Evaluation and Application Technology of New Batteries in UPS Products

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ABSTRACT

In consideration of the environment, Fuji Electric is developing a UPS with a new type of battery to replace lead-acid batteries, which use environmentally regulated materials. We are also developing storage devices and investigating application technology for lithium-ion batteries installed in electric vehicles and hybrid cars in partnership with battery manufacturers. We evaluated olivine-type lithium iron phosphate batteries, which have received attention in Japan as a new type of battery, and are considering adding them to our UPS products. We also launched UPS products equipped with the manganate lithium-ion batteries by evaluating with the similar method.

1. Introduction

An uninterruptible power supply (UPS) is a device that provides a stable power supply regardless of the power-supply variation in the AC input, and numerous UPSs are used to ensure the stable operation of network devices that support advanced information society. In general, UPSs contain a lead-acid battery as a storage medium, which is separated from a commercial power supply, in order to supply power during a power outage.

In consideration of the environment, Fuji Electric is developing a UPS with a new generation battery to replace lead-acid batteries that use environmentally regulated materials. In addition, in order to promptly respond to market changes, we are also developing storage media in addition to a conversion circuit necessary for UPSs.

This paper describes the technology of a lithium-ion battery as a secondary battery to replace lead-acid batteries, and reports on olivine-type lithium iron phosphate batteries, which have received attention in Japan as a new type of battery. Furthermore, as an example of a product, we will present a UPS equipped with a manganese lithium-ion battery.

2. Environmental Changes Surrounding UPS and Need for Battery Evaluation

Amid concerns about natural disasters and energy shortages, UPSs are gaining attention for general household use, not only for commercial purposes, and recently, they have come to be sold in electrical appliance retailers.

In general, UPSs are used to prepare for a relatively short power outage due to disasters or unforeseen circumstances. Meanwhile, as a countermeasure against a planned power outage, there is increasing demand to use UPSs as a backup power supply for longer hours.

Under such circumstances, lithium ion batteries are attracting attention as they do not contain environmentally regulated materials, they are excellent for periodic use and they can provide a backup power supply for long hours.

The properties of lithium-ion batteries change significantly depending on the constituent materials of parts such as the positive-electrode material.

Table 1 shows a comparison of the characteristics

Table 1 Comparison of characteristics of cathode material

Positive-electrode material	Manganese system $LiMn_2O_4$	Cobalt system $LiCoO_2$	Nickel system $LiNiO_2$	Ternary system LiNi/Co/MnO_2	Iron phosphate system $LiFePO_4$
Structure	Spinel structure	Layer structure	Layer structure	Layer structure	Olivine structure
Nominal voltage (V)	3.7	3.7	3.5	3.7	3.2
Discharge potential curve	Flat	Flat	Slope	Slope	Flat
Capacity (Ah/kg) [Theoretical value/practical value]	148/110	274/150	274/190	278/160	170/150
Thermal decomposition temperature (°C)	355	225	180	300	400 or more
Thermal stability	○	△	×	○	◎
Raw material cost (ratio)	1/8	1	1/6	1/6	1/10
Recoverable reserves (Mt)	680	4	47	4/47	83,000

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Table 2 Comparison of characteristics of secondary battery for mounting on mini-UPS

Type of battery	Electrode material: Positive electrode	Electrode material: Negative electrode	Battery capacity	Voltage range	Maximum current: Battery charge	Maximum current: Discharge	Usage environment	Cycle life (20 °C)	Output density Power density	Characteristics
Electric double-layer capacitor	Activated coal	Activated coal	350 to 3,000 F	0 to 2.5 V	1,000 A	1,000 A	−20 to +70 °C	1 million times or more	6,700 W/kg 4 Wh/kg	○ Enables discharge up to 0 V ○ Long cycle life ○ High output density → Peak cut use
Lithium-ion capacitor	Activated coal	Carbon material (Li dope)	1,000 to 2,000 F	2 to 3.8 V	100 A	100 A	−20 to +70 °C	100,000 times or more	3,300 W/kg 12 Wh/kg	○ High working voltage → Few serial connections ○ Used in intermediate range between battery and the capacitor ○ High safety
Lithium-ion battery	Lithium compound	Lithium titanate	4.2 Ah	1.5 to 2.8 V	12 CA	10 CA	−30 to +50 °C	6,000 times or more	1,250 W/kg 65 Wh/kg	○ Enables fast charge → Can be charged in a short time ○ High thermal stability
	Lithium compound (Olivine-type iron phosphate)	Carbon material	3 Ah	2 to 3.6 V	2 CA	6 CA	−20 to +60 °C	5,000 times or more	113 Wh/kg	○ Low material cost → Low-price battery ○ High safety
	Lithium compound (Spinel-type manganese acid)	Carbon material	3.5 Ah	2.5 to 4.2 V	2 CA	5 CA	−20 to +50 °C	5,000 times or more	2,380 W/kg 136 Wh/kg	○ High energy density → Provides backup power for long hours ○ High working voltage → Few serial connections
Lithium-ion (polymer) battery	Lithium compound	Carbon material	4.7 Ah	2.5 to 4.2 V	1 CA	5 CA	−20 to +50 °C	5,000 times or more	158 Wh/kg	○ High energy density due to polymer product ○ Good degradation resistant characteristics at high temperature ○ Little capacity changes due to temperature and high-rate discharge

The contents of this table show extracted pro forma values in order to compare the characteristics of a single cell.

of lithium-ion batteries depending on the positive-electrode material, and Table 2 shows a comparison of the characteristics of a secondary battery to be mounted on a mini-UPS.

Many accidents have been reported with lithium-ion batteries such as those where heat is generated and the battery catches fire. The cause of these accidents is not only the batteries but also the equipment that controls them. Therefore, ensuring safety of the lithium-ion battery mounted equipment has become a big issue.

For that reason, it is necessary to select a battery that is suitable for the purpose, and design the device to ensure safety while maximizing the characteristics of the battery. In order to do so, it is important to evaluate the battery and understand its characteristics.

3. Characteristics and Evaluation of Batteries Required for UPS

The performance requirements for UPS include backup time, charging time and life. The characteristics of a battery that influence this performance are battery capacity, maximum discharge rate and maximum charge rate*1. From these characteristics, UPS backup time and charging time can be determined, and both the battery capacity characteristic and the maximum discharge rate characteristic of the battery change according to conditions such as ambient temperature, charging voltage, cut-off voltage and discharge rate. In other words, it is necessary to understand the battery characteristics under these conditions in order to maximize UPS performance.

Fuji Electric performs the following evaluation and selects the optimal battery for a UPS to develop a UPS by pursuing high performance and safety.

(1) Evaluation of characteristics

We confirms the changes in characteristics of the battery with ambient temperature, charging voltage, cut-off voltage, discharge rate and charging rate as parameters, and optimized the UPS design.

(2) Evaluation of safety

We confirm the safety of a UPS at abnormal times and determine countermeasures and a function to protect UPS.

(3) Evaluation of reliability

We predict battery degradation such as cycle degradation and storage degradation and battery life.

*1: Battery capacity, discharge rate, and charging rate: See “Explanation 2” on page 217

Table 3 Features and issues of olivine-type lithium iron phosphate batteries

	Battery	Precautions for use of battery	Features
Features	No environmentally restricted materials are used	RoHS-compliant	Environment friendly
	Excellent in heat stability in terms of material	Hard to generate heat due to olivine-type crystal structure	High safety
	Good high-rate characteristics	Constant capacity irrespective of discharge current	Long hours of backup power by high-capacity discharge
	Good thermal characteristics	Little capacity change from 0 °C to 60 °C	Backup time does not fall even at low temperature
	Flat discharge curve	Easy to predict capacity, No capacity change due to cut-off voltage setting	Easy to predict remaining backup time, Easy to design UPS (possible to set up narrow converter control range)
	Voltage suddenly increases at charging terminal stage	Easy detection of full charge and overcharge	High safety at abnormal times
	No change in discharge capacity regardless of charging voltage	Can set low charging voltage	Easy to design UPS charger
	No resource restriction on the materials	Stable production Low material cost	Possible to secure stable supply in the future Possible to reduce price
	Popular overseas (China)	Easy to deploy overseas Cost of battery itself is low.	Possible to be used globally Possible to reduce cost
Issues	Low energy density	Low cell voltage (3.2 V)	Large number of mounted batteries (factor of price increase) Complicated protection function (factor of unbalance)
	Large IR drop at discharge start	Large drop in voltage at stand-by Large self-discharge (under examination and investigation)	Influence on management man-hours when stored

4. Characteristics of Olivine-Type Lithium Iron Phosphate Batteries

Because olivine-type lithium iron phosphate batteries use iron-based material for the positive electrode as shown in Table 1, there is no restriction on resources such as cobalt material, which is used in a general way. Therefore, the batteries have attracted attention in Japan as a new type of battery.

4.1 Characteristics and issues with olivine-type lithium iron phosphate batteries

The main characteristics of olivine-type lithium iron phosphate batteries are lower material cost, no oxygen release or heat generation until 400 °C, and good thermal stability. The reason why this battery is called an "olivine-type" is that the crystal structure of the iron phosphate is the same as olivine.

Table 3 shows the features and issues of olivine-type lithium iron phosphate batteries. UPSs that are equipped with olivine-type lithium iron phosphate batteries are very safe compared to general lithium-ion batteries. In addition, there is a potential for them to be low cost, which is one of the issues to solve before UPS can be more widely used in the home to cope with planned outages.

4.2 Characteristic evaluation of olivine-type lithium iron phosphate batteries

Fuji Electric performs tests such as a thermal characteristic test, discharge characteristic test, and discharge capacity test by charging voltage, and is evaluating the characteristics of the olivine-type lithium iron phosphate batteries.

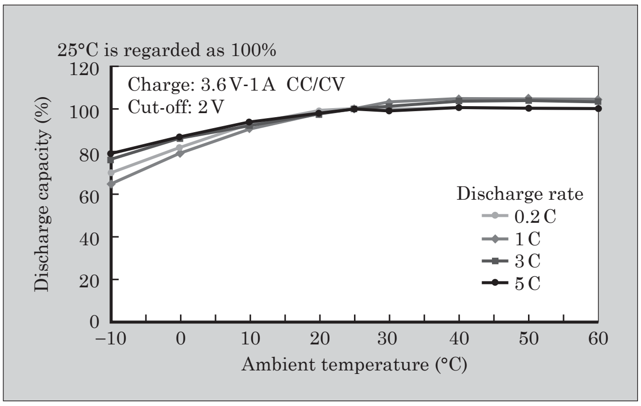


Fig.1 Thermal characteristics of olivine-type lithium iron phosphate batteries

As mentioned in Chapter 3, UPS backup time is influenced by battery capacity. The usable battery capacity is dependent on the using ambient temperature, discharge rate, cut-off voltage and charging voltage, and it is evaluated in the characteristics test.

(1) Thermal characteristics

Figure 1 shows changes in discharge capacity against ambient temperature at various discharge rates. Even at the lowest supported ambient temperature (0 °C) of the UPS, which assumes it is used in a normal interior location, the test results show that the UPS maintains 80% or more capacity at all rates. Because the backup time of a normal UPS that uses a lead-acid storage battery shortens enormously, only a backup time at 25°C is guaranteed in the specifications. However, we can expect a stable backup time with this battery because there is little change in the discharge capacity of the battery even if the using environment changes.

(2) Discharge characteristics

Figure 2 shows changes in the discharge capacity at various discharge rates. From data on discharge characteristics, it is possible to predict the expected discharge capacity; and therefore, this is a fundamental characteristic for judging the performance of the battery. Rated capacity is equivalent to discharge capacity at the condition of 0.2C and the figure shows that the rated capacity of the battery is 3.05 Ah.

In general, if the discharge rate increases, the amount of possible discharge capacity decreases. Even with a high-rate discharge up to 5C, a capacity of 90% (approx. 2.75 Ah) or higher can be maintained, proving good high rate discharge characteristic. Therefore, it is possible to secure a stable backup time even if the UPS load changes.

(3) Discharge capacity characteristics due to charging voltage

The speed at which a lithium-ion battery degrades depends on charging voltage, terminal voltage during storage and using ambient temperature, and it is said that the higher the voltage is, the faster the battery degrades. Therefore, it is possible to reduce the battery's degradation and extend its life by lowering the charging voltage as much as possible. However, when the charging voltage is lowered, the chargeable capacity is naturally reduced and the backup time will be shortened. Therefore, there is a trade-off relationship between backup time (which depends on charging voltage) and life.

Figure 3 shows changes in cell voltage against discharge capacity due to charging voltage. When charging voltage (voltage at discharge inception) and cut-off voltage (voltage at stop of discharge) change, the dischargeable capacity changes. Figure 3 shows that the discharge capacity is dependent on charging voltage and this characteristic is an important data to consider when setting a charging voltage by considering also the battery life.

From Fig. 3, which shows the result of changing the charging voltage within the range of 3.6 V to 3.4 V of recommended charging voltage, it can be found that if charging is performed within the recommended charging voltage, there is no big change in discharge capacity due to changing voltage. Therefore, it is possible to reduce battery degradation if the battery is used by lowering the charging voltage to 3.4 V.

In addition, it can be confirmed from Figs. 2 and 3 that the discharge curve is flat and IR drop (cell voltage depression) is large immediately after discharge inception. This is also a characteristic of olivine-type lithium iron phosphate batteries in terms of material.

Because the discharge curve is flat, even if the cut-off voltage is lowered to a certain degree, it does not affect the discharge capacity. By increasing the cut-off voltage and making the depth of the discharge smaller, it is possible to reduce the degradation of the battery. This is a big advantage in extending battery life.

(4) Charging characteristics

Figure 4 shows temporal variations in charging voltage and discharge current with various charging currents.

A battery's charging characteristic has charging

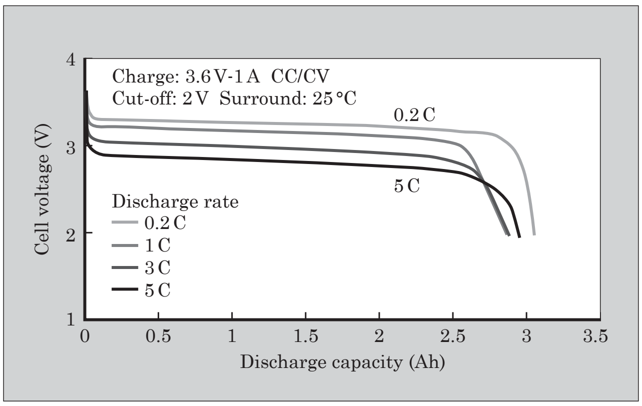


Fig.2 Discharge characteristics of olivine-type lithium iron phosphate batteries

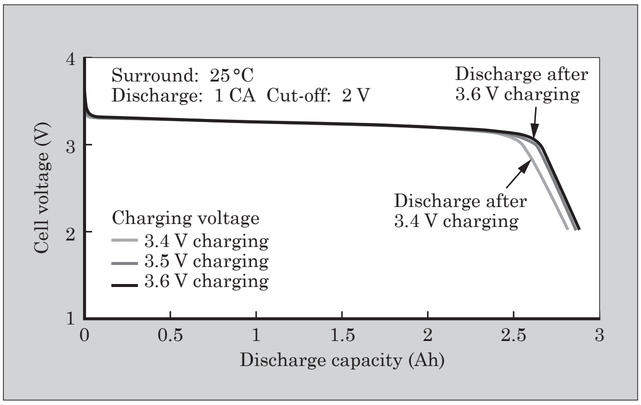


Fig.3 Charging voltage characteristics of olivine-type lithium iron phosphate batteries

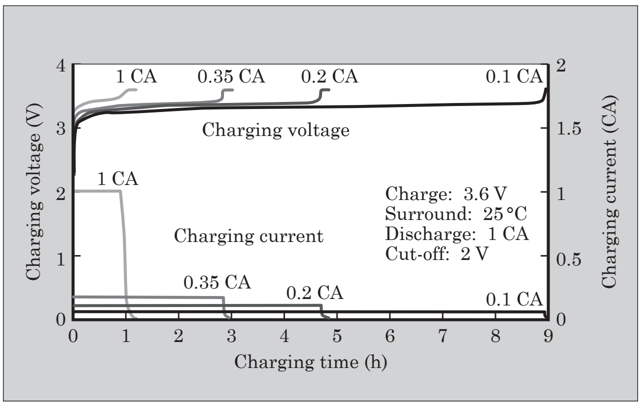


Fig.4 Charging characteristics of olivine-type lithium iron phosphate batteries

current as a parameter and charging time and shift of charging capacity can be confirmed. With this characteristic, the output capacity of the charger can be calculated from the charging time that the customer requires.

The charging characteristic of olivine-type lithium iron phosphate batteries shows an exponential voltage rise at the charging terminal stage. By determining this voltage rise as fully charged, a charging capacity approximate to 95% of the battery is made possible with the existing constant-current charging mode. In addition, because the battery is within the range of constant-current charging until it becomes almost fully charged, it becomes easy to predict the charging time from the charging rate. This is a big advantage when designing devices.

4.3 Issues of olivine-type lithium iron phosphate batteries for mounting

Compared to cobalt acid and manganese acid lithium-ion batteries, the cell voltage of olivine-type lithium iron phosphate batteries is as low as 3.2 V. In order to compensate for this lower energy density, more batteries need to be mounted (number of series connections) in a device. Therefore, the issue is to reduce the price of the UPS safety circuit and battery unit.

In addition, because of the large number of series connections, it is necessary to assume there will be an imbalance between cells. This issue of imbalance is expected to be resolved by battery management system (BMS).

5. Issues and Measures in Evaluation of Lithium-Ion Batteries

There are two issues with all lithium-ion batteries, not only olivine-type lithium iron phosphate batteries: evaluation and measures for safety, and evaluation and prediction of life.

(1) Evaluation and measures for safety

Because lithium-ion batteries have a high cell voltage, a non-aqueous organic solvent is used for the electrolyte. This is inflammable liquid classified under hazardous material Class 4 Petroleum No. 2 of the “Fire Service Act”, the same type of liquid as kerosene, light oil and xylene. Accordingly, if the battery is used incorrectly, there is a risk of catching fire and many accidents have been reported. Evaluation and measures for safety are the highest-priority issue for devices in which lithium-ion batteries are mounted.

Fuji Electric has been promoting verification of safety jointly with a battery manufacturer before these accidents began to be reported, and it complies with a common basic safety standard and has been ensuring safety for UPS by setting up our own safety standard.

The most important two items are safety in terms of short circuits within the cell and safety in terms of overcharging.

An investigation on the cause of accidents that actually occurred showed that accidents with a short circuit within the cell were caused by two overlapping factors; the primary factor was contamination, and the secondary factor was the discharge method. Because an internal short circuit is an issue concerning the battery’s main body, the battery manufacturer that is the joint developer with us has taken measures and Fuji Electric is also internally conducting a test by assuming that an internal short circuit occurs and confirming safety.

A challenge for device manufacturers is to ensure safety against overcharging, and evaluation was performed and measures were taken for safety with a single-body battery. First, it is considered that knowing the behavior of overcharging increases the safety of the device. Fuji Electric internally analyzed the behavior and mechanism of overcharging after conducting an in-house safety test and receiving advice from the battery manufacturer, and it was possible to significantly improve safety with the battery pack.

Figure 5 shows a hazardous zone in which there is a risk of causing a thermal runaway at the charging voltage and charging current of the battery pack after measures are taken, and the safe zone. Even if an abnormality occurs in the charger, if there is enough margin taken for the lower limit of this hazardous zone, it is possible to provide a safe UPS.

Electrical protection by BMS is the secondary measure, and it is important to design devices that use lithium-ion batteries with a safety margin instead of just relying on electrical measures.

(2) Prediction of life

Factors that cause degradation of secondary batteries include degradation of the active material itself, growth of electrode surface membrane, and degradation of electrolytic solution. Furthermore, the factors that accelerate degradation further are related to cell voltage, discharge depth, operating ambient temperature, number of charging and discharging times, and usage period of batteries. It depends on the intended purpose of the device and working conditions, and the materials of the battery also make the difference.

As just mentioned, while many factors are inter-

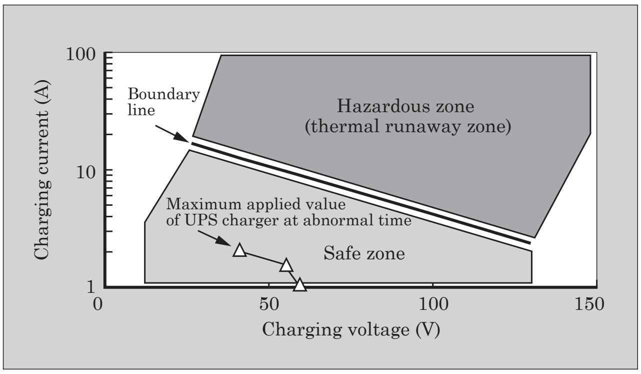


Fig.5 Safe zone of lithium-ion battery

twined, predicting degradation (life) is a big challenge. Currently, each manufacturer is narrowing down the working conditions and performing evaluations while assuming certain operating conditions.

Fuji Electric also predicts battery life based on data from a battery manufacturer and in-house life test data after UPS working conditions are narrowed down and test conditions are clarified.

Also in the future, we must have a cooperative relationship with a battery manufacturer so that we can improve our prediction accuracy. Currently, for a UPS equipped with olivine-type lithium iron phosphate batteries, we are aiming to carry out further evaluations toward commercialization while considering the above advantages and challenges.

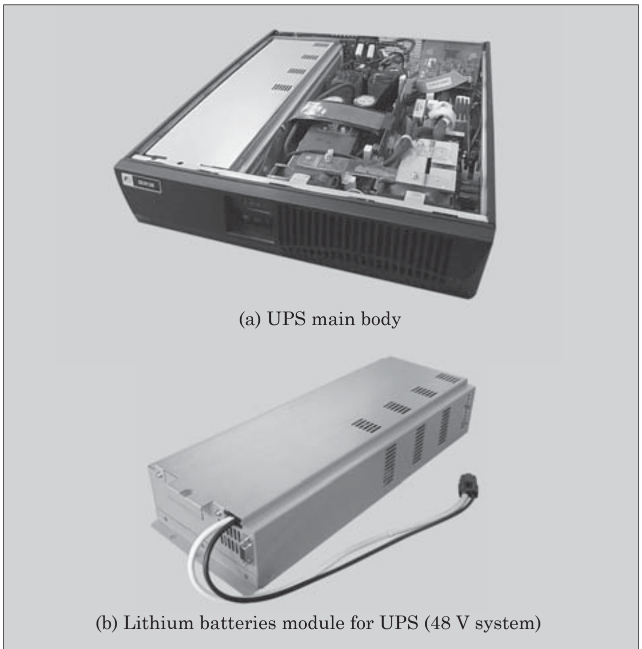
Table 4 Comparison of lead-acid battery and lithium-ion battery

Battery type		Lead-acid battery	Lithium-ion battery
Rated output capacity		1,500 VA/1,050 W	
Rated output voltage		100 (110 V, 120 V)	
Feeding system		Normally with inverter	
Outer shape		432×87×494 (mm) (2U)	
Backup time (25 °C)		6 minutes	11 minutes (83% increase)
Mass	UPS unit	22.5 kg	17.0 kg (24% decrease)
	Battery unit	11.3 kg	5.9 kg (48% decrease)
Battery replacement period (25 °C)		4.5 years	8 years or more (maintenance-free)

6. Case Example of UPS Equipped with Lithium-Ion Battery

In this section, a mini-UPS (1.5 kVA online UPS) equipped with a manganese acid lithium-ion battery, for which the same evaluation was performed as olivine-type lithium iron phosphate batteries as presented in Chapter 5, is presented as a product example (see Fig. 6).

Table 4 shows the result of comparing a lead-acid battery and manganese acid lithium-ion battery when mounted on the UPS.



(a) UPS main body

(b) Lithium batteries module for UPS (48 V system)

Fig.6 UPS equipped with lithium-ion batteries (1.5 kVA)

Compared to the existing lead-acid battery, the backup time is roughly doubled, and the mass of UPS unit decreased by 24%. In addition, the battery life became 8 years or more and maintenance-free was realized. Furthermore, considering the case where a device that can provide many hours of backup is needed, we prepared an expanded battery unit that was half as thick and wide as the main body.

Existing lead-acid batteries have a restriction on the number of battery expansions due to issues with safety and mass. Therefore, there was a limit to the number of hours of backup they could provide. Meanwhile, lithium-ion batteries are fundamentally compact and lightweight without any restriction on the number of parallel connections, and it became possible to connect expanded batteries to the UPS main body and many hours of backup became possible.

7. Postscript

This paper presented an evaluation and application technology of a new battery for UPSs. As a result of the Great East Japan Earthquake, the time has come to consider how energy ought to be and how it is used, not only within companies but also at home. With such rapid changes in the environment, we consider that a UPS that can stably supply power even during a power outage has a major role to play in contributing to society. In order to achieve such UPS, Fuji Electric intends to work on developing products that can provide improved safety and security in the future.

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