Fundamental and Advanced Technologies

Fundamental Technology
Advanced Technology

Outlook

Fuji Electric has been focusing its attention on developing overwhelming competitive components, systems and solutions that create customer value. At the same time, we are energetically researching and developing fundamental technologies that support the development of these products and advanced technologies that differentiate us from competitors.

In the field of materials technology, we are working on research and development to achieve differentiation by applying computational science to the design of insulating gases that can replace SF_6. In order to miniaturize high-voltage equipment, we are currently developing insulating materials with optimally designed permittivity using fillers and designing new materials using computational science.

In order to reduce the resistance and increase the reliability of silicon carbide (SiC) devices, we have been working to clarify their mechanism by making use of the most advanced analysis technologies and computational sciences. As a result, we have developed a molecular simulation technology for analyzing the changes in the molecular structure of materials due to reactions, and are applying it to defect analysis at the gate oxide film interfaces of a SiC-MOSFET to identify defect structures that affect performance.

We are also developing vertical MOSFETs that utilize gallium nitride (GaN) as a next-generation power device that can replace SiC. It is characterized by ion implantation based p-type formation and MOS interface control. We have established a technology for forming a flat MOS interface on the p-type (Mg) injection layer at the atomic level, and formed a vertical MOSFET structure on the GaN substrate using only ion implantation to achieve a normally-off FET.

As for SiC power electronics equipment, we have developed a modular multilevel converter (MMC) equipped with 3.3-kV SiC power devices. This converter can be interconnected with 6.6-kV power systems without the use of an interconnection transformer and achieves our target efficiency of 98.5%. Furthermore, by applying our proprietary single-phase inverter DC voltage equalization control, it can also compensate negative-sequence power.

Moreover, we have also been developing technologies to improve the reliability of high-voltage equipment. We elucidated the discharging mechanism between busbars caused by dust and created a design technology to ensure an appropriate insulation design.

In the field of thermal energy technology, we have developed a highly efficient 150 °C high-temperature steam generator that utilizes a compressor characterized by 2-stage compression. We are currently performing field tests to demonstrate its effective use of low-temperature exhaust heat.

As the use of renewable energies increases, there are concerns about the impact of lightning surge on large-scale wind power stations. In this regard, we have used the surge analysis programs developed by the Central Research Institute of Electric Power Industry to carefully ascertain the surge characteristics of wind turbines and distribution networks and have modeled the characteristics using a power system analysis program. As a result, we have established a technology for analyzing the surge of large-scale wind power generation systems with high accuracy.

In the field of control technology, we have developed a plant model based predictive control technology that is executable on edge devices. This type of control method conventionally required a high-speed computer, but we have made it possible to use it on our "MICREX-SX" programmable controller (PLC) by using mathematical formula manipulation to accelerate the algorithm.

As a means of improving development efficiency, we are adopting model-based development methods that use detailed simulations by modeling development targets from the beginning stages of development. For example, we creates the detailed models for the all components of a servo system, such as a control amplifier, motor and machine loads, and apply control amplifier models based on the results of virtual testing in simulated environments to the control programs of products.

We are also making use of advanced artificial

Intelligence (AI) technologies. We are developing an image recognition technology that uses AI to learn the characteristics of normal products on the basis of image data and classify images with different characteristics in a graded manner. We plan to apply this technology to our in-house inspection lines to automate visual sensory inspections, which depend on inspectors.

AI is also increasingly being used to diagnose abnormalities. In order to clarify the basis for determining abnormalities, we are developing AI that can quantify the impact of the anomaly to explain the cause of its occurrence.

The use of Internet of Things (IoT) technology is growing. In this respect, Fuji Electric is expanding its solutions under the keywords “Small, Quick Start & Spiral-Up” by using feature-rich field devices and advanced one-of-a-kind analysis technologies as differentiating features. In particular, we are developing technologies that provide the security measures required of embedded devices. Furthermore, in order to respond to the expanded use of wireless networks, we are currently developing technologies to efficiently deliver and automatically update the built-in firmware of wireless devices.

Recently, microservices have gained a lot of attention as a software development method. The architecture consists of multiple highly independent systems that quickly and flexibly provide a new service without impacting quality. In order to achieve this, we are developing lightweight, high-speed container-based virtualization.

In this manner, Fuji Electric provides solutions to create responsible and sustainable societies by endeavoring to create advanced technologies and thoroughly strengthening fundamental technologies that support product development.

Fundamental Technology

1 Verification and Design Technology for Dust Contamination of High-Voltage Equipment

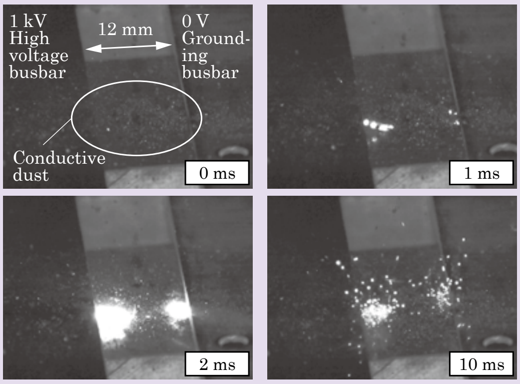
Traditionally, anti-contamination design have been based on the research of salt damage on AC distribution equipment, assuming that discharge occurred due to the water-soluble contamination of dew condensation. In order to improve the reliability of power electronics equipment used in dusty environments, we have constructed a design technology that can ensure the safety of power electronics equipment by verifying the dust contamination between busbars and appropriately providing insulating distance based on the properties of the dust.

(1) Discharge arc occurs between dust particles or busbars at time of switching even when dust does not completely bridge between busbars.

(2) Dust significantly reduces withstand voltage even in dry conditions.

(3) The voltage distribution on the insulation surface during switching changes substantially at the contaminated area or non-contaminated area, and when either of those areas exceeds its threshold, discharge occurs.

Fig.1 High-speed observation of DC discharge due to dust contamination at the insulation surface between busbars

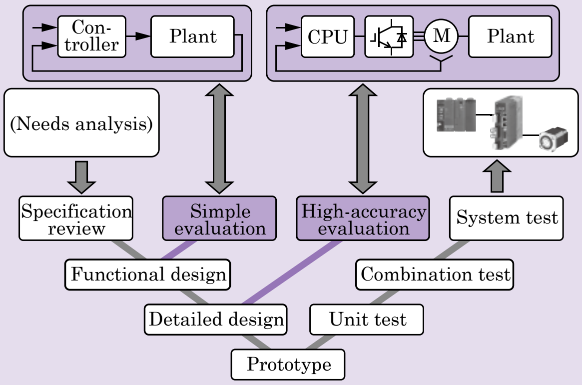


2 Product Development Using Model-Based Development Methods

The use of model-based development methods has been spreading, which uses detailed simulations by modeling products and applications from the beginning stages of development has been increasing and the adoption of model-based development methods has been spreading. Fuji Electric has also been utilizing these methods in its product development.

As an example of servo system development, we create detailed models that include operation timings for all control amplifiers, motors and machine loads and perform virtual testing in various types of simulated environments. Furthermore, we have streamlined our development and verification by applying our test-based control amplifier models to the control programs of products. In addition to servo systems, we are also applying these same development methods to the drive systems of other machinery and equipment.

Fig.2 Initiatives to develop and improve products using model-based development methods



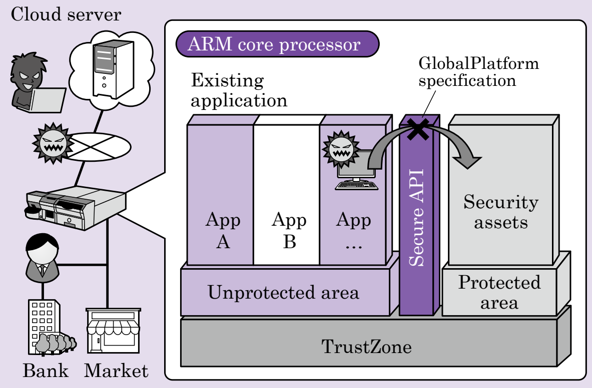
Fundamental Technology

3 Asset Protection Technology for Embedded Devices

The spread of IoT has created the need of greater security measures for embedded devices. Fuji Electric's asset protection technology delivers a secure execution environment using TrustZone, a feature of ARM core processors. The technology separates memory into protected and unprotected areas to guarantee the authenticity of data and programs stored in equipment.

Furthermore, the communication interface between the memory areas employs an API of the Trusted Execution Environment, defined by the GlobalPlatform standardization organization. This makes it easy to design secure structure and also help achieve lightweight systems through function selection.

Fig.3 Execution environment to protect information assets

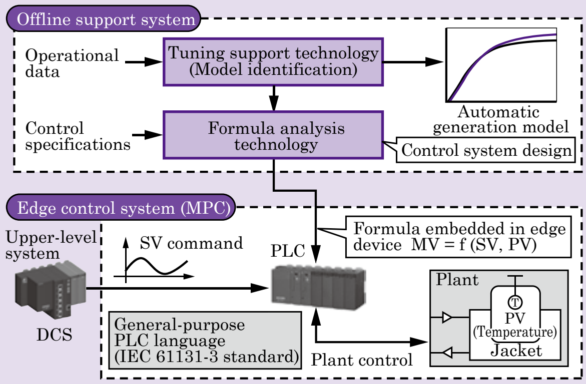


4 Model Predictive Control for Edge Devices Applicable to General-Purpose Controllers

Model predictive control (MPC) is an excellent control method that enables high-precision control while predicting future behavior using plant models. However, MPC requires high-speed computers. Therefore, in order to execute MPC on inexpensive edge devices, Fuji Electric has utilized mathematical formula manipulation to accelerate the computation. We equipped the "MICREX-SX" PLCs with the control by using a general-purpose PLC language compliant with the international standard IEC 61131-3. These industry-proven control systems can be used to achieve high-precision control of customer plants with low costs by applying following technologies:

(1) Tuning support technology to create plant models from operational data
(2) Mathematical formula analysis technology to generate optimal control formula using formula manipulation based on control specifications and plant models

Fig.4 Configuration example for edge type model predictive control

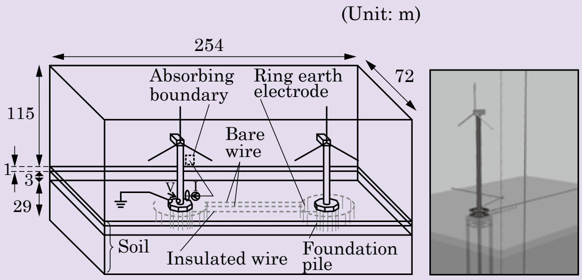


5 Lightning Surge Analysis Technology for Large-Scale Wind Power Generation Systems

Wind power generation facilities hold promise to increase in scale and deployment as a major power source. However, there are concerns about damage to wind power generation facilities due to the penetration of lightning surge. Therefore, the importance of lightning surge analysis for wind power generation systems, including power distribution networks, has been increasing.

In order to perform lightning surge analysis on large-scale wind power generation systems, Fuji Electric has been working to establish a simulation technology using surge analysis program VSTL REV, which is developed by the Central Research Institute of Electric Power Industry, and power system analysis program EMTP. This technology makes it possible to perform high-precision surge analysis on large-scale wind power generation systems by creating simplified models on EMTP from the detailed surge characteristics of windmills and distribution networks obtained using VSTL REV. This enables insulation design to be carried out using detailed lightning overvoltage estimations.

Fig.5 Example of simulation model for large-scale wind power generation system



(a) Windmill model specifications

(b) VSTL REV model

6 Wireless Firmware Update Technology

The spread of IoT is expanding the use of wireless networks for businesses and products. However, this has increased maintenance costs and maintenance periods for updating the firmware in embedded devices in order to improve functionality or fix bugs.

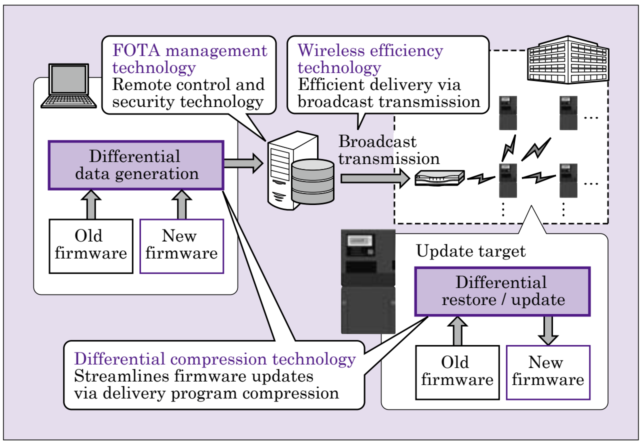
Therefore, Fuji Electric has developed the technology that efficiently distributes and automatically updates the firmware of wireless devices (FOTA: Firmware On The Air). The main features are as follows:

(1) Efficient data distribution via broadcast communications

(2) Fast update with differential compressed data distribution

In the future, we plan to upgrade FOTA to a platform and apply it to products in various business sectors.

Fig.6 System configuration for wireless firmware updates

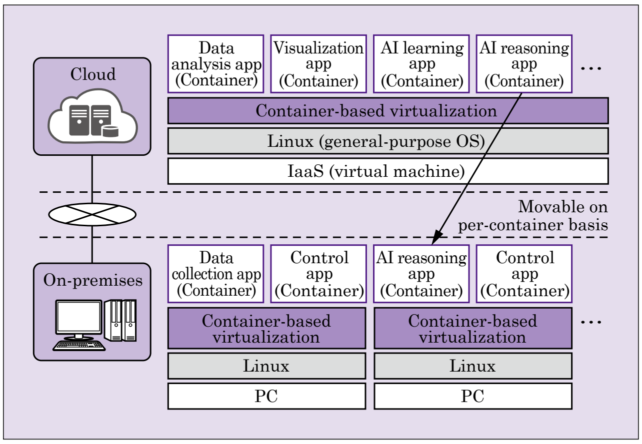


7 Container-Based Virtualization for Microservices

In software development, in order to provide new services that respond to changes in customer needs quickly without compromising quality, microservices have begun to be used, in which an application system consists of multiple highly independent services. One method of achieving microservices is to use container-based virtualization, which is lightweight (low CPU, memory and disk resource consumption) and fast (fast startup and low overhead).

Container-based virtualization can quickly respond to on-premises cloud services and edge-heavy systems that include embedded devices. It also facilitates seamless migration on a container basis and reuse of software.

Fig.7 Example of a system configuration using container-based virtualization



8 Automatic Visual Inspection Technology Using Image Recognition AI

For a traditional visual inspection of industrial products, an image processing expert created the inspection algorithm focusing on a target product by repeating trial and error. However, when there is no specific criteria to identify whether the product is normal or defective, a visual inspection needs to rely on the sensory inspection of inspectors.

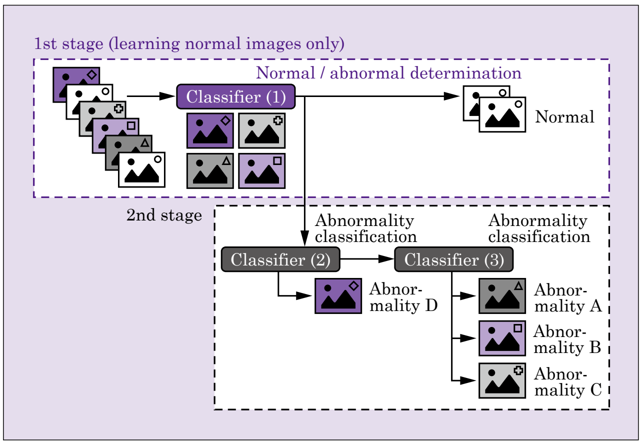
Therefore, in order to automate this sensory inspection, Fuji Electric has developed an image recognition technology using AI by following procedures:

(1) Use AI to learn the characteristics of normal product appearance images

(2) Gradually classify images having characteristics that differ from the learning results

This technology has enabled us to obtain stable inspection results during an automated visual inspection. In the future, we plan to apply this technology to our in-house inspection lines.

Fig.8 Example of image recognition AI detection flow

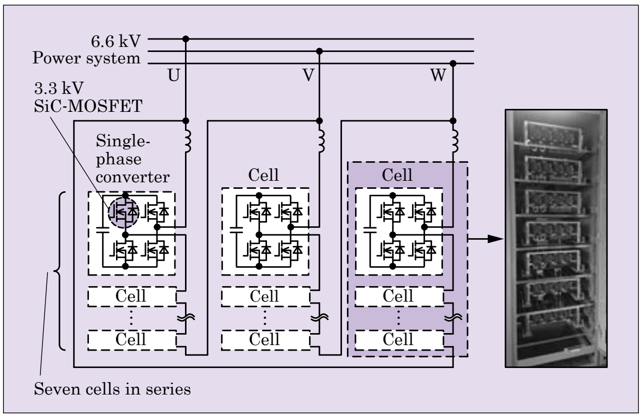


Advanced Technology

1 6.6-kV Transformerless Power Converters

Fuji Electric participated in the “Next-Generation Power Electronics” project of the Strategic Innovation Promotion Program (SIP) promoted by the Council for Science, Technology and Innovation of the Cabinet Office, and it has developed a modular multilevel converter (MMC) type power converter that can directly connect to the 6.6-kV power grid without using an interconnection transformer. In FY2018, we conducted in-house demonstration tests with a 200-kVA test converter and achieved our goal of 98.5% efficiency (power loss: less than a half of that of previous products). The converter comes with 3.3-kV SiC power devices to achieve high efficiency. Furthermore, by using our proprietary DC voltage balancing control for converter cells (single-phase converter), it is possible to compensate negative-sequence power as well as leading and lagging reactive power. In the future, we plan to apply this technology to 10-MVA class reactive power compensators and flicker compensators.

Fig.9 Overall circuit configuration and general view of the MMC demonstration test equipment



2 High-Temperature Steam Generation Heat Pump Recovering Waste Heat

Fuji Electric is developing the industry’s first high-temperature steam generating heat pump capable of generating 150 °C steam. We have participated in a NEDO project since 2015 and have recently been performing the field tests of the heat pump at our Yamanashi Factory. The main features of the heat pump are as follows:

(1) Efficiently generates 150 °C saturated steam by recovering waste heat with a temperature of lower than 100 °C, which has previously been unused.
(2) Achieves the industry’s highest class coefficient of performance (COP) of 3.4 by using a scroll compressor that can perform 2-stage compression with a single unit.
(3) Uses a new refrigerant with a global warming potential (GWP) of 2 in consideration of the global environment.

Fig.10 Steam generation heat pump under field testing

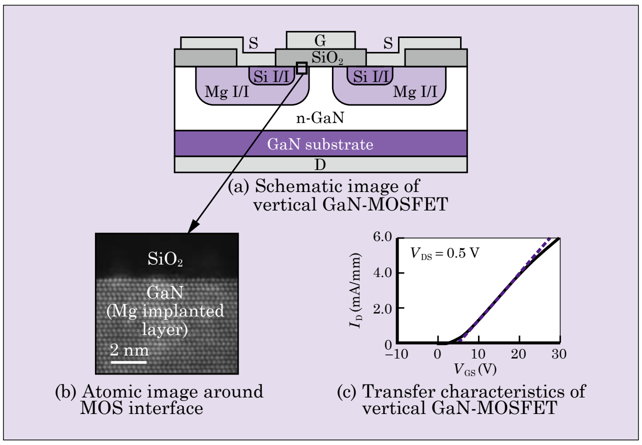
3 Vertical GaN-MOSFETs Fabricated by Ion Implantation

Vertical MOSFETs using gallium nitride (GaN) [see Fig. 11(a)] are expected to become next-generation power switching devices featuring lower loss than those using silicon carbide (SiC). In terms of cost and reliability, formation of p-type layers by ion implantation (I/I) and control of MOS interface are important to realize GaN devices.

Fuji Electric has established a technology for forming a flat MOS interface at the atomic level on the p-type (Mg) implanted layer [see Fig. 11(b)] to control channel characteristics (mobility >100 cm^2/Vs at threshold voltage >3 V). By using this technology, we formed ion implantation based vertical GaN-MOSFET structure on the freestanding GaN substrate and demonstrated normally-off FET operations [see Fig. 11(c)].

We plan to continue improving the characteristics so that we can achieve device characteristics that exceed SiC-MOSFETs.

Fig.11 Structure and electrical properties of vertical GaN-MOSFET



(a) Schematic image of vertical GaN-MOSFET

(b) Atomic image around MOS interface

(c) Transfer characteristics of vertical GaN-MOSFET

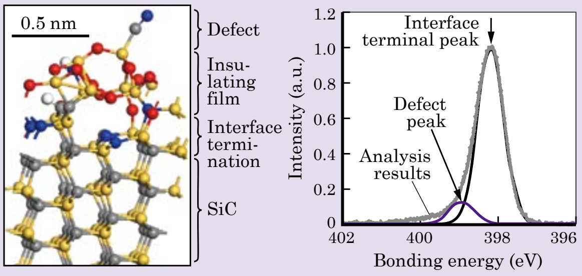
4 Reaction Analysis of SiC-MOSFET Interfaces Using Molecular Level Computation

One of the major factors in device performance degradation is reactions on a surface or at an interface of materials. In order to elucidate the reactions, we developed a molecular simulation technology to analyze the changes in the molecular structure of materials due to reactions. We applied this technology to the defect analysis for gate oxide film interfaces, which are responsible for the mobility reduction in SiC-MOSFETs.

Analyzing the formation of gate oxide film by calculating the reaction between the SiC and process gas, we successfully reproduced the interface termination and defect structure obtained by photoelectron spectroscopy.

With a detailed analysis, we identified the defect structure that causes mobility degradation. In the future, we will work to discover gas conditions to avoid defect generation so that we can improve the mobility of SiC-MOSFETs. This technology is also widely applicable to other materials such as metals and resins.

Fig.12 Reaction simulation and analysis between SiC and process gases



(a) Simulation (b) Photoelectron spectroscopy

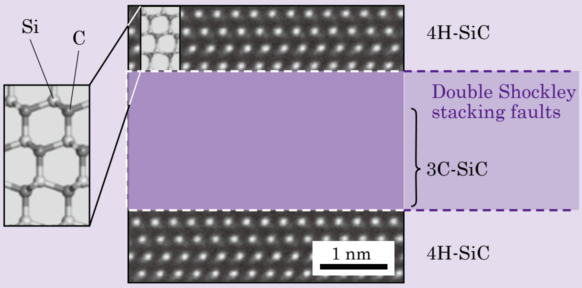
5 Structural Evaluation Technology for Stacking Faults on 4H-SiC Substrates

In order to improve the reliability of SiC-MOSFETs, carefully evaluation is needed for the structure of crystal defects in SiC substrates to elucidate the mechanism that generates the defects.

Fuji Electric has developed an analysis technology for evaluating the structure of crystal defects in SiC substrates at the atomic level. This analysis technology utilizes various analysis methods, such as spherical aberration corrected scanning transmission electron microscopy (Cs corrected STEM) with a spatial resolution at the atomic level.

AS a SiC-MOSFET specimen, we used an SiC substrate with a 4H crystal structure. Under certain manufacturing conditions, we have found that crystal defects, referred to as a double Shockley stacking fault containing a 3C structure, occur in SiC substrates. These crystal defects affect electrical characteristics. We used these findings to improve manufacturing conditions so that we could improve the reliability of SiC-MOSFETs.

Fig.13 Atomic level image of SiC stacking fault cross-section captured by scanning transmission electron microscope



Fuji Electric

Innovating Energy Technology