Encoding and Decoding of Li-Ion Voltage Reading

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Abstract- *The intention of this paper is to compare different encoding and decoding techniques using different AFE's (Analog Front End devices). This paper compares multiple ASICs on both primary and secondary side based on their thermal shutdown temperature, under and over voltage, number of batteries in series, operating temperature range. And we have volunteered our opinion for which ASIC.*

Keywords- Analog Front-end (AFE), Application-Specific Integrated Circuit (ASIC), Battery Management System (BMS),Lithium-Ion (Li-ion) Battery,Safe Operating Area (SOA).

I. INTRODUCTION

To establish basic knowledge of Battery Management Systems (BMS) and usage of Li-ion batteries, our first step towards this paper starts with *"What is a Li-ion battery? [14]"*, Li-ion batteries are type of rechargeable batteries. Its primary functional component is electrodes (anode and cathode) and electrolyte. Lithium ions moves from negative to positive electrode while discharging and positive to negative while discharging. Commercially negative electrode (anode) is made of graphite and positive electrode (cathode) is made of 3 materials (a layered oxide), 2D and 3D structures of graphene is also used as electrode. Electrolytes are mixtures of carbonates (example: Diethyl carbonate containing complex lithium ions). Li-ion batteries are commonly used in portable electronic devices and Electrical Vehicles (EVs).

TYPES OF LI-ION BATTERY: [15]

- Lithium cobalt oxide ($LiCoO_2$) battery: Its key features are high energy density, high level of safety.
- Lithium Iron phosphate ($LiFePO_4$) battery: Its key features are high current capability, longer lifespan.
- Lithium Manganese Oxide ($LiMn_2O_4$) battery: Its key features are high current capability and discharge.
- Lithium Nickel Cobalt Aluminum Oxide battery: Its key features are high energy density, high power density and good lifespan.
- Lithium Nickel Manganese Cobalt Oxide (3 parts Cobalt, 2 parts Manganese and 5 parts Nickel) battery: Its features are high specific energy, energy density not as high as some other type.
- Lithium titanate:It have lower inherent voltage, or lower energy density, than other lithium-ion battery varieties, which can present issues with powering vehicles efficiently
- Which lithium-ion battery is best? [15]

Lithium-ion batteries come in a range of types and have a variety of uses. That means some current lithium-ion batteries are better suited to particular applications than others are. The most important thing is to choose the battery best suited to the task at hand. It's also worth noting that the lithium-ion battery industry is constantly changing. Companies and scientists around the world are creating new batteries to either work alongside lithium-ion batteries or supplant them. As these new batteries develop, it will be important to watch which come to the fore.

ADVANTAGES OF LITHIUM-ION BATTERY

There are major advantages of Li-ion batteries such as they can be recharge thousands of times which makes them ideal to use them in our smartphones, laptops. Also, these batteries play major role in Electric Vehicles and it is becoming popular in military and aerospace applications. But these batteries shall be kept in a Safe Operating Area (SOA) to prevent them from deteriorate its battery life and in the worst-case scenario from catching fire.

II. SAFE OPERATING AREA (SOA)

"What is safe operating area? [26]" Safe Operating Area or Safe Operating Envelope is the area in which a lithium-ion battery can perform efficiently without any complications or safety issues. The limits of the SOA are bounded with voltage, current and temperature. SOA are bound by current, temperature and voltage. Generally, SOA is the typical boundary in which in which battery system should perform. There are 2 limits under and over.

UNDER AND OVER*[26]*

1) The nominal voltage range of Li-ion batteries voltage range is from 2.5V to 4.5V. The voltage across a Li-ion cell is allowed to fall below its minimum operating value is called under or underrated and it will damage the cell.

If the voltage rating exceeds the maximum operating value is called over voltage and lead to increase in temp and damaging battery, at the worst case it will catch fire.

2) Lithium-ion cells or batteries are bound to quick damage and might ignite if operated at high pulse current and discharges rapidly so there are chances of reducing the lifespan of Li-ion battery.The values change according to the type of Li-ion battery is used and the type of BMS used.
3) When a lithium-ion cell is charged or discharged outside the certain temperature range. If the temperature is greater while charging or discharged outside even precise temperature range. So, there are chances of reducing the efficiency and might affect the battery life for long term period. But in the short side if the discharge and charging cross a certain temperature limits the system prone to thermal run away. (Thermal runaway is a situation where the current flowing through the cell or battery on charge or overcharge causes the cell temperature to rise, which increases the current with a further rise in temperature.) **[27]**

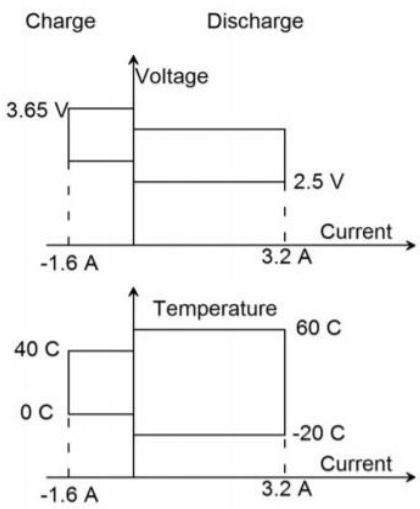

Fig 1:Range of Li-ion battery

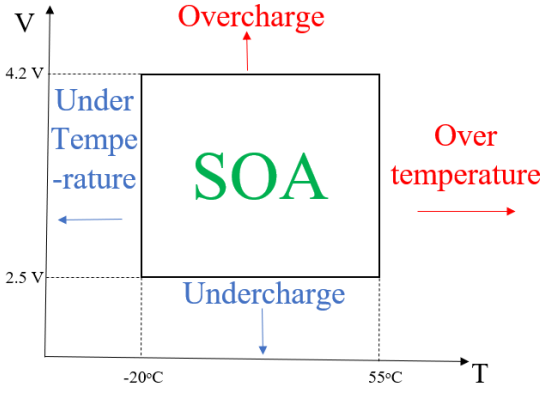

Fig. 2 SOA of Li-ion battery

III. BATTERY MANAGEMENT SYSTEM

"What is battery Management System? **[16, 19, 20]"** To protect batteries from over and under conditions we use a Battery Management System (BMS). The battery management system (BMS) is an essential component of the on-board power electronics. Their primary purpose is safety, where the battery pack is prevented from over-charging or over-discharging. Additionally, they can be designed to ensure the long life of the battery pack by balancing the energy amongst the individual cells, and to provide information about the battery charge level or State of Charge (SoC). [17]

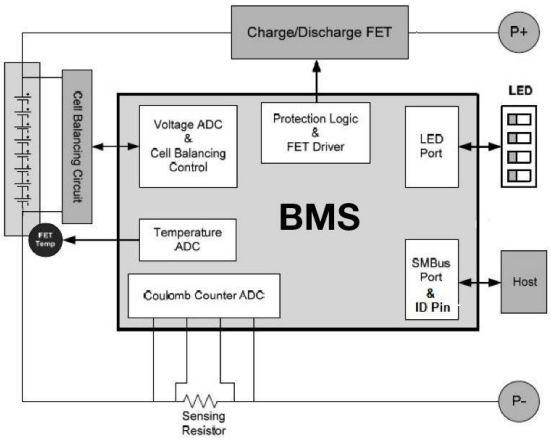

Fig. 3 Block diagram of BMS

"How BMS works? **[18]"** Whenever the BMS faces the situation of crosses the safe temperature limit the micro-controller gives signal to the discharge and charge FETs to cut-off the connection between load and the power supply respectively. The same logic can be applied for over and under conditions.

"Different peripherals used in BMS **[28]"** The BMS is usually consists of microcontroller unit (MCU), the MCU is the brain of the BMS and gives commands the actions that should be done by the BMS. It contains hall affect current sensor, power supply, an SD-card, real time clock and calendrer (RTCC), GPUIO connectors, High Voltage Interlock Loop, Voltage Measurement Port and Analog Front-end (AFE).

"Essential functional blocks of the BMS connected to the AFE **[28]"** Voltage Sensing Channel, Temperature Sensor, GPIO Connectors, Balancing, ISO-SPI Channel, Analog Filtering, PSU AFE. The features of an AFE include: Measuring each cell voltage and setting it to MCU, measuring temperature (usually via NTC thermistor), balancing circuitry for each cell.

IV. REQUIREMNTS OF ENCODINGAND DECODING TECHNIQUES

Now let us consider a battery pack of 256 batteries, therefore a situation might arise where we must give 256 different inputs to monitor each battery individually. But the IC's that are available has less input ports. To feed all the inputs to an IC we use an encoder which encodes 256 input voltages into 8 output voltage (if the encoder used is typical digital encoder). ASIC or AFE in BMS help us in encoding and decoding.

Importance of ASIC: The problem with normal IC's is that they are designed for a general purpose, which can lead to the IC underperforming when used with a BMS. Therefore, to increase the efficiency we use application specific integrated circuit (ASIC). [22, 23] In this case specifically designed to work along with a BMS and obtain best results. In this paper we specifically deal with different types of ASIC's, their efficiency, their specific usage and different types of encoding and decoding methods.

Different companies who fabricate ASIC: companies that manufacture ASIC are IBM Microelectronics, Honeywell, Texas Instruments (TI), Samsung Semiconductor, Toshiba, ZMD America Inc., Synopsys, Advanced Linear Devices Inc., Calogic LLC, Freescale Semiconductor Inc., Fujitsu Microelectronics Inc., Maxim.

Different Types of ASIC: the ASICs which are particularly developed on demands by the customer. From papers as the researcher's states [24] LTC6802-2, MAX1894, MAX11068, MAX11080, DS2726, BQ29330, AD7280, and ATA6870 are some ICs he/she recommends to use in a BMS. This system monitors the overall battery voltage and controls the automatic switch and other peripherals if needed.

LTC6802-2: [1]

- It is a type of ASIC that is specially designed for monitoring of battery systems in qualified automotive applications.
- It can measure up to maximum voltage of 60V that is 12 series of a lithium ion cells.
- Its spec able architecture allows us to monitor high voltage batteries by stacking multiple LTC6802-2.
- The company allows stacking upto 16 LTC6802-2 devices to interface with one microcontroller.
- Every individual LTC6802-2 can be adjusted using a 4-bit addresser.
- LTC6802-2 provides us with on chip passive cell balancing and company also provides us the option for off-chip passive balancing. But major disadvantage is that this IC does not provide active cell balancing techniques which is proven to be much more efficient.
- To prevent the cases of under and over temperature this IC comes with an onboard temperature sensor along with 2 thermistor inputs.
- This comes with a delta sigma converter. The company states that usage of delta sigma converter better than SAR due to following reasons: "The common characteristic is that the input is sampled many times over the course of a conversion and then filtered or averaged to produce the digital output code. In contrast, a SAR converter takes a single snapshot of the input voltage and then performs the conversion on this single sample.", "While SAR converters can have high sample rates, the full-power bandwidth of a SAR converter is often greater than 1MHz", "The front-end sample rate is 512ksps, which greatly reduces input filtering requirements", etc.
- LTC6802-2 comes along with a 12-bit ADC which is used to connect this IC to a microcontroller
- The IC provides us with different modes like monitoring mode, measure modes (to check under and over voltage condition), standby mode (at standby restricts current upto 50mA).
- Each cell has different MOSFET associated to them so that it can discharge and overcharge its cell.
- Operating temperature range is between -40°C to 85°C, thermal shutdown temperature is 145
- Cell voltage range is 5V (12x5=60V), over voltage detection level for each cell is 4.2V and under voltage detection level is 2.3V
- Maximum total measurement error is 0.25%, IC takes around 13ms to measure all cells.
- Its applications are: Electric and hybrid electric vehicles, high voltage DAQ, battery backup systems, high power portable equipment.

MAX1894: [2]

- It is a lithium-ion battery-pack protector IC used for 3 or 4-series Li-ion battery packs.
- "In case of a fault condition, on-board drivers control external P-channel MOSFETs, which disconnect the cells from the pack external terminals."
- The company states that their MOSFET are connected in a common source configuration and hence do not require any external pull up resistor.

- The MAX1894 have low quiescent current and ultra-low shutdown current to pre-MAX1894/MAX1924 have low quiescent current and ultra-low shutdown current and ultra-low shutdown current to pre- vent deep-cell discharge.
- The MAX1894 is designed for 4-series battery packs without hysteresis
- This IC automatically trickle charges any overly discharged cells
- The over voltage limit is between 4V and 4.4V and under voltage range is between 2V and 3.2V. The over and under voltage limits are accurate upto +/- 0.5% and +/-2% respectively.
- The maximum cell voltage that this IC can bear is 28V.
- Temperature range is around -45°C to 85°C.
- Modes of operations are shutdown mode, normal mode.

MAX 11080: [3]

- It is a battery-pack fault-monitor ICs capable of monitoring up to 12 lithium-ion (Li+) battery cells.
- Its operation voltage is from 6V to 72V.The overvoltage levels are pin selectable from 3.3V to 4.8V in 100mV increments, and have a guaranteed accuracy of +/-25mV over the entire temperature range. The under-voltage level is also user selectable from 1.6V to 2.8V in 200mV increments. These levels are guaranteed to +/-100mV over the entire temperature range.
- Under voltage detection can be disabled as one of the user-configuration options.
- The MAX11080 have a built-in level-shifter that allows up to 31 MAX11080 devices to be connected in a daisy-chain fashion to reduce the number of interface signals needed for large stacks of series batteries.
- It has low power dissipation of operating-mode current drain at 80µA, shutdown-mode current at 2µA
- It has wide operating temperature range from -40°C to 105°C, with threshold shutdown voltage is 145°Cand thresholdover voltage is between 3.3V to 4.8V.
- Company says, “The daisy-chain bus relays shutdown and alarm communication across up to 31 stacked modules without the need for isolation between each module. This results in a simplified system with reduced cost. The ALRML line is a heartbeat signal with pulses occurring every 250µs”
- It is mostly used in Electric vehicles, High power battery backups, Solar cell battery backups, Super cap battery backup or any high voltage multi-cell series battery systems.

MAX11068: [4]

- The MAX11068 analog front-end (AFE) combines a 12-channel voltage measurement data-acquisition system with a high-voltage switch bank input. All measurements are done differentially across each and every cell.
- Full-scale measurement range is from 0 to 5.0V, with full stated accuracy guaranteed from 0.5V to 4.7V.
- It is a high-speed, 12-bit successive approximation (SAR) A/D converter is used to digitize the cell voltages. All 12 cells can be measured in less than 107µs.
- It uses a two-scan approach technique for collecting cell measurements and correcting them for errors. The first phase of the scan is the acquisition phase where the voltages of all 12 cells are acquired. The second phase is the error-cancellation phase where the ADC input is chopped to remove errors.
- This two-phase approach yields excellent accuracy over temperature and in the face of extreme noise in the system. It incorporates an internal oscillator that generates a 6.0MHz system clock with +/-3.0% accuracy.
- It has 2 analog inputs for temperature measurements, voltage measurement accuracy is around +/- 0.5%.
- It Supports Multiple Devices, up to 31 SMBus Ladder-Connected ICs.
- Operating temperature range is -40°C to 105°C.

DS2726: [5]

- The DS2726 provides full charge and discharge protection for 5 to 10-cell lithium-ion battery packs.
- The protection circuit monitors individual cell voltages to detect overvoltage and undervoltage conditions. Protection against discharge overcurrent and short-circuit current is provided with user-selectable thresholds using external resistors. Cell balancing can be enabled to ensure that all cells are equally charged.
- Applications are power tools, electric bikes and other home appliances.
- This is pin programmable for 5-10 cells. It can shunt up to 300mA.

- Temperature range is between -20°C to 85°C. Voltage range is between 5V and 50V.
- Over voltage detection level is between 4.1V and 4.5V and under voltage detection level is 2.3V. All the cells can be measured in less than 128ms.

BQ25730: [6]

- It is a battery charge controller to charge 1-5 batteries from a wide range of input sources with adjustable 3.5V to 26V output with 8mV resolution.
- TI patented switching frequency dithering pattern can significantly reduce EMI noise over the whole conductive EMI frequency range (150 kHz ~ 30 MHz).
- 400 kHz to 800 kHz programmable switching frequency to high power density applications, it uses buck-boost NVDC charger for power delivery interface.
- It supports USB 2.0, USB 3.0, USB 3.1, input current settings
- Applications are Oxygen concentrator, ventilators, vacuum robot, Tablet (multimedia), wireless speaker
- This IC has an 8-bit ADC to monitor voltage current and power.
- The company states that the accuracy for the regulation and monitor +/-0.5% Charge voltage regulation.
- The temperature range is between -20°C to 85°C. The thermal temperature lies between 135°C and 155°C.
- Under voltage detection level is 2% of battery voltage and over voltage detection level is 1.2% of battery voltage.

ASICs used in BMS:

BQ29330: [7]

- It is a 2-series, 3-series, and 4-series cell lithium-ion battery pack full-protection analog front end (AFE) IC that incorporates a 2.5V, 16mA and 3.3V, 25mA low dropout regulator (LDO).
- Parameters such as current protection thresholds and delays can also be programmed into the BQ29330 to increase the flexibility of the battery management system.
- It provides safety protection for overload, short circuit in charge, and short circuit in discharge conditions and can also provide cell overvoltage, battery overvoltage and battery undervoltage protection with the battery management host.
- In overload, short circuit in charge and short circuit in discharge conditions, the BQ29330 turns off the FET drive autonomously, depending on the internal configuration setting.
- Supply voltage is between 4.5V and 28V
- Its applications are notebook computer, medical and test equipment, instrument and measurement system.
- Overload detection level is between 50mV to 205mV. Its temperature range is between -40°C to 110°C.

AD7280A:[8]

- The AD7280A1 contains all the functions required for general purpose monitoring of stacked lithium-ion batteries as used in hybrid electric vehicles, battery backup applications, and power tools.
- It has multiplexed cell voltage and auxiliary ADC measurement channels for up to six cells of battery management. An internal +/-3 ppm/°C reference is provided that allows a cell voltage accuracy of +/-1.6 mV.
- The resolution of ADC is 12 bits and allows conversion of up to 48 cells within 7μs. The AD7280A operates from a single VDD supply that has a range of 8 V to 30 V (with an absolute maximum rating of 33 V).
- It provides six differential analog input channels to accommodate large common-mode signals across the full VDD range. Each channel allows an input signal range of 1 V to 5 V. The input pins assume a series stack of six cells.
- The part includes six auxiliary ADC input channels that can be used for temperature measurement or system diagnostics.
- Input voltage range is between 0.5V to 27.5V. It has cell balance interface.
- Daisy chain interface allows up to stacking of 8 similar ICs. Operating temperature range is between -40°C to 105°C
- Its applications are Li-ion battery monitoring, Electric and Hybrid vehicles, Power tools and Power supply backup.

ATA6570: [9]

- It is a stand-alone, high-speed CAN transceiver with partial networking that interfaces a Controller Area Network (CAN) protocol controller and the physical two-wire CAN bus designed for high-speed CAN applications in the automotive environment.

- It provides local and enhanced remote wake-up capabilities and is available in 14-lead SOIC and VDFN packages. It has a very low-power consumption in Standby and Sleep mode.
- A CAN frame decoder evaluates the bus traffic and checks for a matching frame that has been configured into registers via the SPI.
- The device is able to keep the complete Automotive Electronic Control Unit (ECU) in a low-power mode, even when bus traffic is present, until a valid wake-up frame has been received.
- Minimum and maximum supply voltage is 4V and 50V respectively, over temperature threshold is 147°C.
- Under voltage detection level 4.25V.
- There are 6 operating modes like power off mode, microcontroller reset mode, sleep mode, standby mode, normal mode and over temp mode.

Primary side control IC for offline battery charges:
AP3706: [10]

- It is a high-performance AC/DC power supply controller for battery charger and adapter applications. The device uses Pulse Frequency Modulation (PFM) method to build discontinuous conduction mode (DCM) flyback power supplies.
- It provides constant voltage, constant current (CV/CC) regulation without requiring an opto-coupler and secondary control circuitry.
- It eliminates the need of loop compensation circuitry while maintaining stability. The AP3706 achieves excellent regulation and high-power efficiency, the no-load power consumption is less than 200mW at 265VAC input.
- It uses flyback topology in DCM operation.
- Its applications are Adapters/Chargers for Cell/Cordless Phones, PDAs, MP3 and Other Portable Apparatus, standby and auxiliary power supply.

FAN104W: [11]

- It is a highly integrated pulse width modulation (PWM) controller.
- It provides several features to enhance the performance of lower power flyback converters.
- The proprietary topology enables simplified circuit design for battery charger applications. The result is lower cost, smaller and lighter charged compared to conventional design. This mode is called as green mode, it assists the power supply in meeting power conservation requirement.
- Low operation current in burst mode with 600µA and uses a CV mode for cable compensation.
- By using this IC any battery pack can be charged with few external peripherals with low application cost.
- Operating temp range is between -40°C to 105°C
- Its applications are batter chargers for smart phones, tablets, PDA and digital cameras

FL103: [12]

- The third generation Primary Side Regulation (PSW) and highly integrated PWM controller provides features to enhance the performance of LED illumination.
- The proprietary topology enables precise regulation and simplified circuit for LED illumination and applications. The result is lower cost and smaller Led lighting compared to a conventional design or a transformer.
- To minimize the standby power consumption the proprietary function (green-mode) provides an off-time modulation to linearly decrease PWM frequency under light-load conditions. Green mode assists the power supply in meeting power conservation requirement.

MP020-5:[13]

- The MP020-5 is an offline, primary-side regulator that provides accurate constant voltage and constant current regulation without an opto-coupler or a secondary feedback circuit.
- It has an integrated 700V MOSFET. The MP020-5's variable off-time control allows a flyback converter to operate in discontinuous conduction mode.
- The MP020-5 also features protection functions such as VCC under-voltage lockout, over-current protection, over temperature protection, open circuit protection and over-voltage protection. Its internal high-voltage start-up current source and power saving technologies limit the no-load power consumption to less than 30mW.
- The MP020-5's variable-switching-frequency technology provides natural spectrum shaping to smooth the EMI signature, making it suitable for offline, low-power battery chargers and adapters.
- Primary side control without the need of opto coupler or any secondary feedback circuit.

- Operating junction temperature -40°C to +125°C and Operating VCC range is between 6.6V and 28V.

Tabular comparison of different ASIC:

ASIC	No. of series of cells	Temperature Range	Cell voltage range	Over Voltage detection level	Under Voltage detection level	Thermal Shutdown temperature
LTC6802-2	12	-40 to 85	60V	4.2V	2.3V	145
MAX1894	3 to 4	-40 to 85	28V (max)	4 and 4.4 V	2 and 3.2V	NA
MAX11080	12	-40 to 105	6 to 72	3.3 to 4.8	1.6 to 2.8	145
MAX11068	12	-40 to 105	06 to 70			NA
DS2726	5 to 10	-20 to 85	05 to 50	4.1 to 4.5	2.3	NA
BQ25730	1 to 5	- 20 to 85	3.5 to 26V	102% of battery voltage	2% of battery voltage	135 to 155
BQ29330	2 to 4	- 40 to 110	4.5 to 28	50mV to 205mV	NA	NA
AD7280	NA	- 40 to 105	0.5 to 27.5	NA	NA	NA
ATA6570	NA	NA	4 to 50	NA	NA	147

*(The values in the table are as per the respective datasheets provided by their companies)

V. DECODING AND DISPLAY

These are the different types of ASIC used in making of battery management system. But these output of ASIC to microcontroller which decides all the operation happening in battery pack on the basis of the input given to microcontroller. As we discussed about encoding in BMS, now let us assume that the cell in a 4th series of a battery pack is weak and discharging quickly hence this would affect overall efficiency of the battery pack cell balancing is necessary. Now let's say that our ASIC supports passive cell balancing technique. But the output/command our microcontroller gives cannot be easily interpreted without any decoder as the message would be encoded. Hence, we have to decode that command and send it to that particular series IC to switch off/on the MOSFET. There are many other examples and scenarios where decoder plays major role in decoding the encoded command of the microcontroller. And the output of the decoder can also be sent to LCD/LED display module connect to a microcontroller.

VI. CONCLUSION

We have given a detailed comparison of different ASIC used in both primary and secondary side control IC. Hereby I conclude that on these secondary side I personally would use MAX11080 according to the ASIC's we have compared. And the reason is it can handle 12 series of cells with an operating temperature range of -40°C to 105°C with an advantage of user selectable under voltage and over voltage threshold which gives user the freedom of using that particular IC for various scenario. And as per our personal opinion on primary side control IC is MP020-5 (according to the ASIC's we compared) because it has better operating temperature over other IC's and also provides us with a 700V MOSFET.

But the ASIC you choose depends on various other reasons like cell balancing techniques, OV and UV thresholds, number of cells in a battery pack, junction temperature, different types of MOSFET mechanisms used, thermal shutdown temperature and various other factors. It would be inappropriate to use 12 series compatible ASIC for small applications. Hence, I would suggest you to take a look at our comparison and decide your personal opinion.

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