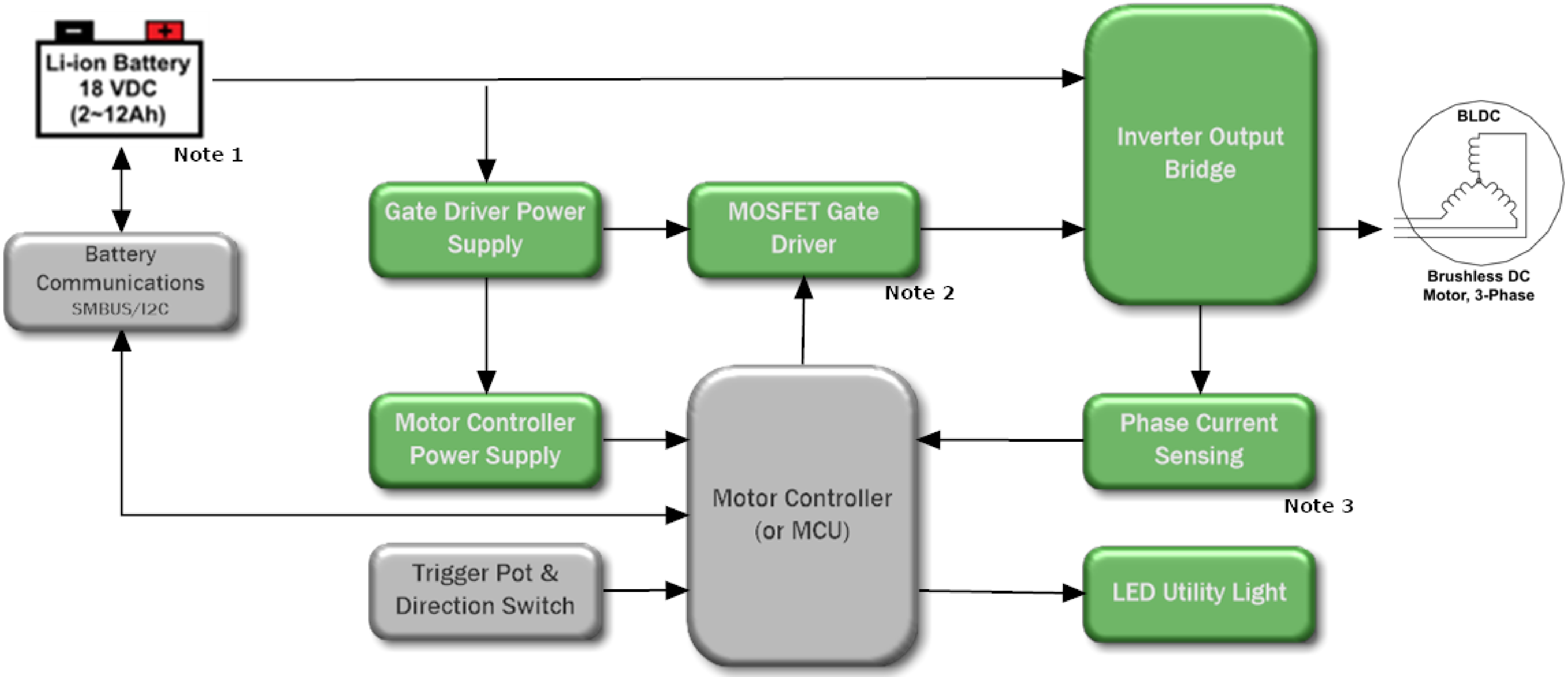
Cordless Power Tool Block Diagram



Solution Description

Product Recommendation Table

Notes:

1) Battery style is Smart Battery (w/internal protections: thermal, overload, charging, etc.)

2) Tool designers require small footprint (DFN) 3-phase gate drivers with minimal features. There is a desire to see gate drivers that do not require external gate resistors.

3) Current sensing with triple low-side shunts is the least expensive solution. Some tool makers use op amps integrated into the MCU package.

Greetings and welcome to another edition of the Block Diagram of the Month. Each month we provide a specific application solution with recommended ON Semiconductor content from various business units. This month we look at the next generation of battery-powered tools utilizing field-oriented control (FOC) techniques.

Cordless Power Tool (Generic Diagram)

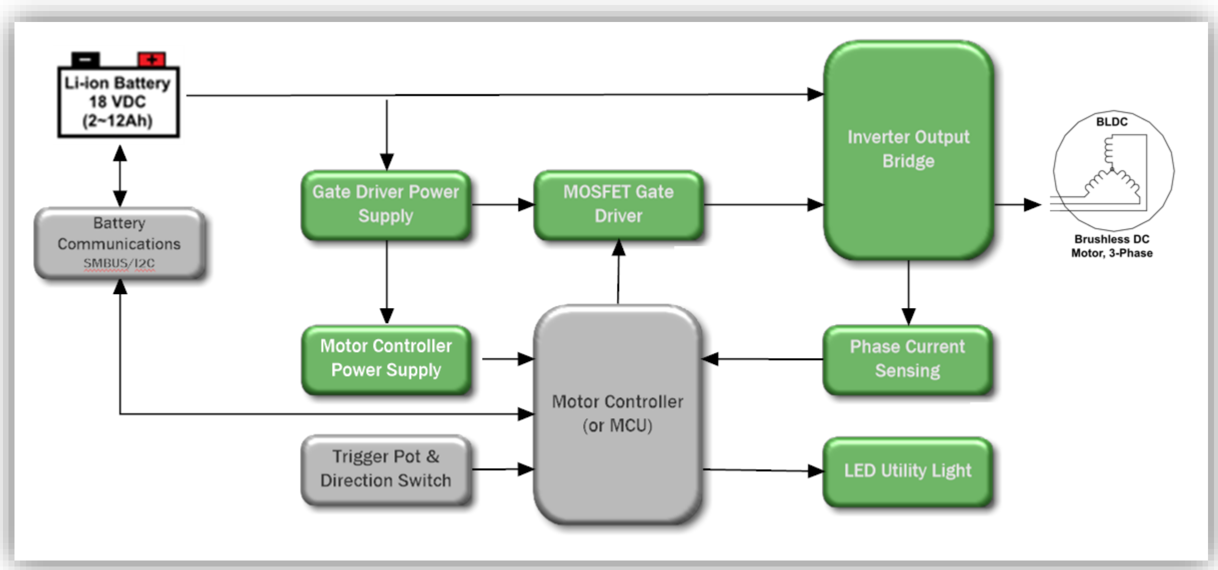
Handheld cordless power tools have finally displaced many of yesteryear's corded tools. In fact, most tool makers have already preplanned the demise of their corded offerings. The time when tool manufacturers balked at the idea of ever using a brushless DC (BLDC) motor has long passed. Modern power electronics has made it possible for tools to be convenient, small, powerful and loaded with advanced features.

Historically, cordless tools were based on simple, low-cost permanent magnet DC (PMDC) motors. These motors required only the simplest electronics - one MOSFET and a timer - to enable their variable speed operation. About 10 years ago, the serious transition from PMDC to BLDC motors was well underway in tool designs. These BLDC tools were based on a trapezoidal modulation scheme that could be easily programmed into low-cost microcontrollers. Today, this is how nearly all BLDC tools operate. The transition to BLDC motors was a push for increased reliability, marketability and other factors.

Trapezoidal control offers reliable, basic performance at a low cost of entry. Increases in microcontroller computing capacity and advanced control algorithm development have brought solutions to the market that were not previously cost-viable. FOC, also known as vector control, requires tremendously more computational capability than the dominant trapezoidal methods. In trade for that effort, however, it is possible to design a tool with improved speed and torque capabilities for virtually the same raw material cost.

In this block diagram, we describe a generic sensorless FOC-based cordless power tool. Why generic? Good question…

Common cordless tools include drills, drivers, impact drivers, ratchets, cut-off tools, jigsaws, circular saws, reciprocating saws, sanders, angle grinders, multitools and more. Each of these tools has a different operating profile from the motor control's perspective. Trying to describe the next generation diagrams for each of these tools would be quite difficult to do in a concise manner. This block diagram and description reasonably represent the basis for the circuitry in these tools enough to allow the reader to have informed conversations about the topic. A state-of-the-art cordless tool has the following design blocks:



- Battery
- Gate Driver Power Supply
- Motor Controller Power Supply
- Inverter Output Bridge
- MOSFET Gate Drivers
- Phase Current Sensing
- Motor Controller (ASSP, MCU, or DSP)
- LED Utility Light
- Battery Communications

Why do we care? Because the typical FOC tool/battery designer want to give us money for these:

- Battery Management Electronics – Coulomb Meter/Charging Controller, MOSFETs, Op Amps and Temperature Sensing
- Low-Voltage, High-Current N-MOSFETs (Six)
- Gate Drivers (Six Singles, Three Half-Bridges, or One 3-phase Driver)
- LV DC-DC Integrated Controller and LDO
- Op Amps (One to three. They are sometimes integrated into the microcontroller.)
- Low-Voltage, Low-Current N-MOSFET (One for the utility light.)
- Motor Controller IC (One. Could be MCU, DSP, ASSP, etc.)

Advanced tool features may expand this list to include:

- Bluetooth or Other Wireless Radios (Anti-theft, configuration or reporting)
- NFC EEPROM (Anti-theft or stats needs.)
- Accelerometers (Tool operator safety needs)

Battery

Cordless tools get their energy from batteries, or more accurately battery packs ranging from two to 12 Ah capacity. Battery packs are containers with multiple battery cells and some sensors or electronics to facilitate their safe and reliable operation. It's often somewhat of a tool design philosophy as to how much electronics are designed into a given manufacturer's battery pack. Some tool companies see their role as a "tool maker," who also sells batteries; while others view themselves as "battery makers," who just happen to sell tools. The trend is to be "battery makers."

A "dumb" battery may have only the cells and a single thermistor to assess the pack's overall temperature during charging or tool operation. These are the least expensive packs to manufacture; but also offer the least protection to the pack, tool and operator.

A somewhat intelligent battery may have cells, thermal sensing, over-charging protection, over-current protection and perhaps some performance statistics that assist the charger or tool in properly utilizing the battery. They will also protect the battery from damaging excessive discharge.

A "smart" battery will have the ability to not only protect and monitor the battery, but also to virtually control the charger's current profile moment-by-moment to ensure that optimal voltages and currents are observed for the safe charging of the battery. This technology allows batteries of multiple chemistries and structures to be properly charged using the same generic charger. These packs are sophisticated and expensive; but offer premium reliability, charging, and safety to the user.

Intelligent batteries can also include wireless technology for geo-location theft protection. In these packs, wireless communications circuits can disable batteries if they cannot connect to a pre-configured, on-site device - like the tool owner's cell phone.

Consumers typically buy more than one battery for each tool they purchase. This fact, combined with the increased pack power density safety concerns, is driving the market toward smarter batteries. The components and technologies used in these batteries is beyond the scope of this block diagram; but should not be ignored as it represents a tremendous amount of power silicon usage.

Gate Driver Power Supply

The purpose of this supply is to efficiently reduce the variable battery voltage to a more consistent and reasonable voltage for controlling the inverter output bridge MOSFETs, typically about 10 VDC. This output is applied directly to the MOSFET gate drivers. It is their responsibility to use this supply to switch the MOSFETs on and off. Most often, this supply is implemented as a low-voltage DC-to-DC buck topology to improve efficiency. This supply is also used as the input to the controller power supply described next.

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Some tool designs use this supply to also power their LED Utility Light described below. This produces a more consistent LED brightness during actual high-current tool operation and over the charge range of the battery.

Controller Power Supply

This supply typically takes output from the gate drive power supply and reduces it to a level that is more compatible with microcontrollers, DSPs, etc. The sweet spot for these devices is usually 3.3 or 5.0 VDC. Because the current levels for this supply are quite low, it is common for an inexpensive low-dropout regulator (LDO) to be used. This supply is responsible for powering the motor controller section of the tool, and may also be used to power the op amps and trigger circuit.

LED Utility Light

Most modern cordless power tools have some sort of built-in LED light that illuminates the area where the work is being done. This is probably the simplest section of the tool. It is typically a single LED, powered either directly from the battery or from one of the two power supplies. Although low-cost tools may use the trigger switch to directly switch power to the LED on/off, quality tools often control this LED from the motor controller via a low-voltage N-MOSFET. This has the noteworthy benefit of allowing the LED to remain illuminated after the tool trigger is released, making it easier to position the tool against the workpiece while it is not in motion.

MOSFET Gate Drivers

In cordless tools, the MOSFET gate drivers most commonly drive N-channel MOSFETs. Gate drivers are synonymous with power steering for MOSFETs. They take the low-voltage, low-current outputs of the motor controller and translate them into higher-voltage, higher-current drive signals to the MOSFET. Power tools have limited internal volume for electronics. For this reason, tool makers prefer small-packaged gate drivers in QFN and DFN.

Inverter Output Bridge

The tool's output bridge in a 3-phase BLDC motor control consists of six N-MOSFETs. This is where the magic occurs. The bridge is responsible for efficiently conducting the batteries energy to the motor windings according to the motor controller's instructions. In an 18 VDC cordless tool, these might be 40 V MOSFETs with ultra-low $R_{DS(on)}$ values below 1mohm in a DFN package. Smaller MOSFETs can be moved closer to the air stream for cooling, and the more efficient they are, the less cooling that is required.

Selecting the optimal MOSFET is a complex process requiring careful evaluation of tool's operating modes, peak stall currents and times, thermal cooling efficiency and reliability, and user comfort. User comfort? Yes, no one wants to hold a tool with a handle so hot that gloves are required. Not all tools can be easily cooled internally.

ON Semiconductor has one of the largest offerings of high-performance, low-voltage MOSFETs in the industry. We offer 40V N-MOSFETs with $R_{DS(on)}$ values below 0.5 mohm in tiny packages.

Phase Current Sensing

Depending on the tool performance requirements and cost trade-offs, phase current sensing can be either one, two, or three channels of sensing. The actual sensing can occur via shunt resistors below the low-side MOSFETs in the inverter output bridge or at the motor winding connections. Shunt resistor sensing is more cost effective, but it does not provide the same quality of information back to the controller. In a sensorless FOC drive, the quality of the current sensing measurements is critical as so much calculation and estimation is based on it to properly spin the motor.

Some FOC designs use a combination of a single physical hall sensor to measure the stator's position and current sensing to produce a more accurate, low-cost stator position estimate. The ultimate decision will depend heavily on the exact type of tool being designed and its target performance; 8 to 10 MHz GBW op amps are common in these applications. They are sometimes integral to the motor controller IC.

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Motor Controller

The Motor Controller manages the tool's operation and is responsible for deciding how energy is conducted from the battery pack to the motor. The controller's firmware is typically designed to precisely control the motor with constant speed, torque, power, or some combination at different operating points.

In an FOC-based tool, the controller must perform an immense amount of mathematical operations per seconds to ensure seamless tool operation. The higher the pole count and peak operating RPM of the motor, the more computation that may be required. FOC algorithms can use either sensors that physically measure the mechanical relationship between the motor's rotor and stator or they can be implemented as sensorless algorithms using additional computation bandwidth to estimate the stator's position from the phase current measurements. As expected, this takes even more MCU capability. The goal here is to save money on the Hall sensors and invest some of that savings in an enhanced controller IC, hoping that the associated loss in stator measurement precision will be tolerable.

ON Semiconductor has multiple controller products in development that are specifically focused on high-performance motor control algorithms. These devices also have integral Gate Drivers, Op Amps, an LDO, and Synchronous Serial Comms (I2C or similar) planned.

Battery Communications

The Motor Controller facilitates some level of communications with the battery pack, depending on the sophistication of the pack itself. For less intelligent batteries, the only communication might be reading the battery's internal temperature sensor, often a thermistor. For more complex packs, single wire schemes, I2C, or SMBus (similar to I2C) are often used to acquire information from the pack: e.g. temperature, charge cycle count, battery health, charge level, etc.

This information can be critical to the reliability and safety of the tool and battery pack. It is also possible to use this link to exchange security information between the tool and battery to prevent stolen batteries from being used. Chargers for intelligent batteries, separate from the tool, use the same communications bus to exchange different information between the charger and battery to ensure optimal and safe charging occurs.

Next Steps

ON Semiconductor has a long history as a leader in the development of power semiconductors for motor control applications for Appliance, Consumer, and Industrial applications. We offer industry leading MOSFETs, Gate Drivers, Power Supply Solutions, Op Amps, and more tailored for Cordless Power Tools. Samples, evaluation boards, design guides, whitepapers, calculators, and development tools are available. Our FAEs and Motor Specialists can assist in your selection of the optimal parts for your next tool design.

Suggested Block	Opt.	Qty.	WPN	Why Select?	WPN Description
Gate Driver Power Supply	1	1	NCP715	24V capable in small package.	LDO Regulator, 50 mA, Ultra-Low Iq
Gate Driver Power Supply	2	1	NCP781	150V capable in small package.	Linear Voltage Regulator, 100 mA, 150 V, High PSRR
MOSFET Gate Driver	1	3	NCP81080	200V capable driver in 2x2 DFN package	High Side and Low Side Gate Driver, High-Frequency, 180V offering 0.5A source/0.8A capability
MOSFET Gate Driver	2	1	FAN7888	200V Integrated Drivers in small package	225V, 3.3/5V input logic compatible, 0.65/0.35A sink/source current, 3-Phase Half-Bridge Gate-Drive IC
MOSFET Gate Driver	3	1	LV8359	Coming 1H'21: 60V integrated Driver in QFN package.	Coming 1H'21: 3 Phase Integrated Half Bridge Driver for Power Tools.
Inverter Output Bridge	1	6	NTMFS4C020N	High Peak current and low Rds ON	Single N−Channel Power MOSFET 30 V, 303A, 0.9mΩ
Inverter Output Bridge	2	6	NTMFS4C302N	Best Avalanche current spec.	Single N−Channel Logic Level Power MOSFET, 30 V, 230 A, 1.15 mΩ
Inverter Output Bridge	3	6	NTMFS4C022N	Low cost FET in 5X6 package.	Power MOSFET 30V 136A 1.7 mOhm Single N−Channel SO−8FL
Inverter Output Bridge	4	6	NTMFS5C410N	High Peak current and low Rds ON	Single N-Channel Power MOSFET 40V, 300A, 0.92mΩ
Inverter Output Bridge	5	6	NTMFS5C426N	Medium cost FET in 5x6 package.	Single N-Channel Power MOSFET 40V, 235A, 1.3mΩ
Inverter Output Bridge	6	6	NTMFS6H800N	Low Rds ON Medium Voltage FET in 5x6 package.	Single N-Channel Power MOSFET 80V, 203A, 2.1mΩ
Inverter Output Bridge	7	6	NTMFS6H801N	Low Rds ON Medium Voltage FET in 5x6 package.	Single N-Channel Power MOSFET 80V, 153A, 2.8mΩ
Inverter Output Bridge	8	6	FDMS86180	Low Qrr Medium voltage FET.	N-Channel Shielded Gate PowerTrench® MOSFET 100V, 151A, 3.2mΩ
Inverter Output Bridge	9	6	FDMS86181	Low Qrr Medium voltage FET.	N-Channel Shielded Gate PowerTrench® MOSFET 100V, 124A, 4.2mΩ
Motor Controller Power Supply	1	1	NCP715	24V capable in small package.	LDO Regulator, 50 mA, Ultra-Low Iq
Motor Controller Power Supply	2	1	NCP781	150V capable in small package.	Linear Voltage Regulator, 100 mA, 150 V, High PSRR
Phase Current Sensing	1	1 to 3	NCS20071	Or NCS20072/4 depending on package needs.	Operational Amplifier, Wide supply range, 3Mhz CMOS Op-Amp
Phase Current Sensing	2	1 to 3	NCS20166	Coming soon: 10MHz opamp with low offset voltage	Coming soon: Rail to Rail Precision opamp with 10MHz GBWP
LED Utility Light	1	1	2N7002	Low cost.	N-Channel Enhancement Mode Field Effect Transistor 60V, 0.115A, 7.5Ω
LED Utility Light	2	1	NSI45090JD	2 Pin Constant current driver.	45V and 90m A Constant current regulator for LED Driver.
LED Utility Light	3	1	NSIC2020JB	2 Pin Constant current driver.	120V and 20m A Constant current regulator for LED Driver.
Smart Battery Pack - Not detailed in block diagram					
Smart Battery Pack	1	1	NCS35010	Coming 1H'21: Low cost and meet basic requirement.	Coming 1H'21: Battery Protection IC with OVP,UVP, cell balancing and charge Indicator
Smart Battery Pack	1	1	NCS35020	Coming 1H'21: Integrated FET Driver and low standby Power.	Coming 1H'21: Smart Battery Protection IC with OVP,UVP,Cell balancing with Charge and Discharge functions
Smart Battery Pack	1	1	RSL10	Low power consumption in standby and sleep mode.	Radio SoC, Bluetooth® 5 Certified, SDK 3.3

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