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# Mitsubishi Electric ADVANCE

## Factory Automation

Changes for the Better

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Mitsubishi Electric ADVANCE

Factory Automation



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# CONTENTS



**Precis**

Mitsubishi Electric Corporation has been contributing to manufacturing around the world and striving to become the leading FA supplier chosen by customers, by providing its integrated FA solution, e-F@ctory, underpinned by advanced technologies and outstanding quality.

This issue introduces our latest FA products that support e-F@ctory.

(1) The FR-E800 Series of next-generation, compact, high-performance general-purpose inverters. The series is helping to make various sectors such as factories and social infrastructure equipment more intelligent by using the latest technologies, including support for multi-networking, including CC-Link IE TSN, a next-generation industrial open network.
(2) The MELFA ASSISTA collaborative robot. This robot can be intuitively manipulated, making it easier to introduce into manufacturing sites, assisting customers in flexibly adapting to the changing business environment, and reducing total cost of ownership (TCO).
(3) The GX-F Series, a new type of two-dimensional fiber laser processing system. We have improved the processing stability and productivity by focusing on reliability, high-speed processing, low running cost, complete automation, and labor saving in the development.

# Overview

Author: *Yoshikazu Miyata**

## Continuous Evolution of FA Solutions - History and New Initiatives -

Recent issues in the manufacturing industry include labor shortages due to the declining birthrate and aging population, handing down of skilled workers' techniques and expertise, and coping with uncertainty. In the last two years, in addition to trade friction, the manufacturing industry was affected by the global spread of COVID-19. Protectionist measures and restrictions on people's movement caused rapid changes to supply chains, business models, and workstyles. We have learned that the unexpected can happen suddenly.

In recent years, the terms "Internet of Things (IoT)" and "digital transformation (DX)" have gained increasing attention. Mitsubishi Electric Corporation noticed the importance of linkages between FA and IT as components advanced. In 2003, before these terms became common, we started proposing manufacturing reform through "e-F@ctory."

In e-F@ctory, accumulated know-how is used to increase productivity, quality, and efficient use of energy to reduce the total cost for development, production, and maintenance. For such linkage between FA and IT, devices are needed to collect and process appropriate data from actual manufacturing sites at appropriate times, as well as systems to use the data.

Our Field Network CC-Link for FA was developed to satisfy the need for wire-saving at first. It was later developed into CC-Link IE Time Sensitive Networking (TSN)*[1] which has been contributing to DX at manufacturing sites as an open global standard.

Regarding elemental technologies, we have been working on automation by merging digital technologies with technologies originating at manufacturing sites required to link, process, and control every type of data at the sites. We have also been working to actively use IoT, robots, AI, the 5th generation mobile communication system (5G), etc.

Our objectives are to achieve: cooperation between humans and robots and labor-saving by using the collaborative robot MELFA ASSISTA; good use of compact AI technology Maisart,*[2] which can be incorporated into devices, for real-time data analysis, diagnosis, and processing; and application of 5G to augmented reality (AR), virtual reality (VR), automated guided vehicles (AGVs), and flexible factory layout.

In addition, in order to achieve the Sustainable Development Goals (SDGs), we use FA and AI technologies to improve productivity, develop convenient working environments, promote sustainable industrialization, expand technological innovation, and secure sustainable production and consumption forms.

Through such efforts to create and support new forms of production and a low-carbon society, we will help build a society where companies and humans are linked, overcoming restrictions of time and space.

[1] CC-Link IE TSN https://www.cc-link.org/ja/cclink/cclinkie/cclinkie_tsn.html
[2] Abbreviation of "Mitsubishi Electric's AI creates State-of-the-ART in technology"

*Senior Adviser

# Next-Generation Compact and High-Performance Inverter "FREQROL – E800 Series"

Authors: *Tomohiro Nimura** and *Takahiro Harada***

## 1. Introduction

The FR-E800 series with higher functionality and performance satisfies new needs such as compatibility with the IoT, easier maintenance, functional safety, compatibility with systems, and environmental adaptability in order to increase the application of general-purpose inverters.(1) This paper describes the latest technologies and functions of the FR-E800 series.

## 2. FR-E800 Series

### 2.1 Models

Several FR-E800 series models with various specifications are available: standard specification, Ethernet specification, and safety communication specification. Customers can select suitable ones flexibly based on the purpose of use (Table 1).

### 2.2 Increase in the number of product types

The capacity of three-phase 200-V/400-V classes was increased to 22 kW (that of the existing FR-E700 series is 15 kW at maximum). Compared to the FR-A800 series having the same capacity, the size was reduced by 20%, saving the space occupied by the devices. In addition, a 575-V class was added to improve the compatibility with systems for overseas power supply specifications (Table 2).

Table 1 Models and main specifications of the FR-E800 series

| Model | Specification | Communication connector | Safety integrity level | Safety communication |
|---|---|---|---|---|
| FR-E800 | Standard specification | RS485 | SIL2, PLd | - |
| FR-E800-E | Ethernet specification | Ethernet (two ports) | SIL2, PLd | - |
| FR-E800-SCE | Safety communication specification (Ethernet + Safety communication) | | SIL3, PLe | Supported |

Table 2 Voltage class and rated capacity range of FR-E800 series

| Power supply specification | Voltage class | Capacity [kW] |
|---|---|---|
| Three-phase | 200 V | 0.1–22 |
| | 400 V | 0.4–22 |
| | 575 V | 0.75–7.5 |
| Single-phase | 200 V | 0.1–2.2 |
| | 100 V (sale planned) | 0.1–0.75 |

*Nagoya Works **Overseas Marketing Div.

## 3. The IoT Era

### 3.1 Provision of CC-Link IE TSN as a standard feature

The FR-E800 series comes with CC-Link IE Time Sensitive Networking (TSN) as a standard feature. High-speed, stable communications allow production site data to be collected in real time, contributing to higher productivity.

### 3.2 Support for multiple protocols

Some FR-E800 series models support the main industrial Ethernet protocols (Table 3). The protocol to be used can be switched by parameter setting, enabling inverters to be introduced as needed for networks in use without additional options.

### 3.3 Provision of two Ethernet ports as a standard feature

The new series has two Ethernet ports as a standard feature, enabling line wiring without switching hubs. When the specification is changed such as adding a device, it is possible to easily establish a network simply by connecting a cable to an available port.

## 4. Maintenance Functions

### 4.1 AI fault diagnosis

The FR-E800 series automatically stores data (e.g., time, current value, and parameter setting values) when an alarm is issued. An engineering tool, FR Configurator2, employing AI technologies can be used to perform AI analysis of such data like development engineers do (Fig. 1). This enables rapid troubleshooting without special skills.

Table 3 Supported Ethernet protocols

| Model | CC-Link IE TSN (100Mbps)[*1] | CC-Link IE Field Network Basic[*2] | MODBUS /TCP[*3] | PROFINET[*4] | EtherNet/IP[*5] | BACnet/IP[*6] | EtherCAT[*7] |
|---|---|---|---|---|---|---|---|
| FR-E800-[]EPA | ● | ● | ● | - | ● | ● | - |
| FR-E800-[]EPB | ● | ● | ● | ● | - | - | - |
| FR-E800-[]EPC | - | - | - | - | - | - | ○ |

●: Supported, ○: To be supported in the future

[1] 1 Gbps will be supported in the future as an option.
[2] "CC-Link IE Field Network Basic" is a registered trademark of the CC-Link Partner Association.
[3] "MODBUS" is a registered trademark of Schneider Automation Inc.
[4] "PROFINET" is a trademark or registered trademark of PROFIBUS & PROFINET International.
[5] "EtherNet/IP" is a registered trademark of Open DeviceNet Vendor Association, Inc. (ODVA).
[6] "BACnet" is a registered trademark of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).
[7] "EtherCAT" is a trademark of Beckhoff Automation GmbH.

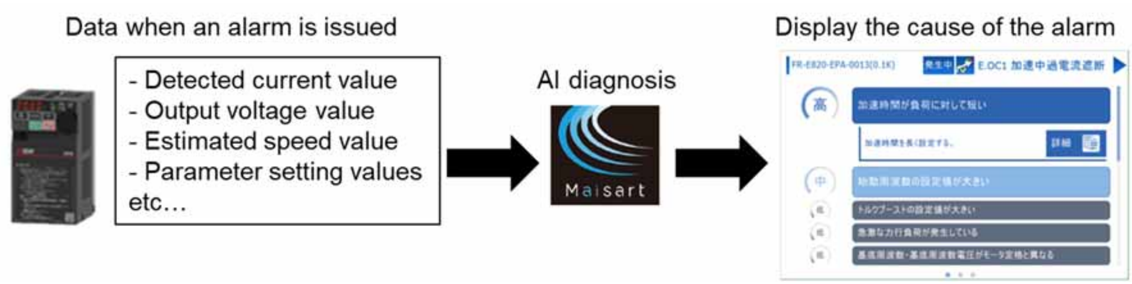


Fig. 1 Overview of AI fault diagnosis

### 4.2 Corrosion-Attack-Level Alert System (CALAS)

The world's first[*1] Corrosion-Attack-Level Alert System (CALAS) can detect signs of damage to inverters caused by corrosive gas (Fig. 2). The system measures the combined resistance value from multiple metal corrosion sensors and senses the degree of corrosion of metal parts due to corrosive gas in the air in stages.

Through such detection of signs of damage, users are encouraged to improve the environment of the production equipment, which helps reduce equipment downtime (provided only on products having coated boards).

### 4.3 Power cycle life diagnosis

The technology used to estimate the temperature of semiconductor chips installed on inverter modules has been improved, making it possible to understand the difference in temperature between heating and cooling with high accuracy. This enables power cycle life diagnosis of modules (Fig. 3). If the life falls below the specified value, a warning signal is output, contributing to predictive maintenance of equipment and more stable operation.

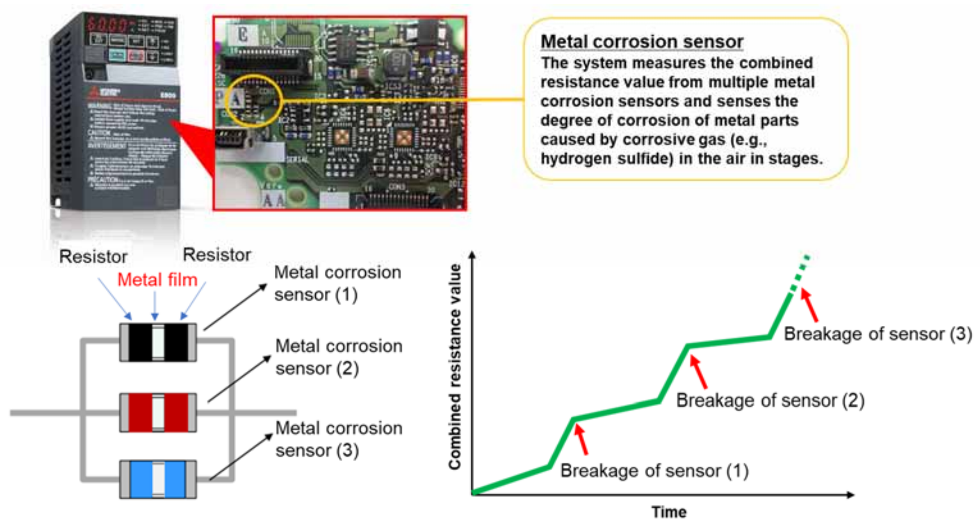


Fig. 2 Overview of Corrosion–Attack–Level Alert System

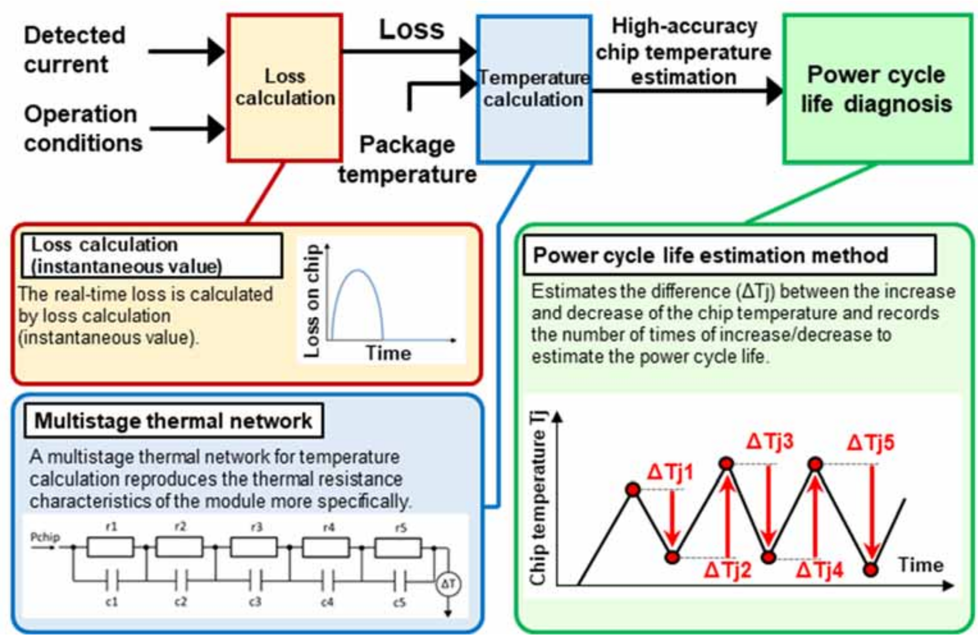


Fig. 3 Power cycle life diagnosis

[1] As of September 10, 2019, researched by Mitsubishi Electric Corporation

### 4.4 Maintenance through power supply from USB

Through power supply from a PC (USB bus powered), even when the main circuit is off, FR Configurator2 can be used to set parameters (Fig. 4), enabling quick and safe maintenance.

## 5. Functional Safety

### 5.1 Compliance with functional safety standards

The FR-E800 series satisfies functional safety standards (e.g., IEC61508 and SIL3) (Table 4), thus reducing the cost of introducing safety certifications. The series supports safety monitoring function standards (IEC61800-5-2), such as safe torque off (STO) and safely limited speed (SLS), contributing to reducing the number of external devices and maintenance time.

### 5.2 Safety communication functions

The FR-E800-SCE supports Ethernet-based safety communication functions approved by international standards (Table 5). Safety signals can be input via networks, which can reduce the number of wires and I/O devices.

The FR-E800-SCE supports the CC-Link IE TSN safety communication function and many other safety communication protocols, which makes it easier to expand safety control systems that match the networks in use.

### 5.3 SLS function without encoders

The FR-E800-SCE employs a speed monitoring circuit that has been certified by functional safety standards and thereby supports the safely limited speed (SLS) function without encoders (Fig. 5). By eliminating the need for encoders, speed monitoring systems can be established with less wiring at lower cost.


Fig. 4 Power supply from USB port

Table 4 Safety standards compliance of the FR-E800 series

| Model | Safety monitoring function | Safety integrity level |
| --- | --- | --- |
| FR-E800<br>FR-E800-E | STO | SIL2, Cat.3, PLd |
| FR-E800-SCE | STO, SS1, SBC, SLS, SSM | SIL3, Cat.3, PLe |

Table 5 Supported safety communication functions

| Model | CC-Link IE TSN safety communication function | PROFIsafe*1 | CIP Safety*2 | FSoE (Safety over EtherCAT) *3 |
| --- | --- | --- | --- | --- |
| FR-E800-[]SCEPA | ● | - | ● | - |
| FR-E800-[]SCEPB | ● | ● | - | - |
| FR-E800-[]SCEPC | - | - | - | ○ |

●: Supported, ○: To be supported in the future

[1] “PROFISafe” is a registered trademark of Siemens Aktiengesellschaft.
[2] “CIP safety” is a registered trademark of ODVA.
[3] “Safety over EtherCAT” is a registered trademark of Beckhoff Automation GmbH.

## 6. Compatibility with Systems

### 6.1 Provision of two ratings (light duty and normal duty)

Thanks to improvements in the thermal design technologies, the models with the three-phase power input specification provide two ratings: light duty (LD) and normal duty (ND), for which the rated current and overcurrent capability vary (Table 6).

In an application in which no overload is required, smaller inverters can be selected based on the LD rating (for example, a 22-kW inverter can drive up to a 30-kW motor at the LD rating).

The rating can be switched simply by a parameter setting, which is useful when equipment specifications change, and also enables stock to be shared.

### 6.2 Model with highly protective structure (IP67) installable on outside panels

We are planning to add a new model with a highly protective structure (IP67) to our lineup, which can be used in severe environments (humid or dusty environments). The new model of inverter contains built-in peripheral devices (e.g., disconnect switch, electromagnetic compatibility (EMC) filter (class C2), and communication options) and so can be installed outside a panel. This reduces the number of wires by systematic distribution of lines, saves space, and ensures safe communications for systems.

### 6.3 Excellent drive performance

For the first time in our compact inverters, the FR-E800 series supports vector control (vector control with encoders) and real sensorless vector control (vector control without encoders) (Tables 7 and 8). The series also supports premium efficiency motors and PM motors, and can be used in drive operations involving various solutions. In addition, the series supports high-speed operation for machining tools where precise machining (e.g., mirror planes) is required.

## 7. Environmental Adaptability

### 7.1 Model having coated boards (conforming to 3C2)

For use in corrosive environments, we have added a standard model having coated boards that conforms to environmental standards (IEC60721–3–3 3C2) to our lineup.

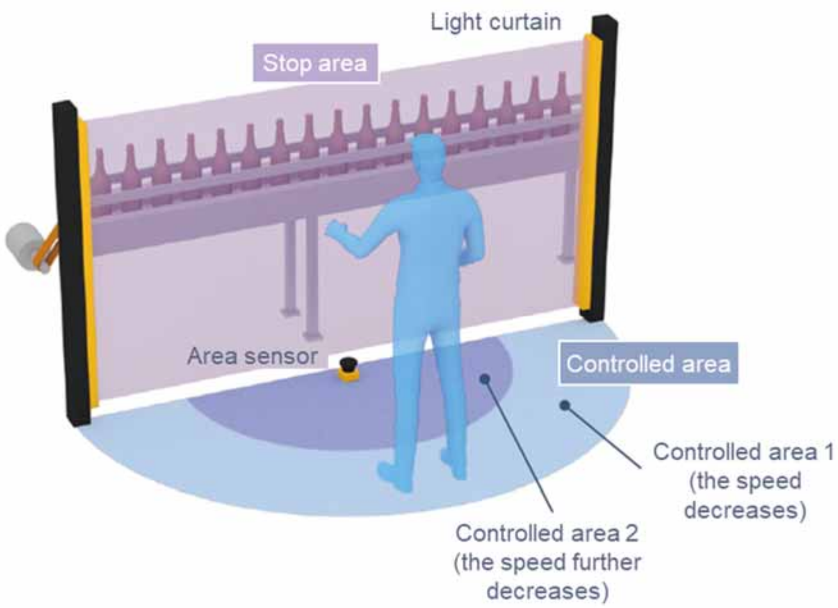


Fig. 5 Example of application of SLS function

Table 6 Multiple rating specification

| Load | Rating | Rated overload current |
|---|---|---|
| Light load | LD | 120% 60 s, 150% 3 s (inverse-time characteristic)<br>Ambient temperature: 50°C |
| Normal load | ND | 150% 60 s, 200% 3 s (inverse-time characteristic)<br>Ambient temperature: 50°C |

Table 7 Performance specifications of the FR-E800 series

| Item | | FR-E700 | FR-E800 |
|---|---|---|---|
| Control methods | V/F control | ● | ● |
| | Advanced magnetic flux vector control | ● | ● |
| | Real sensorless vector control | - | ● |
| | Vector control | - | ● |
| | PM sensorless vector control | - | ● |
| Control modes | Speed control | ● | ● |
| | Torque control | - | ● |
| | Position control | - | ● |
| Output frequency | V/F control | 0.2–400 Hz | 0.2–590 Hz |
| | Other than V/F control | | 0.2–400 Hz |

●: Supported, -: not supported

Table 8 Vector control specifications of the FR-E800 series

| Item | | Description |
|---|---|---|
| Speed control | Speed control range | 1:1500 (for both powering and regeneration) *1 |
| | Speed variation | ±0.01% (at 300 r/min) |
| | Velocity response | 30 Hz |
| | Maximum speed | 400 Hz<br>(However, the number of PLG pulses is 102,400 pulses/s or smaller.) |
| Torque control | Torque control range | 1:50 |
| | Absolute torque accuracy | ±10%*2 |
| | Repeat torque accuracy | ±5%*2 |
| Position control | Repeat positioning accuracy | ±1.5° (motor shaft end) |
| | Positioning feedback pulse | The number of PLG pulses per rotation of motor (Pr.369) × 4 multiplication |
| | Electronic gear setting | 1/900–900 |
| | Positioning completion width | 0–32767 pulses |
| | Excessive error | 0–400K pulses |

PLG: PuLse Generator

1 For regeneration, an optional regeneration unit is required.
2 At the rated load of a vector control motor

### 7.2 Usable up to 3,000 meters above sea level

The insulation distance design conforming to IEC61800-5-1 (overvoltage category III) allows the FR-E800 series to be installed up to 3,000 meters above sea level*2 (the FR-E700 series can be used up to 1,000 meters).

### 7.3 Expansion of the ambient temperature range (−20 to +60°C)

Thanks to improvements in the controlled power source and thermal design technologies, the adaptable ambient temperature range was expanded to −20 to +60°C*3, allowing the FR-E800 series to be used in more diverse environments than existing models (the FR-E700 series can be used at −10 to +50°C).

## 8. Conclusion

This paper described the latest technologies applied to the next-generation compact high-functionality inverter FR-E800 series and the specifications. We will continue developing products with higher functionality and added value.

## References

(1) Tetsuo T., et al.: Next-Generation High Performance Inverter “FREQROL–A800 Series,” Mitsubishi Denki Giho, 88, No.4, 245–248 (2014)

2 The three-phase 575-V class can be installed up to 2,000 meters above sea level. When installing the products more than 1,000 meters above sea level, the current needs to be reduced.

3 The three-phase 575-V class can be used at −10 to +60°C. When the ambient temperature is 50°C or higher, the current needs to be reduced.

# Collaborative Robot "MELFA ASSISTA"

Authors: *Daisuke Terada**

## 1. Introduction

At many manufacturing sites including automobile and electric/electronic part production sites, the demand for automating production lines using robots has been increasing year by year due to labor shortages and rising labor costs. However, mid-ranking manufacturers which do not have enough robot engineers have been unable to introduce many robots, hindering system design and start-up.

In recent years, collaborative robots that can be easily introduced into existing systems without safety fences and that work with humans have become standardized, allowing any workers, even those who are not robot engineers, to easily perform start-up. Collaborative robots are expected to be actively used in various applications and fields of business.

To satisfy such market needs, Mitsubishi Electric Corporation has developed a collaborative robot, MELFA ASSISTA, to allow a production area to be shared between humans and robots without safety fences, enable humans to be replaced easily with robots, and simplify system design and start-up. This paper describes the main characteristics of MELFA ASSISTA.

## 2. Characteristics of MELFA ASSISTA

### 2.1 Safety measures to allow MELFA ASSISTA to work together with humans

MELFA ASSISTA is a vertical 6-axis collaborative robot that can work with humans in the same area without a safety fence and that can carry 5-kg objects. It is highly safe thanks to the arm design and conformance to functional safety standards as described below.

#### 2.1.1 Arm design

Without safety fences, robots may come into contact with humans during operation. Accordingly, MELFA ASSISTA is designed with a rounded shape to reduce collision forces in case of collision with humans. In addition, the joints of the robot are designed with spaces to prevent a person's fingers and hands from becoming caught upon touching the robot arm.

To allow humans and robots to work together in the same area, it is also important for humans to understand the status of the robots. An LED light on top of the robot arm shows the operation status to nearby workers, so humans can work with the robot without anxiety. Figure 1 shows the arm, which is designed to ensure safety.

#### 2.1.2 Functional safety conforming to ISO/TS 15066

MELFA ASSISTA conforms to international standards ISO 10218-1 and ISO/TS (Technical Specification) 15066 and has been certified by an international third-party certification authority for functional safety standards. An example of one functional safety measure is the torque monitoring function (safe torque range (STR)), which detects a collision with the robot arm during start-up and automatic operations and stops it. The safety monitoring function eliminates the need for safety fences and enables manual human operations to be replaced easily by robots, while requiring only the same area (Fig. 2).

### 2.2 Easier manipulation

When introducing a robot, teaching operation is required, in which a teaching box is manipulated to teach the robot the positions to move to. MELFA ASSISTA has operation buttons on the arm as well as a direct teaching function, thus eliminating the conventional need for a teaching box to manipulate robots. The buttons also make it possible even for inexperienced robot operators to perform teaching quickly.

Fig. 1 Arm design for safety

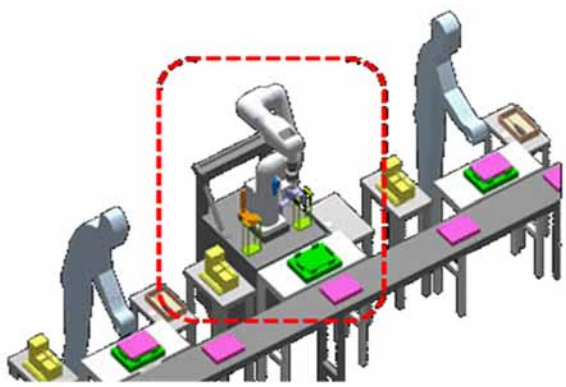

Fig. 2 Elimination of safety fence by functional safety

*Nagoya Works

### 2.2.1 Operation buttons on the arm

MELFA ASSISTA has operation buttons on the robot arm. These buttons can be used to start and stop program operation, eliminating the need for a teaching box and other external control devices. In addition, when creating a robot program, the buttons can be used for teaching, hand opening/closing, hand alignment (the arm end of a robot is made vertical or horizontal), and direct teaching. This allows a robot program to be created with fewer steps.

### 2.2.2 Direct teaching function

The direct teaching function allows an operator to directly push and pull a robot arm to manipulate it and teach behavior. This function is essential to enable collaborative robots to be introduced easily without using a teaching box. MELFA ASSISTA is the first to employ this direct teaching function (Fig. 3). Collaborative robots of other manufacturers typically use torque sensor information to realize a direct teaching function. However, MELFA ASSISTA uses only servo control, not torque sensors, to realize this function. Therefore, no torque sensor needs to be installed in arms, and so wiring and piping can be routed inside arms as described in 2.4.1, and robots can be introduced more easily. The characteristics of the direct teaching function are described below.

(1) Intuitive manipulation

Conventionally, a teaching box or other external control device is required to manipulate a robot. The MELFA ASSISTA robot, thanks to its direct teaching function, can be intuitively manipulated to a desired posture without using an external control device. This reduces the time required for teaching by half or less compared to existing models. In addition, the robot can be easily manipulated without connecting an external control device in various cases, such as when the arm end is directed upward to install a hand or when a robot arm is temporarily removed for maintenance of peripheral equipment.

(2) Three modes of operation

Vertical 6-axis robots offer great flexibility, and so to set them to a desired posture, it used to be necessary to operate an external control device while paying attention to the coordinate system. The direct teaching function on MELFA ASSISTA has three modes of operation as described below; operators can easily set the robot to a desired posture by switching the mode based on the purpose without considering the coordinate system (Fig. 4).

(i) Flexible joint mode

Each axis can be moved to any angle.

(ii) Translation mode

The arm end can be moved while maintaining the same orientation, and thus the hand can be moved in a constant posture.

(iii) Rotation mode

The arm end can be rotated and thereby the arm posture can be changed without moving the hand position.

(3) Safety

To prevent a worker from accidentally starting program operation from the outside when another worker is performing direct teaching, the operation authority can be held using the operation buttons on the arm. Thus, MELFA ASSISTA has a function that allows operators to perform direct teaching safely.

## 2.3 Easier programming

With conventional industrial robots, to program a target behavior, technical knowledge of robots was required. Meanwhile, MELFA ASSISTA is intended for new users who have no such technical knowledge. Therefore, to allow anyone to use our robots easily, we have developed robot engineering software, RT VisualBox, for MELFA ASSISTA. The software performs robot behavior, such as look, take, and carry, through intuitive screen operations using visual programming, interactive initial setting, and vision setting, eliminating the need for technical knowledge of robots.

Fig. 3 Direct teaching

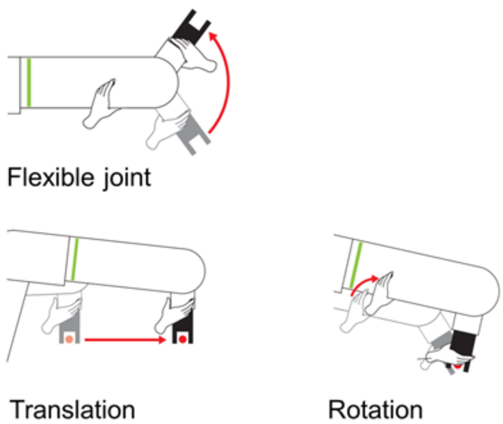


Fig. 4 Three modes of operation

### 2.3.1 Visual programming

A special programming language, MELFA BASIC, is used to program and operate our industrial robot MELFA FR Series.(1) This requires an understanding of the language specifications and special commands. To help users perform programming without acquiring technical knowledge, RT VisualBox provides command blocks for special commands. Programming involves two steps: selecting a block for target behavior from the block group, and placing it by drag-and-drop. These steps are repeated to create a program. In addition, a detailed setting screen is provided for each command block and a command can be specified in detail on this screen. Because the MELFA ASSISTA is for users who have not used robots before, only 10 command blocks for basic operation commands, such as move, hand open/close, signal output, and divergence, are provided, thus simplifying operation programming. Figure 5 shows a programming screen.

Fig. 5 Programming screen

### 2.3.2 Interactive easy setting

To allow MELFA ASSISTA to work in the environment (e.g., installation orientation and installed hand) of each user, it is necessary to set parameters appropriately for the environment, and so a scheme is provided to assist such setting. When RT VisualBox is connected to MELFA ASSISTA for the first time, an interactive initialization screen is displayed; entering and setting values according to instructions completes the necessary setting (Fig. 6). For example, when a hand installed by the user is selected on the hand selection screen, the parameters for the hand specification are set automatically. This makes it easier to specify the various settings based on which the robot behaves.

In addition, work recognition and holding operation using a vision sensor can be made only by performing setting according to instructions displayed on the vision setting screen (Fig. 7). Conventionally, engineering software dedicated to vision sensors needed to be used for setting and programming, making it necessary to use and switch two types of software (robot engineering software and vision sensor engineering software) to make adjustments. When RT VisualBox is combined with our vision sensor MELSENSOR, RT VisualBox alone is enough for vision sensor recognition setting/adjustment and robot operation programming using the vision. This reduces the work hours for start-up.

For complicated programming and detailed setting, the existing robot engineering software RT ToolBox3 for the MELFA FR Series can also be used.

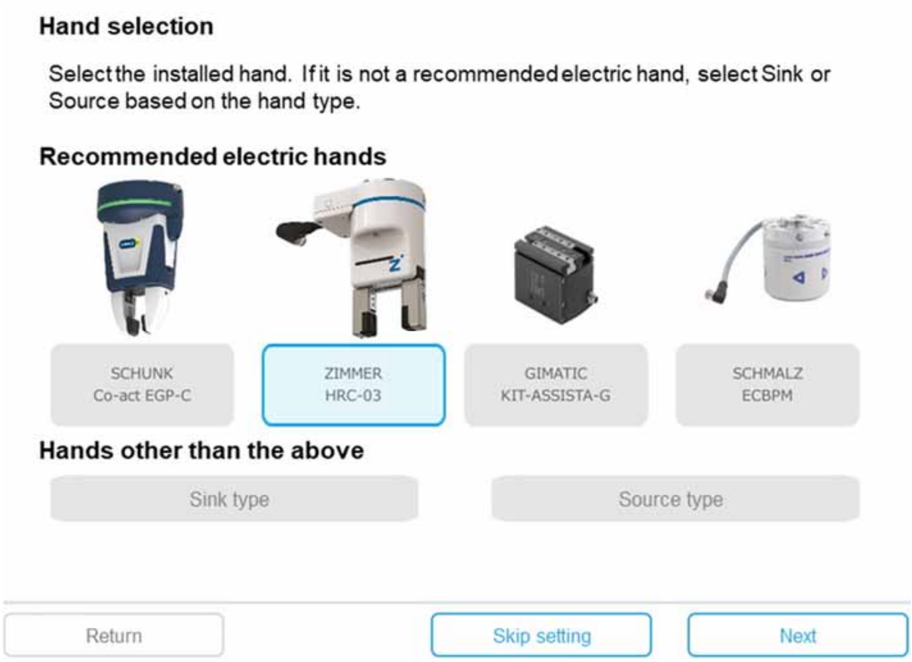


Fig. 6 Initialization screen

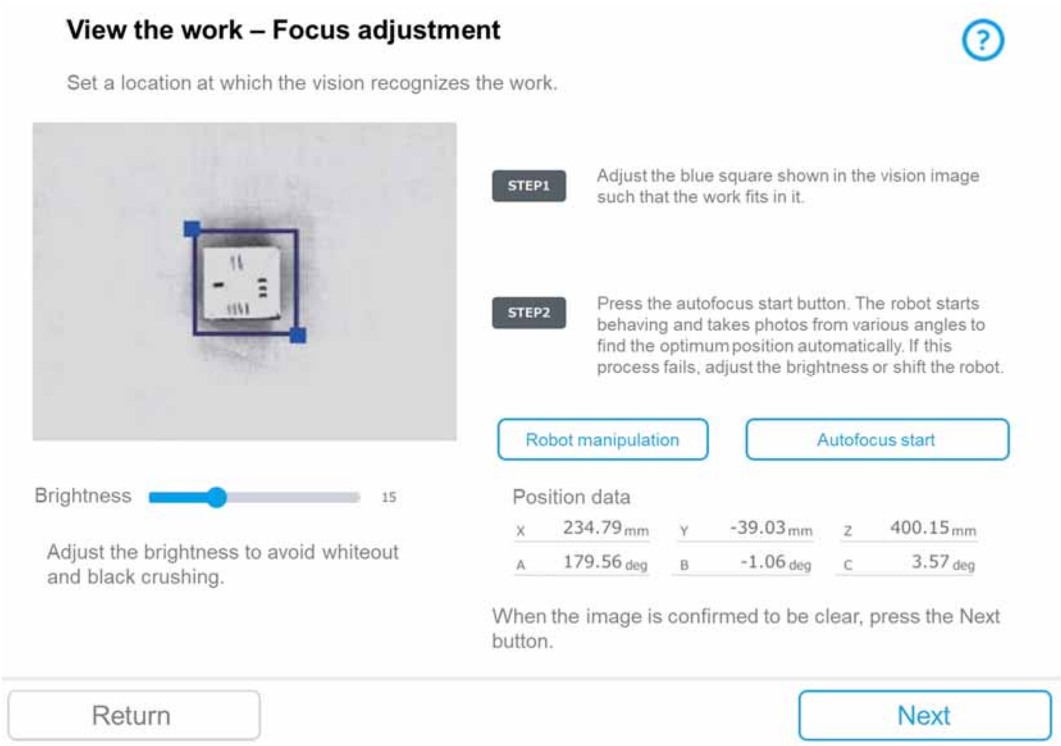


Fig. 7 Vision setting screen

### 2.4 Easier introduction

Because a robot needs to be installed as part of a system, it must be easy to start up not only the robot but also the system. The mechanism and scheme described below are provided to make it easy to introduce MELFA ASSISTA.

#### 2.4.1 Wiring and piping in arms

To have robots perform various tasks, an electric hand, air hand, and vision sensor need to be attached to a robot depending on the purpose. MELFA ASSISTA contains the wires and pipes required to control them in the robot arm, which makes it easy to connect a hand and sensor to the robot.

#### 2.4.2 Cooperation with partners

When MELFA ASSISTA was released, a partner community exclusive to collaborative robots was set up for MELFA robots. We will link our robots to peripheral devices (e.g., hand and camera) that partner companies develop and will develop products that satisfy user needs to further improve the usability.

## 3. Conclusion

This paper described the characteristics of our collaborative robot, MELFA ASSISTA, developed this time. We will add and improve the functions to allow collaborative robots to penetrate the market further in the future.

## References

(1) Masakazu M.: Industrial Robots "MELFA FR Series," Mitsubishi Denki Giho, 91, No. 4, 217–220 (2017)

# Application of Machine Learning to Laser Processing System and Latest Processing Technique

Authors: *Motoaki Nishiwaki** and *Hibiki Yamamoto***

## 1. Introduction

Two-dimensional laser processing systems have become indispensable machine tools at manufacturing sites thanks to dramatic technical progress, while rapid advances in processing techniques have expanded the scope of cutting.

However, in service environments, processing may stop due to differences in the quality of materials used, degradation of consumables, and other reasons, reducing the operating rates of laser processing systems. In addition, in recent years, the number of skilled workers who have a thorough knowledge of laser processing and how to operate processing systems has been decreasing due to the shrinking workforce and aging population. Accordingly, laser processing systems that offer higher productivity without depending on skilled workers are needed.

To satisfy such market needs, Mitsubishi Electric Corporation has developed a two-dimensional fiber laser processing system, GX–F, which provides sophisticated automation solutions.

This paper describes an AI technology incorporated into the GX–F and the latest processing techniques that were made possible by a new type of oscillator and AGR–eco.

## 2. External Shape of the Package

Main Specifications of the GX–F Series and Development Concept

Table 1 lists the main specifications of the GX–F. Its concept is a "non-stop processing" system. The GX–F offers a higher operating rate thanks to its AI functions, which the former ML3015eX–F Series did not have, and also higher productivity thanks to a new type of oscillator and AGR–eco, as well as lower running cost.

## 3. Application of AI to laser Processing Systems

In laser processing, the machining head concentrates the light emitted from the laser oscillator and radiates it to the target to be processed. When laser light is radiated to the target metal, assist gas is released from the nozzle at the end of the machining head and the target is processed at a constant speed. Cutting is performed based on processing conditions defined by various parameters. Standard processing conditions based on material quality and thickness are provided as settings for processing systems. If the processing conditions become unsuitable for the targets due to heat accumulated during the processing or if the nozzle gets damaged by spatters, etc. during the processing, processing defects can occur. To prevent these problems and maintain productivity, operators used to check targets during processing, correct the processing conditions according to circumstances based on their knowledge and experience, periodically check the appearance of the nozzles, and replace them.

For the GX–F, the following functions were developed: an AI assist function that judges whether processing can be accepted or not and automatically corrects processing conditions, and an AI nozzle monitoring function that judges the status of the processing nozzles and automatically replaces them when needed.

Table 1 Specifications of ML3015GX–F

| Item | | New model ML3015GX–F | Former model ML3015eX–F |
|---|---|---|---|
| Movement method | | Optical scanning | |
| Fast feed speed (m/min) | | Synthetic rate: 170 | Synthetic rate: 140 |
| Acceleration | | XY:1.5G Z:1.5G | XY:1.0G Z:1.5G |
| Stroke (mm) | X-axis | 3100 | |
| | Y-axis | 1550 | |
| | Z-axis | 120 | 150 |

*Industrial Mechatronics Systems Works ** Mitsubishi Electric Europe, B.V.

### 3.1 AI assist function

The AI assist function judges whether processing can be accepted or not based on the light and sound emitted during processing and automatically corrects the processing conditions. When this function is enabled and the processing is judged as proper, the processing speed is corrected so as to increase the productivity. Meanwhile, when the processing is judged as improper, the function automatically cleans or replaces the nozzle and feeds back information to the processing conditions to reduce processing defects and processing stoppages (Fig. 1).

For the AI assist function, a machine learning technique of supervised learning was adopted. The AI has learned a large volume of data on proper processing and various improper processing results for each thickness of sheet to be processed that were obtained in advance. The AI assist function consists of two types of AI: one to judge whether processing is acceptable or not based on the light emitted during the processing, and another to judge whether processing is acceptable or not based on the sound emitted during the processing. The judgment results are combined to output the final evaluation value. The discriminator of the AI that makes judgments based on light uses deep learning, while the discriminator of the other AI that makes judgments based on sound uses a mixture Gaussian model (Fig. 2).

### 3.2 AI nozzle monitoring function

The AI nozzle monitoring function automatically judges the status of a nozzle and if it has damage that affects the processing, the function automatically replaces it. This replacement and inspection of nozzles reduces processing defects and also reduces the changeover time by operators. When this function is enabled, the diagnosis is performed in the following processing flow: (1) the camera in the processing system photographs the nozzle, (2) the photo is cut (processed), and (3) the learned model is read to allow the AI to diagnose the nozzle.

For the AI nozzle monitoring function, a machine learning technique of supervised learning (classification) was adopted. The AI has learned proper nozzles and damaged (defective) nozzles based on actual photos. The AI's discriminator uses a convolutional neural network (CNN), which is a neural network dedicated to images. The diagnosis result is output as a score (0: normal, 1: abnormal).

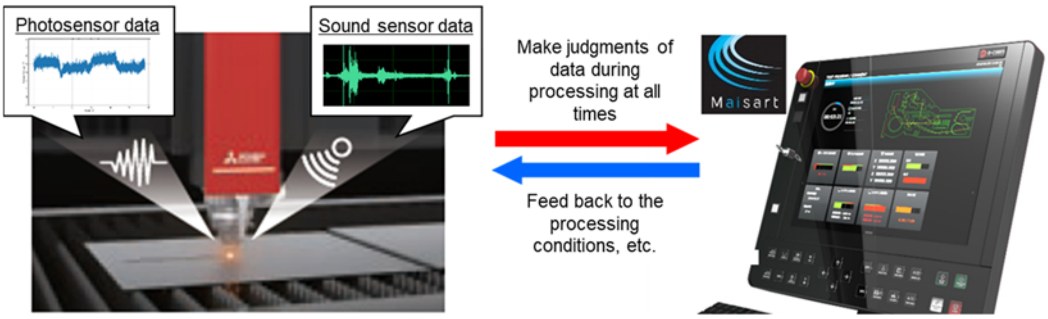


Fig. 1 Anomaly detection of laser-processing with machine learning

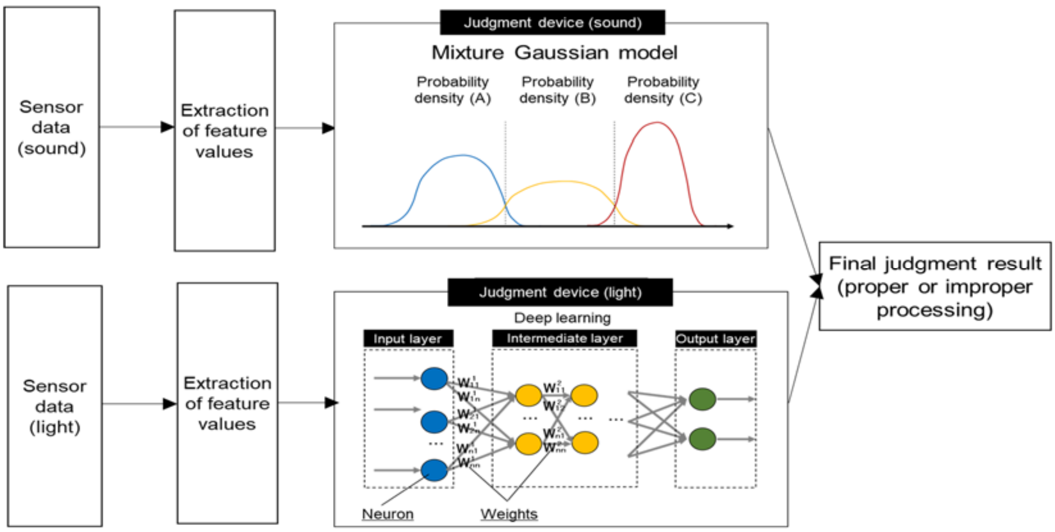


Fig. 2 Detection flow from the sensor data

Figure 3 shows a section that the CNN regarded as important (judgment basis) when calculating the score, visualized as a heat map by gradient-weighted class activation mapping (Grad-CAM). The white hazy section is the part that the CNN judged as important. To prevent CNN's judgment sections from deviating from those by humans, the discriminator was adjusted and the volume of data was increased, thus attaining a level that allows commercialization.

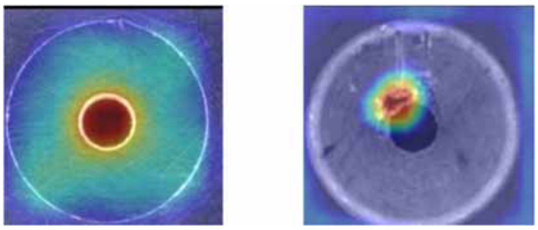

Fig. 3 Anomaly detection of laser processing nozzle (Visualization of feature by Grad-CAM)

### 3.3 Improvement in processing stability by AI technology

When the surface conditions of materials tend to cause processing defects, such defects occur at high frequency and it takes many hours for rework after the processing. In addition, the nozzle may get damaged during processing, further increasing the ratio of processing defects.

Figure 4 compares the simulated results of processing stability when the AI technology was applied and when not applied. The time was calculated from the estimated processing time. When the AI was applied, even when the surface conditions of the materials were not good, the AI assist function reduced the processing speed, greatly reducing the occurrence of processing defects. Although this reduction in speed increases the cutting time, after-treatment is unnecessary and so the total productivity increases. In addition, when processing defects occur due to nozzle damage, the AI assist function can detect the defects and the AI nozzle monitoring function can replace the nozzle automatically, thus improving the processing stability remarkably.

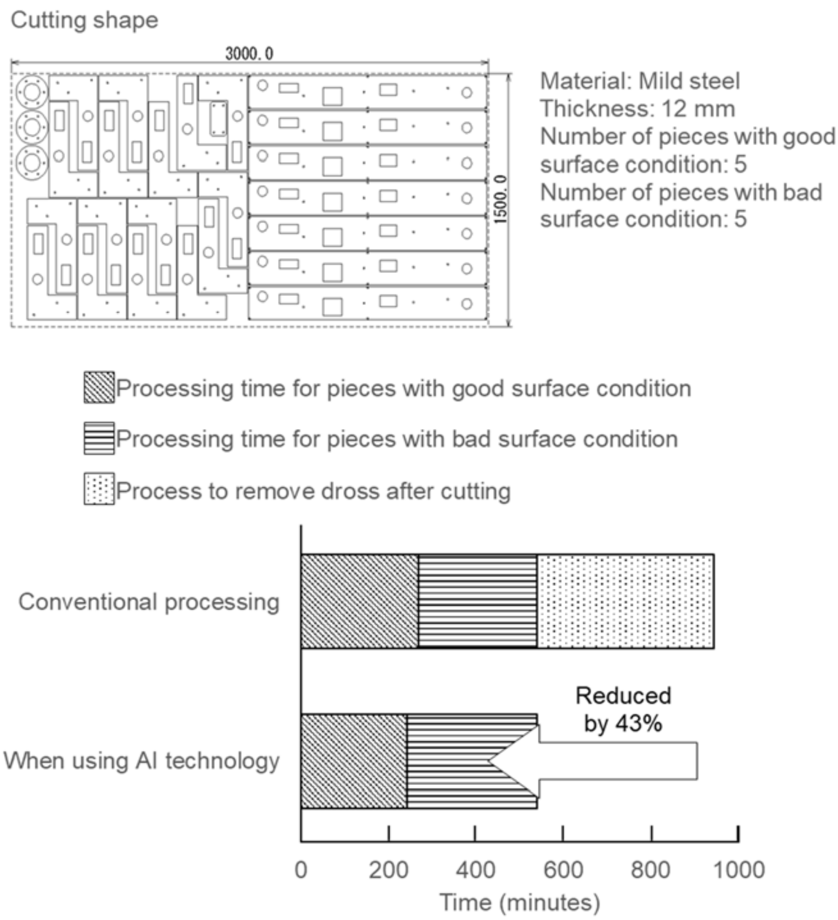


Fig. 4 Highly stable laser processing by AI technology

## 4. Latest Processing Techniques

The above section mainly described the AI technology used in the GX–F. In addition to higher processing stability, the processing capability of the GX–F has also been improved thanks to a new type of oscillator and gas flow control technology, AGR–eco. This section describes the latest processing techniques in detail.(1)

### 4.1 High-speed piercing of mild steel plates

In oxygen processing of mild steel plates with medium thickness or thicker, it takes longer to pierce them (boring before cutting) and the piercing time accounts for a large portion of the total processing time. When there are many holes to be bored and thus many piercing times, the ratio further increases. Consequently, it is important to reduce the piercing time to increase the productivity.

For the GX–F, the high responsivity of the new type of oscillator and a technology for high-speed beam control by zoom heads reduce the piercing time remarkably. When 25-mm-thick mild steel was pierced, the piercing time was reduced by 77% from the conventional time to 0.8 seconds (Fig. 5).

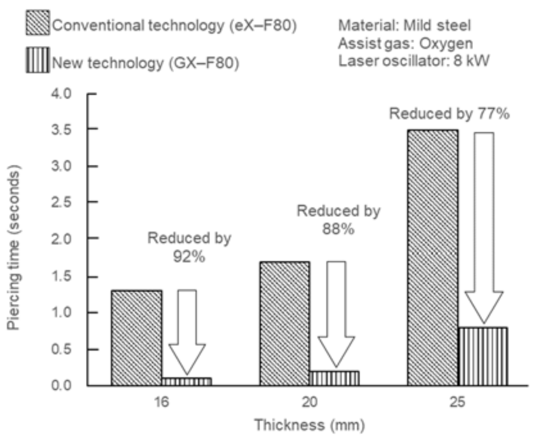


Fig. 5 Piercing time of mild steel


Fig. 6 Small hole processing of 25-mm-thick mild steel

### 4.2 Higher small-hole boring performance

To process plates, plasma cutting and gas cutting machines are generally used in addition to laser processing systems. However, the cutting width of plasma cutting and gas cutting machines is large and the thickness of materials to be cut is the rough minimum diameter of processible holes. For example, when 25-mm-thick mild steel is processed, the minimum diameter of processible holes is approximately 25 mm. Therefore, to process small holes, boring by machining is required after the cutting process. In contrast, laser processing in which concentrated laser beams are used for processing can bore small holes. However, the material melted during piercing builds up near the processed section and abnormal combustion occurs due to heat input during processing. This makes it difficult to bore small holes smaller than approximately half of the thickness. The small-hole boring performance of the GX–F was further improved, surpassing the performance of plasma cutting and gas cutting machines. High-speed piercing of mild steel plates reduces the heat input at the machining point and also beam formation and gas flow control technologies optimized for small-hole boring are applied. These have made it possible to bore small holes with a diameter of 3 mm (smaller than one eighth of the thickness) in 25-mm-thick mild steel (Fig. 6).

### 4.3 Technology to reduce the running cost

During laser processing, assist gas is jetted out coaxially with the laser light. Assist gas is used to discharge heated and melted material from the cutting groove. Different gases (e.g., oxygen and nitrogen) are used depending on the purpose of processing and the application.

In recent years, the power of fiber lasers has been greatly increasing. By combining a high-power fiber laser with nitrogen as the assist gas, it is possible to greatly increase the processing speed. However, when using nitrogen gas for processing, the cost of the gas accounts

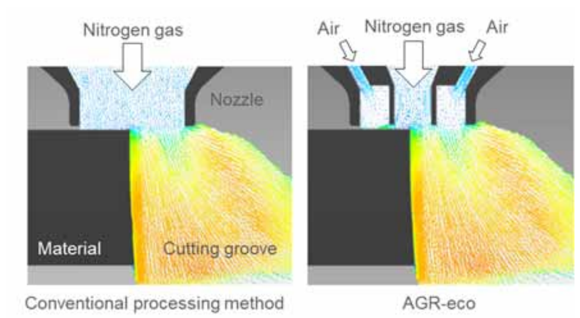


Fig. 7 Method of reducing nitrogen gas by AGR–eco

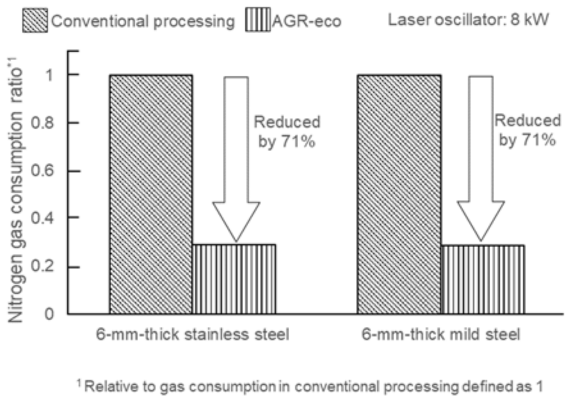


Fig. 8 Reduction of nitrogen gas by AGR–eco


Fig. 9 Cutting of pure copper with nitrogen by new oscillator

for a large portion of the running cost, which increases the production cost. In the GX–F, as shown in Fig. 7, nitrogen is supplied only to the area required to shield the machining point, and cheap air is used for the other sections. Thus, we have developed a gas flow control technology, AGR–eco, in which the consumption of nitrogen gas is greatly reduced while securing the function of the assist gas required to remove molten materials.

AGR–eco can be used to cut stainless steel and mild steel with nitrogen, and can be applied to sheets and plates as is the case with common laser processing. Figure 8 shows the reduction of nitrogen gas consumption by AGR–eco. Compared to the conventional processing method, the nitrogen consumption is reduced by 71% for 6-mm-thick mild steel and 6-mm-thick stainless steel.

### 4.4 Cutting of pure copper with nitrogen

To cut copper, which is a highly reflective material, with a fiber laser, oxygen and air need to be used as assist gases in general. Meanwhile, machined copper parts are often used for electrical components and other similar parts. In such cases, the oxide film needs to be removed after cutting. Although using nitrogen can reduce oxidation on the cutting planes, light reflected from the machining point may damage the machining head and laser oscillator during the processing. To solve this problem, a new type of oscillator having a device to remove reflective light was developed and also nozzle cooling control was developed for the GX–F. As a result, pure copper can be cut with nitrogen, expanding the scope of application of laser processing (Fig. 9).

## 5. Conclusion

This paper described the AI technology and the latest processing techniques applied to the new type of fiber laser processing system, the ML3015GX–F Series. Technologies related to fiber laser processing systems have been rapidly advancing and will continue to do so in the future. In addition to improving the processing system performance, we will also focus on reducing non-processing time (e.g., changeover and sorting) and strive to satisfy various needs at production sites in order to support flexible production for our users.

## References

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# Low-Voltage Air Circuit Breakers “World Super AE V Series C – class”

Authors: *Hideo Shida*, Tomoya Deguchi*, Kenichi Haruna** and *Yuta Sagara***

## 1. Introduction

More than 10 years have passed since Mitsubishi Electric Corporation released the Low-Voltage Air Circuit Breaker World Super AE Series (hereafter "AE-SW Series"), which are the existing models of our low-voltage air circuit breakers. During that period, rival companies in Europe improved their products' performance through model changes and also released low-end series to increase their product models targeting the middle- to low-end markets. In addition, in recent years, there are demands for compatibility with measuring and networks (e.g., centralized monitoring and control) due to increasing needs for saving energy and labor in buildings and production sites.

In response, we developed new models of the Low-Voltage Air Circuit Breaker World Super AE V Series C-class (hereafter “AE V Series C-class”) (Fig. 1). These low-end models, which adopt remote closing operation as standard, are intended for markets such as commercial buildings, hotels, and condominiums overseas which used to be difficult for us to enter with our existing models.


Fig. 1 Low-voltage air circuit breaker "World Super AE V Series C-class"

In addition, new models have received the Winner of the 2021 R&D 100 Award from U.S. publication R&D World. The R&D 100 Awards program identifies and celebrates the top 100 revolutionary technologies of the past year.

This paper describes the main characteristics of the AE V Series C-class and the technological development of the electromagnetic solenoid-type closing mechanism, which is the first in the industry on low-voltage air circuit breakers,*[1] as well as an analysis technique that realized short-time withstand current performance.

## 2. Models and Characteristics of AE V Series C-class

### 2.1 Characteristics of AE V Series C-class

#### 2.1.1 Provision of remote closing operation as a standard function

There is strong demand for remote closing operation as a standard function on low-voltage air circuit

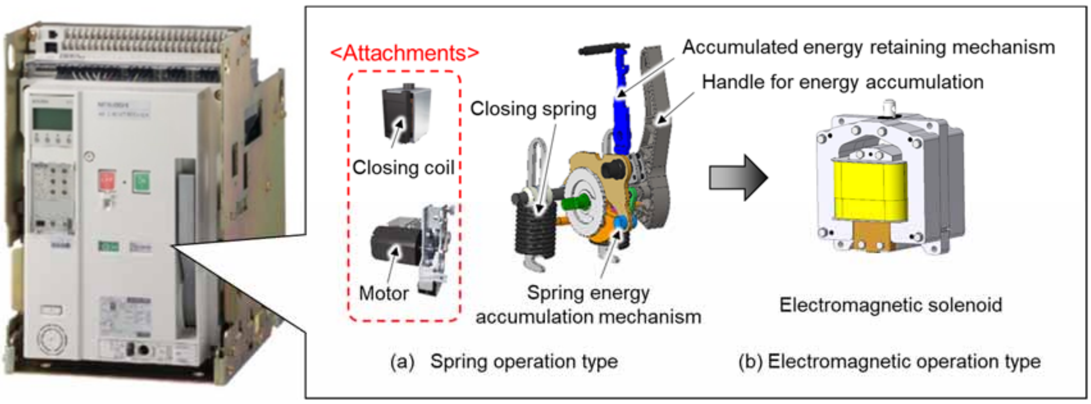


Fig. 2 Former and new remote closing operation mechanisms

[1] As of February 1, 2022, researched by Mitsubishi Electric Corporation

*Fukuyama Works **Advanced Technology R&D Center

breakers to be used on power receiving and distribution panels. For the existing models, in addition to a spring operation mechanism with a closing spring, spring energy accumulation and opening operation are separately required. For this purpose, as shown in Fig. 2, a motor for energy accumulation and a closing coil for opening are used as attachments. To provide remote closing operation as a standard function, it was necessary to combine the aforementioned functions including the spring operation mechanism into one component. Accordingly, we developed an operation mechanism involving an electromagnetic solenoid, which enabled remote closing operation to be provided as a standard function.

#### 2.1.2 User-friendly design

(1) Horizontal / vertical universal terminals

To cope with sudden changes to specifications of power receiving and distribution panels, we developed horizontal / vertical universal terminals structured so as to make it easy to switch main circuit connection terminals between the horizontal and vertical types.

(2) Easier installation of attachments (auxiliary switch (AX), shunt trip device (SHT), and under voltage trip device (UVT))

To save labor in the manufacturing of power receiving and distribution panels, attachments (AX, SHT, and UVT), which are often modified in low-voltage air circuit breakers, have been brought together in the upper section of the main body; the structure allows the cover of only the main body in the applicable section to be separately removed and installed.

#### 2.1.3 Reduction of power consumption and the number of parts requiring maintenance and inspections

The existing AE–SW Series has spring operation mechanisms with closing springs and therefore, before the closing operation, it is necessary to charge the closing spring with a motor (energy accumulation). In comparison, the AE V Series C-class models have electromagnetic solenoid-type operation mechanisms and so do not require charging, reducing power consumption. Furthermore, the new design used for the mechanism section reduces the interruption time during maintenance and inspection, and also the number of parts requiring maintenance and inspection.

## 3. Technical Characteristics of the AE V Series C-class Breakers

### 3.1 Development of the electromagnetic solenoid-type operation mechanism

In developing the electromagnetic solenoid-type operation mechanism, it was necessary to minimize the mechanical reaction force applied to the electromagnetic solenoid (optimizing the closing mechanism) and to increase its output. To do this, we developed a robust minimization technique to optimize the closing mechanism and a new structure to increase the output of the electromagnetic solenoids.

#### 3.1.1 Optimization of the closing mechanism

The closing mechanism was optimized by using a new particle swarm optimization (PSO) method. In this method, for the behavior and balance of forces of the mathematically modeled mechanism, function J, which evaluates the errors from the requirements shown in formula (1), is defined to automatically minimize them. In other words, the method automatically searches for the mechanism layout that matches the requirements. Because there are multiple requirement terms, evaluation function J becomes a multidimensional waveform as shown in Fig. 3. However, this method can search for a minimal solution for the whole instead of a

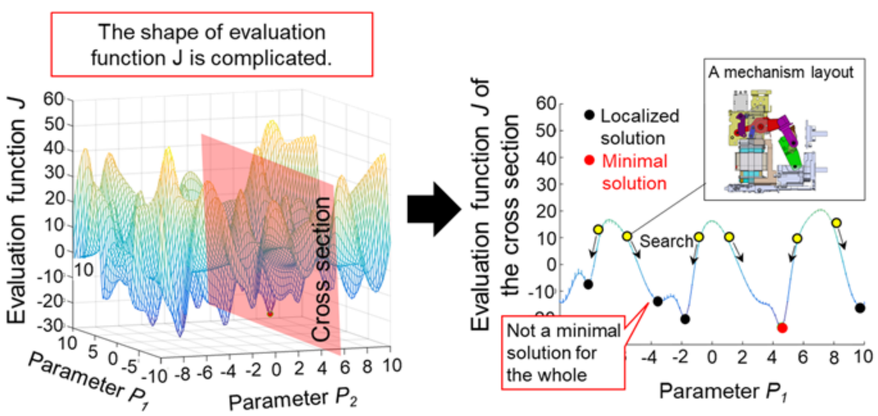


Fig. 3 Evaluation function

localized solution. In addition, evaluation function J includes a term for the mechanical reaction force that is applied to the electromagnetic solenoid; as a result, variations can be reduced including all the requirements compared to general methods.

$$J = a_1(L_1 - L_{1\max})^2 + a_2(L_2 - L_{2\max})^2 \cdots + a_n \sum \left( \frac{\partial F}{\partial P_n} \right) \quad (1)$$

$a_i$ : Weighting factor of each requirement parameter

$L_i$ : Design value of each requirement parameter

$L_{i\max}$ : Maximum value of each requirement parameter

F : Mechanical reaction force

$P_n$ : Location of each mechanism element

#### 3.1.2 Increase in the output of electromagnetic solenoids

To increase the output of the electromagnetic solenoids, operation in the high coil current region is required. Figure 4 shows typical coil current waveforms. When an electromagnetic solenoid starts operating, the current decreases due to the counter electromotive force of the coil. For example, assuming that the operation start of an electromagnetic solenoid having fast initial motion is A, its operation completion is B, the operation start of an electromagnetic solenoid having slow initial motion is A', and its operation completion is B', then when the iron cores are not magnetically saturated, the output is roughly proportional to the square of the coil currents. Therefore, to increase the output, it is important to increase the current at the time of initial motion (initial motion current).

Figure 5 illustrates a general electromagnetic solenoid and the developed electromagnetic solenoid. A common feature is the tapered adsorption faces of the moving and fixed cores. Compared to flat adsorption faces, the tapered form reduces distance b between the moving and fixed cores, thus reducing the magnetic resistance. Accordingly, when the coil current is at a constant level, the output at the initial location can be increased. However, in this configuration, the coil current gradually increases as shown in Fig. 4, making the initial motion current lower in the case of the tapered form than the flat form.

To solve this problem, new projections have been provided between the moving and fixed cores. These give magnetic adsorptive power to the moving core at the initial location in the direction opposite to the output direction, which reduces the output and increases the initial motion current. After the moving core starts operating, the clearance between the projections expands, which increases the magnetic resistance and then the magnetic adsorptive power disappears, which increases the output. Figure 6 compares the output at the rated operation voltage of 110 VDC between a general solenoid and the developed solenoid. This structure increases the initial current to approximately 1.7 times (3.0 to 5.2 A), increasing the output by approximately 50% from that of general electromagnetic solenoids.

### 3.2 Analysis technique to realize short-time withstand current performance

#### 3.2.1 Short-time withstand current performance

Short-time withstand current performance refers to the performance of stably passing a short-circuit current from when the short-circuit current occurs to when it is

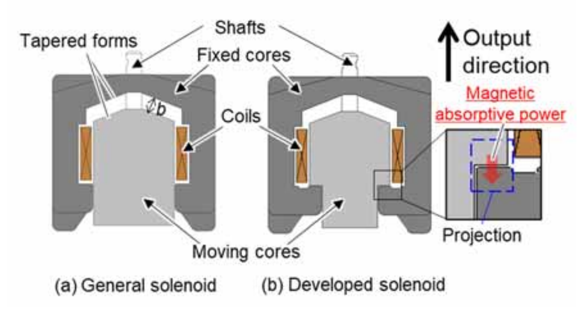


Fig. 5 Schematic diagrams of electromagnetic solenoids

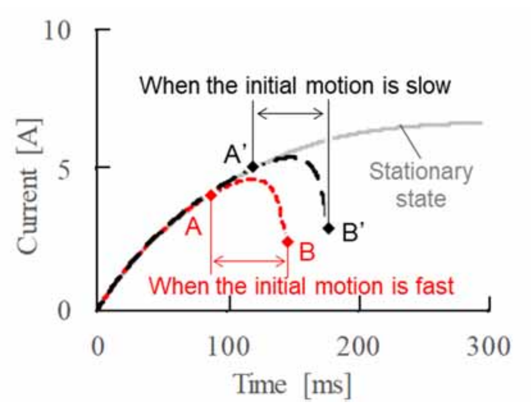


Fig. 4 Current waveforms of electromagnetic solenoid coils

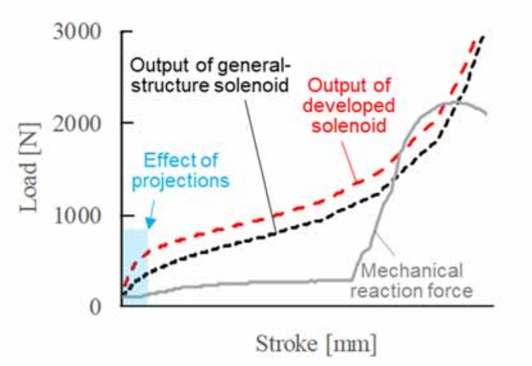


Fig. 6 Comparison of output of electromagnetic

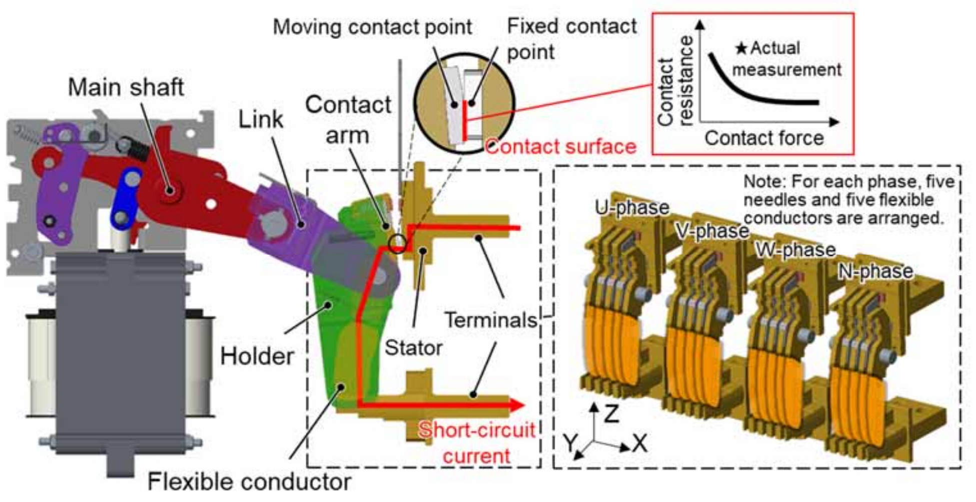


Fig. 7 Electromagnetic field analytical model

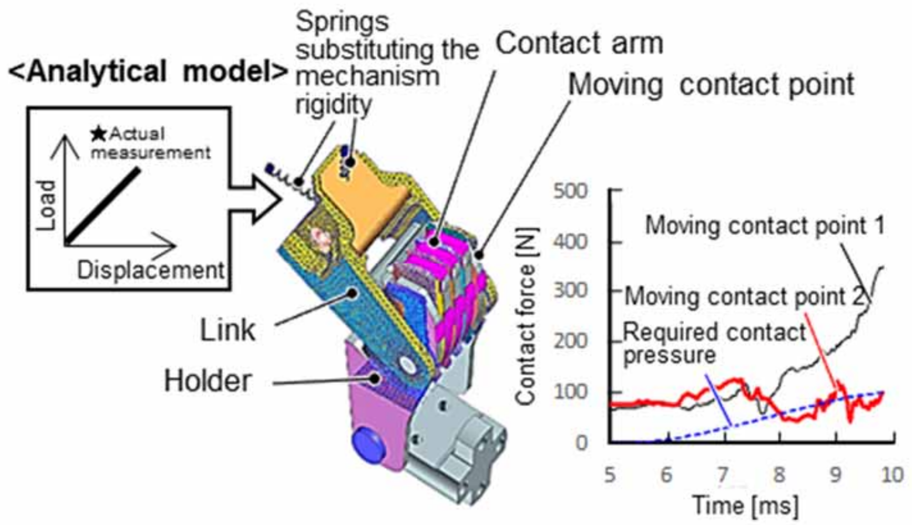


Fig. 8 Analytical model of mechanism

cut off by a breaker, etc. The AE V Series C-class models have a short-time withstand current performance of one second when the short-circuit current is 50 kArms. During this period, the Lorentz force of several hundred to several thousand N that is generated on the energized conductor needs to be controlled to prevent arc flashing caused by improper contact between the contact points, damage to resin parts due to stress concentration, and other factors.

To achieve this, electromagnetic field analysis and mechanism analysis were linked to quantify the behavior of parts when a short-circuit current was passed, and also the generated stress. By controlling these, the short-time withstand current performance was realized.

#### 3.2.2 Electromagnetic field analytical model for short-time withstand currents

Electromagnetic field analysis software was used to quantify the Lorentz force when a short-circuit current was passed. Figure 7 shows the analytical model. A flexible conductor is joined to a contact arm; for each phase, five sets of them are arranged in series for each pole. As input conditions, the three-phase short-circuit current was set at 50 kArms considering the transient current. The distribution of the current (shunt) branched out to each flexible conductor was analyzed and time-series data on the Lorentz force generated in the X, Y, and Z directions was output. Each flexible conductor receives Lorentz force in the Y direction in the magnetic fields on the current paths at the terminal sections. In addition, for each flexible conductor, Lorentz force in the X direction (direction to attract each other) is generated by the branched shunt current. The magnetic fields of the short-circuit currents carried by the other phases also influence the Lorentz force in the X direction.

For this analysis, in order to analyze the distribution of the current in the flexible conductors accurately, the skin effect was considered and the contact resistance occurring on the contact surface between the moving and fixed contact points was measured and incorporated.

### 3.2.3 Analytical model of mechanism for short-time withstand currents

In the mechanism analysis, the time-series Lorentz force on each flexible conductor in the X, Y, and Z directions was input and the transitional elastic deformation of the parts and their transitional motion quantities were analyzed. Figure 8 illustrates the analytical model of the mechanism. Although the stator is not illustrated, it is completely restrained in the analysis. In this analytical model, in order to reduce the calculation cost, the mechanism parts including the main shaft were represented by springs, and actually measured values were incorporated as the spring constants.

This analysis can quantitatively evaluate the stress generated on the link and holder and also the time-series contact force between the moving and fixed contact points. Figure 8 also shows an example of analyzing a case in which arc flashing occurred between the contact points when an accident current was passed. As analysis conditions, the current was 50 kArms and the closing phase (V-phase) was zero degrees. Two moving contact points were extracted from the five points in the U-phase in which the arc flashing occurred and the time-series contact force was shown. The required contact pressure was calculated from the melting voltage and contact repulsive force as a threshold value in which when the contact force falls below the required contact pressure, the contact becomes poor. The analysis results show that at approximately 8 ms, the contact force of contact point 2 falls below the required contact pressure and the time matches that when arc flashing occurs on an actual device, confirming the appropriateness of the analysis results.

By using this analysis technique, it was possible to design taking into consideration the dimensional tolerance of each part and variations in assembly, and thus to establish the short-time withstand current performance quickly and secure high reliability.

## 4. Conclusion

This paper described the characteristics of the new models of our low-voltage air circuit breakers along with the technological development of their electromagnetic solenoid operation mechanism, as well as an analysis technique to realize the short-time withstand current performance. We will actively use the technology to increase the output of electromagnetic solenoids and the analysis technique for linking electromagnetic field analysis and mechanism analysis established in this development when developing new models in the future.

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