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SINUSOIDAL
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DRIVE
RELIABLE
AUTOMATION

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VFDS: ENERGY
SAVING

FAST AND
ACCURATE
OVER-CURRENT
DETECTION

CONTENTS

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WELCOME

In the dynamic arena of motor control, the shift from conventional mechanical drives to electric drives has ushered in a new era of industrial automation characterised by unparalleled precision, efficiency, and adaptability. Breakthroughs in control systems, drive technologies, and microcontroller advancements tailored for motors have fuelled this transformation. These innovations harness sophisticated algorithms, empowering intricate control mechanisms that were once inconceivable within purely mechanical frameworks. As a result, they optimise energy consumption and minimise downtime, marking a significant leap forward in operational efficiency.

Furthermore, the convergence of motor control with robotics, fortified by integrating AI and Machine Learning (ML) algorithms, paves the way for adaptive automation solutions that continuously learn from their environment, making informed, real-time decisions that streamline production processes. This symbiotic relationship fosters a dynamic ecosystem for Industry 4.0 and Industry 5.0, where efficiency is paramount and agility is inherent, allowing for unparalleled customisation to meet diverse operational needs.

In this edition of e-TechJournal, we delve into these cutting-edge developments, exploring how they are reshaping the landscape of motor control and driving the future of industrial automation. We hope you enjoy this edition and welcome your comments and suggestions. Please feel free to drop us a note.

Cliff Ortmeyer Editor, eTech Journal
Email: editor-TJ@element14.com

ARDUINO

PRO ™

VISIT ARDUINO

VFDS: OPEN TO ENERGY SAVING

HOW ARDUINO TURNS OPEN-SOURCE VALUES INTO MAXIMIZED MOTOR EFFICIENCY

There is a huge opportunity to save energy by optimizing the efficiency of electric motors and associated devices, both to slash operational costs and to shrink our carbon footprint.

On the one hand, electric motor systems – often old and inefficient – command a significant 70% share of the electricity demand in industries that rely on motors and drives. On the other, the IEA has emphasized that over 40% of the reduction in greenhouse gas emissions required to align with the Paris Agreement by 2040 and reach climate goals could be achieved through enhanced energy efficiency measures. With hundreds of millions of motor-driven systems currently in use by industries across the world, the impact of higher-efficiency equipment cannot be ignored.

VFDs AND THE FUTURE OF EFFICIENCY

Variable-frequency drives (VFDs) drive electric motors by varying the frequency and voltage of their power supply, and have become extremely common assets on the factory floor – anywhere varying motor speed is essential, such as in pumps, fans, and conveyor systems. Continuously evolving with a focus on energy efficiency, these types of controllers are being integrated with advanced algorithms and features to improve their precision and flexibility. Being able to better monitor and control motor speed, torque, and overall performance leads to enhanced efficiency and reduced consumption, as well as lessened wear and tear over time. All of this contributes to optimize motor performance and lower operational costs.

What's more, VFDs are playing an increasingly important role in the Industrial Internet of Things (IIoT) involving Industry 4.0 and 5.0 systems, which allow for remote monitoring, real-time analytics, and predictive maintenance. The data collected from VFDs can thus be used to further enhance overall system performance and reliability. And while cybersecurity is a critical concern for any connected or smart industrial system, strategies such as encryption, authentication protocols, and other measures are being widely implemented to ensure the integrity and confidentiality of data exchanged between VFDs and control systems.

Finally, the integration of VFDs into existing systems through upgrades or expansions is becoming easier as manufacturers develop modular and scalable VFD designs, adding flexibility in terms of configuration and making it easier for big and small enterprises to adapt to changing requirements even in the future.

5 Trends in VFD development

1. Energy efficiency and sustainability

2. Integration with IoT, Industry 4.0, and Industry 5.0

3. Advanced motor control algorithms

4. Modular and scalable designs

5. Cybersecurity measures

PAIRING VFDS AND PLCS FOR PREDICTIVE MAINTENANCE

When VFDs and Programmable Logic Controllers (PLCs) work together in industrial automation systems, various processes and components can be monitored and controlled to achieve the most efficient and reliable operation – leveraging data originated from sensors on the edge, control signals and feedback loops for real-time adjustments and optimizations. In addition, PLCs can process data gathered from VFDs to identify potential issues before they lead to wasted resources and unplanned downtime.

That was exactly the goal AROL – a leading capping machine manufacturer based in Canelli, Italy, with over 25,000 pieces of equipment currently installed around the world – set out to achieve. With production lines processing up to 100,000 bottles per hour, maintaining their machines' speed and ongoing reliability is critical to operations.

In other words, any outage or unplanned downtime would be detrimental to meeting production quotas and costly to their clients. Therefore, their R&D team decided to integrate diagnostic, prognostic and predictive maintenance capabilities into a smart solution able to gather data from industrial equipment and the surrounding environment, creating a machine monitoring system based on remote wireless sensors that could be powered by battery or 24 V.

The project faced specific challenges in the fact that the sensor nodes had to be mounted in rotating capping turrets, fitting in a small space and yet always remaining connected to a communication unit at the base of the line. What's more, they had to perform part of the data processing on the edge, in order to not overload the central system. And of course, the upgraded capping machine had to be made smart without costing sensibly more.

Fortunately, a solution was on hand: leveraging Arduino Pro's Nicla Sense ME and Portenta Machine Control helped AROL to expedite efforts to a working solution – one which completely avoided vendor lock-in while also upgrading their high-speed production equipment to enable data monitoring and predictive maintenance outcomes.

No less than 15 capping turrets were fitted with as many Nicla Sense MEs, providing vibration and temperature detection thanks to state-of-the-art, onboard Bosch Sensortec sensors – as well as the computational power to process part of the data directly at the level of the sensing nodes. At the base of the machine, one Portenta Machine Control was easily mounted on DIN rail to concentrate communication with all the sensors via Bluetooth®.

Arduino Pro's ME (where "ME" stands for "Motion" and "Environment") is a compact module that brings sensing and intelligence at the edge with a 9DoF smart motion sensor and a 4DoF environmental sensor with AI capabilities. Thanks to its high computational power, it reduces latency and power consumption, offers more privacy and requires less bandwidth – all in a tiny physical footprint.

Arduino Pro's Portenta Machine Control is a fully-centralized, low-power, industrial control unit able to drive equipment and machinery – a "brain" that can be programmed using the Arduino framework or other embedded development platforms, to collect real-time data from the factory floor and support the remote control of equipment, even from the Cloud when desired.

In AROL's case the Portenta Machine Control was the best choice due to its 32 I/Os, while less articulated systems might benefit from the enhanced flexibility of Arduino Pro's new Opta micro PLC solutions – based on the same STM32H747XI Dual ARM® Cortex® processor, and programmable using C++ in Arduino sketches as well having flexibility of incorporating any or all of the 5 traditional automation control languages defined by the IEC 61131-3 standard (Ladder, Functional Block Diagram, Structured Text, Sequential Function Chart or Instruction List).

WHY CHOOSE OPEN SOURCE TO OPTIMIZE YOUR VFD?

Arduino's open-source approach to both software and hardware sets the company apart from all other players in the tech field. What started as a philosophical stance has developed, over time, into the source of a wide array of business benefits for professional clients around the world.

In terms of ensuring no vendor lock-in, greater interoperability, and a reduced energy footprint, for example, choosing Arduino's products can further increase a solutions' efficiency thanks to the company's strong focus on low-consumption and small form factor options. The entire Nicla family, for example, packs industrial-grade sensors and computing power into a mere 22.86x22.86 mm (about the size of a thumb!).

In addition, Arduino's offering brings edge computing into anyone's reach. Processing data where things happen enables the kind of real-time monitoring and control we saw can make a difference for a system's efficiency; in and of itself, it also helps save energy directly by reducing data sent to the Cloud, thereby reducing cloud consumption costs.

Leveraging the Arduino ecosystem and open architecture, edge computing becomes more affordable – thanks to cost-effective solutions that optimize the bill of materials – as well as more accessible for engineers, who can count on great ease-of-use, extensive public documentation and resources, and the choice among a variety of possible coding languages.

In general, Arduino products adhere to widespread industry standards, promoting interoperability between different devices and systems. This, in turn, ensures better compatibility and avoids vendor lock-in – making an open-source solution future-proof.

The flexibility and opportunity for customization of open-source solutions can be particularly valuable when integrating VFDs and PLC capabilities into complex automation systems, as they allow for the fine-tuning of control algorithms, interfaces and more – to meet specific project requirements and adapt to unique industrial processes.

Where security and reliability are paramount, open-source solutions can be more transparent: this can allow developers to identify and fix vulnerabilities faster. Arduino's products undergo strict quality controls and are tested to the highest standards. The Arduino Pro Opta, for example, has been recently put through a cybersecurity posture assessment, resulting in upgrades that make it more reliable than ever.

Last but not least, choosing open-source technology for motor control solutions means tapping into a pool of expertise and support from a vibrant community – over 33 million active users, in the case of Arduino. This can lead to faster issue resolution, continuous improvement, and the availability of a wealth of resources, including forums, documentation, and contributed code.

All in all – whether saving energy is a key global strategy to contrast climate change or a necessity to reduce costs and maintain your own competitive edge – optimizing motor efficiency with VFDs paired with Arduino controllers opens up a variety of benefits you cannot afford to waste.
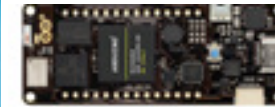
5 Reasons to choose open source for efficient motor control

1. **Cost-effective development**
2. **Community support and shared knowledge**
3. **Flexibility and customization**
4. **Interoperability and standards compliance**
5. **Transparency and security**

FEATURED PRODUCTS

Portenta Boards

Arduino's series of high-performance industry-rated boards

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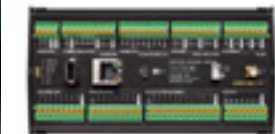
Portenta Machine Control

A fully-centralized, low-power, industrial control unit able to drive equipment and machinery.

BUY NOW

Nicla Family

Arduino's tiniest industrial-oriented board

BUY NOW

CONCLUSION

Learn more about industrial-grade Nicla intelligent sensing and the Portenta family with Industrial IoT capabilities to optimizing motor efficiency.

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ANALOG DEVICES
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VISIT ANALOG DEVICES

DRIVE RELIABLE AUTOMATION WITH
REMOTE MOTION CONTROL FOR INTELLIGENT NODES

Authors: Alessandro Leonardi, Account Manager, Giorgio Paganini, Student at Polytechnic of Milan, and Fulvio Bagarelli, Technical Leader

ABSTRACT

Industry 4.0 brings the promise of intelligence at the edge over long distances, and 10BASE-T1L Ethernet is paving the way forward with its power over data line (PoDL) capabilities, high data transfer rates, and compatibility with Ethernet-based protocols. This article explains how the new 10BASE-T1L Ethernet physical layer standard can be integrated into automation and industrial scenarios to connect controllers and user interfaces with endpoints, such as multiple sensors and actuators—all using a standard Ethernet interface for bidirectional communication.

INTRODUCTION

The 10BASE-T1L is a physical layer standard targeted to industrial connectivity. It offers data rates up to 10 Mbps and power delivery over distances up to 1000 m using a standard twisted pair cable. Low latency and the PoDL capabilities allow devices such as sensors or actuators to be controlled remotely. This article explains how to implement a system composed of a remote host that synchronously controls two or more stepper motors, thereby demonstrating the capabilities of real-time communication over distance.

SYSTEM HARDWARE

The system is composed of four different boards:

> The EVAL-ADIN1100 board features an ADIN1200, 10BASE-T/100BASE-T PHY, used in combination with the ADIN1100 10BASE-T1L PHY to translate messages from one physical standard to the other. It can be configured for different modes of operation. In this project, Standard Mode 15 (media converter) is used. The EVAL-ADIN1100 board also features an integrated microcontroller that performs the basic configuration required for media conversion as well as to read diagnostic information. However, it cannot interact with sent and received messages; this board is completely transparent to the communication.

> The EVAL-ADIN1110 is the core of the remote devices' controller. The ADIN1110 10BASE-T1L MAC-PHY receives data through the 10BASE-T1L link and transfers it to an onboard Cortex®-M4 microcontroller via an SPI interface for processing. This board also exposes Arduino Uno-compatible headers that can be used to install a shield to add functionalities to the board.

> The TMC5160 shield is a custom-developed board based on the Arduino shield form factor. A single shield supports up to two TMC5160 SilentStepStick boards, and multiple shields can be stacked together to increase the maximum number of controlled motors. All the drivers share the same SPI clock and data signals, but chip select lines are kept independent. With this configuration, two communication modes are possible: if chip select lines are asserted individually, the microcontroller can communicate with single controllers—for example, to configure motion parameters. Instead, by asserting more chip select lines simultaneously, all selected drivers receive the same command at the same time. The latter mode is mainly used for motion synchronization purposes. This board also provides some additional input capacitance to the StepSticks to reduce current peaks at motor startup and to smoothen the current profile during normal operation.

This allows the use of PoDL to supply the whole system with a maximum of two NEMA17 motors (with the default setup, the maximum transmitted power is 12 W at 24 V). The board is also used to ease the connection with stepper motors by using screw terminals to make phase outputs from the controllers more accessible.

> Two EVAL-ADIN11X0EBZ boards, one for the media converter and one for the EVAL-ADIN1110EBZ, are used to add PoDL capabilities to the system. This board is a plug-in module that can be mounted on the MDI prototyping headers of the evaluation boards and can be configured for both supplying and receiving power from the data line.

Figure 2 – EVAL-ADIN1110, EVAL-ADIN11X0EBZ, and TMC5160 shield assembled.
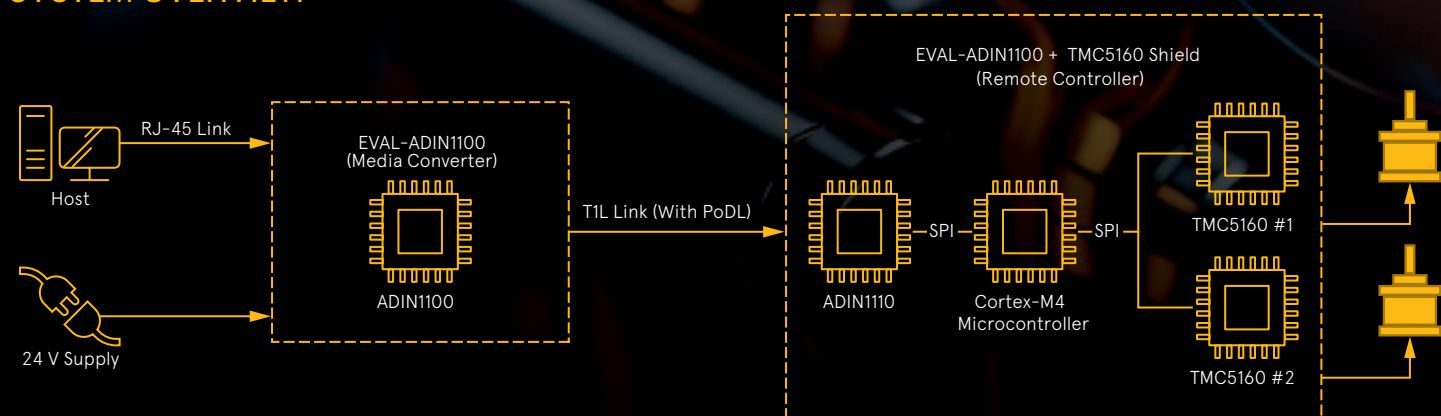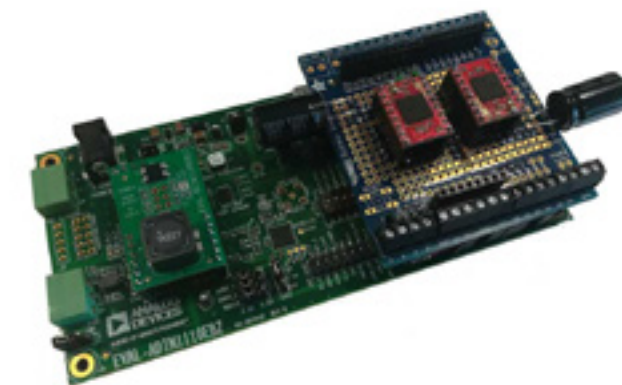

SYSTEM OVERVIEW

Figure 1 – A system overview.

To begin, Figure 1 shows a schematic of the system-level application. On the host side, the conversion between standard and 10BASE-T1L links is managed by the ADIN1100 and ADIN1200 Ethernet PHYs, while, on the remote side, the controller interfaces with the link using the ADIN1110 Ethernet MAC-PHY, which only requires an SPI peripheral to exchange data and commands.

Precise and synchronized motion control is accomplished by using the ADI Trinamic™ TMC5160 stepper motor controllers and drivers that allow the generation of six-point ramps for positioning without requiring any calculation on the controller.

Choosing these components also keeps requirements on the microcontroller low in terms of used peripherals, computing power, and code size, allowing the use of a wide range of commercially available products.

Moreover, up to a predefined power consumption limit, the entire remote subsystem can be directly powered from the data line, so the media converter board is the only module requiring a local power supply.

SYSTEM OVERVIEW

The software code is available for download: Remote Motion Control with 10Base-T1L Ethernet – Code.

To keep the code lightweight and minimize communication overhead, no standard communications protocols were implemented above the data link layer. All the messages are exchanged using the payload field of Ethernet frames with a predefined fixed format. Data is organized into 46-byte segments, composed of a 2-byte fixed header and a 44-byte data field. The header includes an 8-bit device type field, which determines how received data is processed, along with an 8-bit device ID field, which enables the selection of an individual physical device if more devices of the same type are present.

The host interface is written in Python to ensure compatibility with both Windows and Linux hosts. Ethernet communication is managed using the Scapy module, which allows creating, sending, receiving, and manipulating packets at each layer of the stack, including the Ethernet data link. Each device type defined in the protocol has a corresponding class that includes properties to store data to exchange, and a set of methods that can be used to modify these properties instead of having to directly edit the variables.
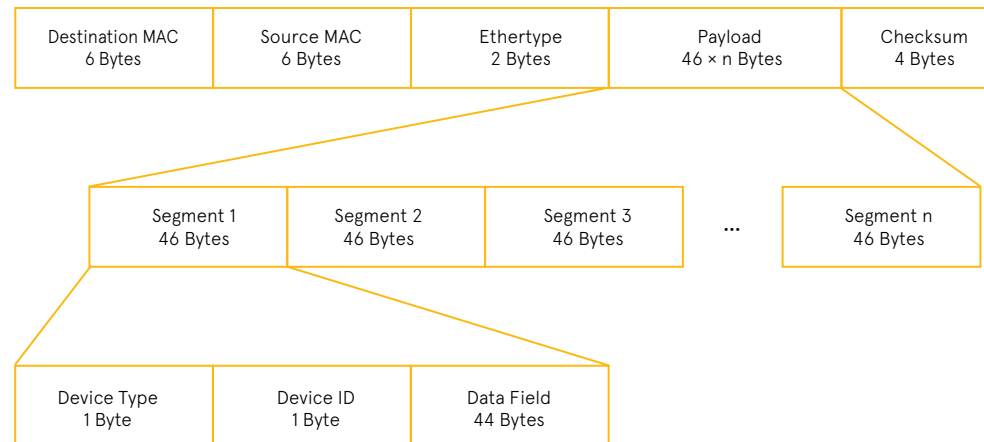

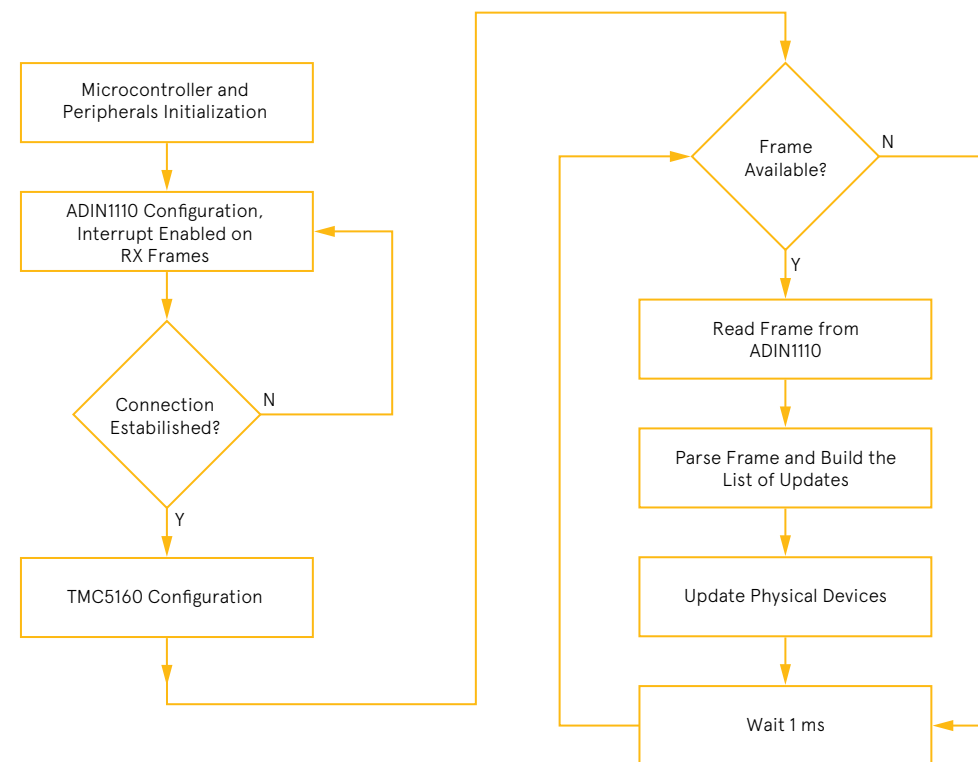*Figure 3 – Communication protocol format*

Figure 4 – A firmware flowchart

For example, to change motion direction in speed mode for the motion controller, methods "setDirectionCW()" and "setDirectionCCW()" are defined, instead of having to manually assign 0 or 1 values to the direction flag. Each class also includes a "packSegment()" method that packs and returns the segment corresponding to the controlled device in the form of an array of bytes according to the predefined format for the considered device type.

Firmware is written in C using the ChibiOS environment, which includes, among other tools, a real-time operating system (RTOS), a hardware abstraction layer (HAL), and peripheral drivers, allowing the code to be easily ported between similar microcontrollers. The project is based on three custom modules:

> ADIN1110.c is the driver used to allow the exchange of data and commands with the ADIN1110 over the SPI interface. It includes low-level communication functions for reading and writing data from device registers, and higher-level functions for sending and receiving Ethernet frames. It also includes the function used to establish communication between 10BASE-T1L transceivers. The pin that notifies if new frames are available is read on interrupt to minimize latency.

> TMC5160.c implements all the functions needed to control the TMC5160 motion controller, configured to operate in full-featured motion controller mode. Both constant speed and position control modes are implemented, allowing smooth and precise positioning with six-point ramps. Communication with multiple motion controllers is achieved through a single SPI bus with independent chip select lines. A set of functions and typedefs is also provided to ease motion synchronization.

> Devices.c is the interface between data received from the T1L link and physical devices connected to the controller. It includes similar structs to the ones defined in the host interface and functions to update them each time a new frame with valid data is received. This module is also used to determine which actions are executed each time a struct is updated—for example, which physical motion controller is related to commands received at a specific device address.

SYSTEM HIGHLIGHTS AND VALIDATIONS

This project aims to demonstrate how the new 10BASE-T1L Ethernet physical layer standard can be integrated into automation and industrial scenarios to connect controllers and user interfaces with endpoints, such as multiple sensors and actuators. This application is targeted to the remote real-time control of multiple stepper motors, widely used in the industry for low power automation tasks, but also utilized in light robots and CNC machines, such as desktop 3D printers, desktop milling machines, and other types of cartesian plotters. However, its use cases can also be extended to other types of actuators and remote-controlled devices. Its main advantages over already existing interfaces used for similar purposes are:

> Simplified wiring, requiring only a single twisted pair. The possibility to also deliver power on the data line allows low power devices, such as sensors, to be directly powered from this connection, further reducing the number of required wiring and connectors, and so lowering the complexity, cost, and weight of the overall system.

> Power delivery using the PoDL standard, which uses a DC voltage superimposed on data lines to supply power to devices connected to the network.

This type of coupling can be achieved by only using passive components, and once the voltage on the receiver end is filtered, it can be directly used to power the device or a DC-to-DC converter without requiring rectification. By correctly dimensioning components used for this type of coupling, a high efficiency system can be achieved. In this project, using standard components installed on the evaluation boards leads to an overall efficiency of about 93% (with a 24 V supply and total load current of 200 mA). However, this result has a wide margin for improvement—indeed, most of the losses are due to resistive drops of the passive components along the power path.

> Versatility, as it can be used for both last-mile and end-point connectivity. Analog Devices 10BASE-T1L devices have been tested for distances up to 1.7 km. They also allow daisy-chaining with a low impact on system complexity. For example, by using the ADIN2111 two-port low complexity switch, it is possible to design devices that integrate daisy-chaining capabilities, making the link suitable also for end-point nets.

> Easy to interface with existing equipment that already integrates an Ethernet controller, including personal computers and laptops. Data frames follow the Ethernet data link standard, and all Ethernet-compatible protocols can be implemented above it, so only a media converter is needed as a bridge with standard Ethernet links. For example, the board used in this project, the EVAL-ADIN1100, can be used as a reference design for a transparent media converter, requiring only two Ethernet PHYs and an optional microcontroller for configuration and debugging.

> High data rate, reaching up to 10 Mbps, full duplex. This, combined with the daisy-chain topology on which industrial Ethernet-based protocols can be implemented, allows it to be used in a real-time application, where deterministic transmission latency is required.

> Isolation between the transceiver and media can be achieved with both capacitive or magnetic coupling, depending on the safety and robustness requirements of the application.

Multiple measurements were done on the system to evaluate its performance. All the peripherals used to communicate with the ADIN1110 transceiver and TMC5160 controllers were configured for the maximum possible speed that is reachable with the standard hardware configuration. Considering the 80 MHz system clock of the microcontroller, the data rate of SPI peripherals was set to 2.5 MHz for the motion controllers and to 20 MHz for the ADIN1110 transceiver. For the TMC5160, by tuning the microcontroller clock configuration and supplying an external clock signal to the IC, SPI frequency can be further increased up to 8 MHz, while for the ADIN1110 the maximum limit by data sheet is 25 MHz.

For the latency, the total time between a data request and the reception of the answer frame has been evaluated at about 4 ms (average on 500 samples, measured with the Wireshark protocol analyzer computing the difference between the timestamps of data requests and corresponding answers). Additional evaluations were made to determine which parts of the system are responsible for this delay.
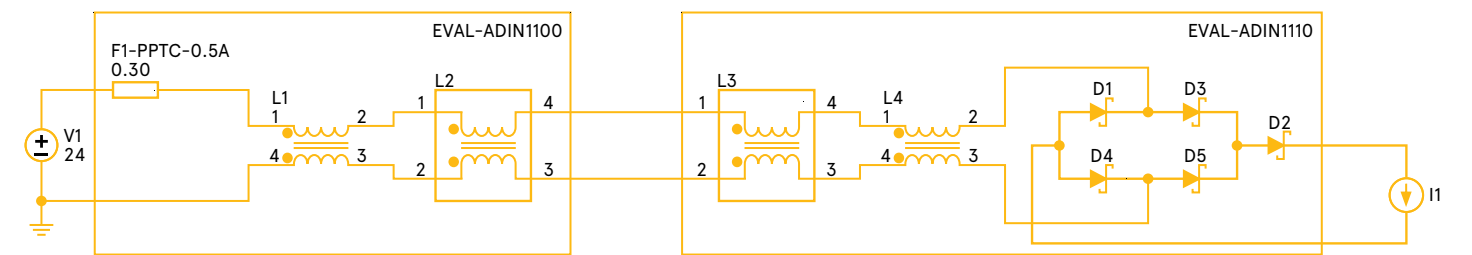
Results showed that the main cause is the delay function provided by the RTOS, which allows a minimum delay of 1 ms, used to set the interval between write and read operations for the TMC5160, while the required delay is in the order of tens of nanoseconds. This could be improved by defining a different timer-based delay function that allows for shorter delay intervals.

The second cause of this delay is the Scapy function used to receive frames, which requires a minimum set-up time of 3 ms after it has been called. In a real-world application, this can be improved by developing the interface directly with network adapter drivers for the operating system, instead of third-party tools like Scapy. However, drawbacks include losing compatibility with different operating systems and increasing code complexity.

Precise execution times for the callback implemented on the microcontroller were measured by toggling a GPIO and measuring the high period with an oscilloscope. Measured execution time includes functions used to read and parse received frames and to send commands to motion controllers.

Figure 6 – A simplified scheme of power path

TABLE 1. MEASURED EXECUTION TIMES

Command	Execution Time (ms)	Cumulative Delay Time (ms)	Optimal Execution Time (ms)
Synchronized motion, two motors (×24 TMC5160 register accesses)	24.058	24.000	0.058
Motor data request (×3 TMC5160 accesses)	3.109	3.000	0.109
Dummy data request (no TMC5160 interactions)	0.080	0	0.080

The second set of measurements was made to evaluate power losses along the transmission path when using PoDL to supply remote devices. Tests were conducted by substituting the motion controller shield with an electronic load set at different currents, starting from 0.1 A up to 0.5 A in steps of 100 mA, to determine which components had a major impact on power losses and, consequently, how to improve the design to achieve higher current ratings.

TABLE 2. SYSTEM EFFICIENCY

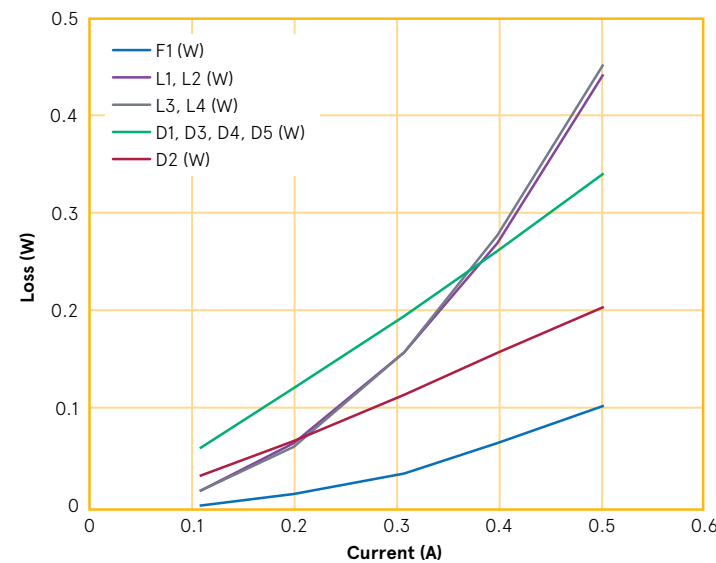| Current (A)	Input Power (W)	Output Power (W)	Efficiency
0.109	2.61	2.47	0.95
0.200	4.70	4.45	0.93
0.308	7.37	6.70	0.91
0.399	9.54	8.51	0.89
0.502	12.00	10.45	0.87

DC POWER LOSSES

Figure 6 – Power losses for each passive component, as a function of current.

FEATURED PRODUCTS

TMC5160 Motor Controller & Driver

A high power stepper motor controller and driver IC with serial communication interfaces.

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EVAL-ADIN1110 and EVAL-ADIN1100EBZ

Revolutionising Remote Motion Control in Industry 4.0

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ABOUT THE AUTHOR

Alessandro Leonardi is an account manager at Analog Devices, Milan. He studied electronics engineering and received a bachelor's and master's degree from Politecnico di Milano. After graduating, he was part of the field applications trainee program at ADI.

Giorgio Paganini is currently earning a degree in electronics engineering at Politecnico di Milano. He was involved with electronics development projects as part of Dynamis PRC, the Formula Student Team of Politecnico di Milano.

Fulvio Bagarelli joined Analog Devices in 2017 as a senior field application engineer and currently holds the position of a field technical leader. Previously, Fulvio worked for Linear Technology (now part of Analog Devices), Arrow Electronics, and STMicroelectronics. He has a master's degree in electronics engineering from Politecnico di Milano in Italy and holds an executive M.B.A. from SDA Bocconi School of Management in Italy.

CONCLUSION

Industry 4.0 is pushing the boundaries of intelligent automation. ADI Trinamic technology used along with the ADIN1100, ADIN1110, and 10BASE-T1L transceivers enable the remote control of sensors and actuators up to 1700 m from their controller without requiring power at the edge. With a reliable method of remote control, stepper motors can easily be controlled in real-time at longer distances without sacrificing any performance or speed. Systems solutions are paving the way toward an industrial transformation that promises unprecedented response times along with maximum performance capabilities.

Explore more about ADI stepper motor controllers and drivers along with ADIN1100, ADIN1110, and 10BASE-T1L transceivers.

CLICK HERE

TOSHIBA

MCU-LESS SINUSOIDAL CONTROL OF **PERMANENT MAGNET SYNCHRONOUS MOTORS**

By Toshiba Electronics Europe GmbH

Although it requires a more complex waveform, the PMSM benefits from lower torque ripple and reduced audible noise. For this reason, it is often the preferred motor type in applications requiring smooth and quiet motion, such as high-end home appliances, power tools and industrial automation.

The main difference between these two motor types lies in the construction of the stator windings. So, the BLDC is ideally commutated using a trapezoidal waveform that can be created relatively easily. In contrast, the PMSM (as shown in Figure 1), requires a sinusoidal commutation waveform that is more complicated to produce.

Although it requires a more complex waveform, the PMSM benefits from lower torque ripple and reduced audible noise. For this reason, it is often the preferred motor type in applications requiring smooth and quiet motion, such as high-end home appliances, power tools and industrial automation.

Historically, sine-wave commutation has been handled using algorithms implemented in microcontroller unit (MCU) firmware that require extensive optimisation and fine-tuning to work with the chosen motor and meet the requirements of the application. Also, the MCU's performance must be adequate to execute the control algorithm up to the maximum required speed, while also handling application-level processing.

Figure 1 – The PMSM is a brushless DC motor that requires a sinusoidal waveform for commutation
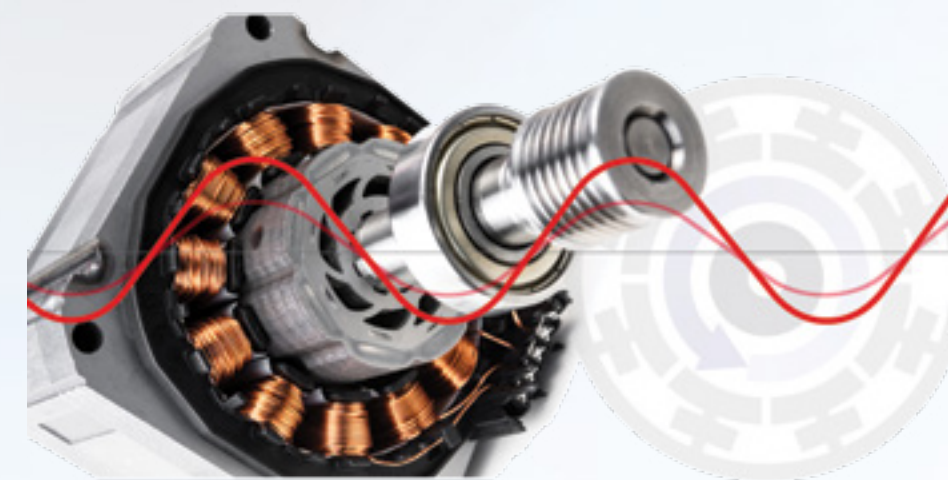
POSITION SENSING AND SOFT-START

Unlike a brushed motor, where simply applying power will ensure the correct coils are engaged to start the motor satisfactorily regardless of where the rotor last stopped, starting and running a BLDC motor requires knowledge of the current rotor position. This is needed to allow the appropriate coils to be excited and the rotor to begin rotating in the correct direction. Sensors are often fitted to brushless motors to detect this position. Alternatively, a sensorless setup saves the expense and the potential reliability issues associated with sensors (such as Hall devices).

In this case, techniques are needed to move the stationary rotor in a known starting position before energising the coils. Without proper precautions, the rotor and anything attached to it could whip back in the wrong direction.

When the coils are energised, this must be undertaken in a manner that prevents PWM switching from generating excessive noise and vibration during the time where no useable back-EMF is available to determine the rotor angle. In essence, the motor control algorithm is driving the motor blind. Once sufficient back-EMF is available, the motor controller can switch to the chosen control method.

FINE-TUNING THE DRIVE

The ability to start the motor and select the speed, however, are only a subset of the functions needed to operate properly. The motor-drive designer must have the flexibility to integrate the controller with MOSFETs of a suitable voltage and power rating for the application. They also require the ability to optimise parameters (such as acceleration, lead angle, and PWM frequency) to ensure the system will respond as required to the user's inputs and maximise energy efficiency in all operating conditions.

ACHIEVING MCU-LESS CONTROL

The Toshiba TC78B011FTG sine wave pre-driver relieves any need for an MCU. This parameterizable chip for sensorless three-phase brushless motor control is a pulse-width modulated (PWM) chopper that can be connected to external low-side and high-side N-channel MOSFETs, allowing for a scalable inverter implementation to match a range of different motors.

While the device provides open-loop speed control, closed-loop control that maintains the target speed unaffected by power supply or load variations, with an adjustable speed curve, is a more typical requirement. This can be achieved by configuring the precise operating mode via the I2C interface, with the option to store the settings in a non-volatile memory (NVM). Hence suitable settings can be programmed during manufacture for circuits that do not use a microcontroller or processor.

On the other hand, the motor speed can be adjusted by writing to a register through the device's I2C interface, and can also be determined using either a PWM input or an analog signal. Braking and direction, also, are controlled via register settings or external pins. The motor current and rotation speed can be read from external pins while the motor is running.

MORE ACCURATE POSITIONING

After powering-on, the TC78B011FTG retrieves the stored device configuration from its NVM (see Figure 2). At this point, a brake sequence may be applied by shorting the appropriate coils through the motor inverter to ensure that the rotor is stationary before attempting to start rotation. Once the initialisation sequence is complete, after around 3.5ms, the driver enters idle mode with all MOSFETs turned off and awaits further instruction from the host system.
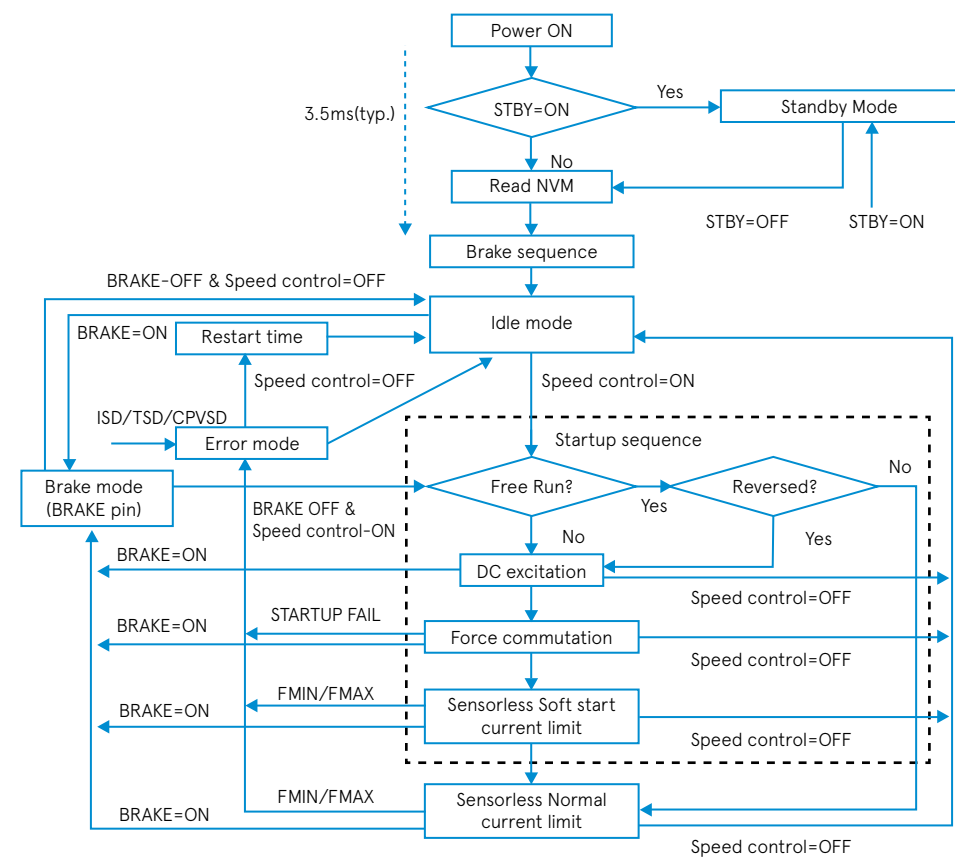

Figure 2 – Operational flowchart showing the initialisation of NVM configuration and forced commutation motor start-up

The required speed can be defined via I2C to the speed command register (SPD) or applied as a PWM or analog signal to the SPD pin. When either of these is received, the motor start-up sequence is engaged. The process begins with a DC excitation of the motor coils that moves the rotor to the starting position. When this is completed, the forced commutation of the motor starts. At this stage, a rough electrical field is applied in 120° commutation to generate an initial back-EMF. A configurable soft-start feature is also included (as illustrated in Figure 3), which limits the current drawn when spinning up the motor. All speed control at this stage is open loop.

The system changes to sensorless control, with the current limit set for normal operation, as soon as the motor is rotating fast enough to generate a back-EMF usable for the control algorithm. Closed-loop speed control can then be engaged.

The rotor may already be rotating before power is applied, which can be caused, for example, by air passing over a fan's blades. In this case, known as idling or windmilling the motor driver will skip the initial excitation and forced commutation steps and proceed directly with sensorless operation. In a typical application the back-EMF measurement capability can be excessively sensitive in this type of situation, causing the driver to incorrectly try to skip the first open loop start-up stages. The TC78B011FTG prevents this by providing a register that allows the designer to change the minimum rotor speed considered fast enough to skip the start-up process. Alternatively, to avoid the challenges associated with starting an idling motor, the controller can be configured to apply the braking sequence each time after leaving standby or power on, enabling the rotor to always start from a stopped state.
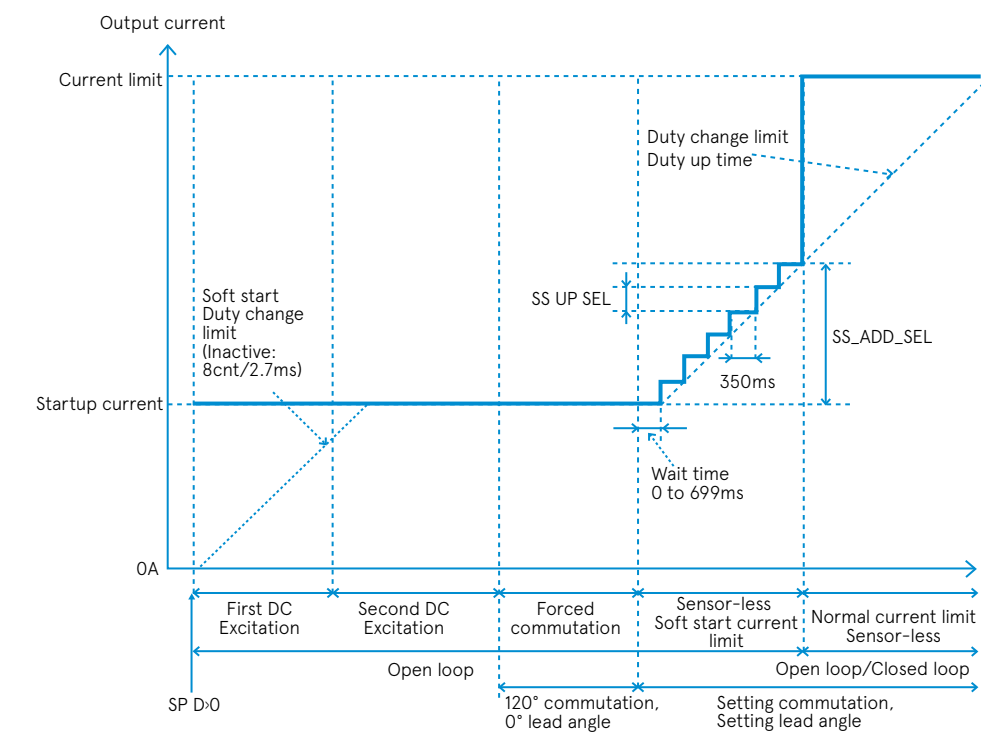

Figure 3 – Output current limit during start-up

GREATER ADJUSTABILITY

To allow flexible speed control in closed-loop mode, the TC78B011FTG IC provides registers for setting the acceleration by specifying the time between each step change in speed and for determining how quickly the speed changes can occur. The supported speed settings are configurable through individual control of the starting, stopping, and maximum duty cycles. The RPM associated with the start and maximum values (as shown in Figure 4) can also be set and up to two speed slopes between the start and maximum RPM may be defined.

The frequency used for the PWM output can be fixed or set to increase automatically as the motor speed increases for optimum efficiency. The available frequency range lies between 23.4kHz and 187.5kHz. Adjusting the PWM frequency also helps designers ensure compliance with the electromagnetic compatibility (EMC) requirements relevant to the application.

There is also a register for adjusting the lead angle according to the motor's characteristics, which helps to optimise energy efficiency and minimise audible noise. For the quietest possible operation, the lead angle can be set so that the back-EMF and motor current are in phase.

The IC contains three half-bridge pre-drivers for external N-channel MOSFETs. These can supply a gate-source (VGSS) voltage of up to 8V above the motor supply voltage and can be configured to deliver gate-source (IGSS) current from 10mA to 100mA for both high- and low-side MOSFETs, while the sink current range is 20mA to 200mA. Applying the electrical brake function or reversing the direction could cause shoot-through in the switches. An ANTITHROUGH register coupled with a DEADTIME setting avoids this with dead time options from 250ns to 1500ns.

The highest usable switching frequency may be limited by the MOSFET choice and motor used. Since the back-EMF is measured for position sensing during the off-time of the PWM, choosing a highly inductive motor, or choosing MOSFETs with low switching performance, can cause position detection to fail.
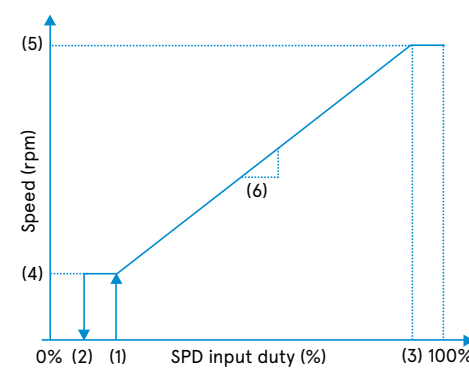
To avoid this, the optimum PWM frequency can be determined by testing suitable settings under all usage conditions.

The device also comes with safety features, including shoot-through prevention with configurable dead-time. A status register indicates abnormal conditions including excessive current draw, low charge-pump voltage, thermal shutdown, and start-up failure. An alert pin is set when any of these conditions arise. This pin is also used to indicate under-voltage and motor operation outside the pre-set maximum and minimum speeds. The controller can be programmed to await a signal from an external source after an abnormal condition is detected or attempt to restart the motor in auto-recovery mode.

Figure 3 – The minimum and maximum speed can be set. And two different speed slopes are available
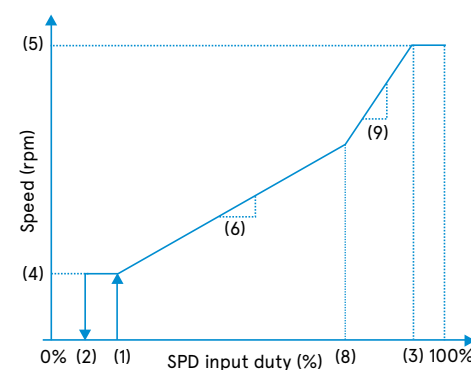
MOSFET SELECTION

The following three parameters should be considered to select a suitable MOSFET that matches the output stage of the TC78B011. The first is the maximum motor voltage VM supply, which is limited for the TC78B011 to 27V max operating voltage. So, a MOSFET with a minimum VDDS of 30-40 could be selected. The second parameter to consider is the minimum charge pump voltage VCP over the maximum VM, which is rated with 7.5V under min conditions for the TC78B011. The minimum gate-source voltage (VGS) for the MOSFET is 1.5V lower than the minimum VCP. So, a MOSFET, which is reasonably conductive at a VGS of 4.5V to 6V, can be used. The third parameter is the achievable current by the charge pump, which is used to load and unload the gate of the MOSFET under the current PWM frequency.

Considering these three parameters, the following selection of MOSFETs from Toshiba are suitable for different possible output power capabilities:

Item	Min	Typ	Max	Unit
VM Power supply voltage	9	14.8	27	V
VCP Charge Pump Voltage	VM+7.5	VM+8	VM+8.5	V
Gate source Voltage	VCP-1.5	VCP-0.3	VCP	V
Drive current	160	200	240	mA

Table 1 – The Output Stage Parameter of TC78B011

Device	V_{DS}	I_D	$R_{DS(ON)}$@4.5V
SSM6N67NU	30V	4A	39.1mΩ
SSM6K804R	30V	12A	12mΩ
SSM6K513NU	30V	15A	8mΩ
TPN8R903NL	30V	20A	10.2mΩ

Further preselected MOSFETs from Toshiba

FEATURED PRODUCTS

TC78B011 Brushless DC Motor Driver

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CONCLUSION

Designers can take advantage of BLDC motors, and the smooth and quiet PMSM type in particular, without embarking on an MCU development project. They can leverage programmable controllers that are featured for standalone operation with closed-loop control and parameterizable speed setting. A MIKROE board featuring the Toshiba TC78B011 IC plus selected MOSFETs is now available for evaluation purposes. This will further facilitate the motor system development process.

Explore more about Toshiba TC78B011 motor driver IC and MOSFETs.

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ACHIEVE FAST AND ACCURATE OVER-CURRENT DETECTION USING **OPTICALLY COUPLED SIGMA-DELTA MODULATORS**

Authors: Wong Chee Heng (IC Design Engineer, Isolation Products Division) and Lim Shiun Pin (Technical Marketing Engineer, Isolation Products Division)

INTRODUCTION

In an industrial motor control system, sensing and feedback of various parameters such as motor phase, DC bus current and voltage, torque, direction, and speed are required for proper operation of the system.

As the trend of the system moves towards higher precision, power, speed, multi-axis, and multi-directional, these requirements become increasingly important. As the motor encoder measures the torque, speed, and direction, the sigma-delta modulator provides high accuracy, high linearity, wide dynamic range, fast-response current, and voltage sensing. Traditionally, current sensing is done by using current transformer (CT) or a Hall effect sensor (HES), but these solutions are bulky, expensive, and less accurate over operating temperature. A smaller, low-cost solution can be realized by directly connecting a shunt resistor to the sigma-delta modulator. Phase current flows through the shunt resistor with a resistance value selected such that the maximum current range corresponds to an optimum low voltage of about ±50 mV (for ACPL-C799) or ±200 mV at the input of the sigma-delta modulator. At this low voltage, power dissipation loss across the shunt resistor is minimized. Figure 1 illustrates the phase current sensing and DC bus voltage and current sensing of a sigma-delta modulator in a motor control system.

MOSFET SELECTION

One of the most expensive devices in a motor control system is a power semiconductor switching device like the IGBT or power MOSFET. Switching at high frequency, these power devices introduce unintended noise and high-voltage transients across the control system. This high-frequency transient may affect the normal operation of the sensitive, costly microcontroller. Sigma-delta modulators in combination with superior optical coupling isolation technology deliver high noise margins and excellent immunity against isolation mode transients. With a minimum distance through insulation (DTI) of 0.5 mm, these sigmadelta modulators provide reliable double protection and a high working voltage suitable for fail-safe designs. This proven isolation performance is superior to magnetic or capacitive-based isolators, where DTI is only a third of 0.1 mm.

Sigma-delta modulators[1,2,3,4] convert the analog input signal into high-speed single-bit data streams by means of a second-order sigma-delta over-sampling modulator. The time average of the modulator data is directly proportional to the input signal voltage. This white paper specifically discusses the ACPL-796J and ACLP-C799 optically isolated sigma-delta modulators.

There are two types of sigma-delta modulators, based on whether the clock source is internally built-in or externally provided to the modulator. For the internally clocked type, a 10 MHz or 20 MHz fixed clock is built in at the primary side of the isolation barrier where the sigma-delta encoder is located.

The clock signal is encoded together with the data and coupled across the isolation barrier to the secondary side of the isolation barrier where the clock and data signals are decoded. The externally clocked-in type receives the clock signal at frequency ranges from 5 MHz to 25 MHz at the secondary side and then it is coupled across the isolation barrier to the primary side. At the secondary side of both types of modulators, data is decoded into a high-speed data stream of digital ones and zeros. Figure 2 illustrates the simplified block diagrams of internally and externally clocked sigma-delta modulators.

Figure 1 – Sigma-Delta Modulator Used in Output Phase with DC Bus Voltage and Current Sensing

Internally Clocked Sigma-Delta Modulator
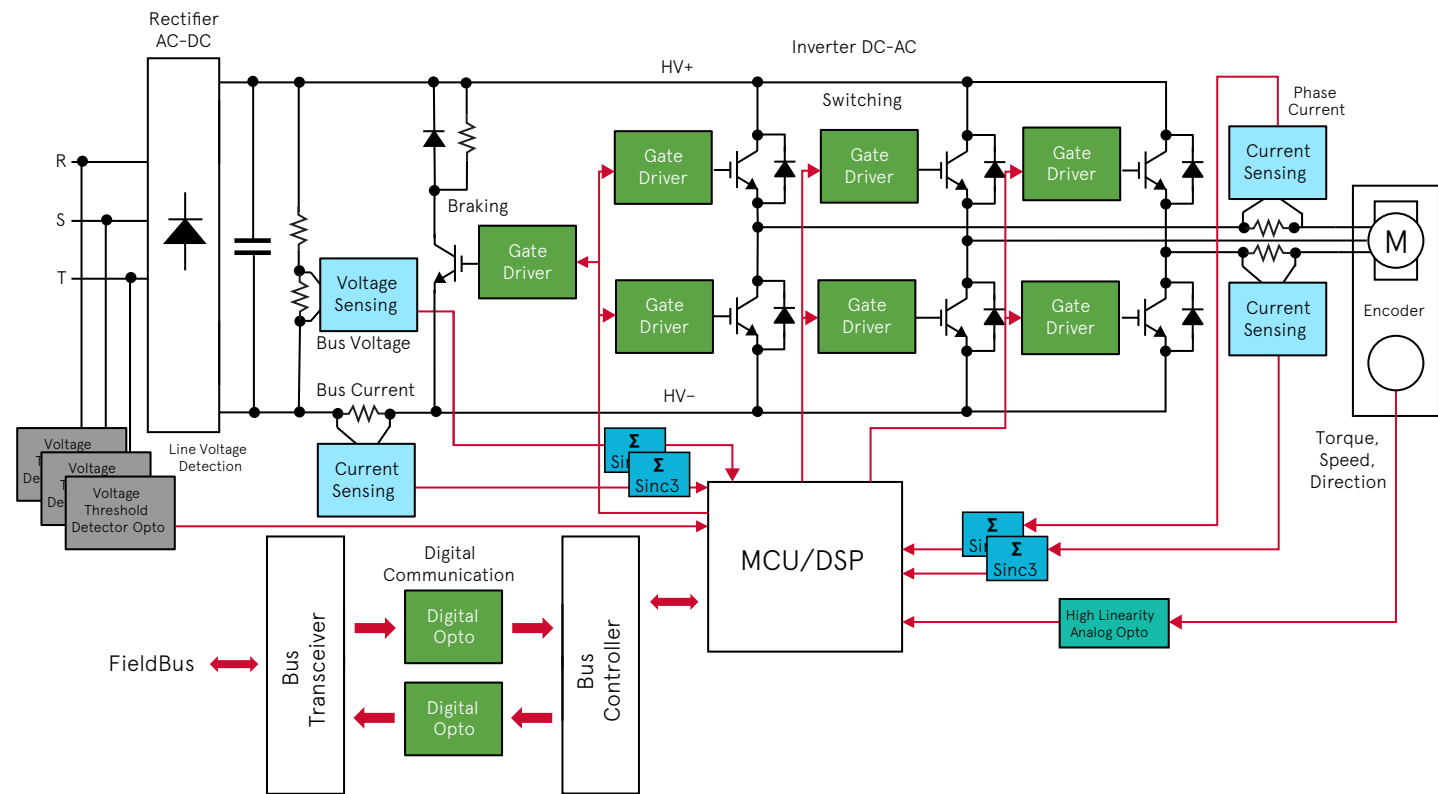
Externally Clocked Sigma-Delta Modulator
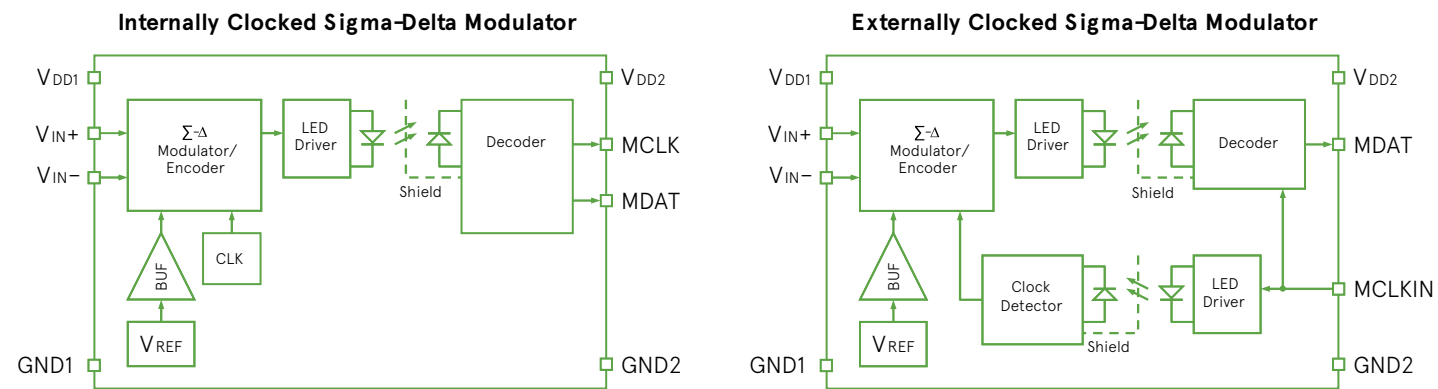
Original analog input information is represented by the density of digital ones or zeros at data output. Table 1 shows the input voltage with an ideal corresponding density of ones at the modulator data output and ADC code. The modulator data received on the isolated side is then sent to a processor for filtering and conversion. A Sinc3 decimation filter can be implemented on an FPGA or microprocessor to recover the desired signal.

The decimation filter averages or decimates the high-speed oversampled bit stream to a lower rate by a factor commonly known as decimation ratio. By selecting a higher decimation ratio, better resolution of the recovered data can be achieved at the expense of longer filter delay time.

Figure 2 – Simplified Block Diagrams of Internally and Externally Clocked Sigma-Delta Modulators

Analog Input	ACPL-796J Voltage Input (±50 mV)	ACPL-C799 Voltage Input (±200 mV)	Density of Ones	Density of Zeros	ADC Code (16b Unsigned Decimation)
Full-Scale Range	640 mV	160 mV	—	—	—
+Full-Scale	+320 mV	+80 mV	100%	0%	65,535
+Recommended Input Range	+200 mV	+50 mV	81.25%	18.75%	53,248
Zero	0 mV	0 mV	50%	50%	32,768
−Recommended Input Range	−200 mV	−50 mV	18.75%	81.25%	12,288
−Full-Scale	−320 mV	−80 mV	0%	100%	0

Table 1 – Sigma-Delta Modulator Input Voltage with the Corresponding Density of Ones and Zeros at Modulator Data Output and ADC Code
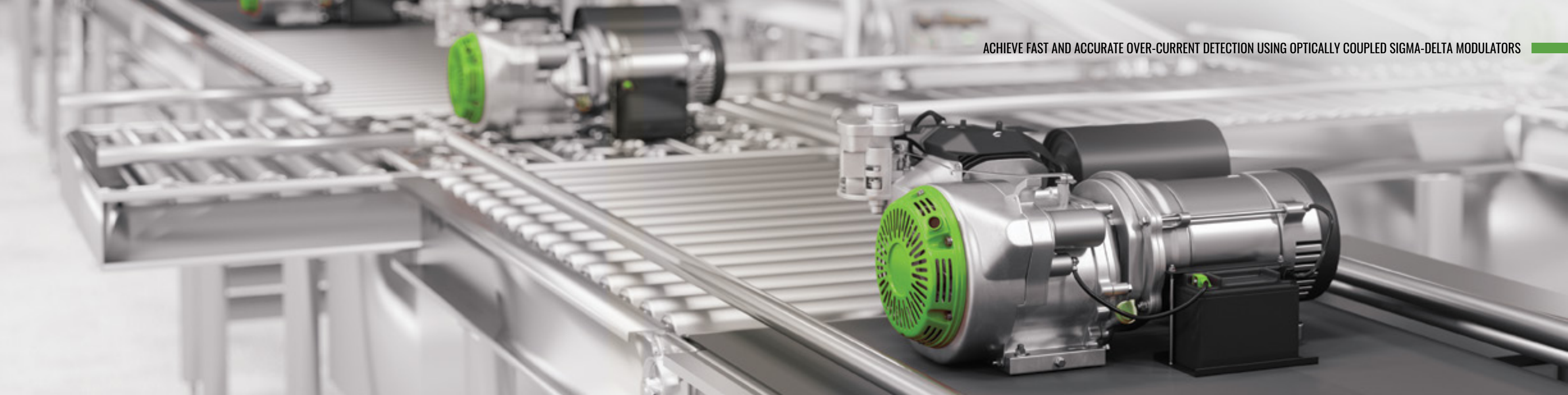
FAST-RESPONSE OVER-CURRENT DETECTION

Over-current or short-circuit conditions in an IGBT can occur due to a phase-to-phase short, a ground short, or a shoot through. Typically, an IGBT can survive short-circuit conditions up to 10 µs5 before failure. Within this time period, a fault must be generated as feedback to the microcontroller to trigger an immediate shutdown procedure within the system. One method is to detect the over-current directly from sensing the phase current using the sigma-delta modulator. Usually, a longer post-processing time of the sigma-delta modulator output data is required to achieve higher resolution of the measured phase current.

As a result, over-current may not be detected quickly enough to shut down the entire control system. One implementation6 uses two Sinc3 filter paths: one with a decimation ratio of 256 for higher resolution and another with a decimation ratio of 32 for fast over-current detection. A typical application using a 20 MHz clock frequency requires about 12.8 µs filter delay time with a decimation ratio of 256 and 1.6 µs with a decimation ratio of 32. Besides the filter delay, an additional 0.5 µs must be considered for the sigma-delta processing and for latency across the isolation barrier.

To shorten the response time further, a simple fault-detection logic block can be used in place of the low decimation ratio Sinc3 filter. This method detects a pre-programmed continuous N-bits of one or zero directly from the data output of the sigma-delta modulator without going through further processing or conversion. This implementation is illustrated in Figure 3 and Figure 4.

Figure 3 - Output Data of an ACPL-796J Connected to Separate Paths Inside the FPGA (For High-Resolution Conversion and Fast Response Detection)
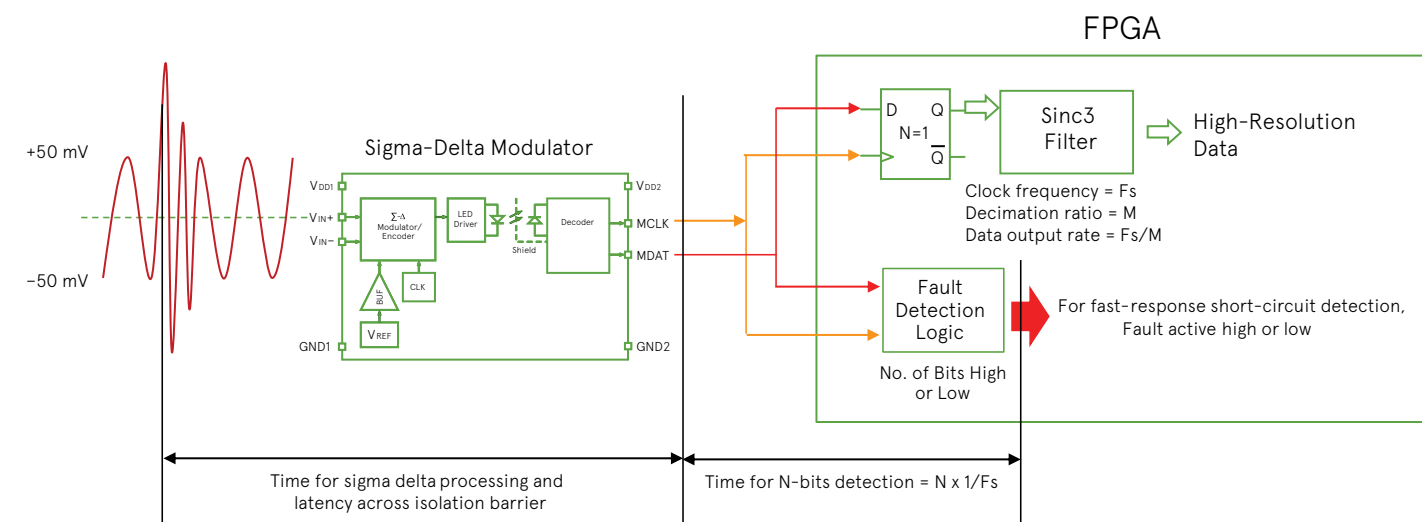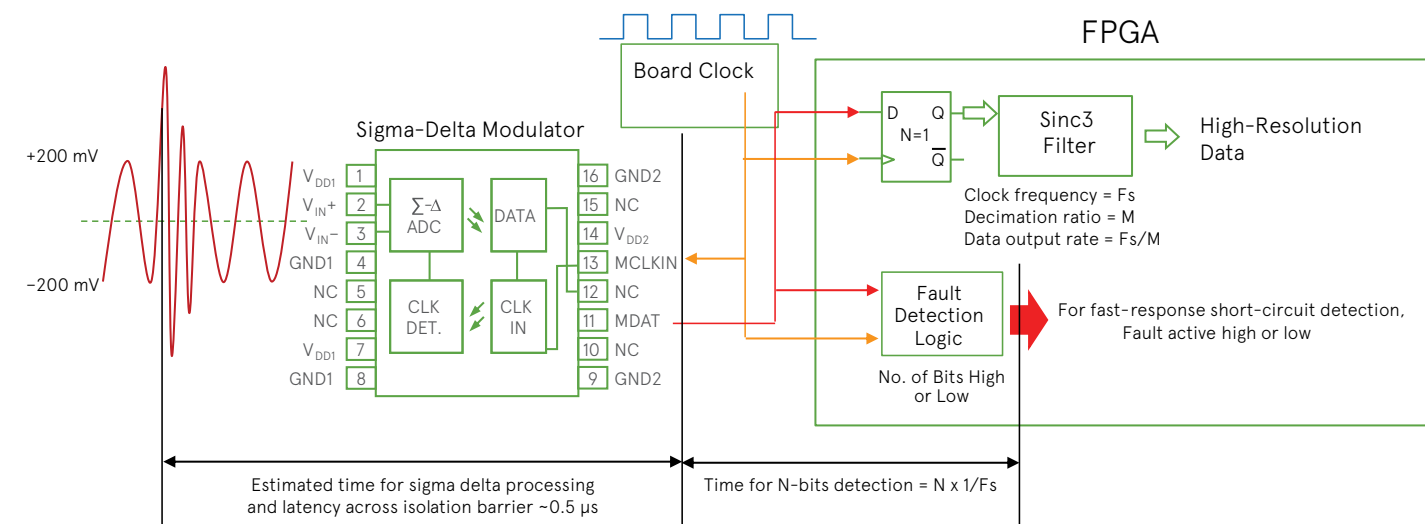

Figure 4 - Output Data of an ACPL-C799 Connected to Separate Paths Inside the FPGA (For High-Resolution Conversion and Fast Response Detection)

Fault detection logic can be easily implemented in an FPGA or microcontroller. One method is to implement an N array of D-type flip-flops. The outputs of the N number of flip-flops are connected to an AND gate for N-bits high detection and to a NOR gate for N-bits low detection. When the first bit of a stream of continuous high or low bits reaches the last flip-flop (n=N), the AND gate output turns logic high for continuous N-bits logic 1 (high). Similarly, the NOR gate output goes high when continuous N-bits logic 0 (low) are detected. This provides fault feedback to the microcontroller. Figure 5 shows the fault detection logic for continuous 20-bits high and Figure 6 shows continuous 20-bits low. To demonstrate this, a fault detection logic block was implemented in the ACPL-C799 Xilinx FPGA evaluation board (as shown in Figure 7) and actual response time was measured.
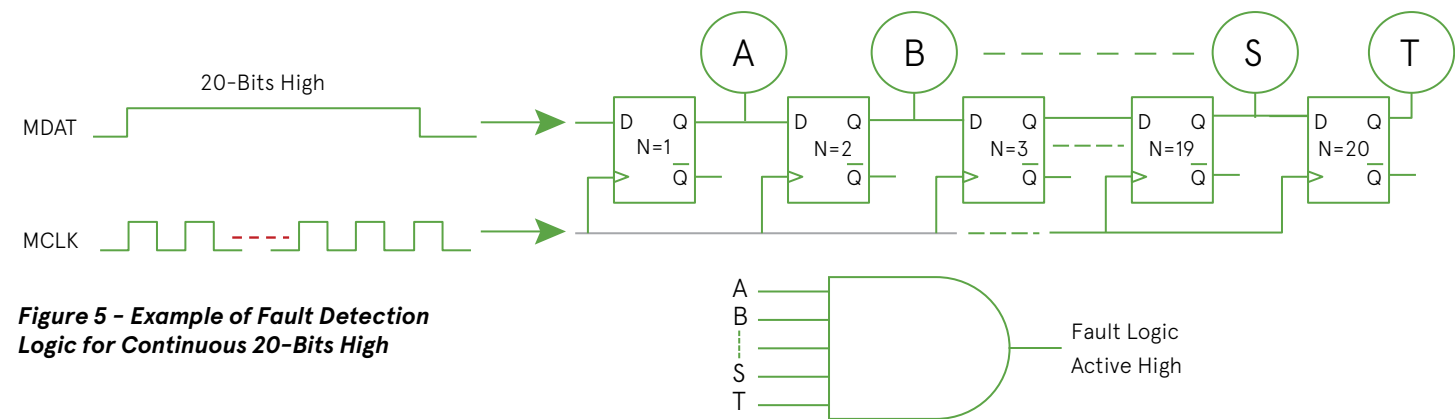

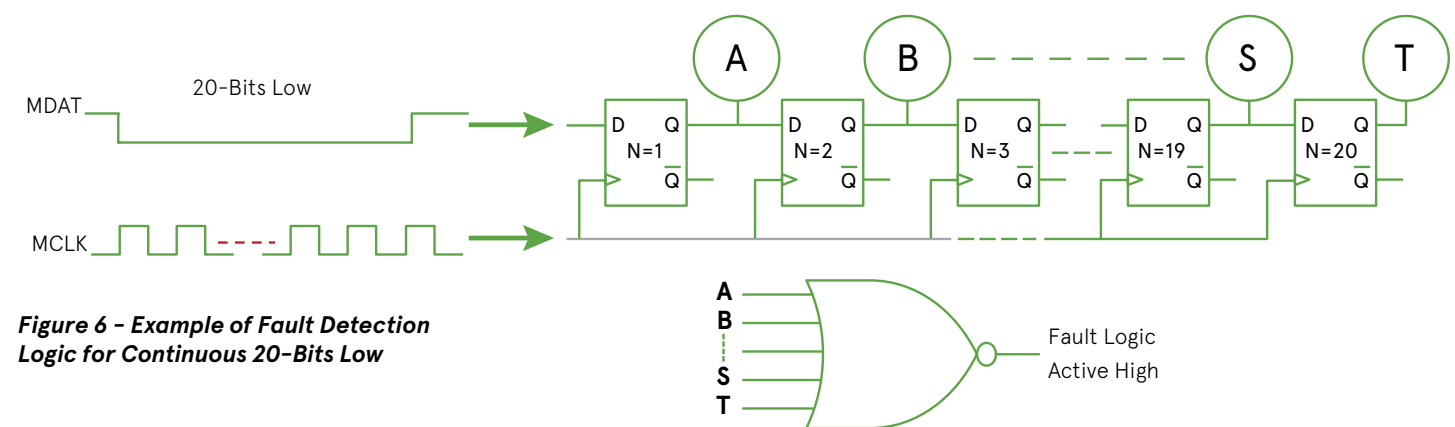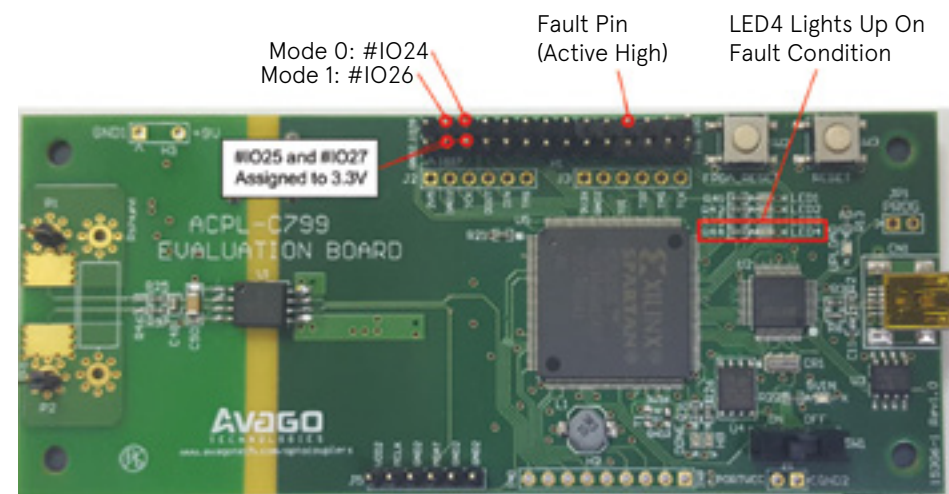*Figure 5 – Example of Fault Detection Logic for Continuous 20-Bits High*

Figure 6 – Example of Fault Detection Logic for Continuous 20-Bits Low

Mode (1:0)	Fault Detection
01	10-bits continuous low or high
10	15-bits continuous low or high
11	20-bits continuous low or high

Figure 7 – Over-Current Fault Detection Implemented on the ACPL-C799 Xilinx FPGA Evaluation Board

Figure 8 – Measured Response Time for 20b High Detection on the ACPL-C799

Device	Continuous N-Bits High or Low	Input Voltage Corresponding to Continuous N-Bits High or Low	Suggested Normal Input Operating Range	Clock Frequency	Measured Response Time
ACPL-796J	5 bits	±100 mV	±50 mV	20 MHz	773 ns
	10 bits	±205 mV	±100 mV		1.01 µs
	15 bits	±240 mV	±200 mV		1.36 µs
	20 bits	±270 mV	±200 mV		1.54 µs
ACPL-C799	10 bits	±47 mV	±30 mV	10 MHz	1.39 µs
	15 bits	±57 mV	±40 mV		2.02 µs
	20 bits	±63 mV	±50 mV		2.52 µs

For the ACPL-796J, a further reduction of response time to sub-1 µs can be achieved if the input voltage range of the sigmadelta modulator is optimized to ±50 mV. When an over-current event occurs, the input voltage level goes beyond ±100 mV and corresponds to 5-bits continuously high or low at the sigma-delta output.

For the ACPL-C799, a further reduction of response time can be achieved if 15-bit or 10-bit detection is used. However, a smaller input operating range results in a lower signal-to-noise ratio (SNR) during normal operation. Table 2 shows various configurations of N-bit detection versus response time and the suggested normal operating input range.

Table 2 – N-Bits Detection vs. Response Time and Suggested Normal Operating Input Range

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C799

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CONCLUSION

Fast shutdown of the motor control system during an over-current event prevents catastrophic damage to the expensive power semiconductor switching devices. Optically coupled sigma-delta modulators not only provide high-resolution current measurement with proven and reliable fail-safe isolation protection, but additional fast-response over-current fault detection functionality can be easily implemented by feeding the single-bit stream output data directly to a simple bit-stream detection circuitry. This can be accomplished without even having to change hardware configuration or increase component count.

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