous sampling of at least two phases is also required, and usually 14-16 bit measurement resolution is sufficient, with microsecond-level latency so that the control loop can respond within the PWM cycle time (Tsw) or in half the cycle time for higher performance control loops.

There are a few different ways to implement the current measurement – these are shown in *Figure 3*, along with some example part numbers to implement the scheme for a 20A application. The most accurate location to measure the motor current is in the actual motor phases, i.e the output lines of the inverter – but this usually requires galvanic isolation, due to the high voltage present at these nodes. Motor current measurements can be inferred from other locations such as inverter leg, and DC bus positive or negative rail – however these measurement locations, while potentially cheaper to implement have other disadvantages associated with them.

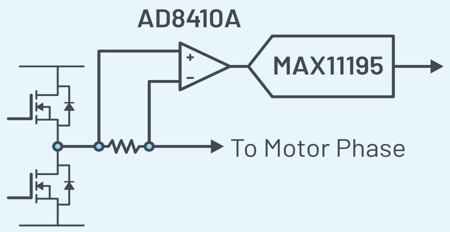
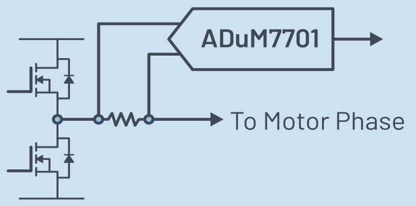
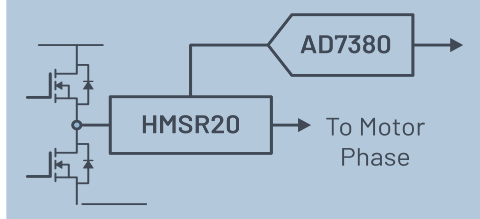
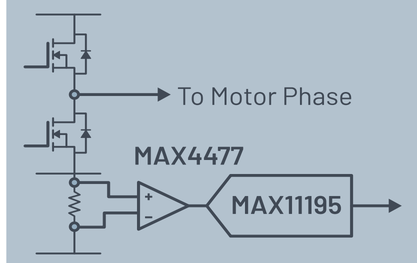
Current Feedback Options	Description	Comments	Example Parts (20A)
	Series shunt resistor + high common mode voltage (CMV) op amp + simultaneous sampling ADC (SSADC)	Usually used in <100V applications, as high CMV op amps are usually rated for this range.	CFN1206AFXR010 (Bourns) AD8410A (ADI) MAX11195 (ADI)
	Series shunt resistor + isolated ADC	Best solution for noise immunity, size and performance. Bitstream output – needs digital filter	CFN1206AFXR010 (Bourns) ADuM7701-8 (ADI)
	Hall current sensing + SSADC	Good solution for higher current levels where shunt resistors become too inefficient	HMSR 20-SMS (LEM) AD8515 (ADI) AD7380 (ADI)
	Leg shunt resistor + opamp + SSADC	Cheapest solution as no isolation needed if controller is DC bus grounded. Less accurate than in-phase shunt	CFN1206AFXR010 (Bourns) MAX4477 (ADI) MAX11195 (ADI)

Figure 3: *Current feedback options*

High fidelity, precision, current feedback is important to the overall control loop of the inverter. It has a big impact on the overall control bandwidth and torque ripple. Bandwidth translates into faster transient performance of the motor control – which can be very important in applications like pick-and-place machines. Torque ripple translates into effects such as machining quality and finish tolerance in applications like grinding, cutting and polishing.

While current feedback is the most important feedback variable from the inverter to the controller, DC bus voltage can also be valuable as a control feedforward variable. It is not used as a controlled quantity, but because variation in the DC bus voltage impacts the dynamics of the current control loop it can be used as a feedforward variable, which improves the dynamics of the overall current controller. The end result of this is as shown in *Figure 4*.

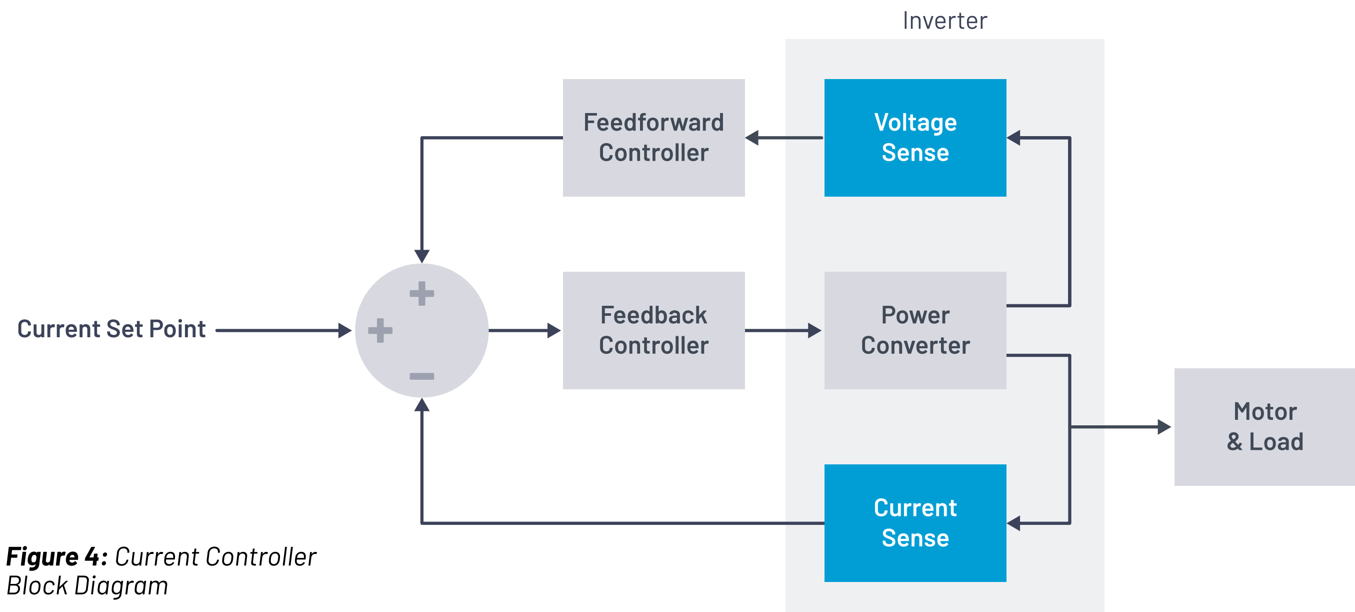


Figure 4: *Current Controller Block Diagram*

The DC bus voltage sense signal can be derived directly from a voltage divider across the DC bus if the controller ground is at the DC bus negative, or else by using an isolated amplifier or ADC (such as the ADuM7701 mentioned previously) connected to the voltage divider output.

The next chapter will look at another important feedback variable – position sensing – that is utilized in another part of the motor control system in conjunction with the current and voltage sensing described in this chapter.

REFERENCES

[1] *"Part 1: Optimized Sigma-Delta Modulated Current Measurement for Motor Control" by Jens Sorensen, Dara O'Sullivan, and Shane O'Meara, https://www.analog.com/en/resources/analog-dialogue/articles/optimized-sigma-delta-modulated-current-measurement-for-motor-control.html*

WHAT'S OUR POSITION ON POSITION SENSING?

In the previous chapter, we explored the current control loop and the current and voltage sensing circuits that provide the feedback variables. This chapter explores the other important sensed variable
in many drives – motor position sensing and feedback.

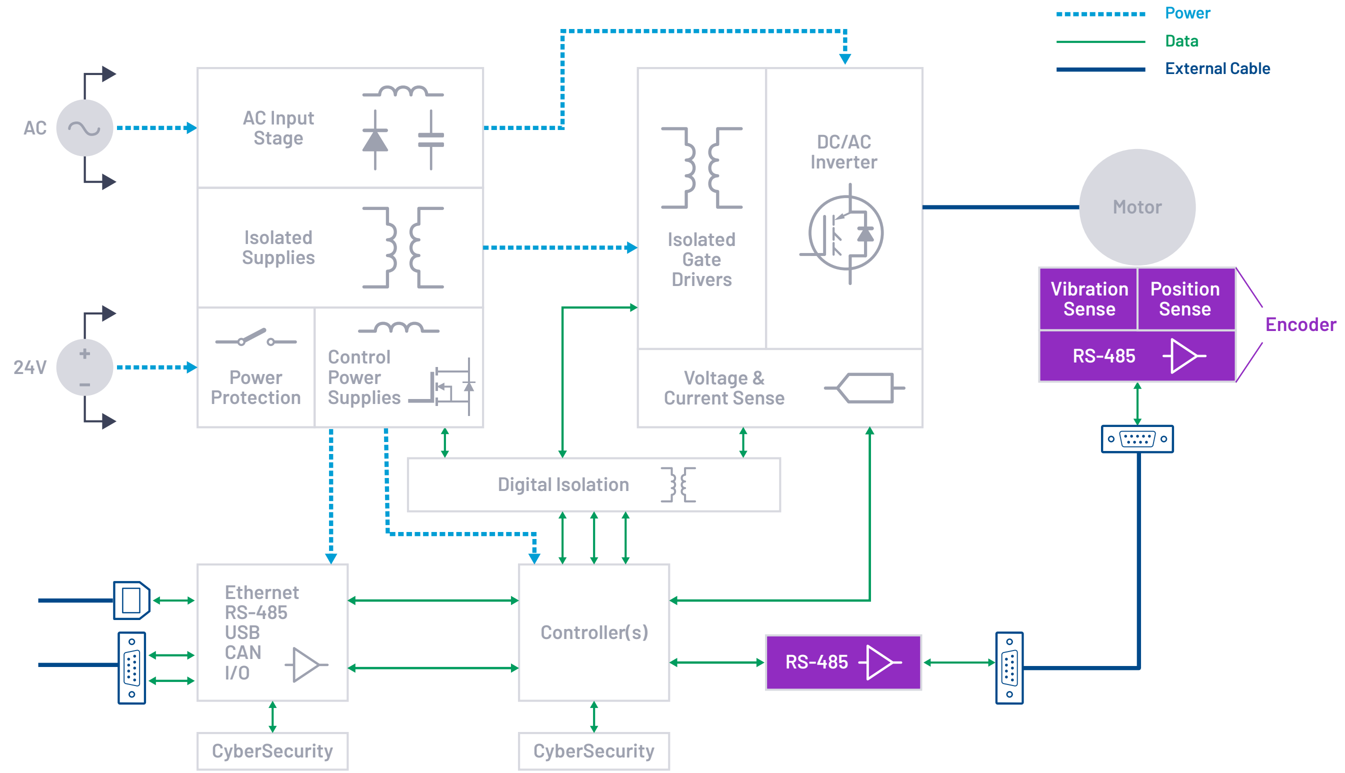


Figure 1: *Servo Drive Architecture Diagram*

The blocks under consideration are highlighted once again in the architecture diagram shown above. The majority of these blocks do not actually reside within the motor drive itself, but rather inside a position feedback device known as an encoder, that is typically integrated with the motor itself, or added on as a separate device that is closely coupled with the motor. The purpose of the encoder is to measure in real time the changing position of the motor rotor (the part that rotates), and in the case of permanent magnet or synchronous motors, the position of the rotor magnetic field as well as its purely mechanical position.

This chapter is not going to cover encoders in detail, instead it will address some specific matters related to position feedback as pertains to the drive itself

> Motor position control is important in applications such as robotics, pick-and-place, and other dynamic applications.

IS POSITION FEEDBACK ALWAYS NEEDED?

It must be pointed out that many lower performance motor drives can operate without position feedback when connected to induction motors. This is due to the fact that the magnetic fields within an induction motor are induced (hence its name) by the applied stator voltage and so the motor rotation frequency will automatically follow the applied three-phase voltage frequency (with a small differential known as slip). In these open loop drives, no encoder is attached to the motor and no position feedback is used in the controller.

WHAT FUNCTION DOES POSITION FEEDBACK FULFILL IN THE DRIVE?

In permanent magnet/brushless DC (BLDC) motor servo drives, position feedback is required for two reasons. Firstly, position feedback is needed in order to synchronize the motor magnetic field position with the applied motor voltages and currents from the servo drive. Motor torque is developed by the interaction of the rotor magnetic field and the magnetic field generated by the application of three-phase currents in the stator windings. These fields must be in synchronism with each other or useful torque will not be generated. In order for maximum torque per Ampere of motor current, in fact, these magnetic fields must be orthogonal to each other in space, as well as being synchronized in time (this is known as field oriented control, FOC).

The second function fulfilled by position sensing is as the feedback variable in a position control or velocity control loop, so that the motor speed or position can be accurately controlled. Motor position control is important in applications such as robotics, pick-and-place, and other dynamic applications. Motor velocity control is also important in applications such as machining, conveyors, rollers, winding etc. For velocity control, the velocity feedback value is generally derived as the derivative of the position feedback. These uses of the position feedback signal in a motor drive controller are shown in *Figure 2*, where the drive has an outer position control loop and inner velocity and current control loops.

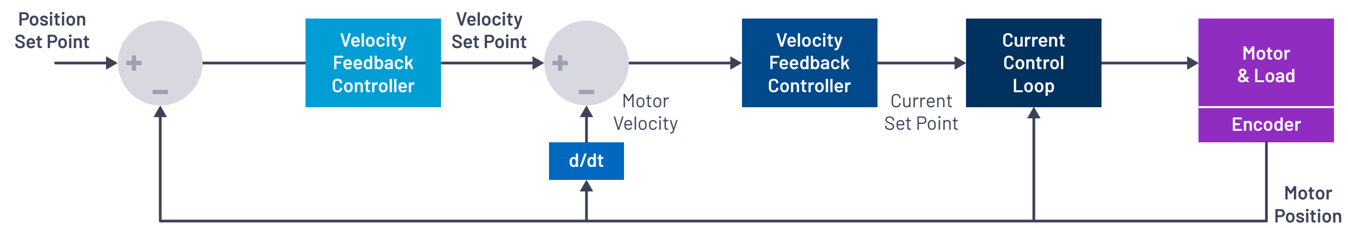


Figure 2: *How Motor Position Feedback is used in a Drive*

HOW IS POSITION FEEDBACK BROUGHT INTO THE MOTOR DRIVE FROM THE ENCODER?

The majority of encoders used in industrial applications utilize either square-wave incremental encoder feedback (known as ABZ or ABI) or digital protocol-based feedback. So most servo drives need to be capable of interfacing to either of these signal types. Some encoders also provide 3 square wave signals from magnetic Hall sensors embedded in the motor windings that indicate the absolute position of the rotor magnet fields at low resolution. Digital protocol-based feedback utilizes specific protocols such as EnDat [1], Hiperface [2], BiSS [3]. Most of these are vendor-specific and are based on RS-422/RS-485 as the physical layer. In all cases, robustness to Electrostatic Discharge (ESD)/ Electrical Fast Transients (EFT) and noise-induced common mode voltages, and the need to potentially interface to long cables is a requirement. Some part suggestions for these different interfaces are shown in the Table below.

Feedback Type	Drive Interface Requirement	Part Suggestions
ABZ	Standard digital I/O – may need to be differential, e.g. RS-422	MAX14890
Hall	Standard digital I/O	Any standard buffer IC e.g.MC74AC125
Protocol	Robust RS-485, up to ~30Mbps, generally not isolated, but sometimes can be	ADM3065E MAX22500E (features for long cables)

The next chapter will look at how both of the control loops discussed in this and the previous chapter - position and current control - are brought together and implemented inside the overall drive controller electronics.

REFERENCES

[1] https://www.heidenhain.us/addl-materials/enews/stories_1012/EnDat.pdf

[2] https://cdn.sick.com/media/docs/5/65/865/operating_instructions_specification_hiperface%C2%AE_motor_feedback_protocol_en_im0064865.pdf

[3] https://biss-interface.com/c/downloads/biss-interface/

THE BRAIN BEHIND THE BRAWN: CONTROLLERS AND PROCESSORS IN MODERN MOTOR DRIVES

In the previous chapter, we looked at the position feedback system and how the motor position is provided to the motor drive via the encoder. This chapter discusses the "brain" of the motor drive system – the controller block.

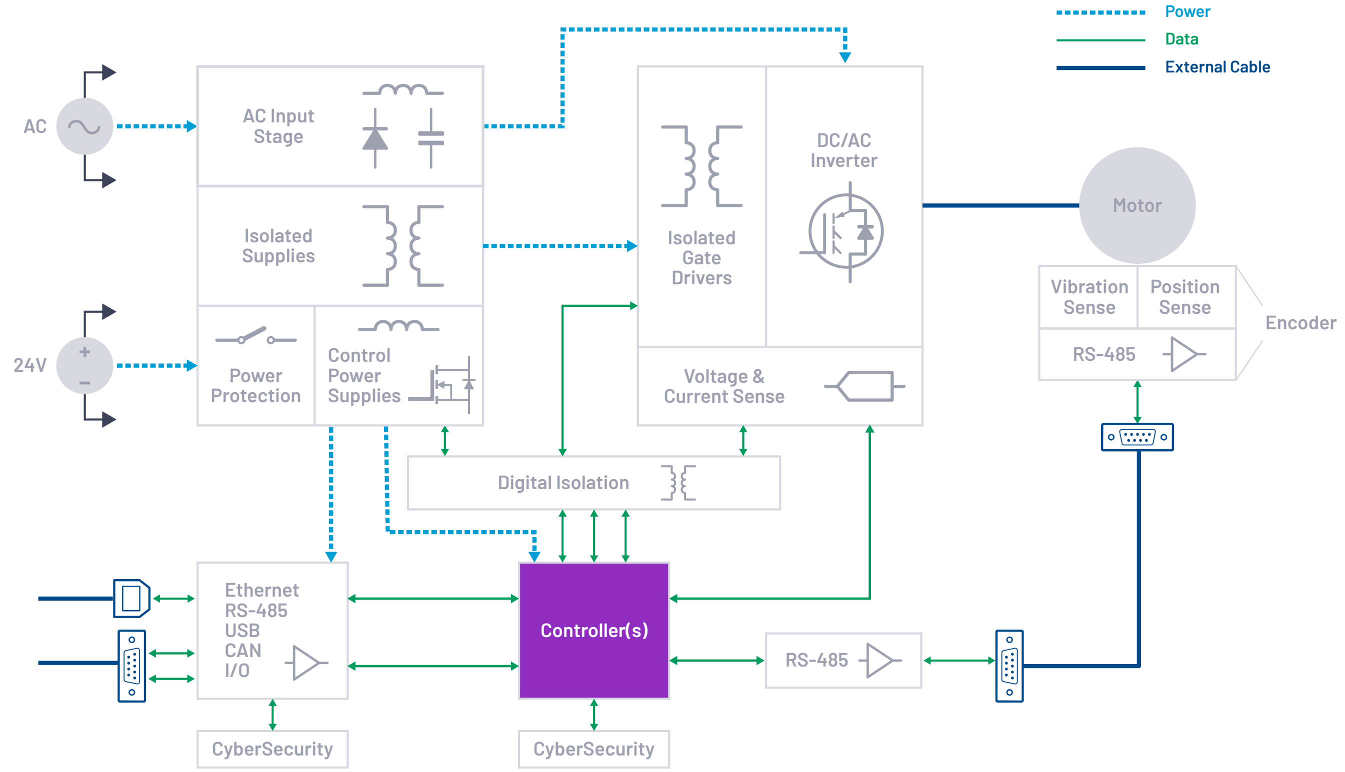


Figure 1: *Servo Drive Architecture Diagram*

The conceptual block under consideration is highlighted once again in the architecture diagram shown above. It is clear from the diagram that the controller is truly at the heart of the system and that every other block has some form of connection to it. We will examine two main aspects related to the controller block in this chapter – namely function, and implementation. It must be underlined from the outset that while conceptually this is shown here as a single block, in reality, it often consists of more than one IC implementation. This aspect will be addressed in more detail in the implementation section.

WHAT FUNCTIONS ARE FULFILLED BY THE CONTROLLER BLOCK?

The controller has one essential core function that impacts its design and architecture and this is the implementation of the motor drive control loops. In a sense, all other functions are subsidiary to this, and in some ways are optional, but the execution of the control loops is the single essential function of the controller. The control loops needed in a motor drive have already been introduced and these are shown again in *Figure 2*, with the shaded part indicating what sits inside the controller.

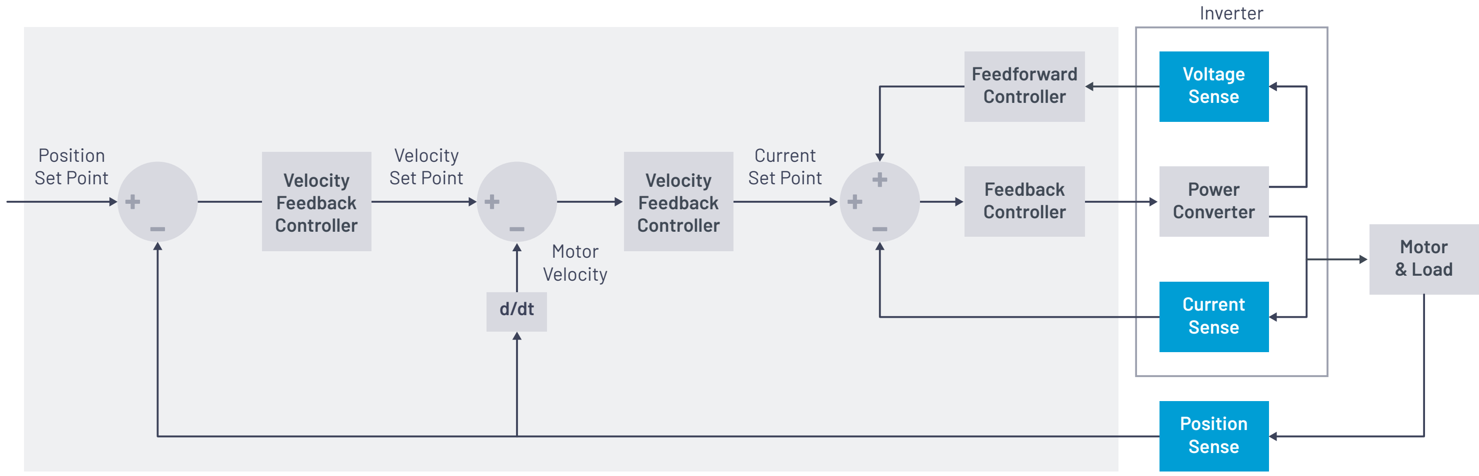


Figure 2: *Motor Control Loops*

In simpler drives, not all of these blocks are implemented, and in the simplest drives, there is not even closed loop control, but typically a very simple open loop controller as shown in *Figure 3*, where again the portion that sits in the controller is shaded.In these very simple systems there is no or very limited feedback, and the controller can be a relatively simple device. A system like that shown in *Figure 2* is assumed for the rest of the chapter discussion. It is also assumed that the control loops are all implemented in a digital engine such as a micro-processor or FPGA. Analog control is not typically used any more in motor control, apart from in some very specialised applications.

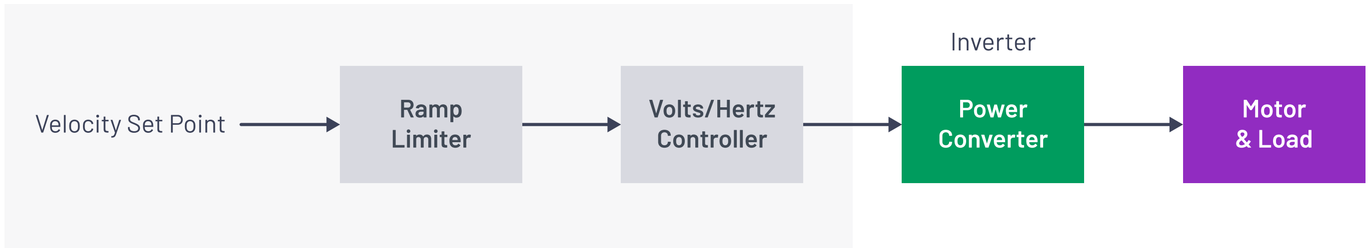


Figure 3: *Simple Open Loop Drive Controller*

> **The execution of the motor drive control loops is the single essential function of the controller.**

One of the key requirements of the controller in implementing the drive control algorithms is that these digital control loops must be implemented in a real-time deterministic fashion. So if the control loop update rate is for example 10kHz, then the control algorithm must be always implemented within the 10kHz time window. Control loop tasks must always take the highest priority. If the control loop task runs over, then the motor control will stop working often leading to the destruction of the motor as the power converter will not switch correctly.

Alongside the control loops (and the associated data handling from the feedback elements such as encoder, and current sensors) the controller must implement a number of other important functions:

- Communications interfaces: Industrial Ethernet software stacks e.g. Ethernet I/P for communication to PLCs and other devices, USB for user interface
- User or diagnostics applications: data logging, drive/motor diagnostics or drive configuration applications
- System management: startup control, monitoring faults in the drive, passing commands and references to the control loops
- Safety functions: monitoring and managing safety functions such as Safe Torque Off (STO)
- Security functions: managing secure boot, secure communication and secure firmware update, usually in conjunction with secure hardware components such as authenticators

HOW IS THE CONTROLLER TYPICALLY IMPLEMENTED?

It's clear from this that the controller has many parallel operations to handle with the need to always ensure that the control loops are implemented in real time without being compromised by the other tasks.

1. Single controller IC

In the single controller IC approach, everything is implemented in the one microprocessor or System on Chip (SoC). This approach is becoming rarer as the complexity of motor drives increases, and as more network interfaces, user functionality, diagnostics, and safety functions are required. It is still seen widely in less complex drives, and in open-loop inverters such as shown in *Figure 3*. In more sophisticated drives, complex SoCs such as Xilinx Ultrascale can be used. The combination of multiple high performance processing cores, and configurable digital blocks can enable successful partitioning of the different controller functions.

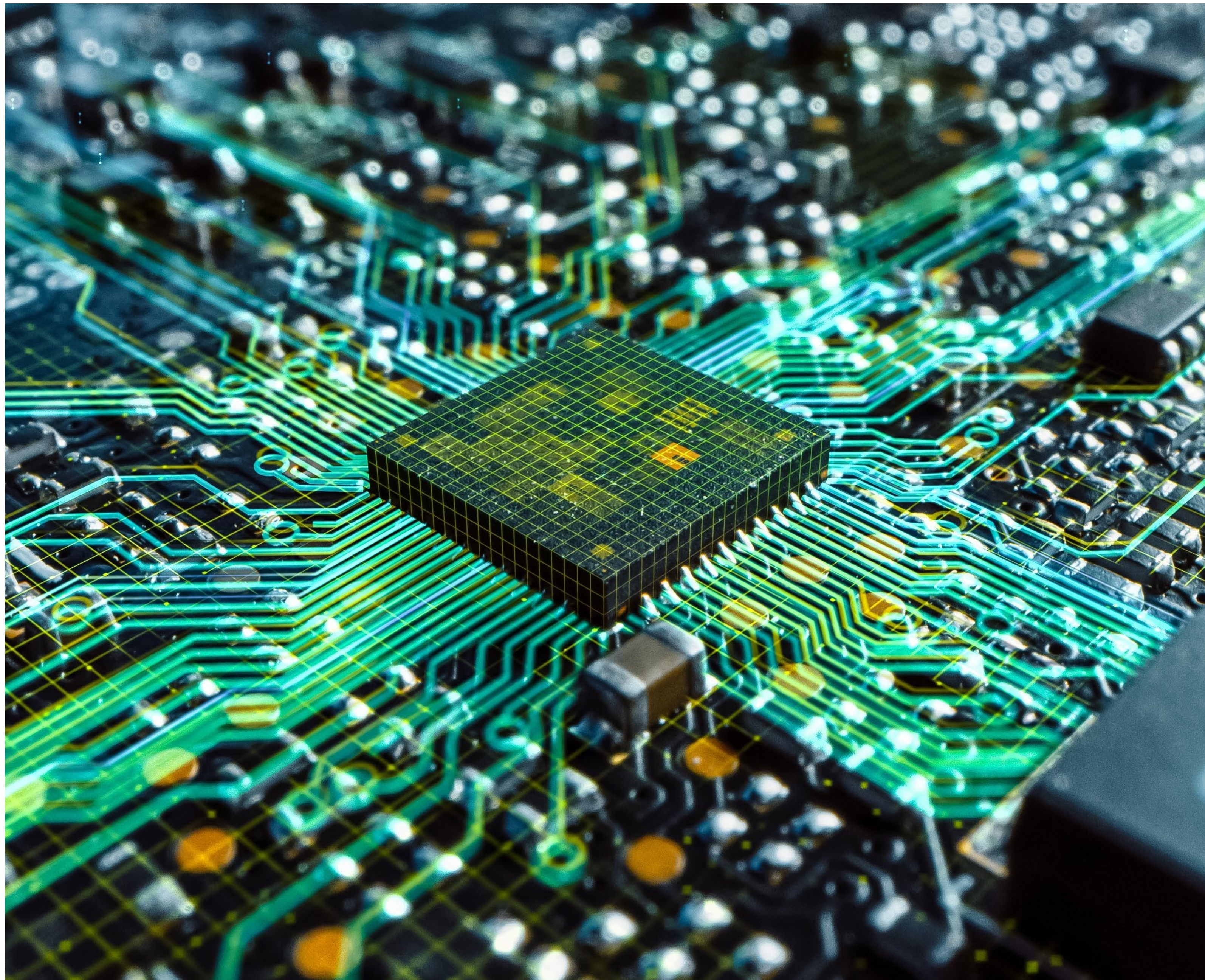
2. Separate current loop controller IC

In many drive architectures the current controller function, which includes the handling of the current feedback, as well as the pulse width modulation (PWM) functions, is handled as an individual IC, typically located on the same reference ground as the power inverter.

This function has the most stringent requirements for deterministic real-time operation, so it can often make sense to have this implemented as a discrete application specific microcontroller with dedicated peripherals for motor control, or indeed as an FPGA SoC implementation (e.g. Xilinx Zynq), or as a combination of small FPGA with microcontroller. In this type of architecture, the position/velocity controller and the remaining controller functions would be implemented on a more powerful microprocessor, typically located on the safety ground side of the drive architecture.

3. Separate network stack and interface IC

Finally, the network interface functions can be separated out into a network stack processor, ASIC or FPGA implementation. This is a useful partitioning in which the complexity of the Industrial Ethernet interface can be handled separately while another processor manages user interface, safety functions and diagnostics. This allows for easier modularisation of the network interface, multiple protocols, and isolation from any network traffic issues.



MAKING THE RIGHT CONNECTIONS WHEN COMMUNICATING WITH YOUR MOTOR DRIVE APPLICATIONS

The previous chapter unveiled the mastermind behind the motor drive application: the main controller. For this chapter, we are diving into the critical role that connectivity plays.

To send desired control inputs to a motor drive from the main system controller (typically a programmable logic controller (PLC)) requires that the system be network connected. As well as control inputs, a drive has many parameters to be configured and parametrized by the user. From the motor drive the user/control system may need to gather live values, such as torque, current, speed, position, and set slopes and units and many more parameters. All of these are communicated over the external interface as highlighted in *Figure 1*. In broad terms, greater drive connectivity, especially Ethernet-based connectivity is seen as a really important factor in the digitalization of the automation industry since it potentially enables visibility and network access to every single end device in an automation system.

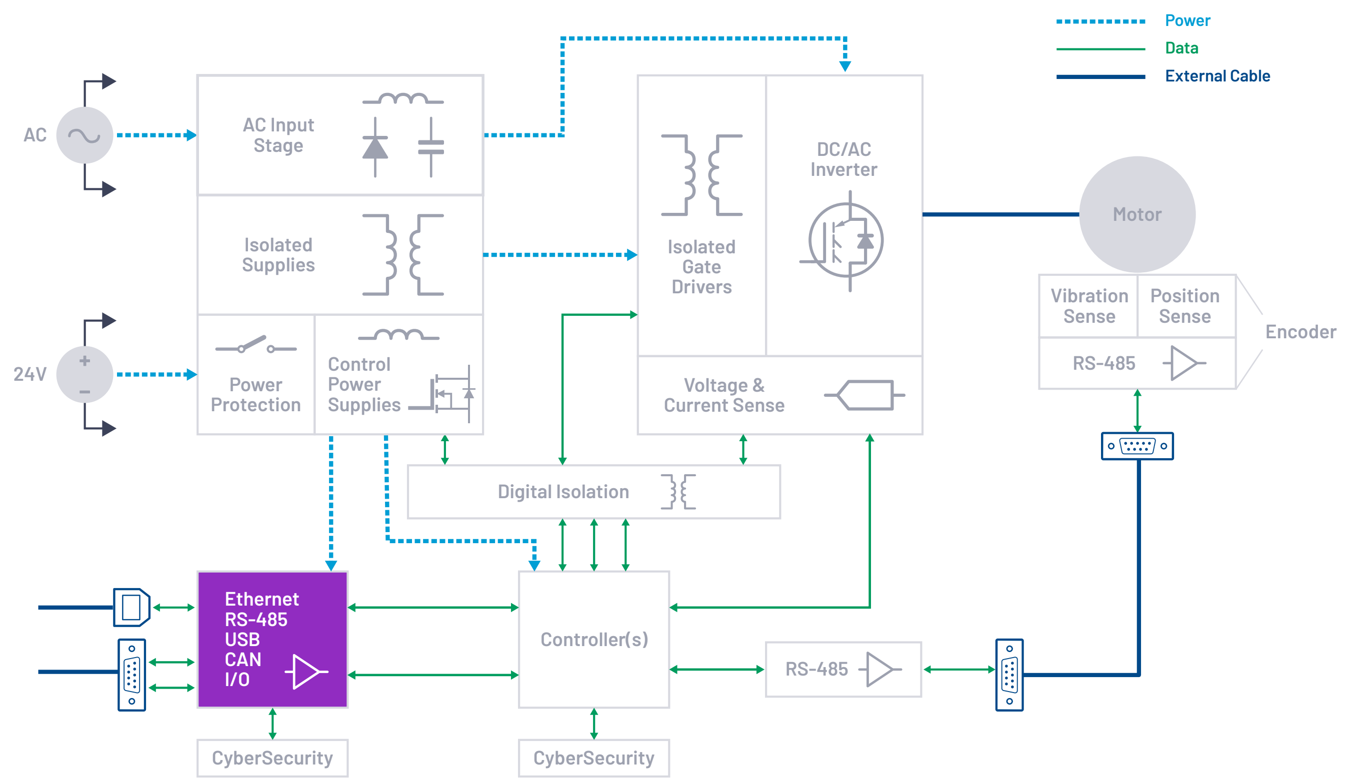


Figure 1: *Detailed Variable Speed Drive Architecture*

Organizations such as ODVA, PI North America and EtherCAT Technology Group help to standardize motor-drive communications by defining protocols such as EtherNet/IP, PROFIBUS/PROFINET and EtherCAT. These represent the most common protocols used in industrial automation today [1]. The most common physical communication layer types are serial links such as RS-485 or RS-422 and Ethernet. The protocols are built on top of these two physical layers. So which protocol should you choose for your connectivity solution? Let's break down the main facts for PROFIBUS/PROFINET, EtherNet/IP and EtherCAT and decide from there.

PROFIBUS/PROFINET

PROFIBUS is the most widely used protocol over serial links (RS-485), and PROFINET uses Ethernet. PROFIDRIVE is the standard "application profile" for drive technology that sits on top of the PROFIBUS and PROFINET communication systems, as illustrated in *Figure 2*.

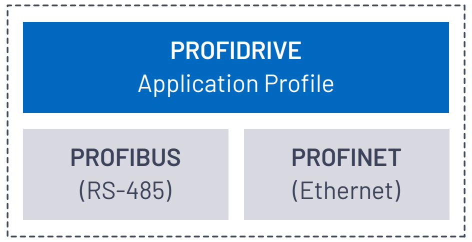


Figure 2: *PROFIDRIVE profile*

A profile such as PROFIDRIVE defines application specific parameters and functions to make it easier to communicate over the network between similar devices such as motor drives [2]. PROFIDRIVE allows for the integration of standard drive and "motion control" functionality with PLC sequencing logic, including functions such as :

- Motor-Current Control
- Speed Control
- Position Control
- Path Interpolation
- Logic Control

EtherNet/IP

EtherNet/IP is based on the standard Ethernet physical layer and enables a peer-to-peer connection that allows for the distribution of real-time motion control information among multiple controllers and drives using the Common Industrial Protocol (CIP). The drive application profile CIP Motion, as a part of CIP, is built on a common, standard Ethernet stack. This means that in addition to the Physical and Data Link layers defined in the IEEE-802.3 specification, CIP uses the standard Network and Transport layers typically deployed in general Ethernet applications. This allows for devices to easily interconnect using standard switches, routers and other infrastructure components.

The CIP Motion peer-to-peer connection is designed to transmit high-speed motion data from a producing controller or device to multiple consuming controllers or devices over a single multicast connection [3].

EtherCAT

EtherCAT is a real-time Industrial Ethernet technology originally developed by Beckhoff Automation. The focus during the development of EtherCAT was on short cycle times (≤ 100 μs), low jitter for accurate synchronization (≤ 1 μs) and low hardware costs. EtherCAT embeds its payload in a standard Ethernet frame. Since the EtherCAT protocol is optimized for short cyclic process data, bulky protocol stacks, such as TCP/IP or UDP/IP, can be eliminated. In applications with spatially distributed processes that require simultaneous action, precise synchronization is particularly important. In contrast to completely synchronous communication, where communication errors have an immediate impact on quality, distributed synchronized clocks have a high degree of tolerance for jitter in the communication system. Therefore, the EtherCAT solution for synchronizing nodes is based on these distributed clocks (DC) [4]. CAN over EtherCAT (CoE) and specifically the CiA 402 profile is the most popular EtherCAT application profile used in motor drives. With the CoE protocol, EtherCAT provides the same communication mechanisms as in CANopenR Standard EN 50325-4: object dictionary, mapping of process data objects (PDO) and service data objects (SDO).

Even the network management is similar. This makes it possible to implement EtherCAT with minimal effort in devices that were previously outfitted with CANopen, and large portions of the CANopen firmware can even be reused. The device profiles, such as the CiA 402 drive profile, can also be reused for EtherCAT.

Protocol	Motor Drive Application	Use Cases/Features	ADI Supporting Products
EtherCAT	CiA 402	EtherCAT is optimised for fast cycle times down to <50us where tight synchronisation is needed - most popular in servo drives	ADIN1200 ADIN1300
PROFINET/ PROFIBUS	PROFIDRIVE	PROFINET has the greatest market share and has connectivity to a very wide range of other automation hardware and infrastructure, especially devices from Siemens.	FIDO5200
Ethernet I/P	CIP Motion	Ethernet I/P has the most transparent capability for use with other Ethernet traffic and systems, and is dominant in USA systems. It generally does not allow for sub-ms cycle times like EtherCAT and PROFINET IRT.	ADIN2299 MAX14942

WHICH PROTOCOL COMES OUT ON TOP?

The following table compares the three communication protocols highlighted in this chapter. Each have their strengths and application specific features and the table below shows some typical supporting products from ADI which cater for all the protocols [5].

REFERENCES

[1] "Industrial Communications Report – 2023 Analysis", Omdia

[2] PROFIdrive - The Leading Drive Control Profile: PROFINET

[3] CIP Motion | Common Industrial Protocol | ODVA Technologies

[4] EtherCAT Technology Group | HOME

[5] Industrial Ethernet Solutions from Analog Devices

SECURING THE FUTURE OF DRIVES

In this final chapter, we will take an overview look at the last element of the conceptual block diagram, highlighted in ***Figure 1***, the cybersecurity elements of the drive.

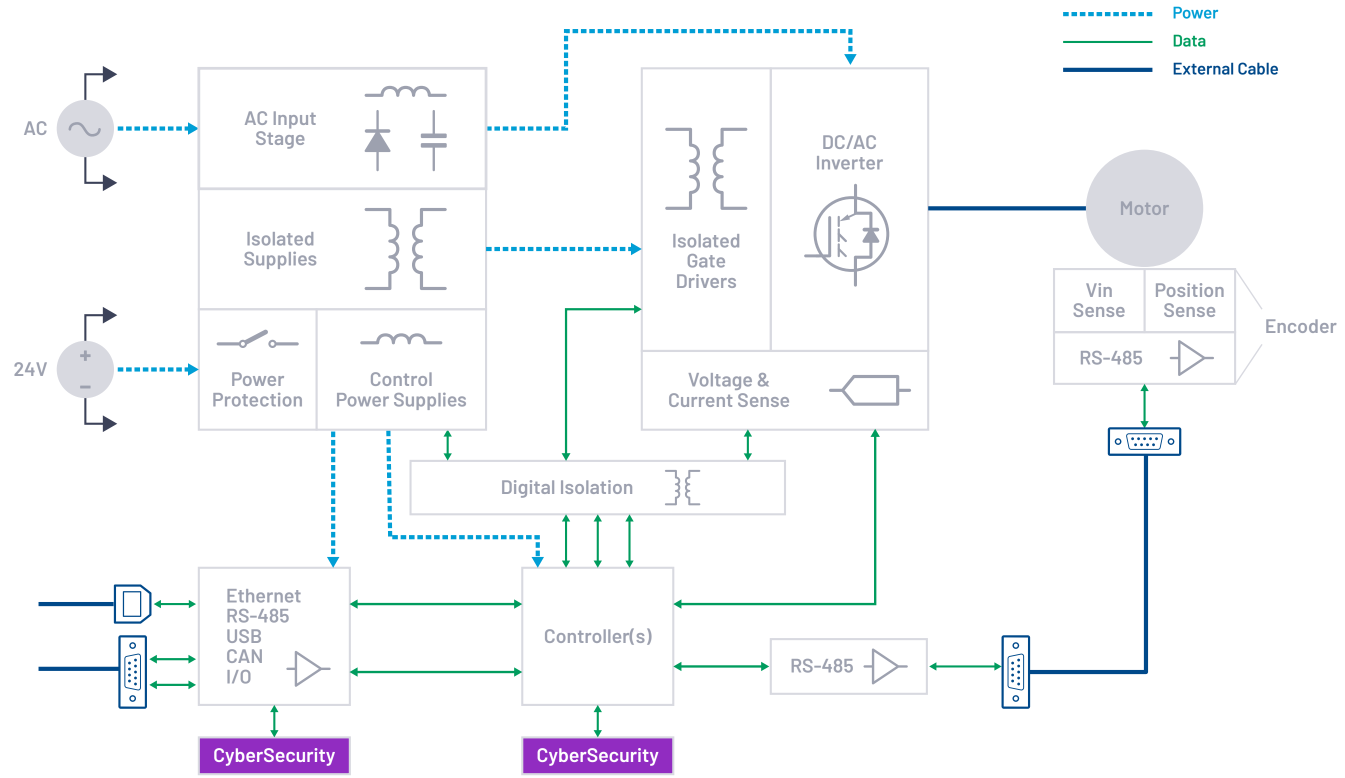


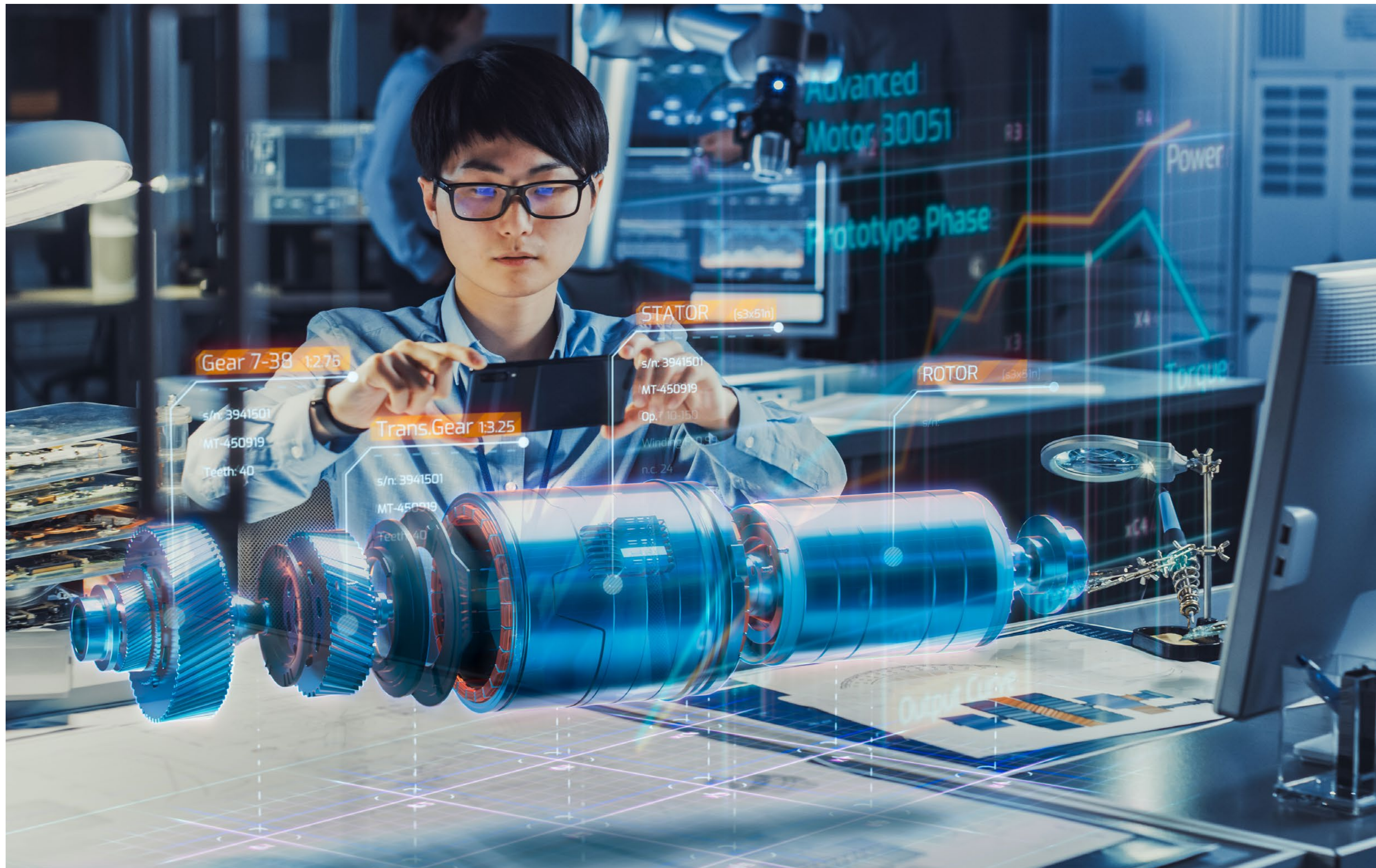
Figure 1: *Servo Drive Architecture Diagram*

Cybersecurity in motor drives is an emerging topic and is not one that historically has been of any major interest to motor drive developers. This is because in the vast majority of applications, motor drives have been completely isolated from any potential access that could lead to security issues. They were not typically connected directly or indirectly to the operational technology (OT) networks within a factory system or to the cloud, so the vulnerability points for unauthorised access have been very limited.

WHY IS THE CYBERSECURITY OF MOTOR DRIVES BECOMING A TOPIC OF GREATER INTEREST?

This situation has been changing primarily as a result of the increased Ethernet connectivity of most drives, as described in the last chapter. Furthermore there is an increased awareness of cybersecurity vulnerabilities and the potential for malicious actors, who can bring significant reputational damage to drive suppliers if their system is compromised. Even for non-connected systems, firmware upgrade over USB is now seen as a security vulnerability for example. The other area of concern is related to IP protection. The motor drive market has become increasingly competitive and drive manufacturers want to ensure that their control software cannot be extracted from the drive memory and copied illegally.

Another pressure that is coming to bear on drive manufacturers who wish to sell their products in the EU is the Cyber-Resiliency Act (CRA). This is a legal instrument that is due to come into force sometime in 2025, and which will require every product with a digital element that is connected directly or indirectly to another device or to a network to be secure by design, and to meet a range of cybersecurity requirements, with likely standard or third-party assessment. Although the details of this instrument have not been finalised yet, there is likely to be significant penalties for non-compliance and it will effectively mean every new motor drive will have to have full cyber-security protection.



WHAT CYBERSECURITY FEATURES WILL BE MOST IMPORTANT TO DRIVE MANUFACTURERS?

With increased digitalization, security becomes an inevitable concern.

Cybersecurity is a very broad ranging topic with many elements to it and it can have differing values or meaning to different applications. For example, in online shopping, the need to protect private data such as credit card details as they are passed across a network is probably the most critical element in the transaction. By contrast, when a motor drive is exchanging data over a network in the course of its normal operation, generally speaking the data itself is not hugely important. This is because the data itself usually has a very short life span. Variables such as voltage, current or motor speed are typically only valid for a number of microseconds, and in themselves do not represent anything confidential at any given moment in time. So data privacy in this context in a drive – requiring a security action such as encryption - is less important. However, what can be critical is ensuring the identity of a connected element, by means of authentication. For example, if a command is being sent to the drive, such as Start/Stop, or to change set speed – this could be from a malicious actor masquerading as a programmable logic controller (PLC), which could bring damage to the process that the drive is operating.

Another important security element for drives is secure firmware update. Upgrading a drives firmware is something that can happen multiple times during its lifecycle, and can open the drive up temporarily to vulnerabilities since its entire control program is being changed. Allowing for a secure update process, and indeed a secure boot in which the update and boot images themselves can be authenticated and proven as valid, are extremely important in order to prevent corruption of the drives operation. Drives are often involved in dangerous and complex processes such as process plant operations, metal forming, centrifuges etc. so the impact of a malfunctioning drive to either inadvertent or deliberate corruption of the drives control code, or commands/parameters delivered over the network can be physically and reputationally damaging.

HOW CAN THESE FEATURES BE IMPLEMENTED?

There are several different approaches to implementation of cybersecurity functions, involving a combination of hardware and software. Analog Devices provides a range of secure authenticator and secure microcontroller products from simpler devices such as the 1-wire secure authenticator DS28E30 to secure microcontrollers such as the MAXQ1065. These products can provide simple root of trust functionality in conjunction with the main system controller, or more complete cryptographic functions to help meet the requirements of the motor drives of the future.

This chapter concludes our motor drive deep dive where we have covered everything from the AC input power stage to the controller, communications and security. Hopefully these chapters have provided a helpful introduction to the fascinating world of electronic motor control - a technology that is ever more pervasive in so many aspects of our modern world.

POWER MANAGEMENT	
LT8315	Micropower No-Opto Isolated Flyback Converter
MAX17690	No-Opto Isolated Flyback Controller
LT4363	High Voltage Surge Stopper
LTC4381	Low Quiescent Current eFuse with Surge Protection
ADP5054	Quad Buck Regulator Integrated Power Solution
MAX14721	High-Accuracy Adjustable Power Limiters
GATE DRIVERS	
ADuM4177	SiC Isolated Gate Driver
ADuM4221	Isolated Half Bridge Gate Driver
MAX22700E	Single-Channel Isolated Gate Drivers with Ultra-High CMTI
CURRENT & POSITION FEEDBACK	
AD8410A	High Voltage, High Bandwidth Current-Sense Amplifier
MAX11195	Dual-Channel 14-Bit Simultaneous Sampling SAR ADC
AD7380	Dual-Channel 16-Bit Simultaneous Sampling SAR ADC
ADuM7701	16-Bit Isolated Sigma-Delta Modulator
AD8515	Low Power CMOS Operational Amplifier
MAX4477	Low-Noise, Low-Distortion, Wide-Band, Rail-to-Rail Op Amps
MAX14890E	Incremental Encoder Receiver
COMMUNICATION	
ADIN1200	10 Mbps and 100 Mbps Ethernet PHY
ADIN1300	10 Mbps, 100 Mbps and 1Gbps Ethernet PHY
FIDO5200	Real-Time Ethernet Multiprotocol (REM) Switch
ADIN2299	Multiprotocol Two-Port Industrial Ethernet Platform
MAX14942	20 Mbps Isolated RS-485/PROFIBUS-DP Transceiver
ADM3065E	50 Mbps Half Duplex RS-485 Transceiver
MAX22500E	100 Mbps Half Duplex RS-485 Transceiver for Long Cables
CYBERSECURITY	
DS28E30	1-Wire ECDSA Secure Authenticator
DS28S60	DeepCover Cryptographic Coprocessor
MAXQ1065	Ultra Low-Power Cryptographic Controller

VISIT ANALOG.COM/INTELLIGENT-MOTION