

High-speed Inspection Technology for Fuel Cell MEAs Using Split-terminal Resistance Measurement System

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ABSTRACT

New fuel cell stacks are being developed with the aim of improving productivity while maintaining the same quality for mass production. In particular, the time it takes to perform shorting inspection of the membrane electrode assembly is an issue that limits productivity, so development has been conducted to help reduce this time. Conventional shorting inspection on flat bases detects the electrical characteristic values of the entire membrane electrode assembly. In this approach, signals of local short circuits are small relative to the change in detected value due to the charge, and thus they could not be judged until the change was complete. In the development discussed in this paper, the detection sensitivity for signals in each local area was increased by using a split-terminal base. Shorting signals greater than the charge change were successfully detected locally. This lowered the impact on the inspection judgment, and the measurement waiting time caused by charging was lowered by 87% compared with the conventional method. In addition, the researchers developed an algorithm for synthesizing peripheral currents to deal with the misjudgment factor of a short circuit in the terminal gap, which presented an issue in the use of split bases. As a result, inspection total time was reduced to 10 seconds, thus contributing greatly to increasing cell productivity.

1. Fuel Cell Stacks

Fuel cells are expected to be used as a circular clean system for achieving carbon neutrality⁽¹⁾.

Honda has been working on the practical application of FC technology since the 1980s⁽²⁾⁻⁽⁵⁾. In 2016, it introduced the CLARITY FUEL CELL^{(6),(7)} with the conventional fuel cell system.

For the next stage, Honda partnered with General Motors to develop a new fuel cell system that helped ensure high durability and low cost and thus helped enable deployment in diverse markets, including commercial vehicles, construction machinery, and stationary power sources⁽⁸⁾. With the production line for this newly structured fuel cell stack, the researchers achieved a fully automated assembly line, from electrode roll feeding to cell stacking⁽⁹⁾.

As Fig. 1 shows, polymer electrolyte fuel cells convert chemical energy directly into electrical energy through an electrochemical reaction between hydrogen and oxygen. The formula for the chemical reaction is as follows.

Hydrogen electrode (-): $2\text{H}_2 \rightarrow 4\text{H}^+ + 4\text{e}^-$

Oxygen electrode (+): $\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$

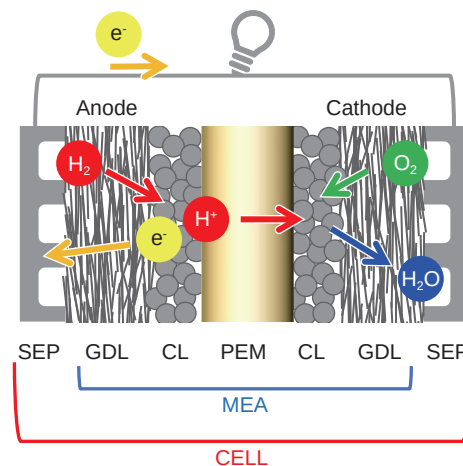


Fig. 1 Mechanism of electricity generation in FC stack

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A polymer electrolyte membrane (PEM), the conductor of hydrogen ions, is sandwiched between two catalyst layers (CL) and gas diffusion layers (GDL) for the hydrogen electrode and the oxygen electrode (air electrode), forming a membrane electrode assembly (MEA). This MEA is sandwiched between two separators (SEP), one on either side, and the structure is called a cell. These cells are stacked and fastened together to form a fuel cell stack.

2. Issues with Shorting Inspection

2.1. MEA Shorting Phenomena

Output performance and durability are key to fuel cell stack performance, and elements for maintaining them are the insulating quality of the electrolyte membrane and the function of shutting off gas. An example of a phenomenon that interferes with the insulating properties of the electrolyte membrane is the conduction between electrodes due to fibrous contamination, as in Fig. 2. Such conduction can cause electricity to flow between the electrodes, which may lead to a decline in electromotive force, and pinholes in the membrane when high voltage is applied between the electrodes, which can cause cross leakage of hydrogen and oxygen. This is why shorting inspection is performed.

2.2. Conventional MEA Shorting Inspection Technique

Because a short circuit in the electrolyte membrane can cause a drop in cell voltage and degradation of membrane durability, the following steps are performed in the conventional model using the shorting inspection system shown in Fig. 3 to confirm that there are no more than a certain number of short circuits.

The inspection steps are:

1. Clamp a pair of parallel plate electrodes with a constant load
2. Apply direct current with a constant voltage
3. Apply a charge until the measured value stabilizes
4. Measure the value of the current flowing between the two electrodes after charging
5. Judge as Pass or Fail relative to a threshold value

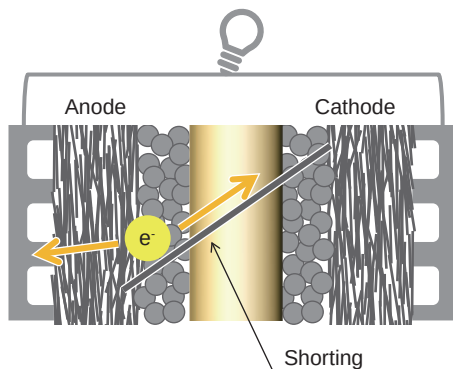


Fig. 2 Imaged figure of MEA shorting

The takt times for the conventional MEA shorting inspection process are shown in Fig. 4. The charging process accounts for 80% of the inspection time, and thus this is the rate-limiting process. This is because the MEA has a capacitor structure in which the insulator PEM is sandwiched from both sides by the conductor GDLs and CLs and has capacitance. To show the impact that capacitance has on judgment, Fig. 5 shows the change in the measured values of MEA current that resulted in a judgment of Fail in the inspection, and the conventional MEA shorting inspection threshold. This shows that the change in current value is saturated and that it takes about 20 seconds until a judgment can be made.

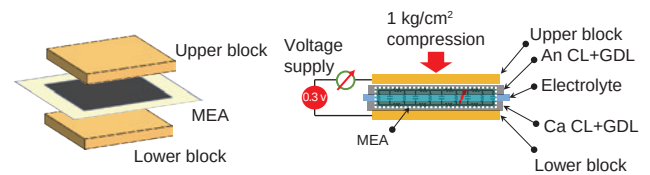


Fig. 3 Shorting inspection system of Honda's previous model

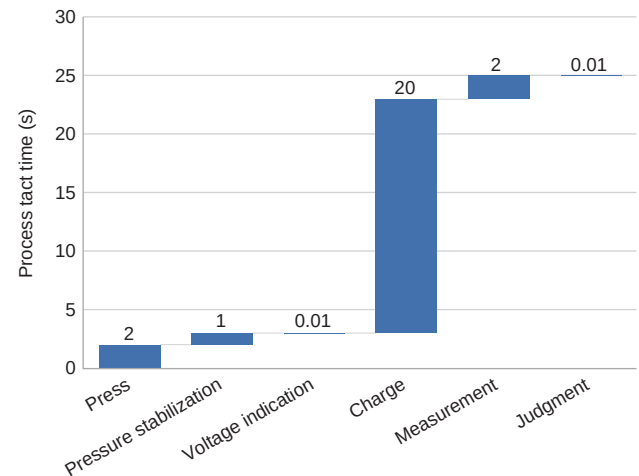


Fig. 4 Takt time of each process in shorting inspection

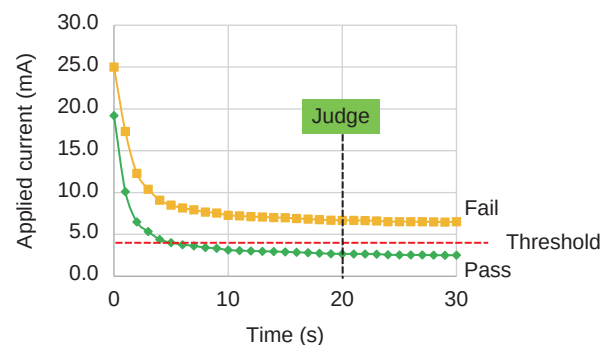


Fig. 5 Variation of measured values due to charging

3. Devising a Split Shorting Inspection System

In order to achieve greater productivity than that of conventional fuel cell stacks, the researchers focused on reducing the time required for charging, which is the rate-limiting step in the shorting inspection process, and devised a split-terminal base that extracts local shorting signals and lowers the impact of charging.

A common method to shorten charging time is to increase the applied current and voltage⁽¹⁰⁾. However, this method was already used when developing the conventional method and resulted in a charge time of 20 seconds, and thus no great advancement can be expected. Therefore, speeding up MEA shorting inspection required a method other than increasing the amount of charge to the capacitor component of the MEA.

Next, when measuring with the conventional uniform plate shown in Fig. 3, an issue is that the inrush current to a large-area capacitor is relatively large compared to the current of local short circuits. Before presenting a solution, an electrical schematic of the MEA is given below. The electrical properties of the MEA are considered to be an internal resistance resulting from the material, in addition to shorting resistance and capacitance. An electrical schematic of the MEA is given in Fig. 6. In a circuit where the locations with shorting and locations without it are separated from each other, as shown in the figure, the shorting signal is anticipated to be locally greater than the other components. As a solution, the authors actively extracted the shorting signal flowing locally, and worked to develop technology as described below to shorten the measurement waiting time resulting from charging by making the short circuit detection value relatively large compared to the change resulting from the charge.

- (1) Develop a split-terminal base for extracting voltage of shorting signals⁽¹¹⁾
- (2) Develop an algorithm to synthesize shorting voltage generated at the split terminal gap⁽¹²⁾

These will be described in turn in the following sections of the paper.

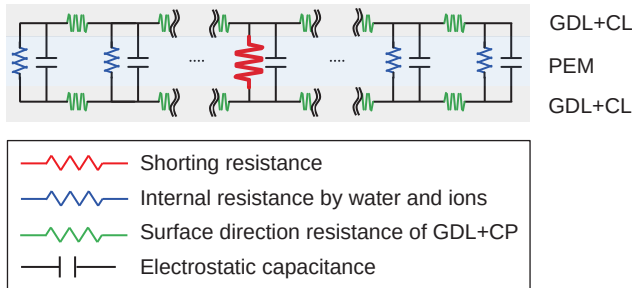


Fig. 6 Electrical schematic of MEA

4. Development of a Split-terminal Base

4.1. Basic Concept of the Split-terminal Base Device

Figure 7 shows the basic concept of the device, in which a multi-channel tester (R-5800i) from Nidec Advance Technology Corporation is connected to the inspection device circuit and voltage meter on a split-terminal base. In the measurement system that is used, shunt resistors whose resistance is known with high accuracy are connected under the split terminals, and the voltage across shunt resistance is measured to calculate the resistance of the MEA.

The following equation is used to calculate the local MEA resistance based on the ratio of series resistance and voltage.

$$\Omega_{MEA} = \frac{\Omega_{shunt} \cdot V}{V_{shunt}} - \Omega_{shunt}$$

Ω_{MEA} : MEA resistance (Ω)

Ω_{shunt} : Shunt resistance (Ω)

V : Voltage supplied from power supply (V)

V_{shunt} : Voltage across shunt resistance (V)

The following is a description of the verification to determine the specifications of the device capable of extracting shorting signals based on the basic concept.

To extract shorting signals with high accuracy, it is first necessary to establish a state in which a large amount of shorting current flows to the sensor directly below the shorting area in the circuit shown in Fig. 7. However, as the MEA electrical schematic in Fig. 6 shows, there are plane-direction conductive paths in the GDL and CL parts of the MEA as an inhibiting factor, which may cause shorting current to disperse in the plane direction. Suppressing this is a necessary condition for extracting the voltage of the shorting signal. The factors involved in dispersion are

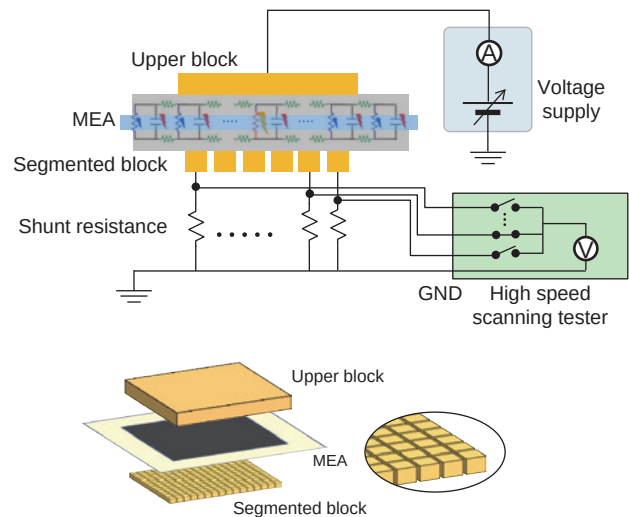


Fig. 7 Circuit diagram of shorting inspection system

terminal size, shunt resistance, and terminal pitch. The specifications were set for each of these.

4.2. Setting the Terminal Size

To evaluate current dispersion by terminal size, the shunt resistance, which is resistance in the terminal direction, was set to a fixed value of $10\ \Omega$. The current dispersion, which is the relationship between the detection rate and distance at the peripheral terminals when the amount of current directly below the shorting area is 100%, was verified with four standards of split bases with terminal sizes ranging from 3.0 to 10.0 mm. The results are shown in Fig. 8. The results showed that smaller terminal sizes better suppressed current dispersion, and a terminal size of 3.0 mm was selected due to constraints imposed by the number of available tester channels.

4.3. Setting the Shunt Resistance

The basic policy for setting the shunt resistance was to make the shunt resistance in the direction directly below the short circuit smaller than the resistance of dispersion in the plane direction. However, to suppress measurement variation, the voltage detected by shunt resistance needs to be sufficiently large for the measurement accuracy of the tester. For this reason, it is necessary to increase the shunt resistance and increase the detection voltage.

As a result of the verification and to evaluate shunt resistance measurement accuracy and the challenge of current dispersion, Fig. 9 shows the voltage ratio of the adjacent terminal voltage when the terminal voltage at the center of the short circuit is 100%. A shunt resistance of $0.5\ \Omega$ was selected as the balance point because it has low current dispersion and a sufficiently high measurement accuracy of 1/10 at $3\ \sigma$ with respect to the short circuit judgment threshold of $900\ \Omega$.

4.4. Setting the Terminal Pitch

Theoretically, the narrower the terminal pitch, the shorter the distance in the plane direction, and thus the resistance in the MEA's plane direction would be relatively small

compared to the resistance in the direction of the circuit directly below. This would make it easier for current to flow to adjacent terminals, resulting in lower accuracy. On the other hand, if the terminal pitch is widened, shorting areas are more likely to be present in the terminal gaps, which may result in a decline in accuracy due to signal dispersion and make it challenging to locate the short circuit, and thus the terminal pitch should be narrow. For that reason, the authors confirmed the impact of terminal pitch on current dispersion by taking measurements. For this verification, terminal size was set at 3.0 mm. The verification evaluated the degree of current dispersion with respect to distance when the voltage immediately below the short circuit was set to 100%. The results are shown in Fig. 10. No difference in current dispersion was observed between the 0.3 mm and 0.7 mm terminal pitch. Although the verification results confirmed the possibility of shortening the terminal pitch, 0.3 mm was set as the lower limit of the terminal pitch in consideration of the need to help prevent short circuits in the terminal gap during processing, and thus it was determined to use a terminal pitch of 0.3 mm.

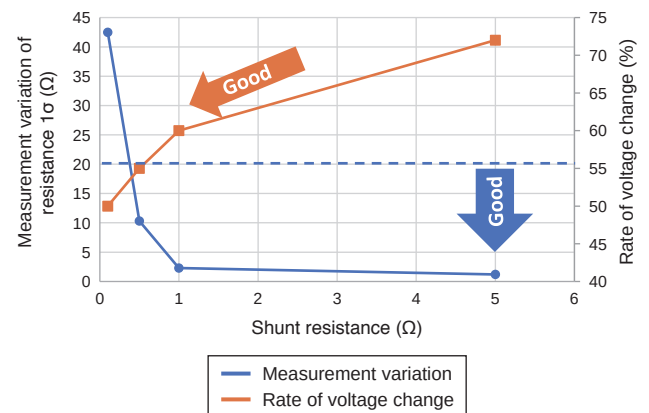


Fig. 9 Measurement variation and detection signal ratio with adjacent terminals due to shunt resistor specification differences

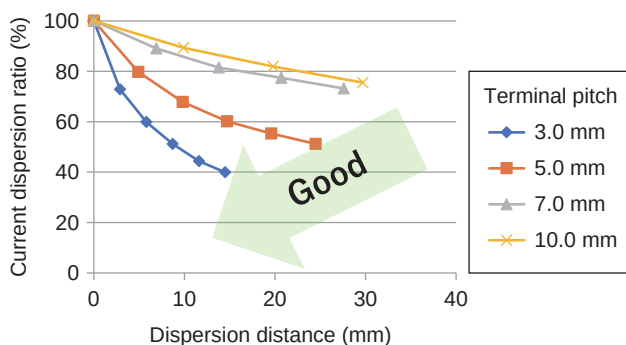


Fig. 8 Relationship between segment size and current dispersion

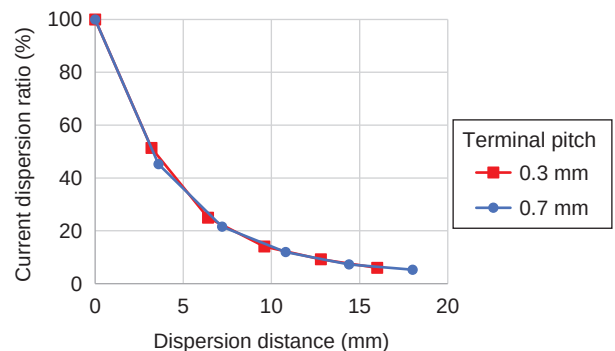


Fig. 10 Distance between terminals and current dispersion

4.5. Split Base Effect

A terminal size of 3.0 mm, a terminal pitch of 0.3 mm, and a shunt resistance of $0.5\ \Omega$ were selected as the final base specifications.

Figure 11 shows the voltage data for the X and Y positions obtained with the split base as the measurement results with a split base. The data confirmed that the signal was clearly detected. Figure 12 shows the results of cross-sectional observation of the center of shorting and non-shortening areas by X-ray CT. The cross-sectional observation results show that with the split base, it is possible to accurately detect the shorting phenomenon, as it was confirmed that the shorting area has a fibrous contamination that penetrates the membrane.

Next, the change in time of resistance to charging of shorting and non-shortening areas is shown in Fig. 13. Compared to non-shortening areas, shorting areas have a sufficiently small change in measured values and reach a steady state within 2.0 seconds. As non-shortening areas show a time change of more than 15 seconds, the charging effect is considered to be present in shorting areas as well. However, the shorting signal is large and less sensitive to changes due to charging, suggesting an apparent steady state. These results confirm that there is sufficient saturation

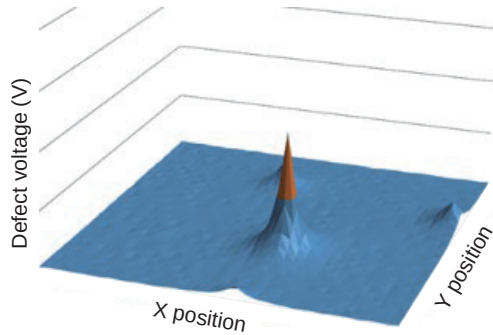


Fig. 11 Voltage measurement data on split-base MEA with short circuit

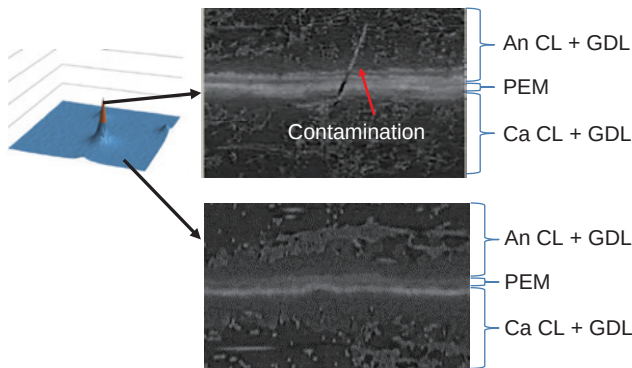


Fig. 12 X-ray CT image of shorting area

in about 2.0 seconds to make an inspection judgment. The final inspection time was set at 2.6 seconds, as the time that can be allocated to charging to achieve the 10-second target time for the production process. In the end, there was an 87% reduction in charge time, from 20 seconds for the conventional system shown in Fig. 4 to just 2.6 seconds.

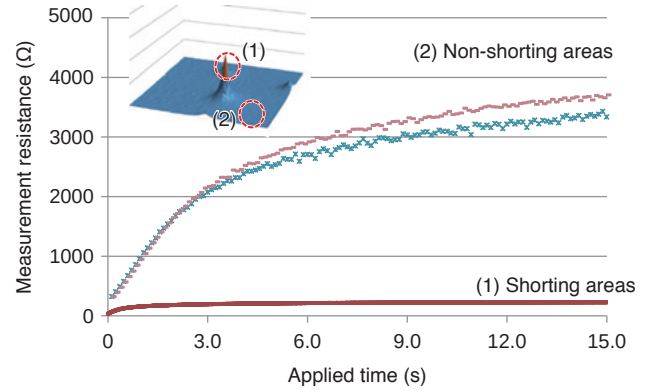


Fig. 13 Charge time variation between shorting and non-shortening areas

5. Development of Synthesizing Algorithm to Detect Short Circuits with Split Terminals

5.1. Issues with Detection Using Split Base

As shown in Fig. 14, a characteristic phenomenon resulting from split-terminal bases is that detection results differ depending on whether there is a short circuit on a terminal or one in the terminal gap. If it is in the terminal gap, the same level of current flows through adjacent terminals. Figure 15 shows the detection voltage of terminals A and B at the short circuit positions (1) and (2) in Fig. 14. These results indicate that if a short circuit is present in the terminal gap, the detection value per terminal may be low.

The following techniques were developed as a solution to this phenomenon:

- (1) Synthesize the range of the voltage flowed to the split terminals
- (2) Remove variability factors of range synthesis

5.2. Synthesis Process

Considering that the total amount of current flowing at a short circuit phenomenon at the terminal gap as shown in Fig. 14 would not change, the authors devised a method to help prevent a possible decline in judgment accuracy by synthesizing the dispersing current. To determine an appropriate synthesizing range, voltage values for expanding the synthesizing range were evaluated. The area was expanded to a square centered on the shorting area as a way to verify the range to synthesize. An image of the

synthesizing range is shown in Fig. 16. Figure 17 shows the results of the synthesis, with the horizontal axis showing the number of synthesized terminals, the vertical axis showing the synthesizing voltage values, and the curves in the plot showing data for different shorting MEAs. The synthesized value was calculated by combining the voltage V_{shunt} detected by shunt resistance as a parallel circuit, as shown in Fig. 6.

As a result of the synthesis of shorting voltages, it was confirmed that the sizes of results were interchangeable for the same synthesizing range. Two factors may be responsible for this. The first is that the radial range centered on the

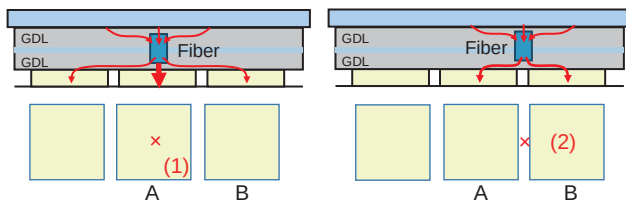


Fig. 14 Image of current bifurcation by segment and short-circuit position

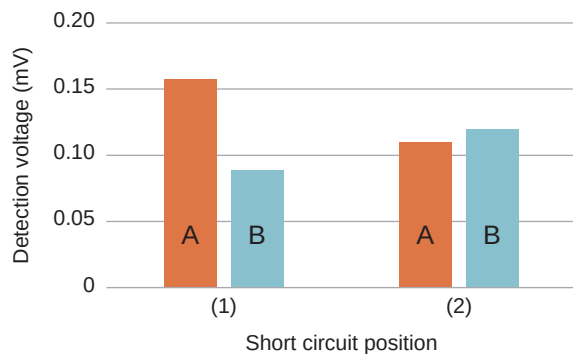


Fig. 15 Detection voltage value according to position of segment and short circuit

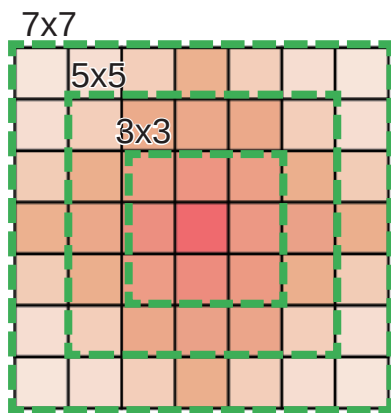


Fig. 16 Image of synthesizing range from the short circuit center

short circuit does not perfectly coincide with the center as found by synthesis calculation in this method, and thus it is treated as variance if the synthesizing range is small. The second is that the voltage resulting from the internal resistance of the material as results from ions and water, as shown in Fig. 6, varies from MEA to MEA.

To address the latter, the calculation needs to consider the variation of internal resistance of each MEA, which will be discussed in the next section.

5.3. Removing Internal Resistance Voltage

To address variations in judgment results due to differences in the internal resistance voltage of each workpiece, the researchers considered the possibility of removing the internal resistance voltage from the calculation prior to the synthesis calculation.

Because it is necessary to clarify the distribution of the internal resistance voltage in order to properly remove it where it varies, the distribution of shorting resistance and the internal resistance voltage values was observed, as shown in Fig. 18.

The results show that the resistance distribution has two peaks. The distribution of lower resistance values indicates

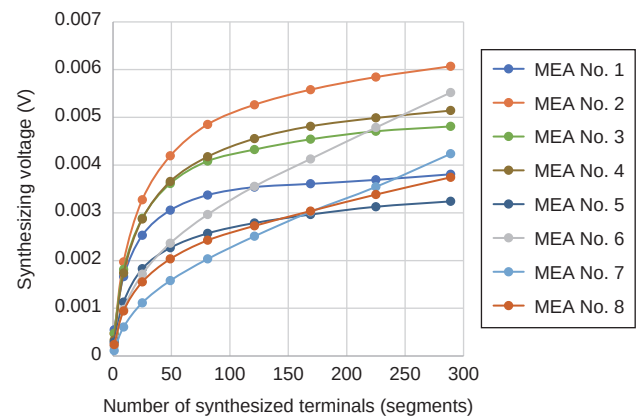


Fig. 17 Change in synthesizing voltage value relative to synthesizing range

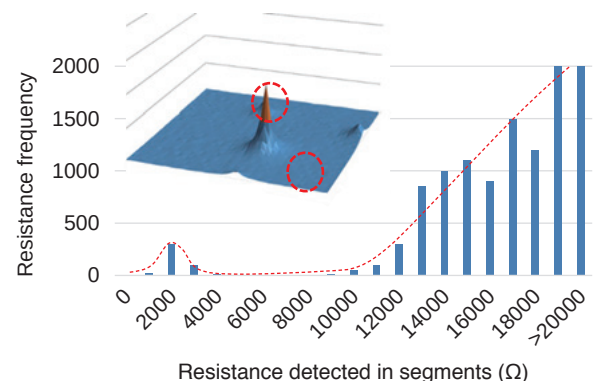


Fig. 18 In-plane resistance distribution of MEA

short circuits due to contamination. The distribution of higher resistance values can be considered a distribution of internal resistance rather than a short circuit. In the researchers' approach, 8000 Ω , which is at the base of the distribution, is taken as the lower limit of internal resistance, and the internal resistance voltage is removed as described by the following arithmetic steps. An image of this is shown in Fig. 19.

The arithmetic steps are:

1. Extract data of 8000 Ω or more from the data for all terminals
2. The average of the extracted data is taken to represent the internal resistance voltage of that MEA
3. The representative internal resistance voltage is subtracted from the data for all terminals
4. The data for terminals in the specified range from the center of each terminal is synthesized as a parallel circuit and used as the detection value
5. Judge as Pass or Fail relative to a threshold value

To confirm whether removal is effective and to determine an appropriate synthesizing range, voltage values for expanding the synthesizing range were evaluated, with the results shown in Fig. 20. The internal

resistance fluctuation effect was eliminated without any interchange of the size relationship in the synthesis over a range of 100 terminals or more. There was increased robustness against fluctuation of measured values resulting from the material.

The synthesis condition was set to a synthesis range of 121 terminals, which is 11x11 terminals, in which no change of the size relationship is seen for each MEA.

6. Conclusion

As a fast shorting inspection technology for fuel cell MEAs to increase the productivity of fuel cell stacks, the researchers developed a split-terminal base and a synthesizing algorithm to help prevent declines in judgment accuracy, which are characteristic of split terminals.

- (1) Using a split-terminal base lowers measurement waiting time resulting from the charging required for shorting inspection by 87%.
- (2) The synthesizing algorithm for short circuits in the gap between split terminals helps prevent a decline in judgment accuracy due to short circuits at locations with large measurement errors, such as the gap between split bases, and further increases the robustness of the inspection.

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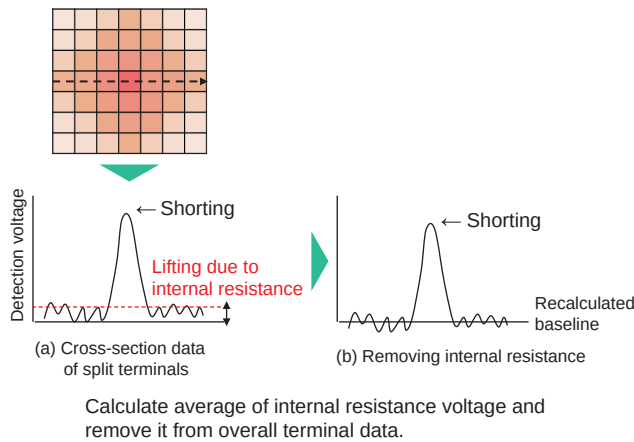


Fig. 19 Image of removal of base voltage lift due to internal resistance

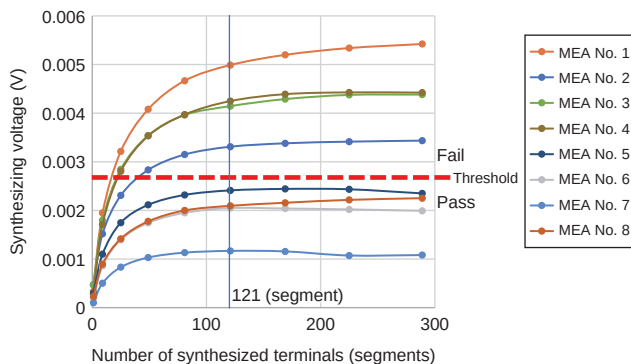


Fig. 20 Synthesizing range and voltage convergence

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