Application Brief
7-MOSFET for Cordless Power Tools

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Power tools are used in various industrial and household applications such as drilling, grinding, cutting, polishing, driving fasteners, and so forth. Cordless power tools use battery power to drive DC motors, and products are available in different power levels.

For a **high current level** application, this is typical to place a switch between battery and motor driver to make sure of safe operation when connecting or disconnecting power supply. Also, turning off the switch can reduce quiescent current of equipment, thus saving power during shipping status.

Traditionally, mechanical switches are used in this scenario due to simplicity and low cost. However, the switches are **not reliable enough**. Frequent switching affects the life of mechanical switches. Electric arc can be triggered during switching, which can do harm to other devices on board.

To avoid the problem caused by mechanical switches, electrical MOSFET switches can be used. Since motor inverter usually consists 6 MOSFETs to drive three-phase brushless DC (BLDC) motors, this additional MOSFET switch is usually called **the seventh MOSFET (7MOS)**.

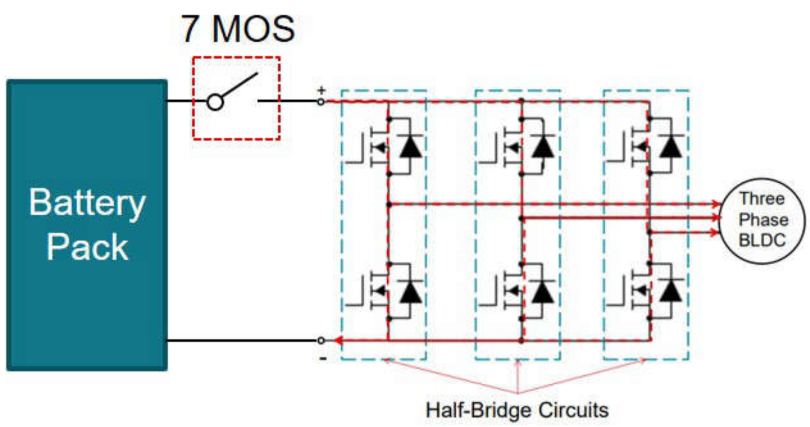

Figure 1. 7MOS in Cordless Power Tools System

Guide to Appropriate 7MOS Implementation

7MOS can be implemented in different ways. To select the appropriate design, go through this section to identify your need.

What Type of MOSFET to use – NMOS or PMOS?

MOSFET can be divided into two categories: N-channel MOSFET (NMOS) and P-channel MOSFET (PMOS). Both can be used as a switch. Compared with PMOS, NMOS is popular for lower cost and lower power consumption due to lower $R_{DS,ON}$, and smaller size to realize the same current rating. Therefore, this application brief only talks about designs with NMOS.

Note that NMOS needs to be driven by a positive V_{GS}, which means the gate voltage needs to be higher than the source voltage to turn on the switch. If NMOS is placed at high side, the source voltage equals to the supply voltage, and therefore the gate voltage needs to be higher than supply. To achieve this gate voltage, additional driver circuit is required.

Table 1. NMOS vs PMOS as a Switch

	$R_{DS,ON}$	Cost	Driver Circuit Design
NMOS	Low	Low	Extra design needed in high-side control
PMOS	High	High	Simple

Which Board to Install 7MOS: Battery-Side or Motor-Side?

Usually, battery management and motor control are implemented on two different boards, where battery management board is placed near battery (battery-side), and motor control board is positioned around motor (motor-side). The 7MOS switch can be installed on either board.

Wherever the switch is placed, the switch can add to PCB size, power consumption and heat. To decide the switch position, you need to consider which side can tolerate the deterioration of these specifications.

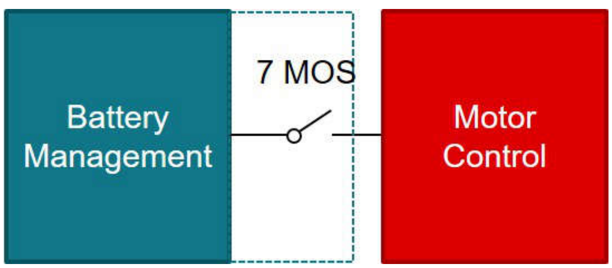

Figure 2. 7MOS Placement: Battery-side

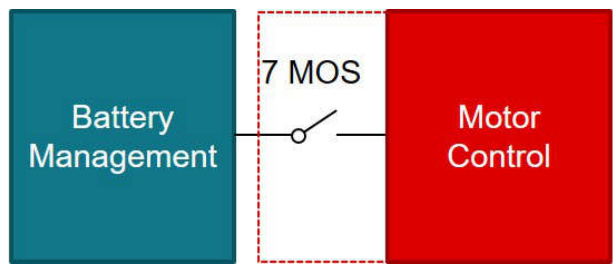

Figure 3. 7MOS Placement: Motor-side

Battery-side 7MOS

Control Method: High-Side or Low-Side?

At battery side, 7MOS can be placed between the supply and the load (high-side) or between the load and the ground (low-side).

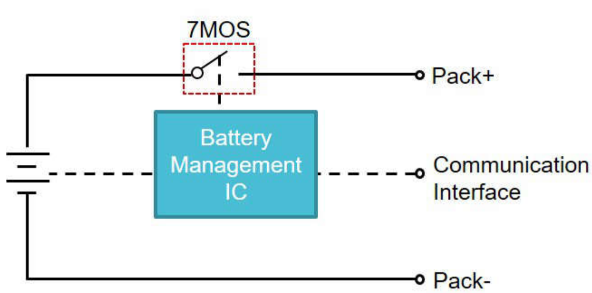

Figure 4. Battery-side 7MOS Control Method: High-side

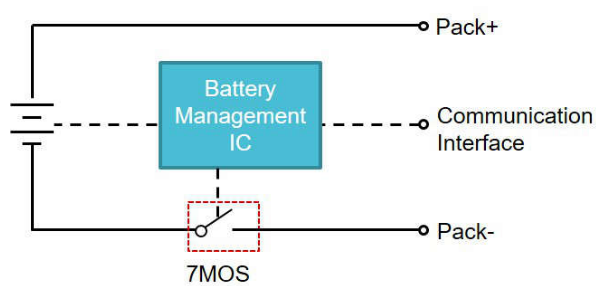

Figure 5. Battery-side 7MOS Control Method: Low-side

When implemented at low-side with NMOS, the switch does not require a gate voltage higher than supply to turn on, which saves the cost and area for additional circuit. However, the drawback is that when the switch is off, the ground reference for other parts of circuits (communication, motor driver, and so on) is lost. The floating ground is not safe, and isolation is required for communication in this case.

Although high-side NMOS switch needs driver circuit to generate voltage higher than supply, this implementation can maintain the same ground reference across the system all the time.

Table 2. NMOS Control: High-Side vs Low-Side

	Ground Reference	Driver Circuit Design	System Cost
High-side NMOS control	Maintained all the time	Need to generate voltage higher than supply	High
Low-side NMOS control	Cut off when NMOS is off	Simple	Low

FET Driver: Integrated or External?

Driver circuit is required to generate the control signal for 7MOS. Some battery management IC has already integrated the FET driver, while others need external circuit to realize this function.

Whether the driver circuit is integrated in battery management IC or not, this has to be **low-power**. At battery-side, the board power consumption is under tight control in shutdown mode to achieve low loss of battery power during shipment or long-term storage.

Battery management ICs with integrated FET driver have already taken the power of driver into consideration during the design stage. Therefore, achieving the low-power goal. Plus, the integrated driver **saves the cost, board size, and extra effort to design circuit**.

External driver circuit for low-side control can be built with **low-cost** passive devices to transfer control signal from MCU. The circuit is **low-power, but consumes some PCB area**.

In the design of extra driver circuit for high-side control, a driver device is usually used to generate control voltage higher than supply, which simplifies design and reduces area. **This driver device requires careful selection** to keep the power consumption under control in shutdown mode. Passive devices are still needed to build peripheral circuit for IC. The driver device can be configured with **extra protection features** (over-voltage protection, over-current protection, etc.), but **adds to the total cost**.

Table 3. Battery-side 7MOS Control: high-side vs low-side, integrated vs external FET driver

	Control Method	PCB Size	Main Cost
Integrated FET driver	High-side	Small	Battery management IC
	Low-side	Small	Battery management IC
External FET driver	High-side	driver device (small) + passive devices (medium)	Battery management IC + driver device
	Low-side	passive devices (medium)	Battery management IC

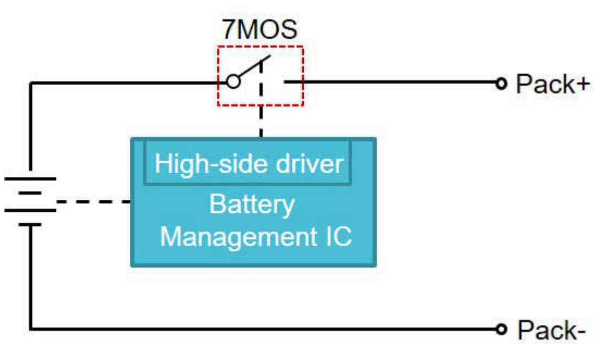

Figure 6. FET Driver for Battery-Side 7MOS: Integrated

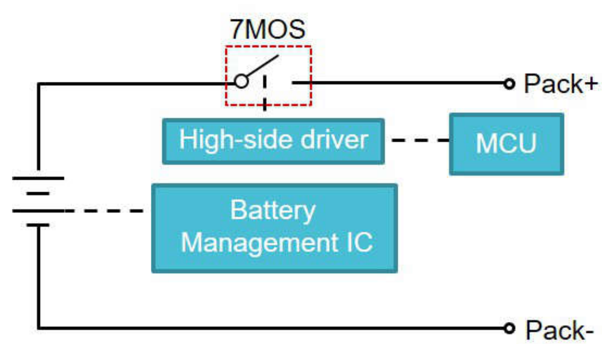

Figure 7. FET Driver for Battery-Side 7MOS: External

Motor-Side 7MOS

At motor side, the situation is similar with that at battery side. You can use either high-side or low-side control for 7MOS, with **less limitation on power consumption** in shutdown mode.

For low-side control, since motor driver IC usually does not integrate low-side MOSFET driver, external driver circuit can be built with **low-cost** passive devices as in battery-side 7MOS.

For high-side control, motor driver ICs usually integrate FET drivers to drive the high-side NMOS in motor inverter. The driver structure varies in different motor driver ICs. Some **support extra load** current while some don't. For those supporting extra load, high-side control only needs simple peripheral circuit with **low-cost** passive devices. For those not supporting extra load, extra driver must be used. This driver can be implemented by driver device or passive circuit. Driver device is more **compact in size** than passive circuit, and can have **extra protection features**, but **costs more**.

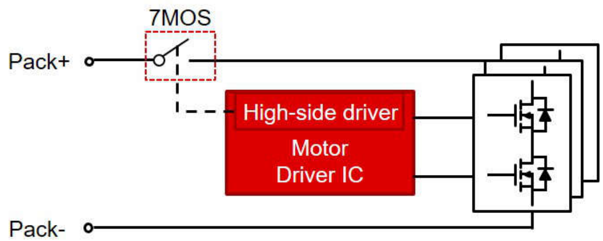

Figure 8. FET Driver for Motor-Side 7MOS: High-side

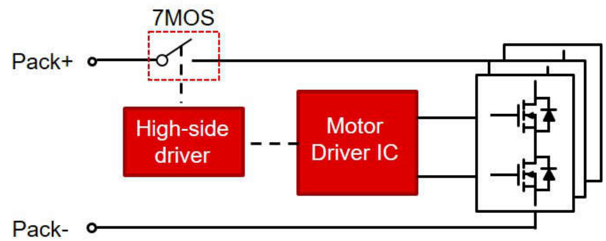

Figure 9. FET Driver for Motor-Side 7MOS: High-side

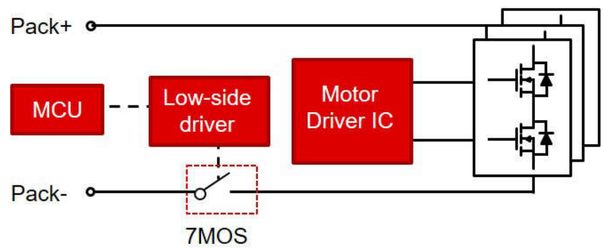

Figure 10. FET Driver for Motor-Side 7MOS: low-side

Table 4. Motor-Side 7MOS Control: High-Side vs Low-Side

	Driver Structure	PCB Size	Main Cost
High-side	Support extra load	Passive devices (medium)	Motor driver IC
	Not support extra load	Driver device (small) + passive devices (medium)	Motor driver IC + driver device
		Driver circuit (large) + passive devices (medium)	Motor driver IC
Low-side	None	Passive devices (medium)	Motor driver IC

7MOS Control with Power Switch

High-side power switch ICs have charge pump inside to generate voltage higher than supply. When configured as 7MOS controllers, the switch can be triggered by signal from MCU and output gate voltage at the corresponding pin. The switches are **easy to implement and have high integration to save PCB area**. This design is useful when not wanting to change other ICs on the board.

Although many power switches integrate the MOSFET, heat dissipation can be a problem since the peak current in power tools application can reach tens of amperes. Therefore, power switches with discrete NMOS are designed for this application.

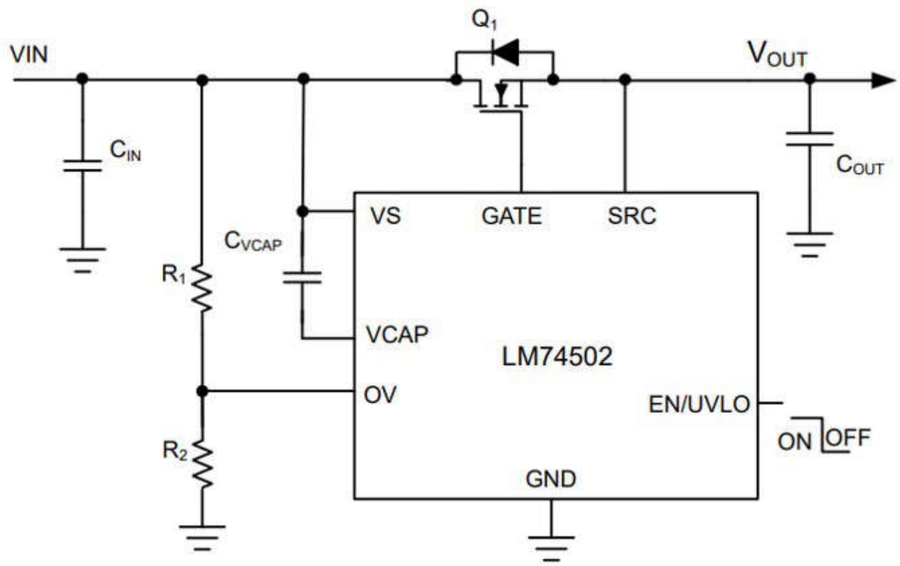

Figure 11. 7MOS Control With Power Switch (LM74502)

Different types of IC integrate various **protection features** as well, such as reverse polarity protection (RPP), reverse current blocking (RCB), overvoltage protection (OVP), undervoltage lockout (UVLO), overcurrent protection (OCP), and so on.

Two types of power switch are recommended: ideal diode/ORing controllers and hot swap controllers. When selecting the device, take the following specifications into consideration: input voltage, power consumption, package area, cost, and protection features you need.

Table 5. Recommended Ideal Diode, ORing, Hot Swap Controllers

Part Number	Input Voltage (V)	Shutdown Supply Current (uA)	Package Area (mm2)	Cost	Protection Features
LM74502	65	1.5	8.12	Low	RPP, UVLO, OVP, and so on
LM74500-Q1, LM74501-Q1	65	1.5	8.12	Low	RPP, UVLO, and so on
LM5050-1	80	475	8.12	Medium	RPP, RCB, and so on
LM5060	65	15	14.7	Medium	OVP, UVLO, OCP, and so on

TI Design for High-Side 7MOS Control

As discussed previously, a main challenge to realize high-side 7MOS control is to generate a gate control voltage higher than supply. This section focuses on solving this challenge.

The following methods can be considered:

Motor-side

- Add a power switch
- Use a motor driver IC with integrated FET driver

Battery-side

- Add a battery protector or low-power power switch
- Use a battery monitor with integrated FET driver

7MOS Control with Motor Driver IC

Most BLDC motor driver ICs integrate a charge pump or bootstrap structure to turn on the high-side NMOS in the motor inverter. This part of circuit can be reused to control 7MOS as well.

- Motor driver IC with integrated charge pump

This design is already described in the application note Cut-Off Switch in High-Current Motor-Drive Applications. The VCP pin of motor driver ICs can offer Supply + 10V to turn on the 7MOS with the help of low-cost but area-consuming discrete circuit.

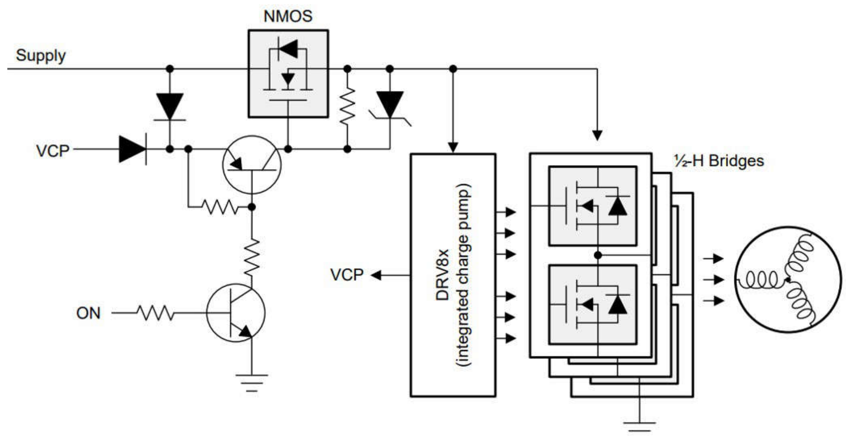

Figure 12. 7MOS Control With Motor Driver IC (Integrated Charge Pump)

- Motor driver IC with integrated bootstrap

The bootstrap architecture alone cannot be used to generate Supply + 10V to control 7MOS, because this relies on the switching operation of motor inverter to maintain a constant voltage. A **trickle charge pump** is used in TI devices with bootstrap architecture to provide high-side NMOS gate voltage (Supply + 10V) when the input PWM duty cycle is close to 100%(Like DRV8328 and DRV8329). However, the trickle charge pump can withstand very light current load, which makes this difficult to drive the 7MOS directly. We can use a driver circuit to drive the 7Mos ,below is a exmple to use DRV8328 and driver circuit to drive the 7Mos :

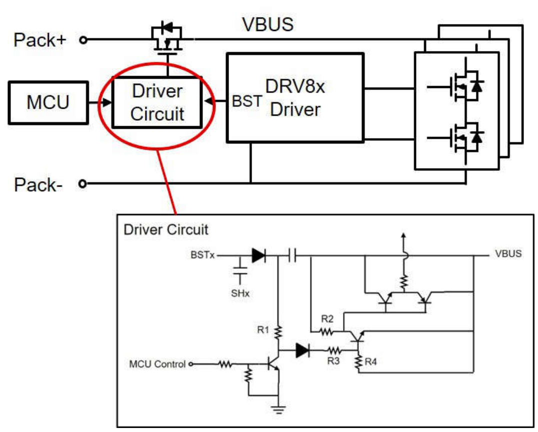

Figure 13. 7MOS Control With Motor Driver IC (Integrated Bootstrap)

Resistor R1, R2, R3 and R4 needs to be chosen carefully since the resistors can form an unwanted path from bootstrap architecture to VBUS and carry load current.

Also, a large resistor value is preferred to relieve the load current burden of trickle charge pump. Also, high resistance makes the circuit vulnerable to noise and interference, and slows down the switching time.

For demonstration, R1, R2, R3 and R4 are chosen at MΩ level. In real application, smaller resistor value (100kΩ level) can be chosen, but the low-side NMOS in the inverter needs to be turned on first for a while to make sure the bootstrap capacitor is fully charged.

A demonstration circuit is built and the test result is shown in Figure 14, where Channel 1 is the MCU control signal, and Channel 2 represents the drain voltage of high-side NMOS in motor inverter (VBUS):

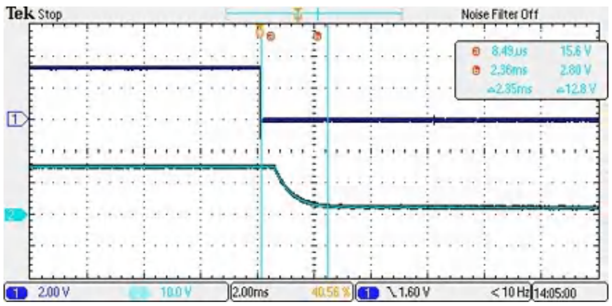

Figure 14. Turn On 7MOS With Driver Circuit

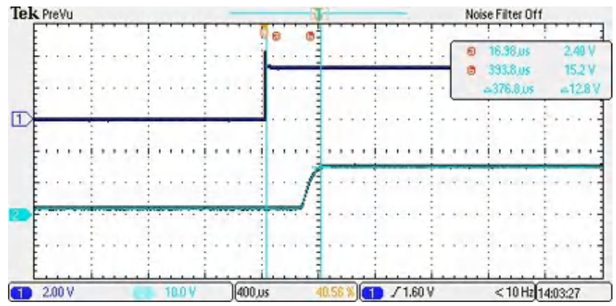

Figure 15. Turn off 7MOS With Driver Circuit

When 7MOS is turned on, the battery supply (15V) is connected to motor inverter, and VBUS equals to supply voltage; when 7MOS is turned off, the battery supply is disconnected, and VBUS is pulled down to a low voltage level by a load resistor to ground. Therefore, the MCU can successfully control the 7MOS to connect or disconnect the supply with this driver circuit.

The demonstration design is built with **low-cost passive devices and JEFTs**, but this consumes about 30mm×30mm PCB area, which can be a concern for compact size design.

The above is just an example. In this case, the MOS cannot be turned on and off very quickly and cannot support fully 100% duty operation. We need to pay attention to this.

Table 6 lists the recommended devices:

Table 6. Recommended Motor Driver IC

Part Number	Driver Structure	Maximum Input Voltage
DRV8320, DRV8323	Charge pump	60V
DRV8350, DRV8353	Charge pump	100V
DRV8328, DRV8329	Bootstrap	60V
DRV8334	Bootstrap	60V
DRV8161, DRV8162	Bootstrap	100V

For motor driver IC with bootstrap architecture, future products of TI can upgrade the driver design to **support higher load current** and enable **smaller size** of peripheral circuit.

7MOS Control With Battery Protector or Low-Power Power Switch

As discussed in FET Driver: Integrated or External? **low-power** devices must be used at battery side to save battery power in shutdown mode. To achieve this, designer can use either battery protector with driver function or low-power power switch.

TI's battery protector BQ76200 consumes less than 9.5uA in shutdown mode. This integrates a charge pump and can be controlled by signal from outside (MCU or battery monitor), which matches the requirement of 7MOS control.

Low-power power switches introduced in 7MOS Control with Power Switch can also be used here. With shutdown current consumption less than 20uA, these devices can also hold the power budget under control.

Table 7. Recommended Battery Protector or Low-Power Power Switch

Part Number	Type	Shutdown Supply Current (uA)	Maximum Input Voltage (V)	Package Area (mm2)	Cost	Protection Features
BQ76200	Battery protector	9.5	27.5	32	High	None
LM74500-Q1, LM74501-Q1,	Ideal diode	1.5	65	8.12	Low	RPP, UVLO, and so on
LM74502	Ideal diode	1.5	65	8.12	Low	RPP, UVLO, OVP, and so on
LM74700-Q1,LM74701-Q1	Ideal diode	1.5	65	8.12	Medium	RPP, RCB, UVLO, and so on
LM5060	Hot swap controller	15	65	14.7	Medium	OVP, UVLO, OCP, and so on

Conclusion

7MOS provides a reliable way to connect or disconnect power supply of cordless power tools. 7MOS can be implemented by an NMOS transistor with either high-side or low-side control. The main challenge to realize high-side control is to generate a gate voltage higher than supply. Table 8 summarizes TI's designs to 7MOS control and compares performance.

Table 8. TI's Design to High-Side 7MOS Control

TI Design	Architecture	Recommended Devices
Motor-side		
Control with power switch (ideal diode/ ORing controllers)	motor driver and power switch	LM74502, LM7450x-Q1, LM7470x-Q1,LM5050-1
Control with power switch (hot swap controller)		LM506x, TPS249x
Control with motor driver IC (charge pump)	motor driver	DRV8320, DRV8323, DRV8350, DRV8353
Control with motor driver IC (bootstrap)		DRV8328, DRV8329, DRV8334, DRV8161, DRV8162
Battery-side		
Control with battery protector	battery monitor + battery protector	BQ76200
Control with low-power power switch	battery monitor + power switch	LM74502, LM7450x-Q1, LM7470x-Q1,LM5060
Control with battery monitor	battery monitor	High-side: BQ769x2 Low-side: BQ76905, BQ76907

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