

TOSHIBA

Cordless Power Tools: Delivering
High Output Power, Extended
Operation and Smaller Form Factors



Cordless Power Tools: Delivering High Output Power, Extended Operation and Smaller Form Factors

Ease-of-use, portability and enhanced safety are driving the growth of cordless power tools by both professional and 'do-it-yourself' communities. Manufacturers of these tools are under pressure to continually lower the weight and size of these tools. They are also looking to extend operational life from a single battery charge and ensure reliable operation in a variety of use cases over many years. Advanced lithium-ion batteries can play a role in meeting these requirements, but are only one part of the story. Correct selection of power semiconductors is also a vital in designing a successful product.

This whitepaper looks at the challenges facing the developers of next-generation cordless power tools and identifies how the latest advances in power MOSFET technologies can help address these challenges in key functional blocks ranging from battery charging to motor control.

Introduction

Ease-of-use, efficiency and convenience are just some of the reasons that both professional tradespeople and "DIYers" are increasingly using power tools. In fact, sales of power tools are fast outpacing sales of hand tools as more consumers take on small tasks themselves.

According to research firm Future Market Insights, the power tools market was worth US\$27.58 billion in 2015 and will reach US\$46.47 billion by 2025. North America, Western Europe and Asia-Pacific account for over 70% of these figures.

The significant resurgence in the housing market and rapidly expanding infrastructure in developing countries is driving greater demand among professional users. Yet, DIY is becoming more popular globally, and especially in the developing world where rising incomes and increasing urbanisation are swelling the ranks of property-owning DIYers.

For many reasons, not least convenience, portability and safety, there is a strong shift from mains-powered corded power tools to cordless equivalents. Improvements in battery technology have enabled a large part of this growth. Older Ni-Cd technology is rapidly being replaced by Li-Ion, enhancing weight, operational life and efficiency of modern cordless power tools.

Motor options

The motor is pivotal to every cordless power tool, converting the electrical energy from the battery into movement that performs the task that the tool is dedicated to. By definition, all cordless power tools use some form of DC motor. These motors allow speed to be controlled over a wide range and offer a high starting torque - key attributes for cordless power tools. However, there are multiple options available, each with different advantages and performance parameters.

Brushed motors are the oldest form of DC motor and have been around for a long time. Simple brushed motors comprise an armature (rotor), commutator, brushes, spindle and permanent magnets. Current travels through the brushes, which are electrically and physically in contact with the commutator. The essential magnetic field is created by the current passing through the armature.

The permanent magnets that surround the armature interact with the armature-generated fields, thereby causing the armature to rotate around the spindle. If greater current is applied, stronger magnetic fields are created in the armature, increasing the magnetic interaction forces, thereby increasing rotational speed.

Another option is Brushless DC (BLDC) motors. As the name suggests, BLDC motors have no brushes, removing a wear-out mechanism as well as any frictional energy losses. Permanent magnets are located on the brushless rotor with the armature's electromagnetic coils in fixed positions surrounding it.

In a brushed motor, the commutator reverses the current flow through the armature coils, flipping the magnetic fields so that the rotor continues to spin. In a brushless motor, an electronic control switches the phase of current through the armature windings at precise timings to accomplish the rotational response.

In general BLDC motors cost more than brushed motors and are more complex to control. On the positive side they offer a longer, low-maintenance lifetime, and they are typically more powerful than a similarly sized brushed motor.

Key building blocks of cordless power tools

While different manufacturers each have their own approach to designing cordless power tools, the fundamentals of the power train between the power source and the motor are very similar.

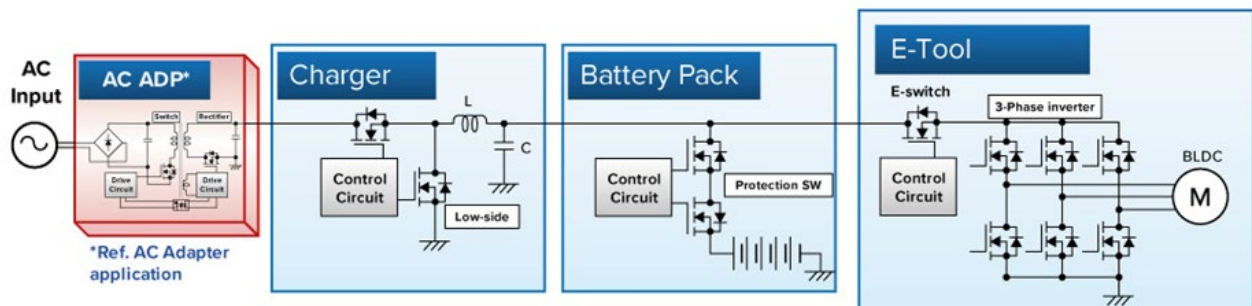


Figure 1: Most cordless power tools have a similar fundamental layout

All cordless devices, including power tools, need to be recharged at some point. In almost all cases this is from AC mains power, although other options such as solar recharging are possible. In most cordless power tools, the battery pack can be detached from the tool to allow long-term continuous working. Each exhausted battery is plugged into a charger that is often separate from the tool itself.

The charging station will normally take its power from the mains; the front-end is an AC adapter that rectifies and conditions the AC mains. The power then flows to a charger circuit that charges the battery. Because the type and size of battery to be charged is known so the charger can be highly optimized.

Battery packs themselves are becoming increasingly sophisticated and now hold significant amounts of energy. Alongside multiple compact cells they incorporate control and protection circuitry, ensuring safe and consistent delivery of power to the tool.

The tool contains the motor drive circuitry, which comprises a control circuit and discrete semiconductors that form a 3-phase inverter. This inverter creates the interleaved power signals for correctly driving the BLDC motor.

Challenges facing designers

With cordless power tools, designers face a number of challenges; many of these interact and, in some cases, compete with each other.

One challenge, for example, is ergonomics as this defines the form factor of the tool. As the tools are often used for long periods user comfort and convenience is fundamental key to the success of a product in the market. The shape is important, as this is the tactile interface with the user; it also defines the available room for the motor and other electronics. Features such as the ability to use a tool either right- or left-handed can sometimes constrain the space available for the technology or define where certain switches have to be placed on the device.

Weight is another key criterion and this drives design decisions about the motor technology (BLDC is lighter), battery and housing. Users now expecting important information such as battery life indication, or inbuilt LED lights, which make working in dark, cramped spaces easier. All of these require additional circuitry and consume battery power.

The battery itself is one of the biggest and most obvious trade-offs. With users wanting lighter, more convenient tools and also extended operational lifetimes, designers are faced with finding the 'sweet spot' that balances these two competing requirements. One solution is to offer a range of battery sizes and capacities for the tool. The real answer lies in selecting the battery technology with the most energy per unit weight, and ensuring that all aspects of the design are as efficient as possible so as not to waste energy.

Despite their value to the user, tools often have a tough life. Even in normal use, the nature of the work means that they will endure both mechanical and electrical stresses and peaks. Particularly tight nuts or a jamming drill will demand peaks of current to deliver the requisite torque. Yet, control and protection circuitry must ensure that the battery does not deliver so much instantaneous power that the electronics or motor are damaged.

Tools will inevitably be used in harsh environments; dust, dirt and damp are just some of the hazards they will face. Temperature is another. Not only may the tool be required to operate in a high ambient temperature but it is, itself, a source of heat. Improving efficiency allows the tool to run cooler and, therefore, work at higher ambient temperatures.

Finally, there is little more frustrating than a tool that is not working. It could mean that a critical safety job is delayed, or that the contractor loses money by using less efficient methods to complete the job another way. One thing is always true: a failed tool will damage the reputation of the manufacturer, meaning that reliability and robustness are high on the agenda of all cordless power tool designers.

Addressing the efficiency challenges

Obtaining the most usable energy from the battery and then processing that energy as efficiently as possible are two critical challenges for the tool designer.

Batteries have advanced significantly in recent years and will continue to do so. In general, voltages are increasing with the older 12V and 14.4V solutions being replaced with batteries in the 18V to 21V category. More recently, we have seen a growth in 36V options. These give the ability to deliver more power rapidly and are popular in larger items such as garden tools and professional-grade hand tools.

The basic battery technology has moved from NiCd through NiMH to Li-Ion. While NiCd was inconvenient as it had to be discharged fully before charging (the so-called 'memory effect') it is a robust technology and many batteries remain in use. NiCd was superseded by NiMH - this could be charged at any point in the discharge cycle and also offered higher ampere-hour capacities.

Almost all tools on sale today have Li-Ion based batteries. This technology also has no memory effect and can be topped up as needed. The big advantage of Li-Ion is that it typically weighs 40% less than the equivalent NiMH battery.

Designers are challenged to ensure that cordless power tools operate at the highest possible efficiency to make best use of the available battery power. This impacts all aspects of the electronic design, but the key switching elements - the

MOSFETs - have the biggest impact. By selecting the right power conversion topology and selecting the optimum MOSFET, designers have an opportunity to create winning products.

Referring back to Figure 1 above, each of the key building blocks rely on MOSFET technology for converting and processing the energy. Firstly converting the mains power to charge the battery and then delivering that stored energy in the most efficient way possible to the motor through the MOSFET-based inverter circuit.

Advanced MOSFET Technologies meet the power tool challenge

For success in demanding power applications - especially in compact battery powered equipment - modern power MOSFETs need to offer low loss levels in a small convenient package.

One of the more recent technologies specifically aimed at meeting the challenging needs of cordless power tool design is the trench LV MOSFETs from Toshiba. The Company's U-MOS VIII MOSFET technology, for example, offers a 30-250V class MOSFET series that boasts a broad product line up with a wide voltage range. U-MOS IX technology supports 30-60V class MOSFETs with some of the lowest on- resistance values on the market. Within the U-MOS IX series, the 3mm x 3mm 40V package has $R_{DS(ON)max}$ values as low as 2.3m Ω , while the 5mm x 6mm 40V package drops RDS(ON)max values to 0.85m Ω .

In developing this technology, Toshiba has focused on three main parameters that affect the losses in power switching applications; Gate charge (Q_g), On-Resistance ($R_{DS(ON)}$) and Recovery charge (Q_{rr} - sometimes Q_{oss}/E_{oss}). The gate charge and recovery charge are discharged during every switching cycle and therefore have the greatest impact in the fastest switching devices. The on-resistance is sometimes known as the conduction loss because the resistance generates waste heat while the MOSFET is conducting current.

As can be seen from the table below, the U-MOS range offers various different performance levels and combinations of these critical parameters, allowing designers to select the most appropriate for their particular application.

◎ excellent fit, ○ good fit, △ fair fit

Characteristics		Q_g (Q_{sw})	$R_{DS(ON)}$	Q_{rr} (Q_{oss}/E_{oss})	Voltage Lineup
Influence		Switching speed	Conduction loss	Recovery charge	
U-MOS for Low voltage (20V-250V)	U-MOS IX-H	◎	◎	◎	30V-60V
	U-MOS VIII-H	◎	○	○	30V-250V
	U-MOS VII-H	△	△	○	20V-30V

Figure 2: The U-MOS range offers various combinations of performance parameters

Each of these advances has been achieved through specific, targeted developments. The relationship between Q_g and $R_{DS(ON)}$ is important as there is a trade-off between the two parameters, meaning that an improvement in static losses can negatively impact dynamic losses and vice-versa.

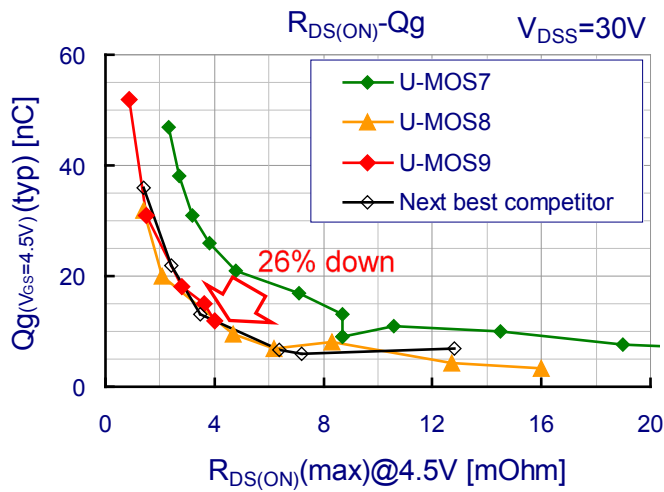
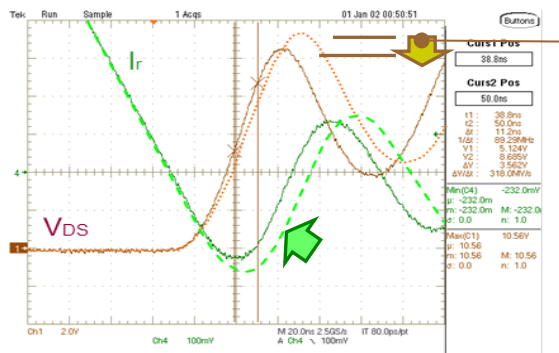
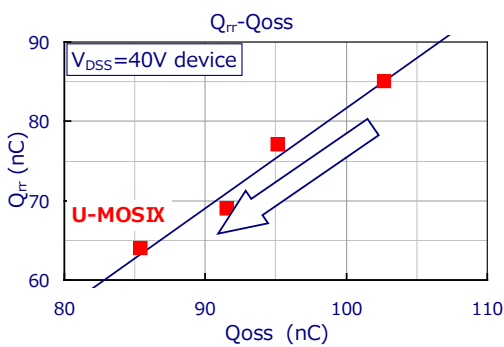


Figure 3: Successive U-MOS generations have shown continued improvement in Q_g vs $R_{DS(ON)}$

Each successive U-MOS generation has improved the trade-off of these key parameters. The latest U-MOS IX (U-MOS 9) shows a 26% improvement in $R_{DS(ON)}$ vs Q_g when compared to the earlier U-MOS VII (U-MOS 7).

The latest U-MOS IX-H achieves reduced recovery loss through tuning of the Q_{oss} parameter, which directly affects the all-important recovery charge. Recovery charge effects not only loss, but also EMI, and sometimes leads to current monitoring error.



V_{DS}

Figure 4: Recovery charge (Q_{rr}) against Q_{oss} for a 40V device

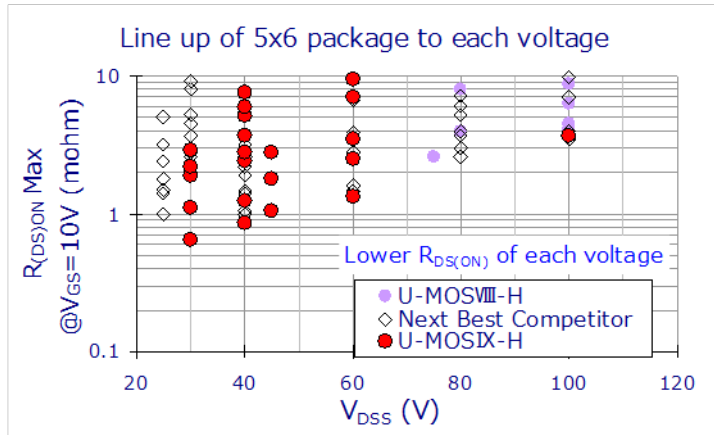


Figure 5: $R_{DS(on)}$ MAX against V_{DS} for U-MOS IX devices

From the chart, it can be seen that U-MOS IX is a market-leading device in terms of $R_{DS(on)}$. The range will be further broadened with the future introduction of 100V and 80V devices.

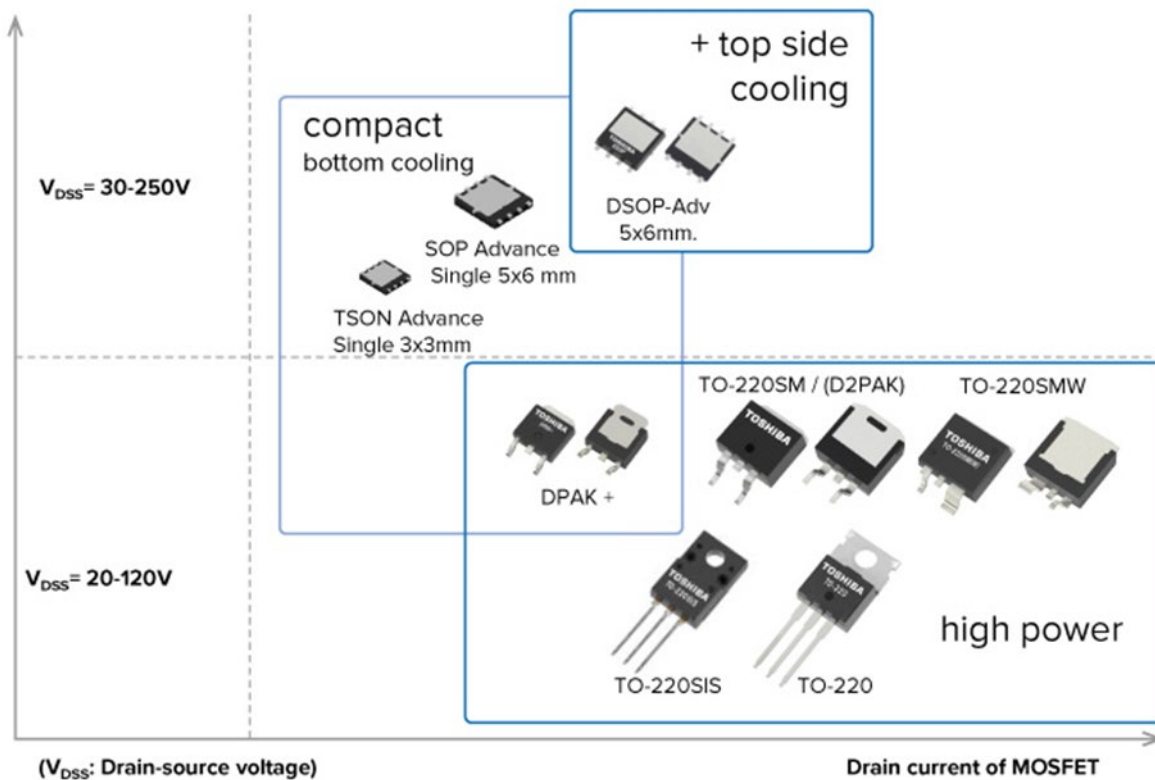


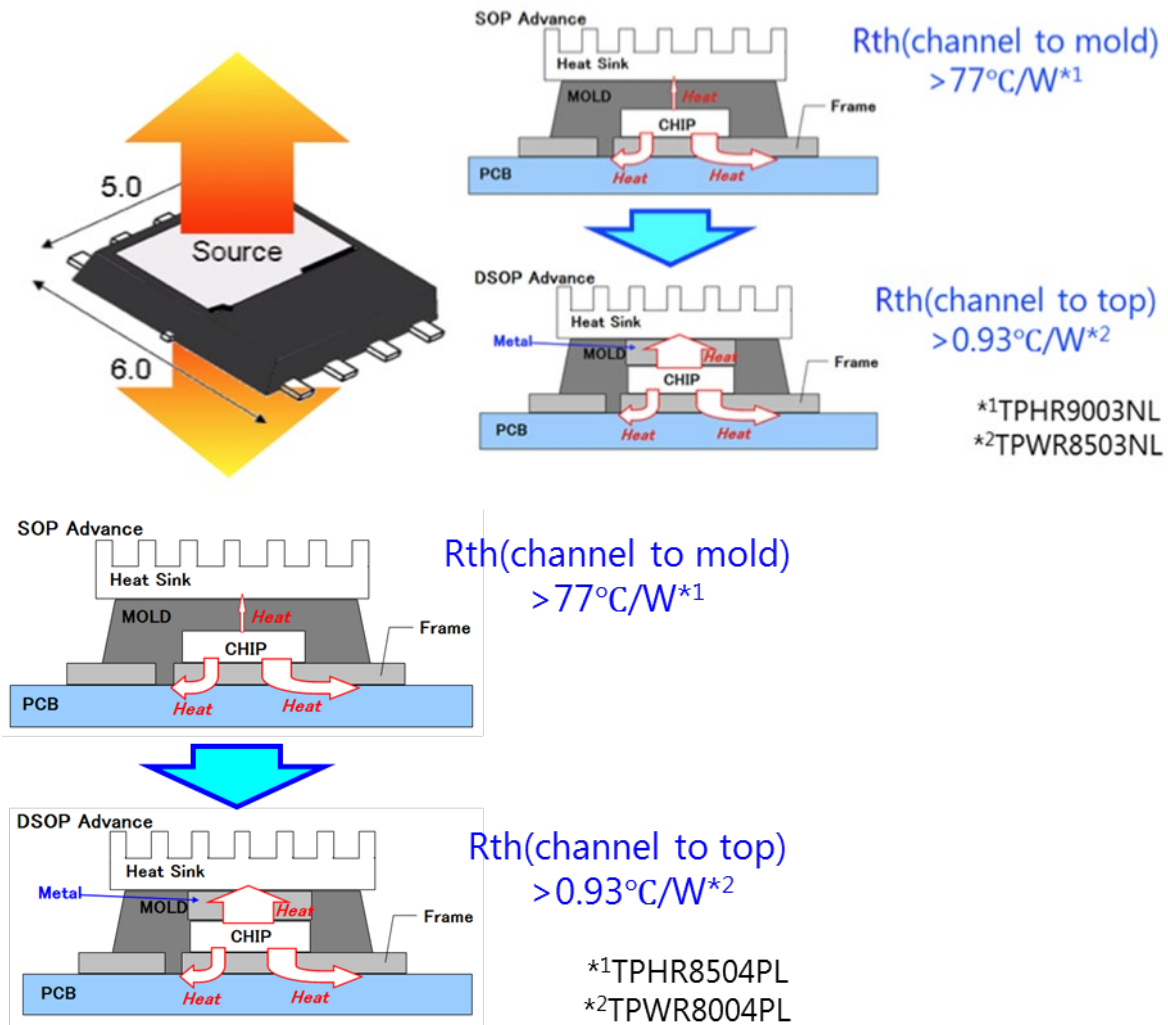
Figure 6: Toshiba LV-MOSFET range offers multiple package types

In enclosed applications, a wide range of available package types is important in order to be able to fit the devices in the available space. Additional cooling features allow heat to be quickly and easily channelled away to the case of the tool and, ultimately, the environment. Toshiba's LV-MOSFET range offers a wide range of packaging. This includes industry-standard package types such as 3mm x 3mm TSON Advance and 5mm x 6mm SOP Advance, which feature underside cooling, and DSOP-advance that offers additional topside cooling.

A further benefit of the wide range of industry-standard packages is the ability to upgrade existing silicon on the same footprint, thereby allowing the latest developments to be deployed in legacy product without the risk of a PCB redesign.

While SOP Advance is considered to be a high-performance package, DSOP advance offers dramatic performance enhancements as the silicon die ('chip') has direct thermal connection to the PCB and heatsink. This allows it to achieve a significant increase in thermal conductivity. Devices in this package are ideally suited to cordless power tools where space and convection cooling is often limited.

The DSOP package is competing with conventional and relatively expensive metal can packages. These require solder joint control by x-ray, whilst a DSOP package a portion of the PIN is exposed. Also, compared to other vendors offering plastic mold solutions with dual sided cooling, the Toshiba DSOP has the advantage of a wider top side connector. This ultimately leads to significantly improved R_{th} to the topside. Therefore it is a simple step for customers to upgrade from the existing concept of 5mm x 6 mm standard items with advanced DSOP solutions.



Characteristic	Max		Unit
	DSOP Advance	Other Competitive	
Top-side thermal resistance, channel to case ($T_c=25\text{deg.C}$)	0.93	2.3	deg.C/W
Bottom-side thermal resistance, channel to case ($T_c=25\text{deg.C}$)	0.88	1.0	deg.C/W

Figure 7: DSOP advance delivers huge gains in thermal conductivity

Within a typical cordless power tool, such as a screwdriver / drill, each of the main building blocks will benefit from the high performance MOSFET technology. Within the charger, MOSFETs act as the high- and low-side switching elements. In the battery pack, MOSFETs provide protection, with the ability to disconnect the battery rapidly in fault conditions. In the tool itself, MOSFETs are used for the E-switch as well as forming the six-element, 3-phase inverter that provides the motor drive.

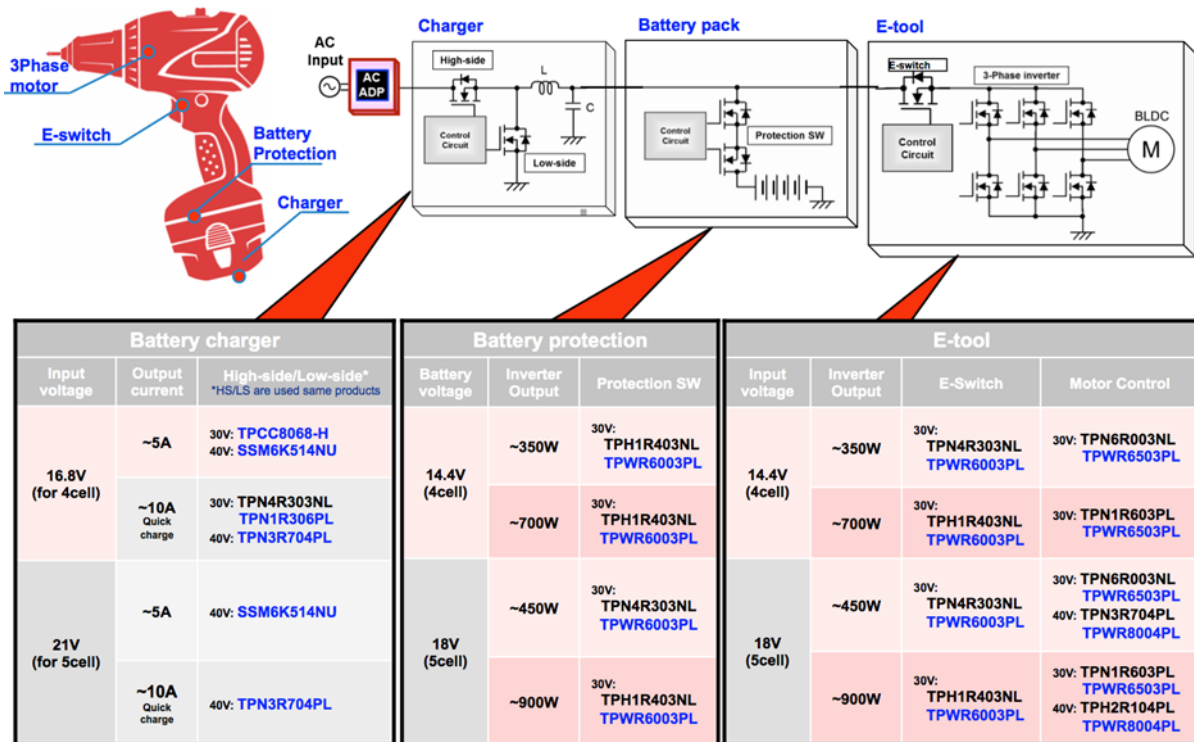


Figure 8: Examples of suitable MOSFETs for the various applications in a typical cordless power tool

As shown above the U-MOS LV-MOSFET range offers numerous options for different battery voltages. The example above is for a tool with four or five battery cells, powering a BLDC motor. The devices in blue offer the ultimate performance for high-end tools while the devices in black offer the best price / performance trade-off and would be very well suited to cordless tools aimed at the DIY market.



Contact us to discuss incorporating
our products and solutions into your
design:
<http://apps.toshiba.de/web/ContactUs/>
toshiba.semicon-storage.com



Restrictions On Product Use

Toshiba Corporation and its subsidiaries and affiliates are collectively referred to as “TOSHIBA”.

Hardware, software and systems described in this document are collectively referred to as “Product”.

- TOSHIBA reserves the right to make changes to the information in this document and related Product without notice.
- This document and any information herein may not be reproduced without prior written permission from TOSHIBA. Even with TOSHIBA’s written permission, reproduction is permissible only if reproduction is without alteration/omission.
- Though TOSHIBA works continually to improve Product’s quality and reliability, Product can malfunction or fail. Customers are responsible for complying with safety standards and for providing adequate designs and safeguards for their hardware, software and systems which minimize risk and avoid situations in which a malfunction or failure of Product could cause loss of human life, bodily injury or damage to property, including data loss or corruption. Before customers use the Product, create designs including the Product, or incorporate the Product into their own applications, customers must also refer to and comply with (a) the latest versions of all relevant TOSHIBA information, including without limitation, this document, the specifications, the data sheets and application notes for Product and the precautions and conditions set forth in the "TOSHIBA Semiconductor Reliability Handbook" and (b) the instructions for the application with which the Product will be used with or for. Customers are solely responsible for all aspects of their own product design or applications, including but not limited to (a) determining the appropriateness of the use of this Product in such design or applications; (b) evaluating and determining the applicability of any information contained in this document, or in charts, diagrams, programs, algorithms, sample application circuits, or any other referenced documents; and (c) validating all operating parameters for such designs and applications. **TOSHIBA ASSUMES NO LIABILITY FOR CUSTOMERS' PRODUCT DESIGN OR APPLICATIONS.**
- **PRODUCT IS NEITHER INTENDED NOR WARRANTED FOR USE IN EQUIPMENTS OR SYSTEMS THAT REQUIRE EXTRAORDINARILY HIGH LEVELS OF QUALITY AND/OR RELIABILITY, AND/OR A MALFUNCTION OR FAILURE OF WHICH MAY CAUSE LOSS OF HUMAN LIFE, BODILY INJURY, SERIOUS PROPERTY DAMAGE AND/OR SERIOUS PUBLIC IMPACT ("UNINTENDED USE").** Except for specific applications as expressly stated in this document, Unintended Use includes, without limitation, equipment used in nuclear facilities, equipment used in the aerospace industry, lifesaving and/or life supporting medical equipment, equipment used for automobiles, trains, ships and other transportation, traffic signalling equipment, equipment used to control combustions or explosions, safety devices, elevators and escalators, and devices related to power plant. **IF YOU USE PRODUCT FOR UNINTENDED USE, TOSHIBA ASSUMES NO LIABILITY FOR PRODUCT.** For details, please contact your TOSHIBA sales representative or contact us via our website.
- Do not disassemble, analyze, reverse-engineer, alter, modify, translate or copy Product, whether in whole or in part.
- Product shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable laws or regulations.
- The information contained herein is presented only as guidance for Product use. No responsibility is assumed by TOSHIBA for any infringement of patents or any other intellectual property rights of third parties that may result from the use of Product. No license to any intellectual property right is granted by this document, whether express or implied, by estoppel or otherwise.
- **ABSENT A WRITTEN SIGNED AGREEMENT, EXCEPT AS PROVIDED IN THE RELEVANT TERMS AND CONDITIONS OF SALE FOR PRODUCT, AND TO THE MAXIMUM EXTENT ALLOWABLE BY LAW, TOSHIBA (1) ASSUMES NO LIABILITY WHATSOEVER, INCLUDING WITHOUT LIMITATION, INDIRECT, CONSEQUENTIAL, SPECIAL, OR INCIDENTAL DAMAGES OR LOSS, INCLUDING WITHOUT LIMITATION, LOSS OF PROFITS, LOSS OF OPPORTUNITIES, BUSINESS INTERRUPTION AND LOSS OF DATA, AND (2) DISCLAIMS ANY AND ALL EXPRESS OR IMPLIED WARRANTIES AND CONDITIONS RELATED TO SALE, USE OF PRODUCT, OR INFORMATION, INCLUDING WARRANTIES OR CONDITIONS OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OF INFORMATION, OR NONINFRINGEMENT.**
- Do not use or otherwise make available Product or related software or technology for any military purposes, including without limitation, for the design, development, use, stockpiling or manufacturing of nuclear, chemical, or biological weapons or missile technology products (mass destruction weapons). Product and related software and technology may be controlled under the applicable export laws and regulations including, without limitation, the Japanese Foreign Exchange and Foreign Trade Law and the U.S. Export Administration Regulations. Export and re-export of Product or related software or technology are strictly prohibited except in compliance with all applicable export laws and regulations.
- Please contact your TOSHIBA sales representative for details as to environmental matters such as the RoHS compatibility of Product. Please use Product in compliance with all applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive. **TOSHIBA ASSUMES NO LIABILITY FOR DAMAGES OR LOSSES OCCURRING AS A RESULT OF NONCOMPLIANCE WITH APPLICABLE LAWS AND REGULATIONS.**