Motor Control Inverters: An Overview of Architecture and Control Algorithms

Key Features

- Scalability for different voltage and power ratings
- Energy Efficiency and Power Optimization
- Robust Protection and Safety Mechanisms
- Onboard step-down converter for single supply systems
- Flexible Motor Type Support
- Real-time measurement of three-phase voltage and current for the motor and DC bus voltage
- High-Precision Speed and Position Control
- Ultra-fast desaturation protection to safeguard from overcurrent
- Provides high isolation voltage between digital and power circuits
- Industrial Communication and Connectivity
- Separate circuits for discharging the DC bus capacitor

Motor control inverters, formally known as Power Drive Systems (PDS) in the IEC 61800 standard family, are critical power electronic systems widely used across industrial manufacturing environments. They enable efficient and precise control of electric motors in applications such as conveyors, pumps, robotic arms, compressors, and CNC machinery.

By converting a fixed voltage, fixed frequency AC supply into a variable voltage, variable frequency three-phase output, these inverters ensure motors operate smoothly and efficiently under varying load and speed conditions.

IEC 61800-2 defines the general requirements, ratings, and performance specifications for adjustable-speed AC drive systems and includes the inverter, control circuitry, protection, monitoring, and machine interfaces.

The typical motor control inverter generates a controlled three-phase AC signal to drive induction motors, allowing fine control of speed and torque. Its modular, compact, and scalable design supports various voltage levels and power ratings, making it adaptable to a broad range of industrial requirements. With integrated control algorithms, thermal management, measurement systems, and support for modern motor types including AC induction, PMSM, and BLDC, these inverters form the backbone of industrial motion systems.

As industries move toward higher efficiency, better power quality, more stringent safety expectations, and digitalization, inverters must satisfy not only performance constraints but also compliance with standards such as:

- **IEC 61800-2** — general requirements, rating specifications, classification
- **IEC 61800-3** — EMC requirements
- **IEC 61800-5-1** — electrical safety
- **IEC 61800-5-2** — functional safety
- **IEC 60034 series** — motor requirements

This white paper provides an engineering-focused overview of inverter architecture, motor control algorithms, engineering challenges, and design considerations for compliance with international standards.

Architecture of Motor Control Inverters

A typical industrial motor control inverter consists of the following parts:

Power Stage - The power stage manages the electrical power supplied to the motor, including an AC–DC rectifier for voltage-source inverters, a DC-link with filtering, and a DC–AC inverter bridge (IGBT, MOSFET, SiC/Si-based devices).

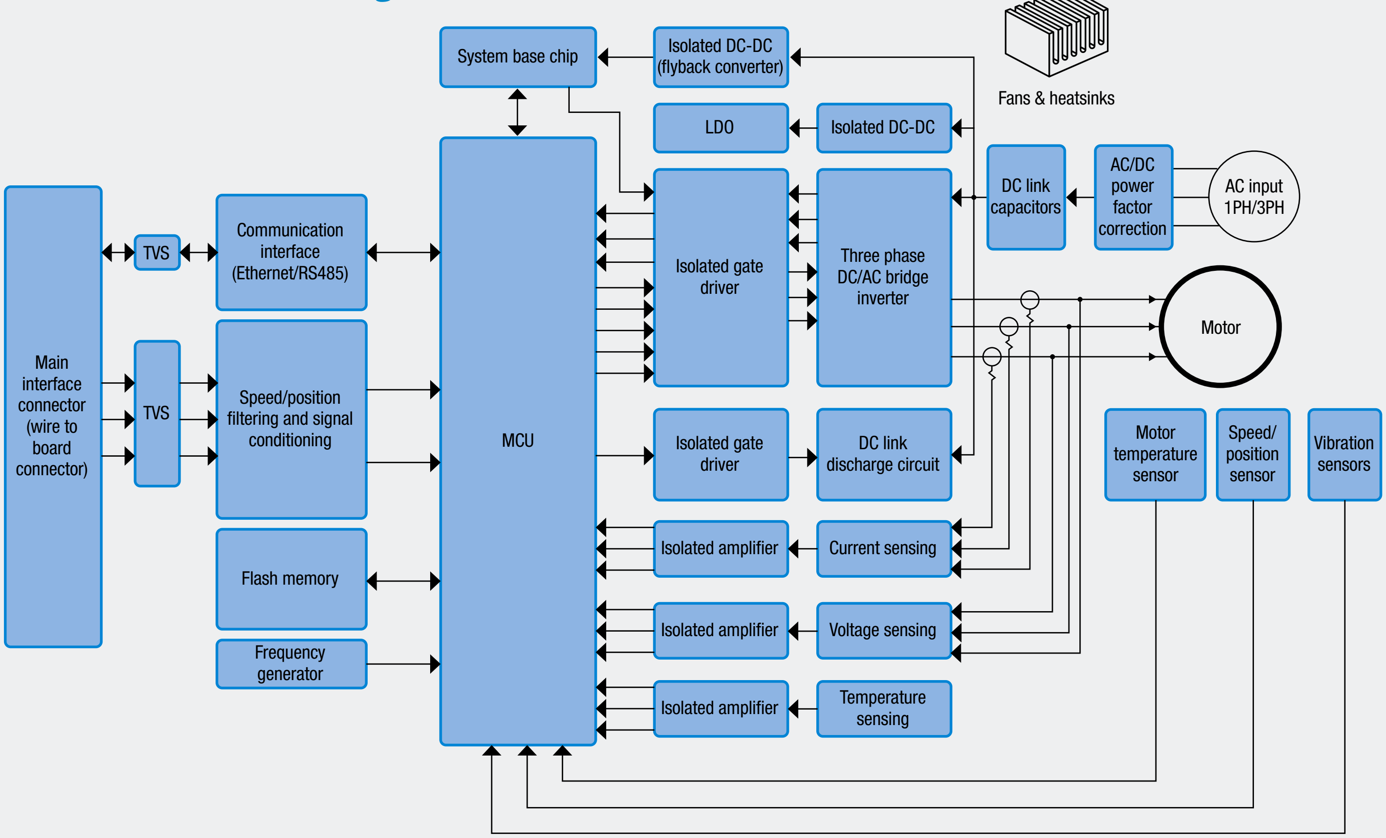
Control and Processing Unit – This unit includes PWM generation, real-time motor control algorithms, protection logic, and communication protocols like EtherCAT, CANOpen, Modbus, etc.

IEC 61800-2 and related sections (61800-3/-5-1/-5-2) specify requirements for these subsystems, including EMC behavior, electrical isolation, and safety functionality.

Measurement and Feedback - These functions are enabled by the current sensors, voltage sensors, and rotor position sensors (e.g., encoder, resolver) as applicable; these sensors support both sensor-based and sensorless control implementations.

IEC 61800-2 requires the Power Drive System (PDS) to include control and sensing features to satisfy environmental, EMC, and performance criteria.

Architecture & Block diagram



Functional Description

Main System Components

Three-Phase Motor: Factory automation applications often use three-phase motors. The motor needs three-phase AC with variable voltage and variable frequency to control speed and torque. The advantages of three-phase induction motors are low maintenance, cost-effectiveness, reliability, and efficiency. It works well with a wide range of power ratings, making it suitable for both small and large power designs. When paired with an inverter, it offers variable voltage and frequency control, enabling smooth acceleration and deceleration, and precise torque control.

Control Board: The control board is responsible for several functions. It communicates with external devices. Next, it drives the power board with a PWM output to control the power MOSFET that is fully isolated from the high-power section. It measures the three-phase voltage/current and measures temperature using the integrated ADC on the MCU. Finally, Field-Oriented Control (FOC) is executed on the MCU in real time to achieve accurate regulation of motor torque and speed.

The control board comprises the following components that are needed to perform necessary operations.

Microcontroller: The MCU parameter selection is the most important in the system. The Real-Time Control Loop Latency is the primary technical hurdle to ensuring the MCU can complete the entire control loop by sampling motor current via Analog-to-Digital Converters (ADCs), calculating algorithms like Field-Oriented Control, and updating Pulse-Width Modulation (PWM) outputs within a very short cycle. As systems move toward silicon carbide (SiC) architectures, switching frequencies increase, requiring even lower latencies (often <4 µs) to maintain efficiency and handle higher RPMs.

Also, peripheral synchronization and precision necessitate specialized hardware peripherals for the MCU that work in tight coordination. A major challenge is synchronizing the ADC sampling rate precisely at the midpoint of a PWM period to accurately sense phase current. Additionally, the MCU needs high-resolution PWMs with built-in deadband compensation to prevent short-circuits during FET switching without adding software overhead.

System Base Chip (SBC)

The **SBC** integrates power management and safety features into a single chip. It should support all supply rails of the design and monitor all safety-related signals in the MCU. It should also go to a safe state in case of any issue, according to the functional safety standard IEC 61508.

The SBC must reliably manage the power supply and monitor safe torque off (STO) functions, preventing the motor from generating torque during a safety-related stop.

MOSFET Gate Driver

Selecting a MOSFET gate driver is a complex task because the driver acts as the critical bridge between low-power control logic and high-power motor switching. The primary challenges in this selection process are managing slew rates and efficient trade-offs. When using fast slew rates, it reduces switching power dissipation but causes severe EMI and voltage spikes. Slow slew rates improve the EMI and voltage spikes but increase power loss. The second challenge is driving dynamic gate capacitance. A MOSFET gate behaves as a non-linear capacitor. The driver must provide enough peak current to quickly charge and discharge this capacitance, particularly during the Miller Plateau phase. The Miller plateau is a temporary, flat region in a MOSFET's gate-source voltage waveform during switching, caused by the Miller effect where the gate-drain parasitic capacitance is charged/discharged as the drain voltage drops. Additionally, the high side isolation and voltage margins requirements in the gate drivers are often necessary to protect low-voltage microcontrollers from transients in the high-power side. The last challenge is the integration of protection features in MOSFET gate drivers. This is strongly required in the safety application, as they must actively protect the system using dead time control, undervoltage lockout (UVLO), and desaturation detection to rapidly turn off the MOSFET during a short-circuit event.

Voltage/Current Measurement

In industrial inverter motor drives, designing accurate voltage and current measurement systems is a significant challenge due to the high-power switching environment and the need for high-speed, synchronized data. Two significant challenges must be addressed. First, the challenge of high common mode transients (dv/dt) due to switching noise must be addressed. To do this, the measurement amplifiers must have an exceptionally high Common-Mode Rejection Ratio (CMRR) to block these fast-toggling voltages and extract only the small differential signal representing the actual current or voltage. Second, measuring currents and voltages directly at the motor phases requires galvanic isolation according to **IEC 61508** to protect the controller and human operators from high-voltage DC buses.

The main software challenge is that advanced control algorithms (like Field-Oriented Control) require simultaneous phase current readings to accurately calculate the d-q rotating coordinates. Any phase delay introduced by the measurement signal chain directly limits the motor's dynamic performance. This can be addressed with a circuit that consists of an isolated analog amplifier designed for demanding applications such as industrial motor drives. It should provide scalable voltage measurements across different input AC voltages, with configurable gain based on the motor's voltage/current rating.

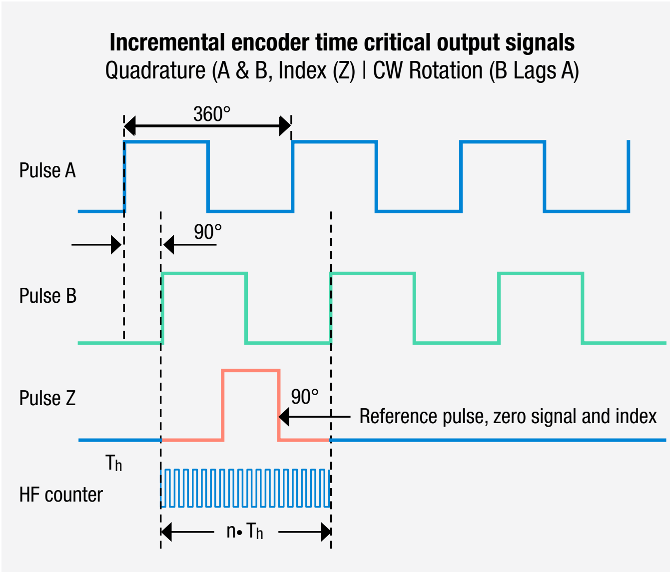
Temperature Measurement

Measuring the temperature of MOSFET modules and motors is less about "reading a thermometer" and more about predicting thermal stress before the silicon fails. The primary challenge is keeping the temperature below the silicon junction temperature. However, sensors are typically mounted on the module substrate or heat sink, and there is a significant thermal time constant between the MOSFET heating up and the sensor reacting. By the time the sensor detects an over-temperature condition, the MOSFET may have already entered thermal runaway. Also, the sensor must be galvanically isolated from the power stage to prevent the MCU from thermal failure if the module's internal insulation is exceeded.

This circuit measures the three MOSFET modules' temperatures using a thermistor embedded in each module. It delivers a conditioned, isolated analog signal to the MCU's ADC using an Isolated Analog Amplifier, with a filter to strip PWM noise from NTC signals. Next, software-based thermal estimators are used to predict junction temperature.

Motor Position/Speed Sensor

The position/speed sensor is an essential element in a motor, especially in closed-loop systems. There are many types of position/speed sensors, but the most common type is the **quadrature encoder**.

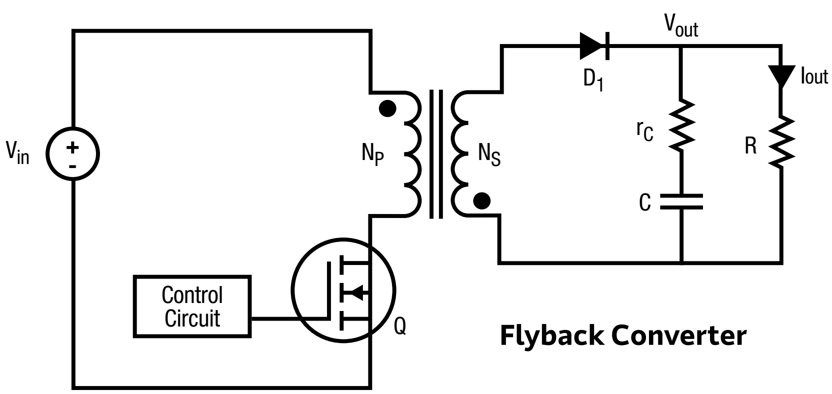


A quadrature encoder outputs two square wave signals (A and B) that are 90° out of phase, and by comparing which signal leads the other, the system can determine the rotation direction. Then, by counting the pulses and their phase relationship, position and speed can be accurately measured. The Z (Index) pulse is a once per revolution reference (narrow pulse) used to precisely zero or home the position count.

In industrial environments, the challenge with quadrature encoders (ABZ signals) is maintaining signal integrity over long distances while the inverter is generating massive amounts of electrical noise. One can cover these issues by selecting differential line receivers with high noise immunity and designing digital filters (de-glitching) for the PWM inputs.

Isolated Flyback Converter

When designing a single-supply inverter architecture, generating a stable and isolated low-voltage rail, such as 12V from the main supply, becomes a critical need for reliable operation. One of the most efficient and cost-effective solutions for this requirement is the flyback converter. The flyback converter is a type of isolated DC-DC converter widely used in low-to-medium power applications. This topology inherently provides galvanic isolation, which is crucial for safety compliance in inverter systems according to IEC 61508, and supports multiple output voltages from a single transformer.

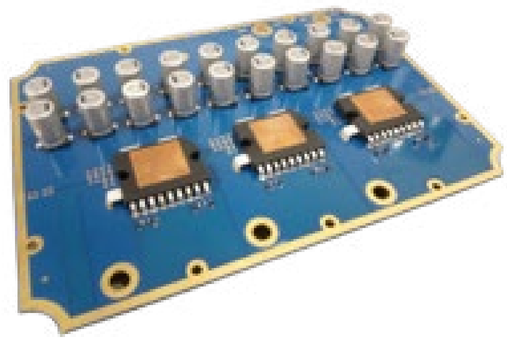


Flyback Converter

The flyback converter stores energy in its magnetic core when the transistor switches ON, and current flows through the primary winding of the transformer. When the transistor turns OFF, the magnetic field collapses and transfers the stored energy to the secondary winding, allowing the diode to conduct. The output capacitor is then able to store and smooth this delivered energy to provide a stable DC output.

Power Board

Designing a power board that integrates high-power switching (MOSFETs) with heavy-duty terminals and thermal management is perhaps the most difficult hardware challenge in an inverter. The system must manage massive current flow, high-speed switching noise, and intense heat all in the same physical space.



The power board contains the power MOSFET, including the current measurement and MOSFET temperature sensor, the DC bus capacitor, and the power connector interface with the main battery and the motor.

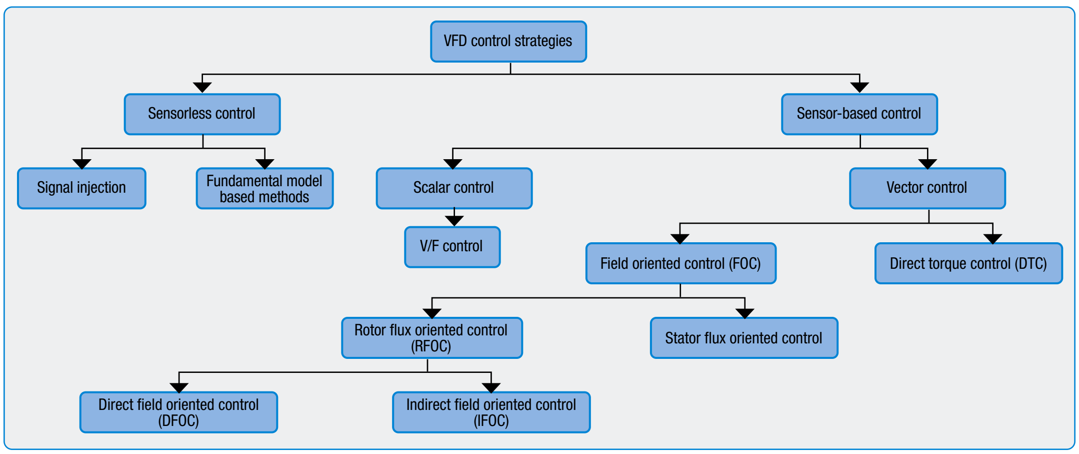
The primary challenge here is the parasitic inductance; every millimeter of copper trace between the DC-link capacitors and the MOSFETs acts as an inductor. When you switch hundreds of Amps in nanoseconds, this inductance creates huge voltage spikes. These spikes can exceed the MOSFET's breakdown voltage and destroy it instantly. One must achieve a **low-inductance layout** using wide copper planes (busbars) and "laminated" structures where the positive and negative paths are stacked directly on top of each other to cancel magnetic fields.

Next, the layout must be symmetrical; every MOSFET in a parallel branch must see the same impedance and thermal environment to prevent current distribution and "Hot Spotting" issues. Then, for creepage and clearance at the terminals, one must strictly follow standards like IEC 61800-5-1 for spacing. This often forces the board to be larger than desired, conflicting with keeping traces short to reduce inductance. Lastly, one must analyze the isolation of the heat sink because the MOSFET tabs (the drain) are usually electrically live. To mount them to a metal heat sink, you need an insulation pad (Sil-Pad) or a MOSFET module normally isolated from the drain terminal.

Control Algorithm Methods

A motor control algorithm is a mathematical and software-based method used to regulate the torque, speed, or flux of an electric motor. It interprets feedback (or estimated states) and drives the inverter's switching patterns (e.g., PWM). Good control algorithms ensure precision and dynamic response, high efficiency, smooth torque production, robustness against load disturbances, and compliance with safety and performance standards like IEC 61800-2. IEC 61800-2 establishes criteria for the performance of the overall drive system, meaning the control algorithm directly influences compliance. The algorithm must satisfy requirements for steady state behavior, transient response, motor compatibility, environmental performance, and safety margins.

Ultimately, selecting the right control strategy depends entirely on the specific demands of the application. Sensor-based control is the clear choice for systems requiring exact positioning, rapid dynamic response, and full torque at a standstill. This includes robotics, heavy lifting equipment, safety-critical drives, and electric vehicle traction systems. Conversely, sensorless control is ideal when minimizing hardware complexity and cost is the priority. It is the preferred solution for continuous-running applications like pumps, fans, and home appliances, as well as systems exposed to harsh environments with extreme dust or vibration, such as automotive cooling compressors and general industrial machinery.



In **Sensor-Based Control**, hardware like encoders or resolvers are used for rotor position feedback. The advantages are high accuracy, better low-speed and zero-speed performance. Sensor-based control designs are required for functional safety functions (per IEC 61800-5-2) in many cases. However, disadvantages like high cost due to the sensor cost, reduced reliability due to mechanical components, and environmental vulnerability (temperature, vibration) exist.

In **Sensorless Control**, rotor position is estimated from voltage and current measurements using observers or estimators. The advantage of this path is lower cost, higher reliability, reduced wiring, and simpler installation. However, performance degrades at low speed and becomes more dependent on signal quality.

Scalar Control (V/f): Scalar control is the most basic control. It maintains a ratio between Voltage and Frequency to keep flux constant. This is used only for fans and pumps where dynamic response is irrelevant.

Direct Torque Control (DTC): This advanced motor control method regulates motor speed by directly regulating torque and stator flux, rather than indirectly through current control as in FOC. The algorithm estimates torque and flux from the stator voltage and current measurements, enabling fast dynamic response without requiring a coordinate transformation.

Field-Oriented Control (FOC): FOC is a vector control method for controlling the torque or speed of PMSM or induction motors by independently controlling the stator current components that produce torque and magnetic flux. This is achieved by using mathematical transformations to convert the motor's three-phase currents into a rotating reference frame, where they become two separate, time-independent DC values: the direct current (D-Axis) for flux, and the quadrature current (Q-Axis) for torque.

There are two main methods:

1. Stator Flux Oriented Control

2. Rotor Flux Oriented Control (RFOC)

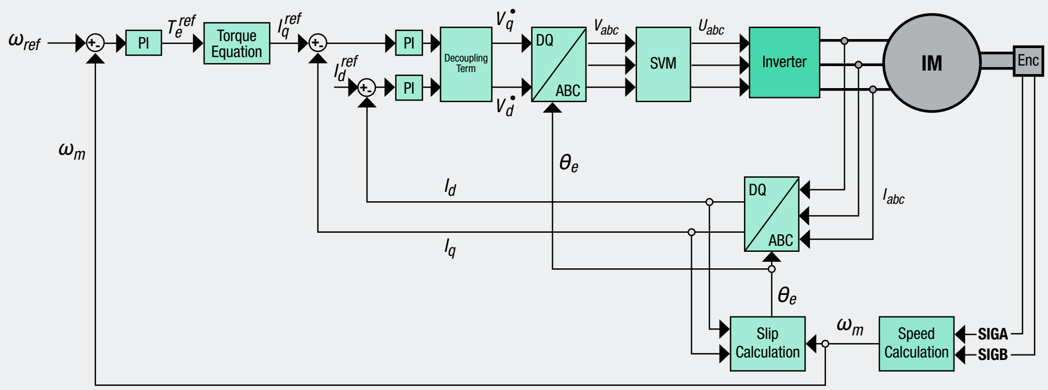
   a. Direct Field Oriented Control (DFOC): Uses Hall-effect sensors or flux-sensing coils installed in the stator slots to measure the flux in the air gap.

   b. Indirect Field Oriented Control (IFOC) Estimates the flux angle without direct flux sensors. It relies on the mathematical relationship between the stator current, rotor speed, and machine parameters.

2. **Slip Calculation Block:** The electrical angle (Electrical Theta) is the result of the discrete integration of electrical rotational speed (Electrical Omega), which is a summation of rotor rotational speed and the electrical slip rotational speed. This rotor rotational speed is a product of mechanical rotational speed and the pole pairs. On the other hand, the electrical slip rotational speed is a relationship between the motor time constant and the reference currents of the D-Q frames. Please read this link for more information.

3. **3 Phase Currents to D-Q Currents**: Measuring the 3-phase currents is done by using 3 shunts and providing them to the Clarke/Park Block (ABC to DQ) to transform them into D-Q current feedback signals. This block uses the electrical theta calculated from the slip calculation block. Please read this link for more information.

Rotor Flux Oriented Control (RFOC)



This image illustrates a Cascaded Vector Control structure for a Three-Phase Induction Motor. It represents an Indirect RFOC topology because it relies on a Slip Calculation block to estimate the rotor flux angle rather than measuring flux directly. Please read this link for more information.

Let's break this figure into different phases:

Measurement Phase:

1. **Speed Calculation Block:** Speed must be calculated or measured. Measuring speed can be done using incremental encoders or resolvers for high accuracy applications such as robotics. Sensorless estimators could be used instead if such accuracy is not needed.

Control Phase:

1. **Speed Outer Loop:** The system begins with a speed reference compared to the actual measured speed. A speed PI controller processes the error to generate a torque reference. Please read these links for more information.

2. **Reference Current Computation:** The direct current reference (D Frame Current) is set independently based on the rated magnetizing current which is in relation to the rotor flux value. The quadrature current reference (Q Frame Current) is calculated from the torque reference command generated from the speed loop. Please read this link for more information.

3. **Current Inner Loops:** Two parallel PI controllers regulate the d-axis (flux) and q-axis (torque) currents. They compare the references D-Q currents against the feedback D-Q currents. Then, the controllers process the errors to generate output signals into the decoupling block. Please read these links for more information.

4. **Decoupling Term:** Canceling out the cross-coupling voltages and back-EMF effects that occur between the d-axis and the q-axis at high speeds is critical in induction motors. Please read this link for more information.

5. **D-Q Voltage to 3 Phase Voltages:** The outputs are voltage references which are transformed from the rotating frame D-Q to the stationary frame ABC using the Inverse Park/Clarke Transform (DQ to ABC). Please read this link for more information.

6. **SVM (Space Vector Modulation):** SVM is a PWM technique that synthesizes a reference voltage vector from inverter switching states to improve DC bus utilization by up to ~15% within the linear modulation range. This enables a higher fundamental AC output voltage from the same DC source for applications like motor inverters. Its waveform is mathematically equivalent to adding a zero-sequence (third-harmonic) component. Please read this link for more information.

   The most robust industrial implementation for generating SVM signals from the 3-Phase voltages is the Zero-Sequence Injection **(Min-Max)** method. It achieves the exact same result computationally in an efficient manner. Refer to Space vector pulse width modulation section in this link. Refer also to this link.

Other Challenges and Technical Considerations

- High execution time for the SW can become a problem. One could examine the data types and possibly consider using single data type (32bit) instead of double data type (64bit) to reduce the execution time.
- Speed sensor calibration needs to be addressed. Any sensor must have an offset, so an important step is always finding a way to overcome this by calibration or real-time offset correction.
- All transistors do not switch instantly, although the theoretical algorithm assumes instant transitions between transistors. To prevent short circuits, one can insert "dead-time" between the turn-off of the upper switch and the turn-on of the lower switch.
- For getting the initial PI gain values, it's better to use the Pole Placement method instead of the Zero-Pole Cancelation method in your equations. This approach helps get robust control and lowers the risk of instability.

Conclusion

Motor control inverters, defined within the IEC 61800 standard family, form the technological foundation of modern industrial motion systems by enabling efficient, precise, and safe control of electric motors across manufacturing environments. Their architecture integrates high power conversion stages, real time control electronics, isolated sensing, robust gate driving, thermal management, and advanced algorithms such as FOC, DTC, and sensorless observers. Designing these systems requires careful handling of fast switching power devices, EMC behavior, galvanic isolation, measurement accuracy, thermal prediction, parasitic effects, and functional safety considerations. As industries push toward higher efficiency, digitalization, and stricter regulatory compliance, engineers must balance performance, reliability, and safety while meeting IEC 61800 and related motor standards. The result is a complex multidisciplinary system where power electronics, embedded control, and safety engineering converge to deliver high performance, standards compliant inverter solutions for next generation industrial applications.

Motor Control Linecard

Technology	Manufacturer	Part Number	Arrow Link	Datasheet
Motor Control MCUs	NXP Semiconductors	S32K396	Arrow Link	Datasheet
	Microchip Technology	ATSAMV71Q21B-AABVAO	Arrow Link	Datasheet
	STMicroelectronics	STM32H7B3ZIT6Q	Arrow Link	Datasheet
System Basis Chip	NXP Semiconductors	MFS2633AMDAHAD	Arrow Link	Datasheet
	Infineon Technologies AG	TLE956	Arrow Link	Datasheet
Gate driver	NXP Semiconductors	MGD3162	Arrow Link	Datasheet
	Skyworks Solutions	SI8285CD-IS	Arrow Link	Datasheet
	onsemi	NCD57001DWR2G	Arrow Link	Datasheet
	Infineon Technologies AG	1EDI3025ASXUMA1	Arrow Link	Datasheet
POWER MOSFET	VISHAY	VS-HOT200C080	Arrow Link	Datasheet
	onsemi	NTHL020N090SC1	Arrow Link	Datasheet
	Littelfuse	IXSJ25N120R1	Arrow Link	Datasheet
	STMicroelectronics	M1P45M12W2-1LA	Arrow Link	Datasheet
	Infineon Technologies AG	IMSQ120R040M2HHXUMA1	Arrow Link	Datasheet
Module Isolated DC-DC	RECOM Power	RS-1212D/H3	Arrow Link	Datasheet
	Murata Power Solutions	MGJ2D241505SC	Arrow Link	Datasheet
Power Terminals	Molex	2183710001	Arrow Link	Datasheet
Main interface	Molex	0348250200	Arrow Link	Datasheet
	TE Connectivity	DTF15-12PB	Arrow Link	Datasheet
	Amphenol	ATF13-12PA-BM13	Arrow Link	Datasheet
Isolated Amplifier	Skyworks Solutions	Si8921	Arrow Link	Datasheet
	Vishay	VIA2000SD	Arrow Link	Datasheet
Communication interface Ethernet	Microchip	KSZ8091RNACA	Arrow Link	Datasheet
	onsemi	NCN26010XMNTBG	Arrow Link	Datasheet
NOR Flash memory	onsemi	LE25U20AQGTXG	Arrow Link	Datasheet
DC BUS Capacitor	TDK	B43601B5477M	Arrow Link	Datasheet
Current sensor	Allegro	ACS758LCB-100B	Arrow Link	Datasheet
Oscillator	Abracon LLC	ASE-25.000MHZ	Arrow Link	Datasheet
Amplifier	onsemi	NCS210RMUTAG	Arrow Link	Datasheet
	onsemi	NCS20164DR2G	Arrow Link	Datasheet
Flyback controller	onsemi	NCV3843BVD1R2G	Arrow Link	Datasheet
AC Power Relay	Omron	G9KA-1A-E-DC24	Arrow Link	Datasheet
DC Power Relay	Omron	G9KB-1A-E DC24	Arrow Link	Datasheet
Brushless DC Motors	MOONS INDUSTRIES	57BL120L2	Arrow Link	Datasheet
Servo Motors	MOONS INDUSTRIES	SM0602DE2-KCF-NNV	Arrow Link	Datasheet
MOV	Littelfuse	V20E320P	Arrow Link	Datasheet
TVS	Littelfuse	AQ4020-01FTG-C	Arrow Link	Datasheet
Fuse	Littelfuse	0607063.UXTH500P	Arrow Link	Datasheet
Shunt resistor	Vishay	WSLP3921L1000FEA	Arrow Link	Datasheet
Temperature Sensing	Vishay	NTCLE413E2103F106A	Arrow Link	Datasheet
LoRaWAN Wireless Vibration Sensors	TE Connectivity	20023687-90	Arrow Link	Datasheet
Angular and Linear Position Sensors	TE Connectivity	2367254-1	Arrow Link	Datasheet
DVK-CONVENTION-AL-HALL-CORE-V1	Melexis	DVK-CONVENTION-AL-HALL-CORE-V1	Arrow Link	Datasheet

For any engineering questions regarding motor control design, please contact Arrow Engineering.

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