Custom-Waveform Power Supply for Metal Surface Treatment

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1. Introduction

Thyristor rectifiers have been used conventionally for metal surface treatments such as the color anodizing of aluminum window sashes and electroplating of various kinds of metals. However, such treatments using direct current from thyristor rectifiers have limitations on the extent to which they can improve yield rate, color tone, uniform coloring, etc. Meanwhile, due to recent technological progress in power electronics, it has become possible to generate specialized waveforms unobtainable by thyristor rectifiers and to pursue conditions optimum for each process according to the waveform of the power supply.

In this paper, we introduce principles of the color anodizing of aluminum window sashes and examples of power supplies delivered by Fuji Electric for that application. Moreover, as an example of the expanding scope of applications, the copper plating of printed circuit boards is introduced.

Table 1 General specifications for custom-waveform power supply

Item	Description
Input	Three phase, 50/60 Hz, 200 V, 440 V, 3.3 kV, 6.6 kV (able to correspond to requirements)
Output range	Current : up to 10 kA (peak) Voltage : up to 300 V (peak)
Control method	Automatic current control, automatic voltage control, automatic power control
Accuracy of control	Standard : ±2 % (non-standard unit can be produced)
Specification for inverter	Element used : IGBT
Cooling system	Transformer : ONAN or AN Diode rectifier : WF or AF Inverter : WF or AF
Examples of approximate outer dimensions	80 V, 300 A unit : 800 width×1,000 depth ×1,950 height (in mm) 50 V, 4.5 kA unit : 5,200 width×2,000 depth ×2,350 height (in mm)

2. General Specifications for Custom-Waveform Power Supply

A custom-waveform power supply can generate specialized waveforms suited for each process and Fuji Electric has a proven track record of delivering custom-waveform power supplies mainly for the color anodizing of aluminum window sashes. General specifications, a simplified diagram of the main circuit and example waveforms of a custom-waveform power supply are given in Table 1, Fig. 1 and Fig. 2, respectively. This power supply is an inverter that uses single-phase pulse width modulation (PWM). High frequency, high capacity operation is supported through the use of insulated gate bipolar transistors (IGBTs). Although the output waveform may be set arbitrarily, in many cases, the waveform is fixed to a suitable degree for use in actual production.

Fig.1 Simplified diagram of main circuit of a custom-waveform power supply

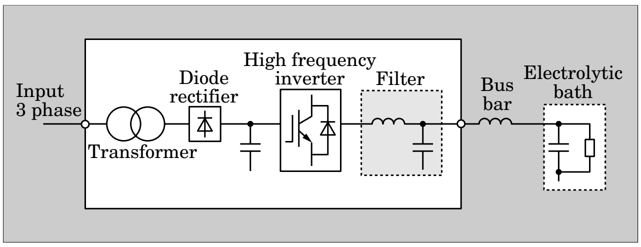
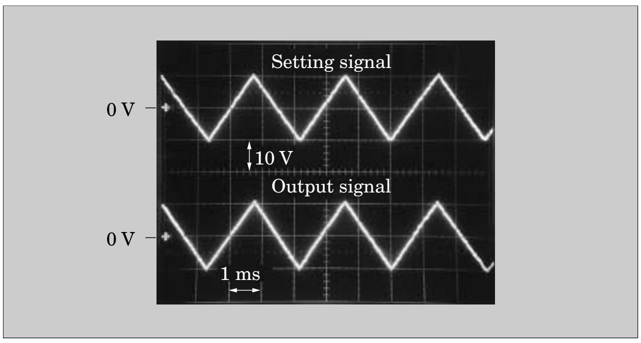


Fig.2 Example of waveform of output voltage



3. Power Supply for Color Anodizing of Aluminum Sashes

3.1 Principles and process of aluminum surface color anodizing

As shown in Fig. 3, the surface treatment of aluminum consists of anodic oxidation treatment to form oxide film on the aluminum surface, followed by color anodizing.

In the first process of anodic oxidation, oxide film is formed on the surface by flowing a DC current with the aluminum material as the positive pole. The chemical reactions are given by the following equations.

$Al \rightarrow Al^{3+} + 3e$, $H_2O \rightarrow O^{2-} + 2H^+$

$2Al^{3+} + 3O^{2-} \rightarrow Al_2O_3$ (aluminum oxide)

As shown in Fig. 4, the oxide film consists of a non-porous film called the barrier layer and a porous oxide film called the porous layer. The shape of pores in the porous layer can be altered according to the type of solution and electrolytic conditions (waveform of the power supply etc.). Recently, development of special functional applications (optical, photoelectric, magnetic etc.) using this porous layer is being pursued.

In the color anodizing process, current is flowed with aluminum as the negative pole and metal is electro-deposited in pores in this porous layer as below:

$M^{n+} + ne^- \rightarrow M$ (M^{n+}: metal ion)

The processing sequence of electro-deposition is shown in Fig. 3.

Color tone of the aluminum material subjected to color anodizing will change according to the degree of deposition in the pores. Although the mechanism in which metal is electro-deposited by the flow of electric current through the barrier layer, an insulator material, is not completely understood, it is known that yield rate, color tone and color uniformity can be controlled by using different waveforms such as DC, AC or specialized waveforms. Those methods of control represent the expertise of the manufacturer.

The metal to deposit is usually nickel and the colors obtained have been mostly blackish brown. Recently, however, it has become possible to achieve a grayish-blue color by a method known as third electrolytic coloring. In this method, as tolerances of the required electrolytic conditions for coloring are narrow, the role of the power supply becomes more important and consequently requirements for the waveform setting function and accuracy of the output waveform are more stringent.

3.2 Custom-waveform power supply

In the color anodizing of aluminum sashes, the type and temperature of electrolytic solution, and shape and arrangement of electrodes influence the quality of coloring. Electric current and voltage that are output by the power supply are also important factors. By accurately controlling the current and voltage waveforms, improvement in the yield rate and coloring of specialized colors is realized.

In this paper, a power supply unit recently delivered to Toyama Light Metal Industry Co., Ltd. is described as an example. Its specifications, appearance and simplified circuit diagram of the unit are given in Table 2, Fig. 5 and Fig. 6, respectively.

Output voltage waveforms consist of DC waveforms and AC square waves, having asymmetric positive and negative components with soft start. Color anodizing of brownish colors is performed by using DC output with soft start and that of blackish colors is performed by using a square wave with soft start. Further, a similar power supply unit delivered to the Pilot Center uses an AC square wave to perform grayish-blue color anodizing by the third electrolytic coloring method, in addition to brownish and blackish coloring. In the DC electrolytic coloring method to obtain brownish colors, error in output voltage during the soft start has a significantly harmful influence on color evenness. Also, in the third electrolytic coloring process in which a square wave AC voltage is applied

Fig.3 Typical processing sequence of aluminum surface treatment

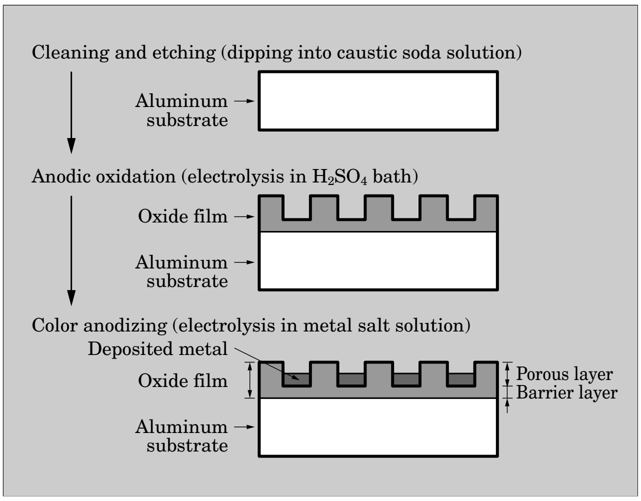


Fig.4 Surface condition of aluminum

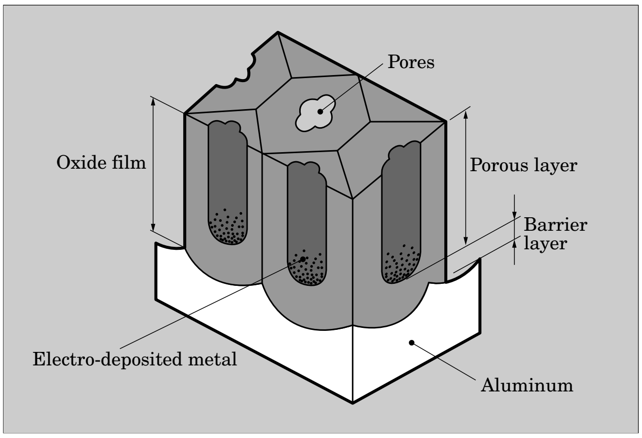


Table 2 Specifications of a ±50 V, 10 kA unit delivered to Toyama Light Metal Industry Co., Ltd.

Item	Description
Input	Three phase, 60 Hz, 6.6 kV
Output	DC: 50 V, 10 kA
	AC: 50 V (peak), 10 kA (peak)
Output waveform	DC and square wave Specification for square wave : frequency: 10 to 100 Hz, ratio of current duration positive/negative : 0.1 to 10
Control method	Automatic voltage control
Accuracy of control	±0.2 %
Main circuit components	Step-down transformer, diode rectifier, inverter
Specification for inverter	Composed of 6 IGBTs in parallel/stack×28 stacks Type of IGBT : 2MBI400N-060 Carrier frequency : 7.5 kHz
Cooling system	Transformer : ONAN Diode rectifier : WF Inverter : WF
External dimensions	5,500 width×1,960 depth ×3,200 height (in mm)
Mass	9,400 kg

to aluminum materials to obtain grayish-green colors, a highly accurate value is required for peak amperage of the AC square wave, over the entire range from low voltage to rated voltage.

In order to achieve the requirement for highly accurate control, the following items were taken into consideration to obtain an accuracy of 0.2 %.

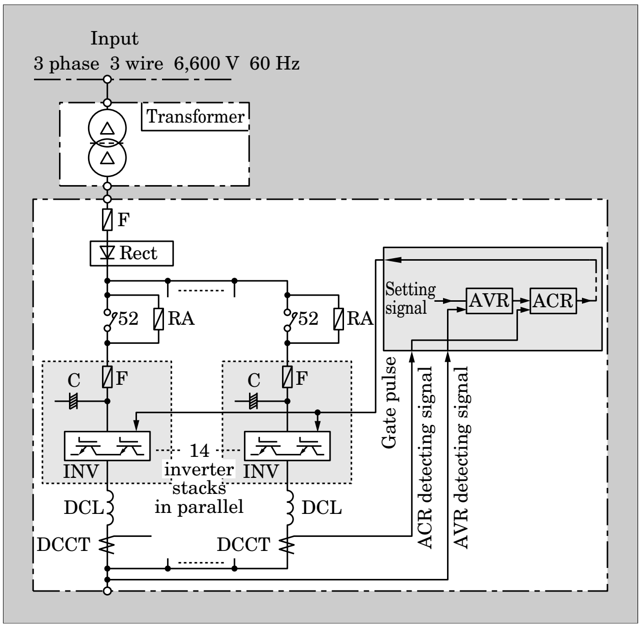
(1) Adoption of components with low drift for use in the controller
(2) Adoption of output voltage detector with high accuracy
(3) Adoption of isolation amplifier for setting command signals with high accuracy
(4) Elimination of noise infiltration into control line

On the other hand, high-speed response is required of the square wave rise-time of the output voltage. This is because a delay in rise-time becomes dead time during an AC square wave color anodizing process. By accelerating the rise-time, electrolytic deposition time can be shortened and productivity improved.

In applications for coloring aluminum sashes, the capacitance is largely due to the load, that is, the conditions of oxide film on the aluminum sash surface (thickness of barrier layer and structure of porous layer), the type of electrolytic solution and the arrangement of electrodes. Moreover, inductance due to the bus bar connecting the power supply to the load is significant because of the high current that flows there. Since the equivalent circuit, as shown in Fig. 1, contains capacitance and inductance in the load side, it is difficult to achieve control that is both high-speed and stable. Furthermore, capacitance is not constant, but varies largely depending on the quantity of aluminum material, stage of current flow (beginning or final) and waveform (DC or square wave AC). Accordingly, the magnitude of these variations should be taken into account by the control.

Fig.5 Appearance of a ±50 V, 10 kA unit delivered to Toyama Light Metal Industry Co., Ltd.

Fig.6 Simplified diagram of main circuit of a ±50 V, 10 kA unit delivered to Toyama Light Metal Industry Co., Ltd.



To resolve these problems, high-speed response is improved by adopting a design to give sufficient voltage allowance. And to improve stability, automatic voltage control with an automatic current control minor loop is provided and is used together with current limit control to suppress current overshoot at the rising edge of the waveform. Furthermore, it is possible to changeover control constants according to whether the operation is DC or AC.

To handle the high current output of 10 kA, the inverter part of the unit is configured as a single-phase inverter consisting of 28 water-cooled stacks, 14 in parallel, with each 600 V and 400 A rated unit consisting of 6 IGBT modules in parallel with upper and lower arms. Figure 7 shows the appearance of one of

Fig.7 Appearance of an IGBT inverter stack

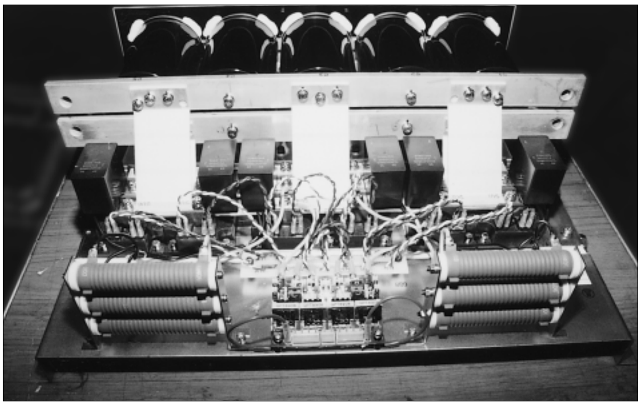
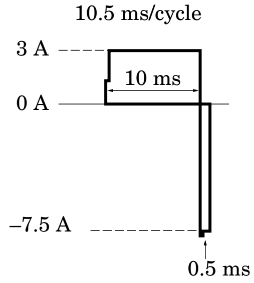


Table 3 Experimental conditions

Area to be electroplated	673.3 cm^2
Duration of electroplating	60 min.
Pulsed waveform (Amperage is per 100 cm^2)	

the stacks. The current flow among the stacks in this multi-parallel connection is made uniform by performing automatic current control for each inverter unit. Additionally, a DC reactor is added to the output of each inverter unit to suppress cross-current among inverter units. Also, the bus bar inverter unit is positioned so that magnetic flux can be canceled to prevent local heating in the unit.

To optimize onsite maneuverability and monitoring ease, load side (aluminum sash) expertise is incorporated into the control hardware and software. This directly leads to improved productivity. By utilizing this unit, the inferiority rate of color difference is reduced to 1/3 compared to that of the former system using a thyristor rectifier and induction voltage regulator.

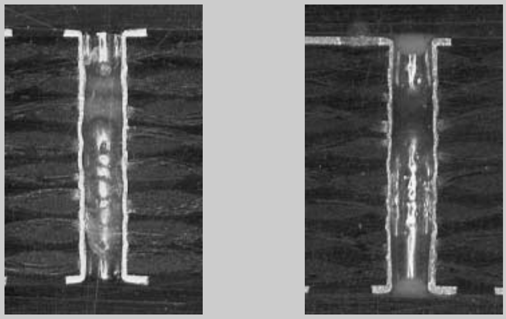
4. Custom Wave-Form Power Supply for Copper Plating of Printed Circuit Boards

In addition to use for the surface treatment of aluminum, this power supply can be applied to various kinds of electroplating where specialized waveforms are useful. The application of a custom waveform power supply for the copper electroplating of printed circuit boards is described below.

4.1 Process of copper plating printed circuit boards and recent trends

In the process of copper plating circuit boards, electroplating is performed after electroless plating. Until now, a rectifier has been used for the process of electroplating. Recently, as printed circuit boards become more dense, plating technology for manufacturing and processing minute parts such as minute through-holes, minivias, fine bumps, built-up circuit boards, etc., has become more important. However, DC electroplating has the problem of non-uniform film. That is, at corners and projecting points, plating thickness increases due to the electric field concentrated there, while on the other hand, plating thickness is reduced in areas where the electric field is weak such as the middle of through-holes. These problems must be resolved for the sake of future progress of fine processing.

Fig.8 Photos showing cross-section of through-hole



(a) Electroplating using special waveform (Throwing power : 105 %)

(b) Electroplating using DC (Throwing power : 49 %)

4.2 Results of applying the custom-waveform power supply

The results of applying a specialized current waveform generated by a custom-waveform power supply are described below. The plating thickness distribution on the interior surface of a through-hole deposited by a square wave output current is compared to that from a DC current.

The experimental conditions are given in Table 3. The output current waveform is a square wave having asymmetric positive and negative components as shown in this Table. The waveform on the positive side deposits the metal plating, as in the case of usual DC electroplating. The short term pulsed wave on the negative side re-dissolves into the electrolytic solution the electroplating deposited on areas such as the edges of through-holes, where metal is usually excessively deposited and also equalizes ion concentrations near the surface of the aluminum. Thus, the combination of positive and negative waveforms aims to achieve uniform plating thickness.

The command signal for a square wave with asymmetric positive and negative components is somewhat compensated to suppress overshoot of the output

Table 4 Comparison of physical properties of through-hole

Item \ Waveform		Electroplating using pulsed waveform	Electroplating using DC
Expansion (%)	Sample 1	27.3	22.0
	Sample 2	27.0	21.4
	Average	27.2	21.7
Tension (kN/cm^2)	Sample 1	38	35.9
	Sample 2	37.8	36.2
	Average	37.9	36.1
Throwing power (%)	Sample 1	105	49
	Sample 2	104	50
	Average	104.5	49.5
Heat cycle (number of cycles)		20	20

Expansion : Evaluation for flexibility. (The larger, the better)
Tension : Evaluation for peeling resistance of wiring pattern. (The larger, the better)
Throwing power : Ratio of plating thickness at entrance of through-hole to that at middle of through-hole. (The nearer to 100 %, the better)
Heat cycle : The number of heat cycles before occurrence of an abnormality. (The more, the better)

current and to realize rapid rise-time. Automatic current control is used as the control method to output the current within a definite time.

The distribution of plating thickness on the interior surface of a through-hole is as shown in Fig. 8. Comparison with DC plating is given Table 4. The distribution of plating thickness (throwing power) is remarkably improved compared with that of DC electroplating.

Other physical properties are also better than or equal to those of DC electroplating.

5. Conclusion

In this paper, the color anodizing of aluminum sashes and copper plating of printed circuit boards are introduced as example applications of the custom-waveform power supply for metal surface treatment. As for aluminum, special functional anodic oxide film, anodizing for special colors, etc., are possible applications. Further advantages are expected in applications of surface treating other metals such as magnesium, where the range of application is expected to grow in the future. Utilizing these advantages, Fuji Electric intends to develop further applications for this type of power supply.