Analog circuit simulator as research tool for AC anodizing of aluminum

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Equivalent circuits of AC electrolysis and analog circuit simulators are introduced in general. Distorted waveforms of alternating current during AC anodizing of aluminum are analyzed using the analog circuit simulator

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1. Introduction

Physical properties of oxide film and reaction mechanisms of alternating current electrolysis have been studied since the past by using the equivalent circuit. However, very little research has been carried out to examine equivalent circuits by analog electric circuit simulator. The equivalent circuit and the analog electric circuit simulator are described in this paper. Experimental results of AC anodizing of aluminum are studied using the analog electric circuit simulator. The following items are presented:

(1) Introduction to analog circuit simulator
(2) Current waveforms observed by oscilloscope during AC anodizing of aluminum
(3) Equivalent circuit of distorted current waveform during AC anodizing of aluminum
(4) Discussion on experimental results of AC anodizing by analog electric circuit simulator
(5) Useful information by simulation of the distorted current wave forms.

2. Introduction to the analog circuit simulator

2.1 History of analog circuit simulator

Various kinds of electric circuit simulators are available in the market. The electric circuit simulator developed at Berkeley campus of University of California in the mid seventies. These electric circuit simulators are more expensive than software used in offices such as word-processing software. However, light versions of software with limited functions for electric circuit simulator are in the public domain. The equivalent circuit in electrolysis is simpler than the electric circuit in electrical engineering, and it can be analyzed by such light version software.

2.2 Simulation of some basic electric circuits by analog circuit simulator

To enhance the understanding of AC circuits and analog circuit simulators, some basic electric circuits were simulated. A sinusoidal wave voltage of 50 Hz was applied on the AC circuit consisting of only electrical resistance and the alternating current was simulated by the electric circuit simulator. Figure 1 shows the simulation method. Figure 2 shows the results of the simulation. The waveform of alternating voltage applied on the AC circuit is shown in Figure 2(A). The vertical axis shows the voltage and the horizontal axis shows time. Figure 2(B) shows the waveform of the alternating current which flows through the AC circuit. The vertical axis in this figure shows the current and the horizontal axis the time. In this case, there is no phase difference between the alternating voltage and the alternating current. The phase difference and the current value were the same for high frequencies in this electric circuit.

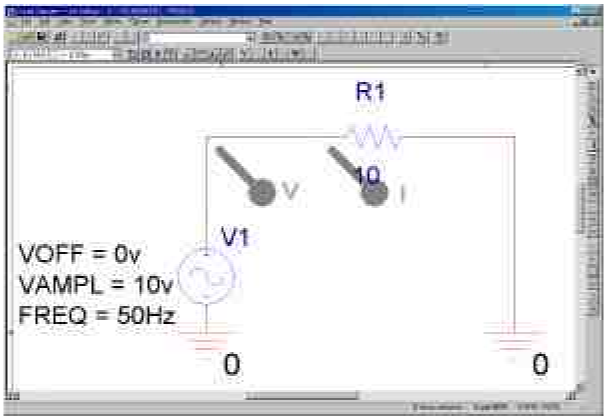


Fig.1
Method of simulating electric current in AC circuit consisting only of electrical resistance.

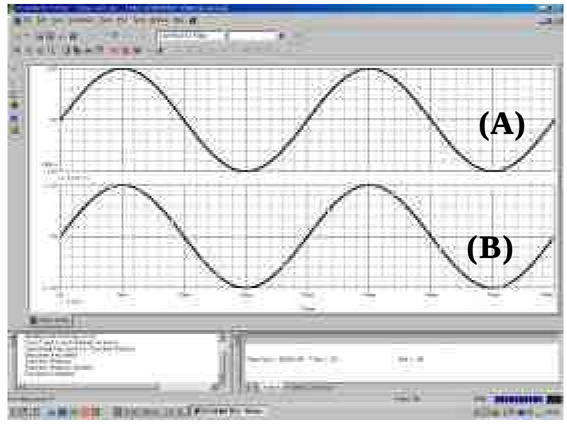


Fig.2
Simulation results of AC circuit consisting only of electrical resistance.

A sinusoidal wave voltage of 50 Hz was applied on an AC circuit consisting only of capacitor, and the alternating current was simulated by the electric circuit simulator. Figure 3 shows the simulation method. Figure 4 shows the results of the simulation. The waveform of alternating voltage applied on the AC circuit is shown in Figure 4(A). The vertical axis shows the voltage and the horizontal axis the time. Figure 4(B) shows the waveform of the alternating current which flows through the AC circuit. The vertical axis shows the current and the horizontal axis the time. In this case, a phase difference of 90 degrees exists between the alternating voltage and the alternating current. The current value has grown by as much as 25 times compared with the case of 50 Hz though the phase difference was 90 degrees when the frequency of this electric circuit was adjusted to 1 KHz.

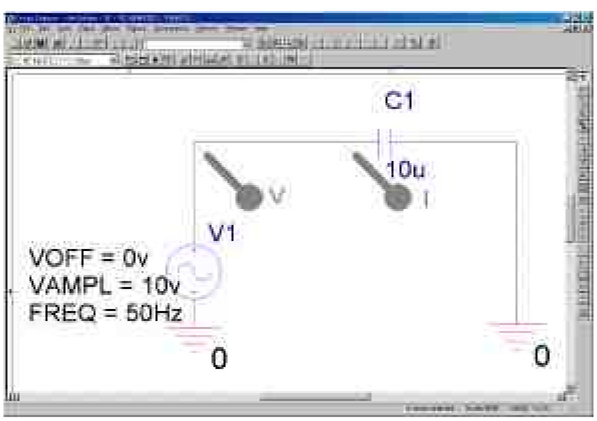


Fig.3
Method of simulating electric current of AC circuit consisting only of capacitor

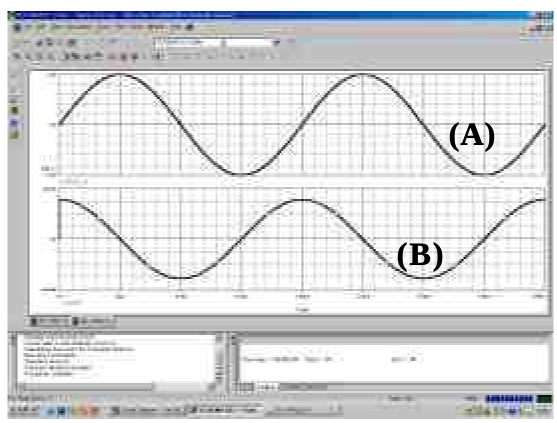


Fig.4
Simulation results of AC circuit consisting only of capacitor

A sinusoidal wave voltage of 50Hz was applied on the series circuit of the electrical resistance and capacitor, the alternating current was simulated by the electric circuit simulator. Figure 5 shows the simulation method. Figure 6 shows the results of the simulation. The waveform of alternating voltage applied on the AC circuit is shown in Figure 6(A). The vertical axis shows the voltage and the horizontal axis the time. Figure 6(B) shows the waveform of the alternating current which flows through the AC circuit. The vertical axis shows the current and the horizontal axis the time. In this case, a phase difference of 90 degrees exists between the alternating voltage and the alternating current. At a phase difference of 90 degrees, the current value increased by as much as ten times compared with the case of 50 Hz when the frequency of this electric circuit was adjusted to 1 KHz.

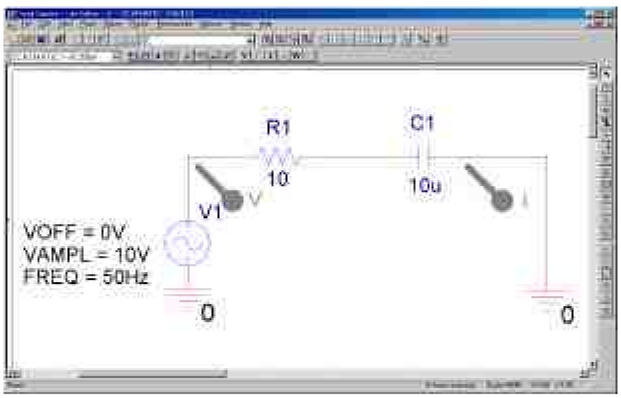


Fig.5
Method of simulating the series circuit of electrical resistance and capacitor

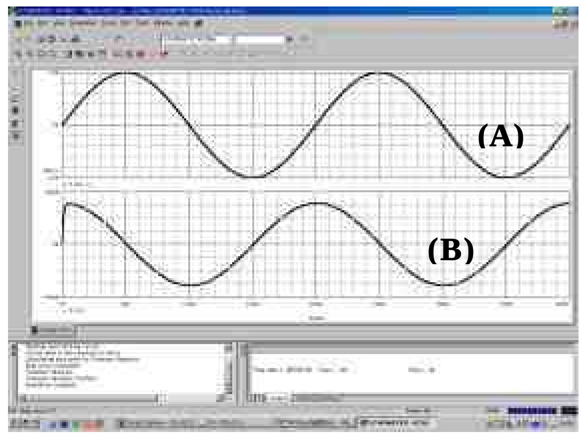


Fig.6
Simulation results of the series circuit of electrical resistance and capacitor

A sinusoidal wave voltage of 50Hz was applied on a parallel circuit consisting of electrical resistance and the capacitor, and the alternating current was simulated by the electric circuit simulator. Figure 7 shows the simulation method. Figure 8 shows the results of the simulation. The waveform of alternating voltage applied on the AC circuit is shown in Figure 8(A). The vertical axis shows the voltage and the horizontal axis the time. Figure 8(B) shows the waveform of the alternating current which flows through the AC circuit. The vertical axis shows the current and the horizontal axis the time. In this case, the phase difference between the alternating voltage and the alternating current was very small, and the greater part of the electric current passed through the electric resistance. When the frequency of this electric circuit was adjusted to 1 KHz, the phase difference as shown in Fig.9 occurred, and the current value has also increased a little compared with the case of 50 Hz.

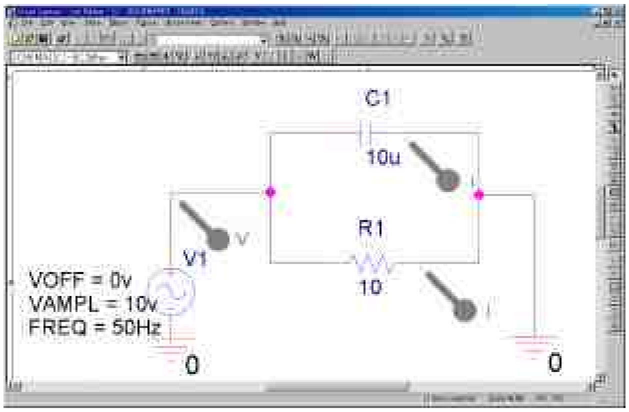


Fig.7
Method of simulating the parallel circuit consisting of electrical resistance and capacitor

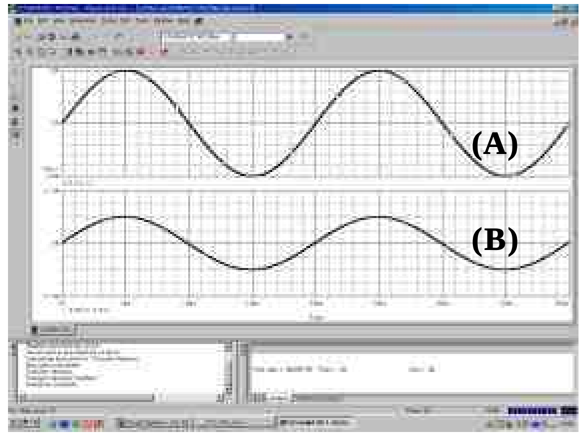


Fig.8
Simulation results of the parallel circuit consisting of electrical resistance and capacitor (50 Hz)

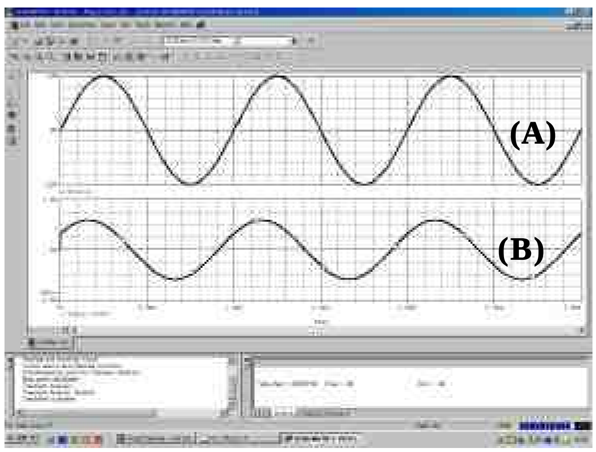


Fig.9
Simulation results of a parallel circuit consisting of electrical resistance and capacitor (1 KHz)

The AC circuits explained above are the same as the circuits one studied in “High School Physics". However, the explanations in Figure 1 to Figure 9 are necessary to understand the simulation of the electric current by the sinusoidal alternating voltage superimposed on direct voltage. The so called "AC anodizing of aluminum" is often carried out by superimposing sinusoidal alternating voltage on direct voltage. Therefore, the change in the electric current by superimposing the sinusoidal alternating voltage on direct voltage was simulated. The “sinusoidal alternating voltage superimposed on direct voltage" is indicated as "AC+DC voltage" hereafter. The frequency of AC voltage is 50 Hz in the normal case.

The AC + DC voltage was applied on the circuit consisting only of the electrical resistance, and the alternating current was simulated by the electric circuit simulator. Figure 10 shows the simulation method. Figure 11 shows the results of the simulation. The waveform of the AC +DC voltage applied on the circuit is shown in Figure 11(A). The vertical axis shows the voltage and the horizontal axis the time. Figure 11(B) shows the waveform of the alternating current which flows through the circuit. The vertical axis shows the current and the horizontal axis the time. In this case, there is no phase difference between the AC + DC voltage and the alternating current, and only anodic current flows. The current value was same as the value at high frequencies of this electric circuit.

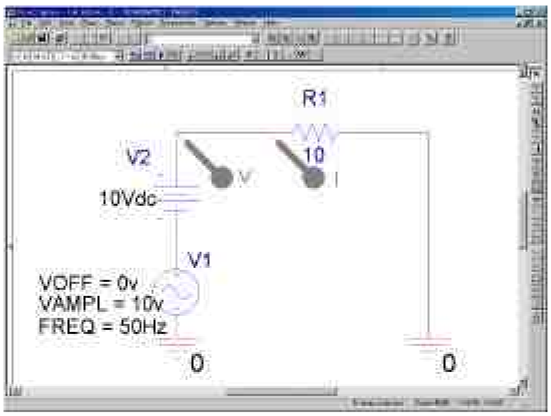


Fig.1 0

Method of simulating electric current of the AC + DC circuit consisting only of electrical resistance.

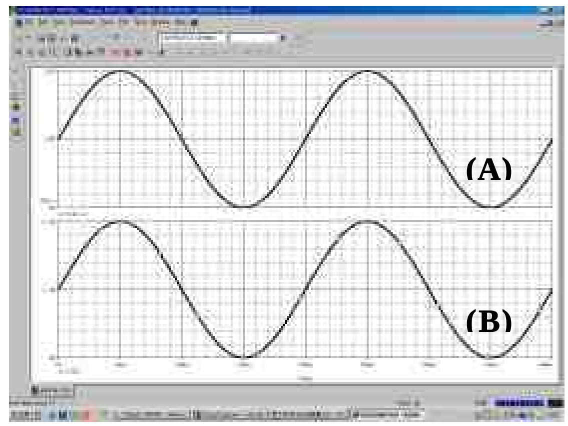


Fig.11

Simulation results of the AC + DC circuit consisting only of electrical resistance.

The AC + DC voltage was applied on a circuit consisting only of electrical capacitor, and the alternating current was simulated by the electric circuit simulator. Figure 12 shows the simulation method. Figure 13 shows the results of the simulation. The waveform of the AC + DC voltage applied on the circuit is shown in Figure 13(A). The vertical axis shows voltage and the horizontal axis shows time. Figure 13(B) shows the waveform of the alternating current which flows through the circuit. The vertical axis shows current and the horizontal axis shows time. In this case, not only the anodic current but also the cathodic current flowed, and the phase difference between the AC voltage and the alternating current was 90 degrees. The current waveform is symmetrical with respect to the ground level, and the DC component of electric current does not flow. This is an important point to be borne in mind during the anodizing of aluminum by the AC+DC voltage. When the frequency of the AC voltage applied to this electric circuit is high, the current increases.

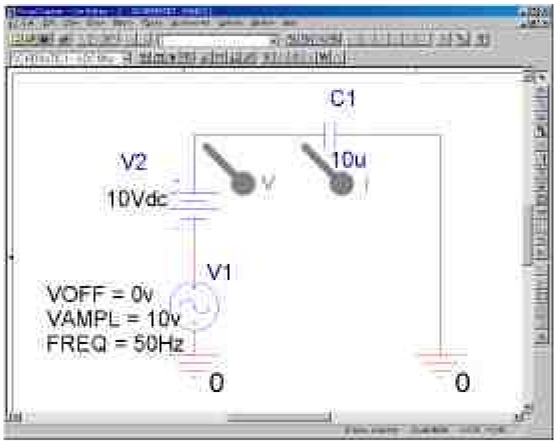


Fig.12
Method of simulating electric current of AC+DC circuit consisting only of electrical capacitor

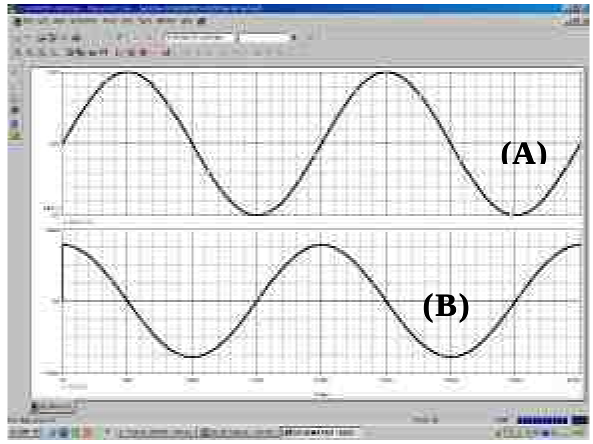


Fig.13
Simulation results of the AC + DC circuit consisting electrical only of capacitor.

The AC +DC voltage was applied on a series circuit of electrical resistance and the capacitor, and the alternating current was simulated by the electric circuit simulator. Figure 14 shows the simulation method. Figure 15 shows the results of the simulation. The waveform of the AC +DC voltage applied on the circuit is shown in Figure 15(A). The vertical axis shows voltage and the horizontal axis shows time. Figure 15(B) shows the waveform of the alternating current which flows through the circuit. The vertical axis shows current and the horizontal axis shows time. In this case, the phase difference between the AC + DC voltage and the alternating current is le 90 degrees. Both the anodic current and the cathodic current flowed. The current waveform was a symmetric alternating current. The current value is large at high frequencies of this electric circuit.

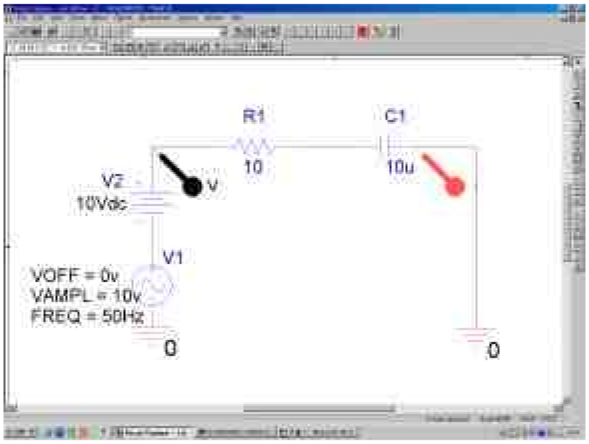


Fig.14
Method of simulating series circuit consisting of electrical resistance and capacitor by the AC + DC voltage

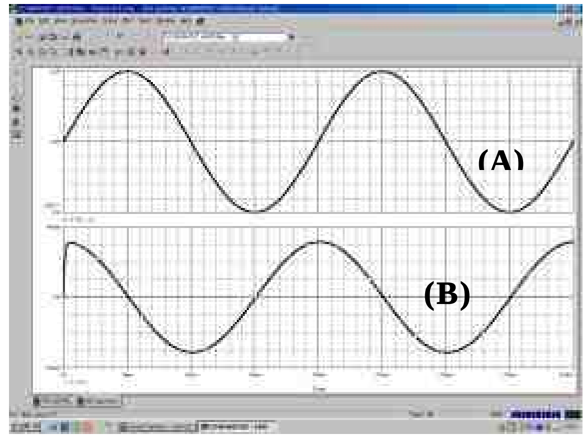


Fig.15
Simulation results of the series circuit consisting of electrical resistance and capacitor by the AC +DC voltage

The AC +DC voltage was applied on a parallel circuit consisting of electrical resistance and capacitor, and the alternating current was simulated by the electric circuit simulator. Figure 16 shows the simulation method. Figure 17 shows the results of the simulation. The waveform of the AC +DC voltage applied on the circuit is shown in Figure 17(A). The vertical axis shows voltage and the horizontal axis shows time. Figure 17(B) shows the waveform of the alternating current which flows through the circuit. The vertical axis shows current and the horizontal axis shows time. In this case, the phase difference between the AC voltage and the alternating current is very small. The cathodic current was also very small. The greater part of electric current flows through the electrical resistance route. When the frequency of this electric circuit was adjusted to 1 KHz, the phase difference and the current value increased a little as shown in Figure 18. The cathodic current can be observed on the graph. A large electric current flows through the electrical resistance route even in the case of 1 KHz. As a result, the difference between current in the case of 50Hz and current in the case of 1 KHz was small.

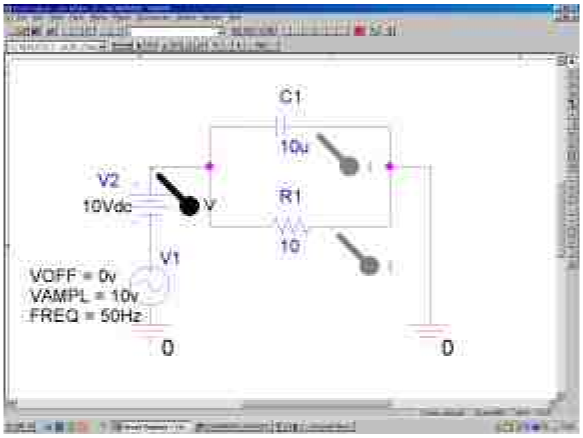


Fig. 16
Method of simulating the parallel circuit of electrical resistance and capacitor by AC + DC voltage

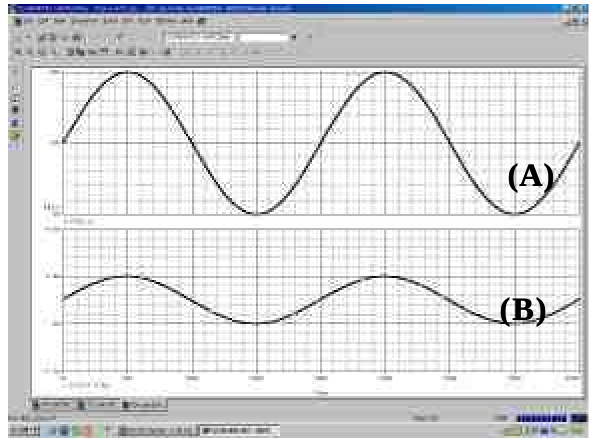


Fig.17
Simulation results of parallel circuit of electrical resistance and capacitor by AC +DC voltage (50 Hz)

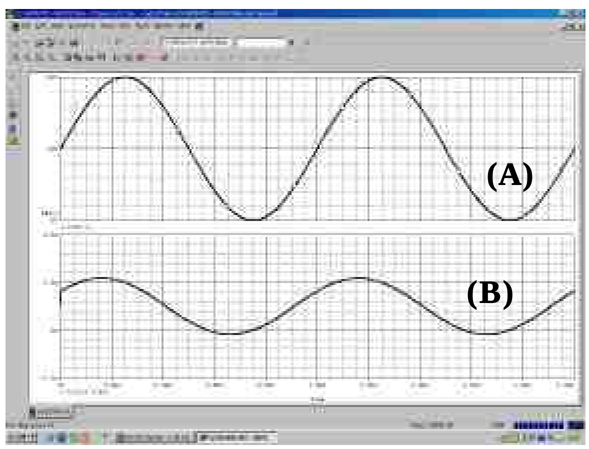


Fig.18
Simulation results of the parallel circuit of electrical resistance and capacitor by AC + DC voltage (1 KHz)

3. Current waveforms observed by oscilloscope during AC anodizing of aluminum

The curve in the upper part of photograph 1 shows the voltage waveform applied on aluminum. The curve in the lower part of Photograph 1 is an alternating current waveform generated by applying sinusoidal voltage on aluminum in a sulfuric acid bath. The current waveform is a distorted waveform. This distorted waveform may be divided into three kinds of electric currents (Figure 19).

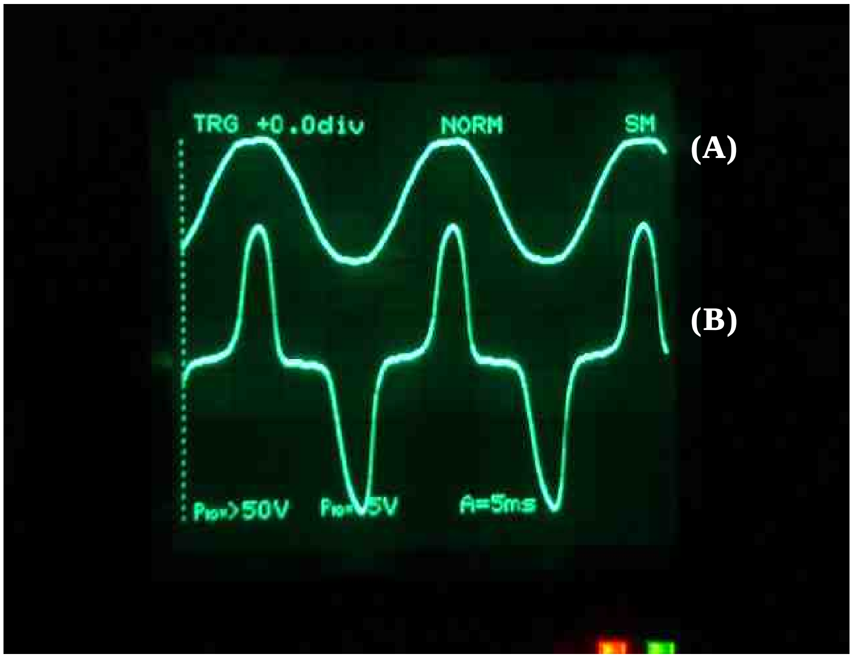


Photo.1
Sinusoidal waveform of alternating voltage and distorted waveform of alternating current

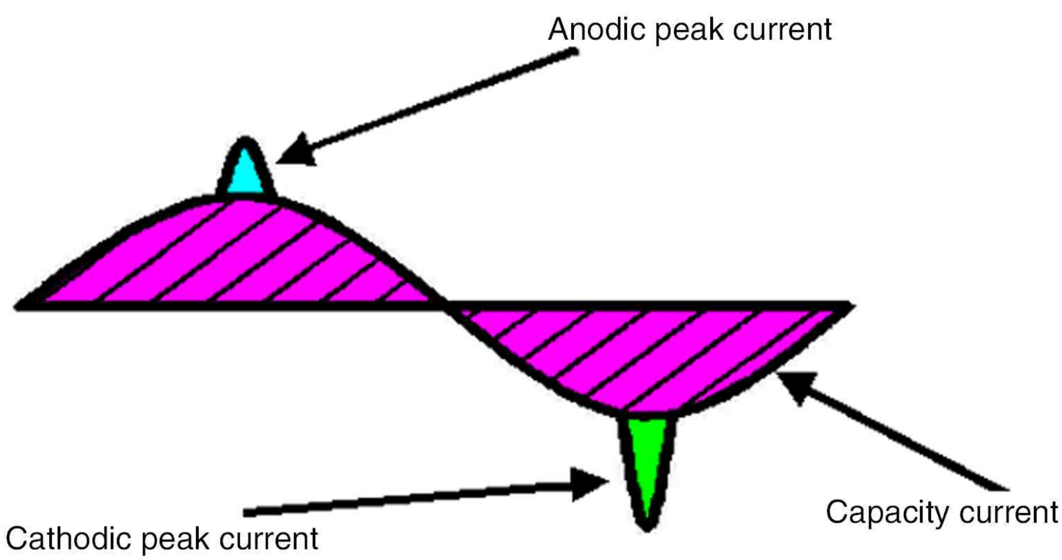


Fig.19
Electrochemical meaning of the distorted waveform of alternating current

These are the anodic peak current (Ia,p), the cathodic peak current (Ic,p) and the capacitive current (Icap). Ia,p is the anodic reaction current caused by anodic voltage of the AC voltage. Ic,p is the cathodic reaction current caused by cathodic voltage of the AC voltage. Ic,p is larger than Ia,p because the cathodic reaction occurs more easily than the anodic reaction, Ia,p is the electric current for oxide film formation. However, Ic,p is the current that generates hydrogen gas. The electric current of the sine wave shown in Figure 19 is called capacitive current (Icap). The capacitive current is a physical electric current and does not contribute directly to the anodic reaction nor the cathodic reaction. Therefore, the capacitive current is said to be a "non-Faradic current".

4. Equivalent circuit of distorted current waveforms during AC anodizing of aluminum

"Equivalent circuit" is often adopted as an investigative method in the field of electrochemistry in alternating current electrolysis. As shown in Fig. 20, the notion that “electrolysis is identical to the phenomenon of passing electric current in an electric circuit" also prevails. If the method of the equivalent circuit is adopted, it may sometimes be possible to interpret the reaction mechanism of the alternating current electrolysis.

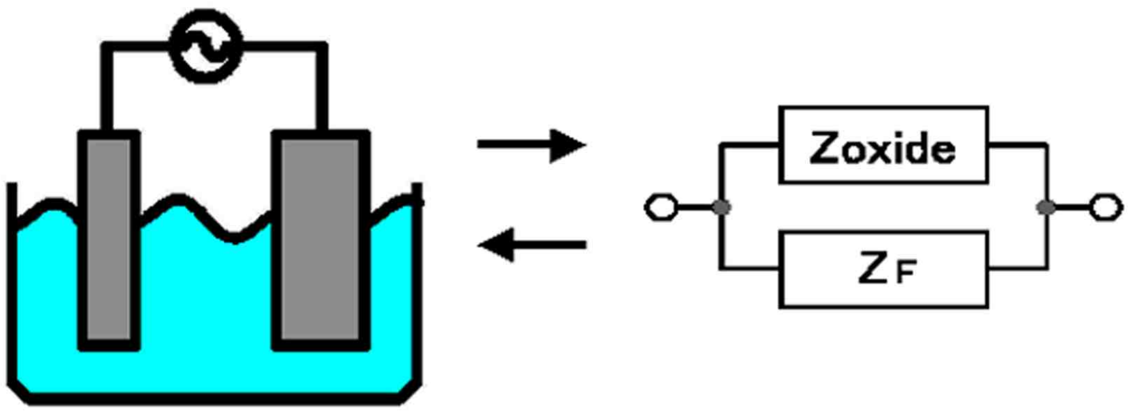


Fig.20
Electrolysis and equivalent circuit

The equivalent circuit of aluminum alternating current electrolysis is shown in Figure 21 and Figure 22.

Roxide may be omitted in many cases of anodizing of aluminum because Roxide is very much larger than the impedance due to Coxide. Moreover, Cf may be omitted as the impedance due to Cf is much larger than Rf. As a result, the equivalent circuit in Figure 21 can be represented by the simplified equivalent circuit of Figure 22.

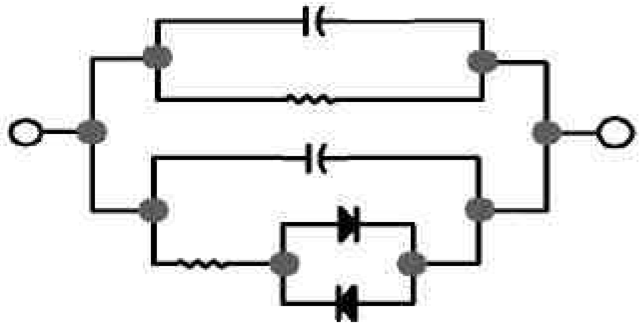


Fig.21
Equivalent circuit of AC anodizing of aluminum

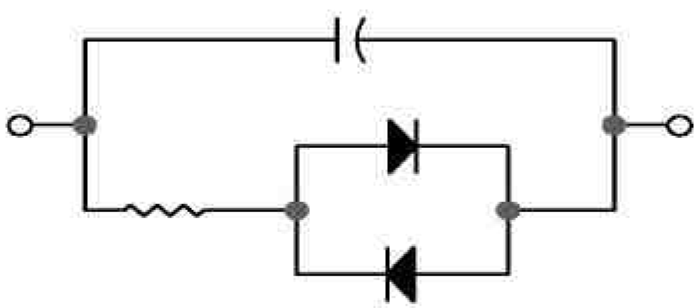


Fig. 22
Simplified equivalent circuit of AC anodizing of aluminum

5. Discussion on experimental results of AC anodizing of aluminum by analog circuit simulator

Figure 23 shows the analog circuit chart for simulation. Figure 24 shows the simulation results. The simulation results practically agreed with the current waveform shown in photograph 1.

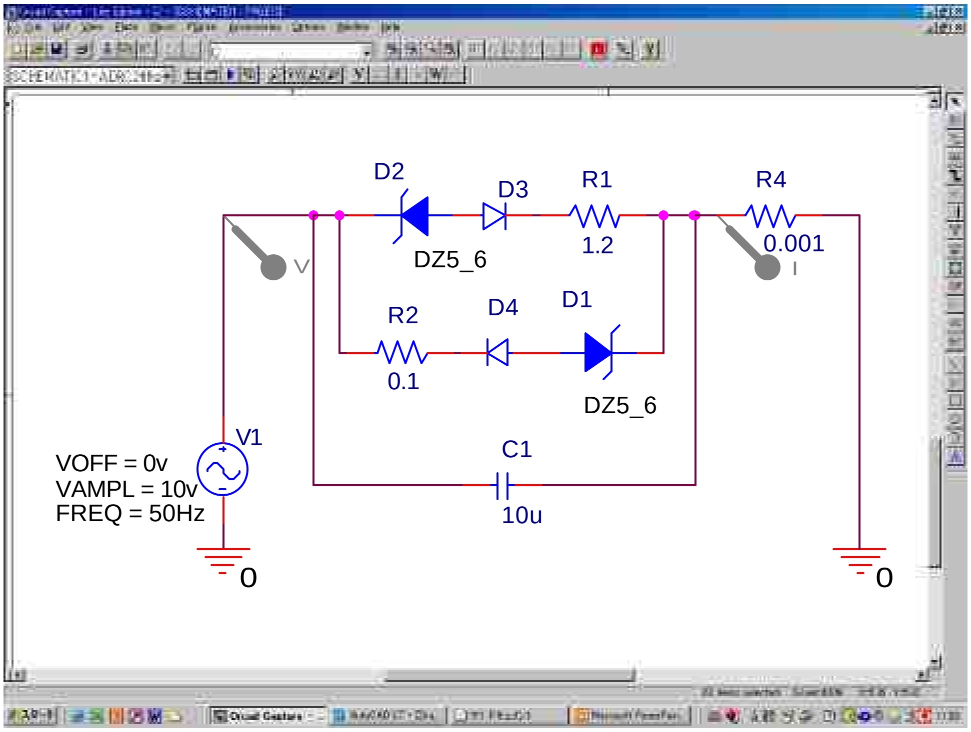


Fig.23

Circuit diagram for simulation of AC anodizing of aluminum

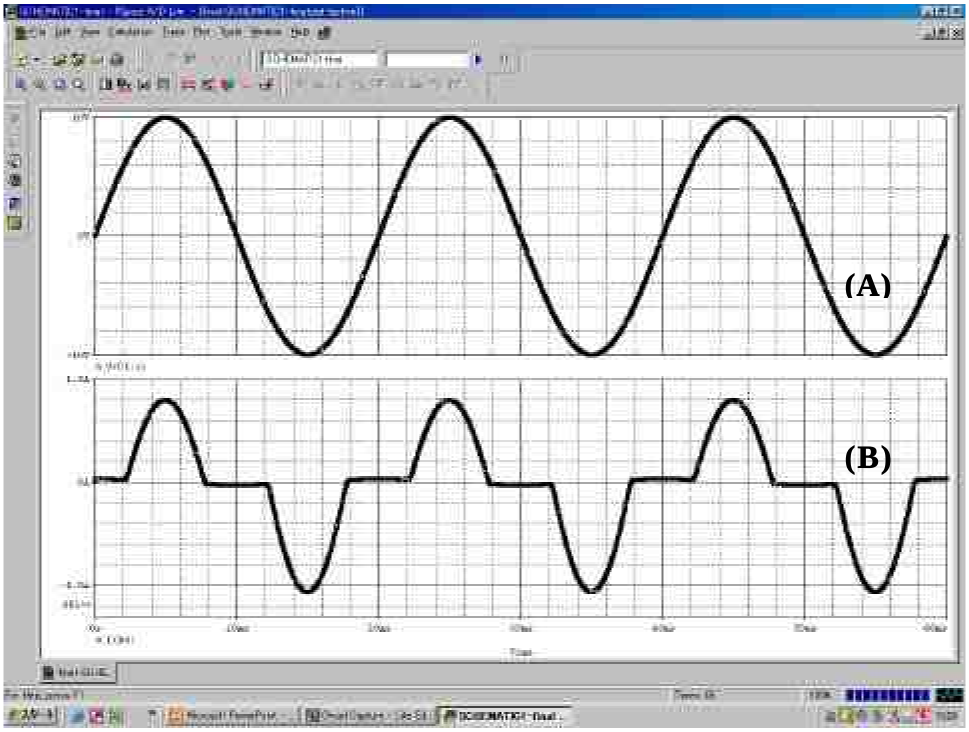
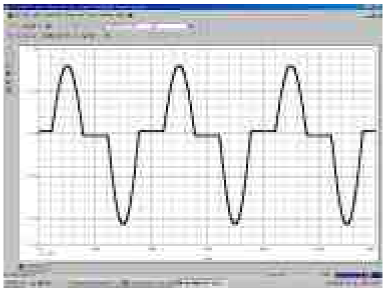


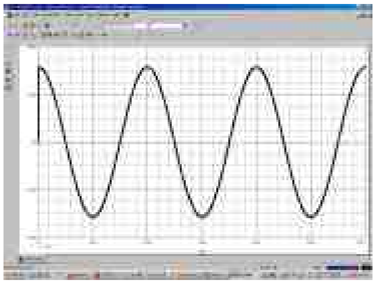
Fig.24
Simulation results of AC anodizing of aluminum

6. Useful information by simulation of the distorted current wave forms
We can get the following three useful information.

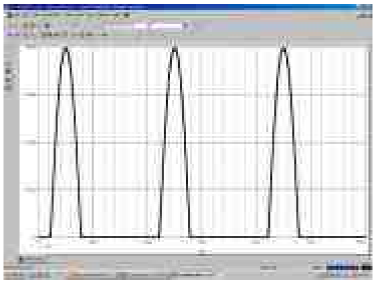
(1) We can know the partial current through each pass of the electric circuit



(A) Total current



(B)Partial current though the lowest pass.



(C)Partial current though the top pass.

Fig.25
Total and partial current through the equivalent circuit.

(2) We can know the joule heat during AC anodizing

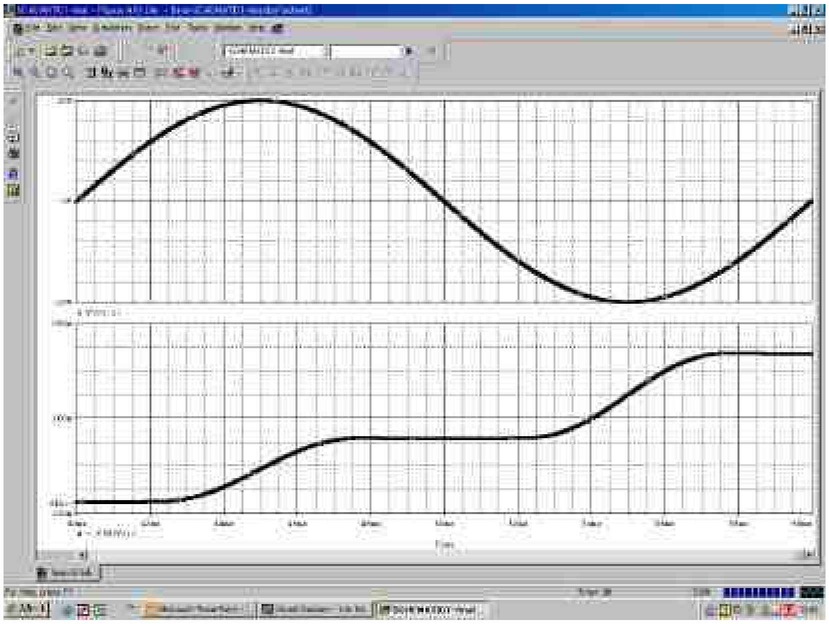
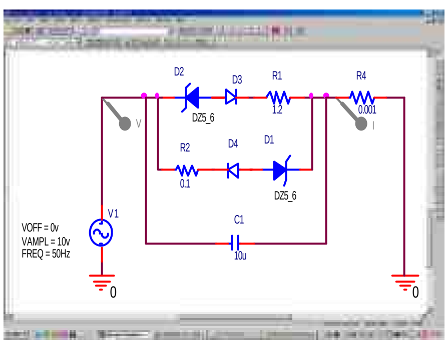


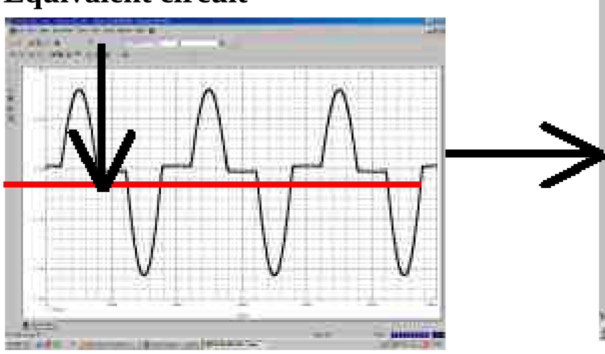
Fig.26

Applied AC voltage and the electric power consumption
during AC anodizing(the simulated joule heat during AC anodizing)

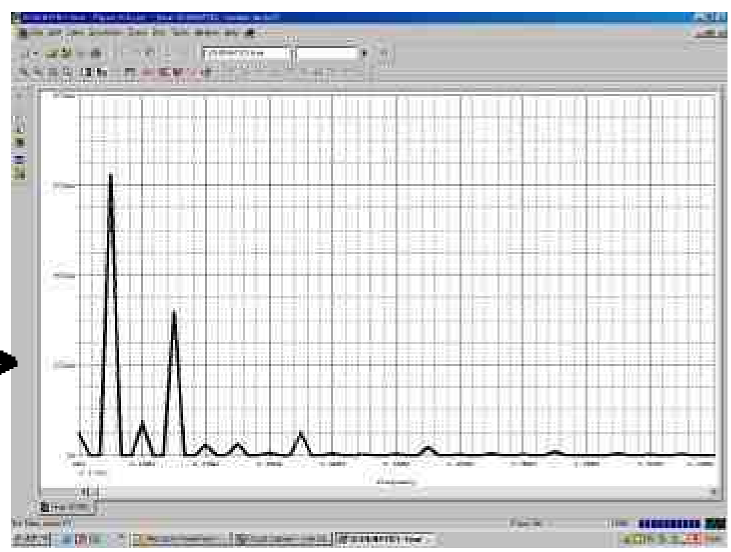
(3) We can know the degree of distortion of the electric current waveforms



Equivalent circuit



Distorted current waveform

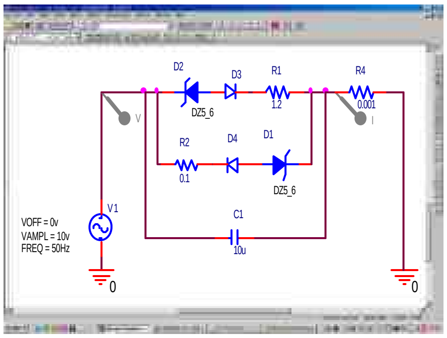


Fourier analysis of current wave form

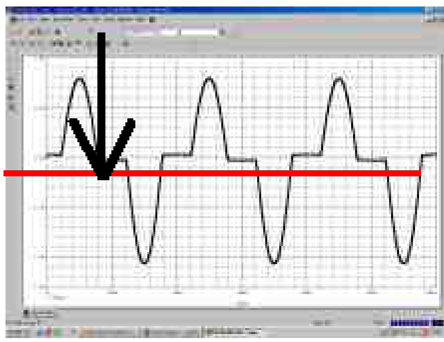
Fig.27

Fourier analysis of current wave form

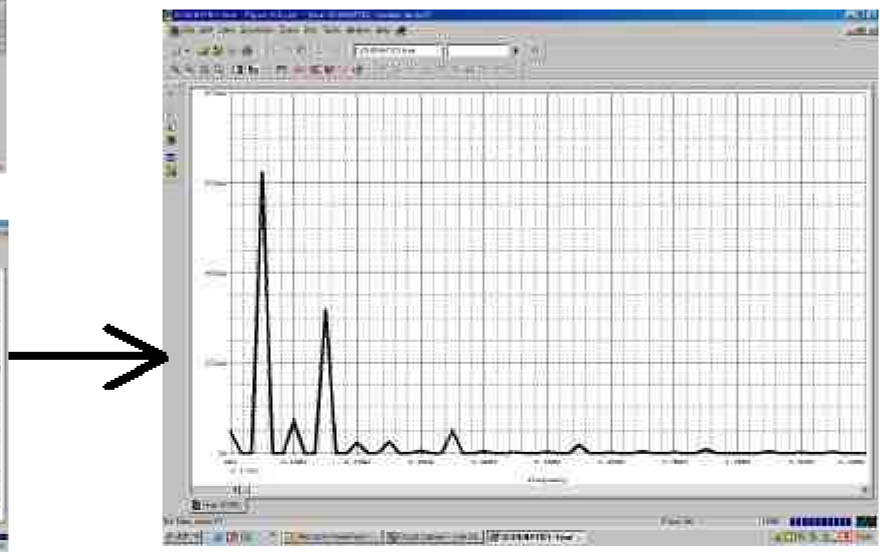
(3) We can know the degree of distortion of the electric current waveforms



Equivalent circuit



Distorted current waveform



Fourier analysis of current wave form

Fig.27

Fourier analysis of current wave form

7. Conclusion

Distorted electric current waveform was simulated by analog circuit simulator. As a result of the simulation, three useful information were obtained.

1. We can know the partial current through each pass of the electric circuit
2. We can know the joule heat during AC anodizing
3. We can know the degree of distortion of the electric current waveforms