CASE 14

Evaluation of Electric Waveforms by Momentary Values

Abstract: In this report a new method of evaluating the performance of four-terminal circuits is proposed. In circuit design, sinusoidal waves are frequently used as the input signal to generate responses. From the viewpoint of research efficiency, responses are not good outputs to use. Here, pulses that include wave disorder are used as input instead of sinusoidal waves. One SN ratio was used to evaluate the robustness of four-terminal circuits. The results showed good reproducibility of the experimental conclusions.

1. Introduction

The most fundamental elements in an electric circuit are a capacitor, coil, and resistor, expressed as C, L, and R. These circuit elements represent the relationship between the current, i, and the terminal voltage, e. For instance, the resistance, R, whose unit is the ohm, is the coefficient of i to e. The coil's terminal voltage is proportional to the rate of current change, and its coefficient is denoted as L. Similarly, the coefficient of the capacitor, in which the current is proportional to the rate of voltage change, is represented as C.

In general, although these coefficients are designed on the assumption that they are constant in any case, they are not invariable in actuality. For example, they vary in accordance with environmental temperatures, frequencies, and magnitudes of input. Therefore, we design these coefficients such that an overall system can be robust. However, in most cases this robust design cannot be repeated.

2. Evaluation of the Functions of an Electronic Circuit

Although a coil and capacitor can be expressed in the form of a time-variable function because both of them accumulate and emit energy, we normally handle them as time-constant functions, due to difficulty in measuring. In other words, by pruning their momentary values, we see only the average values.

This approach can improve measurement accuracy by canceling out noises through the averaging process; however, it hides their change rates because the smoothness of energy conversion according to the change rate is regarded as the essential criterion of the functionality of an electronic circuit and a key factor to secure repeatability. This holds true for the elements, as illustrated in Figure 1. Thus, as a new approach, we designed the parameters of a filter by using pulses as input signals. The reason that we chose pulses is that we concluded that the waveform of a pulse would be most appropriate to use to observe second-by-second changes of output energy to input energy. If this purpose could be satisfied, the observation of only a single cycle of a sine curve would be sufficient.

As a signal to be used for circuit evaluation, we usually consider a unit function. Response to the unit function, called *indicial response*, has been used to assess the pattern of the waveform qualitatively and to evaluate the quality characteristic of ramp-up time in case the high-frequency band used for a pulse amplifier or television display amplifier is

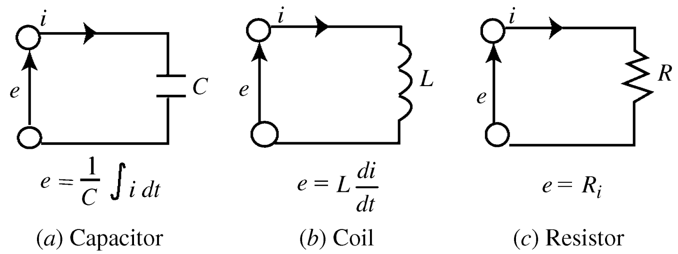

Figure 1
Relationship between the voltage and current of typical elements

required. Yet these adjustments are made primarily to align ramp-up times to target values, not necessarily to stabilize functions.

3. Ideal Functions and Measurement Characteristics

By utilizing a pulse, which can be regarded as a repeated unit function, and computing a single SN ratio, we evaluated the robustness of a four-terminal circuit. The functionality of the circuit is (Figure 2) to convert input signals into output signals in accordance with functions tailored for each circuit. Although different circuits naturally have different output waveforms, a stable circuit should not have any disturbed patterns of waveform, even if conditions such as input voltage, part characteristics, or environmental temperature alter it to some extent.

We selected a pulse voltage as an input signal and output voltage as the measurement characteristic. Next, we measured the input and output in a synchronized manner, and each measurement was taken for a certain time at a constant interval. As for the unit function, at $t < 0$, $e = 0$, and at $t \geq 0$, $e = 1$. Although basically we needed no signal data, actually we observed input data.

As illustrated in Figure 3, the generic function was to obtain output voltages proportional to input voltages. However, the important point is that both voltages were proportional to each other at every point in time, and this indicated the smoothness of energy conversion to the change rate. Although time was essentially regarded as a signal, we considered it as an indicative factor because we did not have any common methods to express all functions for various types of circuits in a proportional equation.

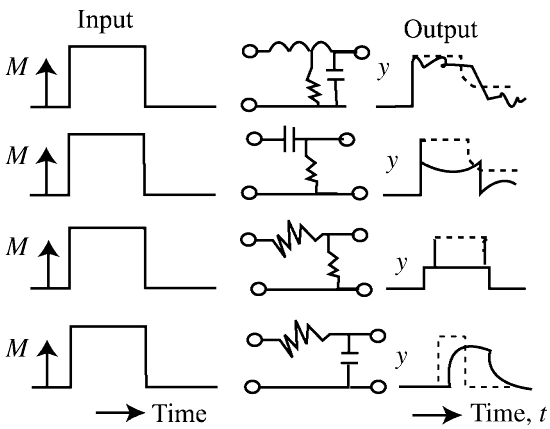

Figure 2
Examples of waveforms in four terminal circuits

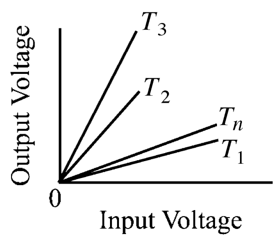

Figure 3
Input and output of an electronic circuit

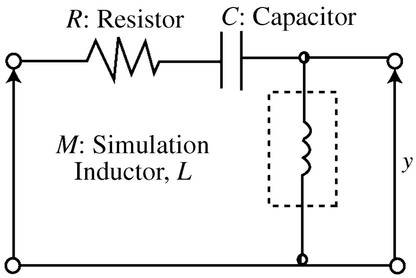

Figure 4
Filter circuit

4. Experimental Procedure

Next we considered an *LC* type of high-pass filter circuit (Figure 4). *L* is a simulation inductor consisting of two operational amplifiers, four resistors, and one capacitor. We measured the outputs by generating pulses with a function generator, then synchronizing the waveforms of input and output of a filter with a storage oscilloscope (Figure 5).

As control factors we assigned six elements chosen from resistances and capacitances in an L_{18} orthogonal array, since levels of the elements can be selected independently. The types and levels of control factors are given in Table 1. We set 250 and 500 mV as levels of the signal factor. For the time, *t*, as an indicative factor, we measured 15 points at a time interval of 8 μs between 8 and 120 μs. Finally, as a noise factor, we picked up low and high environmental temperatures, N_1 and N_2.

Table 1
Control factors and levels

Control Factor		Level 1	2	3
A:	capacitor	0.1	0.22	—
B:	coil	−10	±0	+10
C:	coil	470	1000	2200
D:	coil	4.7	10	20
E:	coil	*D*(0.5)	*D*(1.0)	*D*(2.0)
F:	coil	*D*(0.5)	*D*(1.0)	*D*(2.0)
G:	resistor	430	820	1600
H:	*A*'s type	H_1	H_2	H_3

5. SN Ratio and Sensitivity

Our analysis of the SN ratio and sensitivity was as follows. The data used for this analysis were based on experiment 1. Except that the levels of signal factors differ according to the levels of indicative factor and the calculation is somewhat cumbersome due to the number of levels, this analysis is the same

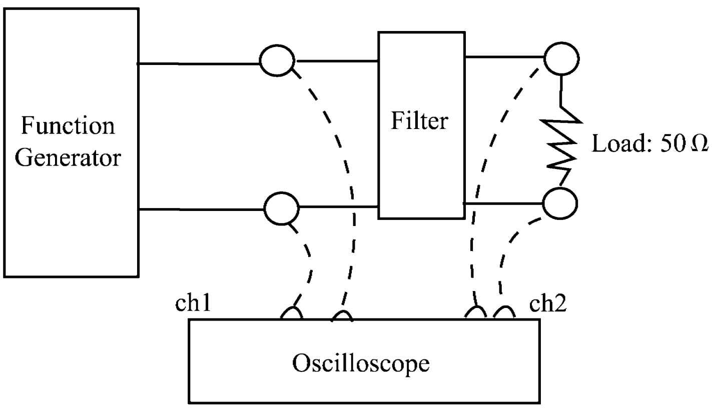

Figure 5
Measurement circuit for a filter circuit

as that of a proportional equation. Table 2 shows the data from experiment 1. The effective divider, r, the magnitude of input, is expressed as:

$$T_1N_1r_{11} = M_{111}^2 + M_{211}^2 \quad (1)$$

$$T_1N_2r_{12} = M_{112}^2 + M_{212}^2 \quad (2)$$

Total sum of effective dividers at a certain time:

$$r = r_{21} + r_{22} + \cdots + r_{215} \quad (3)$$

Linear equation L is expressed as follows:

$$T_1N_1L_{11} = M_{111}y_{111} + M_{211}y_{211} \quad (4)$$

$$T_1N_2L_{12} = M_{112}y_{112} + M_{212}y_{212} \quad (5)$$

Total variation:

$$S_T = 284.2^2 + \cdots + 328.9^2 = 9{,}395{,}685.60 \quad (f = 60) \quad (6)$$

Variation of proportional term:

$$S_\beta = \frac{(L_{11} + \cdots + L_{152})^2}{r_{11} + \cdots + r_{152}} = \frac{(4{,}474{,}591.41 + \cdots + 4{,}814{,}868.42)^2}{9{,}494{,}979.22} = 9{,}088{,}388.92 \quad (f = 1) \quad (7)$$

Variation of proportional terms with respect to time difference:

Table 2
Results of experiment 1 (mV)

Time	Noise	Signal M_1	Signal M_2	Effective Divider	Linear Equation
T_1	N_1	M_{111} (263.2) y_{111} (284.2)	M_{211} (500.0) y_{211} (578.9)	r_{11} (319,274)	L_{11} (364,251)
	N_2	M_{112} (257.9) y_{112} (294.7)	M_{212} (513.2) y_{212} (605.3)	r_{12} (329,886)	L_{12} (386,643)
T_2	N_1	M_{121} (257.9) y_{121} (284.2)	M_{221} (500.0) y_{221} (565.8)	r_{21} (316,512)	L_{21} (356,195)
	N_2	M_{122} (257.9) y_{122} (331.6)	M_{222} (513.2) y_{222} (592.1)	r_{22} (329,887)	L_{22} (389,385)
⋮	⋮	⋮	⋮	⋮	⋮
T_3	N_1	M_{1151} (252.6) y_{1151} (226.3)	M_{2151} (486.8) y_{2151} (328.9)	r_{151} (300,781)	L_{151} (217,272)
	N_2	M_{1152} (252.6) y_{1152} (236.8)	M_{2152} (500.0) y_{2152} (328.9)	r_{152} (313,807)	L_{152} (224,266)

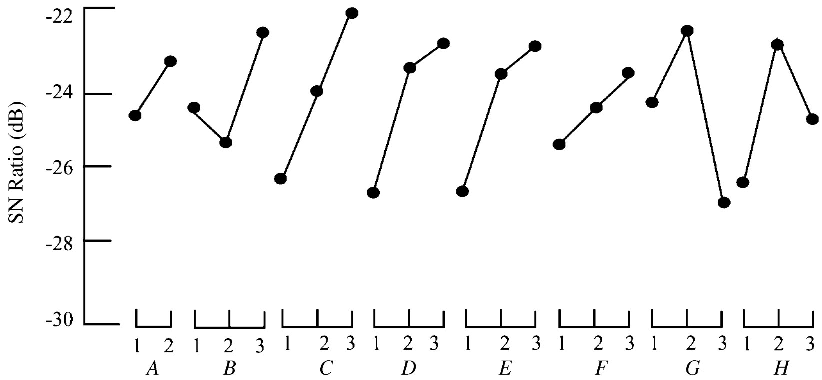

Figure 6
Response graph of SN ratio

$$S_{T\beta} = \frac{(L_{11} + L_{12})^2}{r_{11} + r_{12}} + \frac{(L_{12} + L_{22})^2}{r_{12} + r_{22}} + \cdots + \frac{(L_{151} + L_{152})^2}{r_{151} + r_{152}} - S_\beta$$

$$= 9{,}318{,}717.24 - 9{,}088{,}388.92$$

$$= 230{,}328.32 \qquad (f = 14) \qquad (8)$$

Variation due to noise factor:

$$S_{N\beta} = \frac{(L_{11} + L_{21} + \cdots + L_{151})^2}{r_{11} + r_{21} + \cdots + r_{151}} + \frac{(L_{12} + L_{22} + \cdots + L_{152})^2}{r_{12} + r_{22} + \cdots + r_{152}} - S_\beta$$

$$= \frac{4{,}747{,}591.41^2}{4{,}651{,}433.52} + \frac{4{,}814{,}868.42^2}{4{,}843{,}545.71} - 9{,}088{,}388.92$$

$$= 2444.63 \qquad (f = 1) \qquad (9)$$

Error variation:

$$S_e = S_T - S_\beta - S_{T\beta} - S_{N\beta}$$

$$= 9{,}395{,}685.60 - 9{,}088{,}388.92 - 230{,}328.32 - 244.63$$

$$= 74{,}523.73 \qquad (f = 44) \qquad (10)$$

Error variance:

$$\frac{V_e = S_e}{44} = 1693.72 \qquad (11)$$

Total error variance:

$$V_N = \frac{S_{N\beta} + S_e}{45} = \frac{2444.63 + 523.73}{45} = 1710.40 \qquad (12)$$

Whereas functionality was evaluated based on SN ratios of total data, sensitivity adjustment to target values was made based on time because time was regarded as an indicative factor in our case.

Function stability (SN ratio):

$$\eta = 10 \log \frac{[1/(r_{11} + \cdots + r_{152})](S_\beta - V_e)}{V_N}$$

$$= -32.52 \text{ (dB)} \qquad (13)$$

$$S_i = 10 \log \beta_i^2 \qquad (i = 1, 2, 3, \ldots, 15) \qquad (14)$$

For $T = 1$,

$$\beta_1^2 = \frac{1}{r_{11} + r_{12}} \left[\frac{(L_{11} + L_{12})^2}{r_{11} + r_{12}} - V_e \right] \qquad (15)$$

For $T = 15$,

Table 3
Results of SN Ratio Confirmatory Experiment

Configuration	SN Ratio: Estimation	SN Ratio: Confirmation
Optimal	−12.47	−17.69
Current	−19.69	−24.44
Gain	7.22	6.75

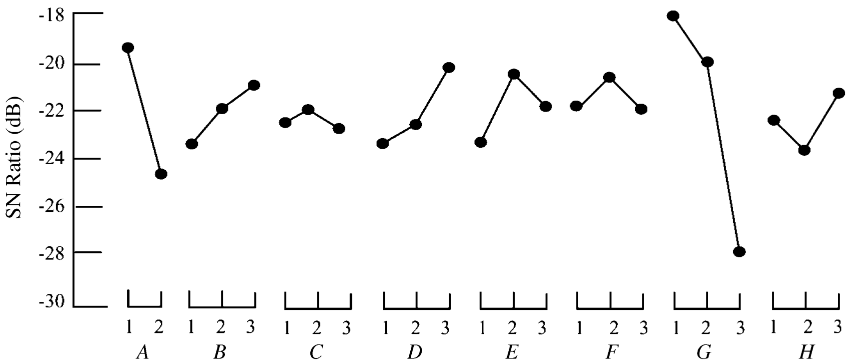

Figure 7
Response graph of sensitivity

$$\beta_{15}^2 = \frac{1}{r_{151} + r_{152}}\left[\frac{(L_{151} + L_{152})^2}{r_{151} + r_{152}} - V_e\right] \quad (16)$$

Although sensitivity adjustment is needed when each sensitivity at a certain time is different, we omitted it in this case.

6. Response Graphs and Confirmatory Experiment

Based on the SN ratios and sensitivities calculated so far, we drew the response graphs shown in Figure 6. Although, in fact, all factor effect diagrams for T_1 to T_{15} were required because sensitivity needs to be adjusted to target frequency characteristics by the least squares method, we omitted such fine tuning for now.

Looking at the factor effect diagram of the SN ratio, we found that factor H had a peak, but it was a capacitor type, which is a noncontinuous factor. Factors B and G were much less peaked. Now using the factor effect diagrams, we estimated optimal and current conditions. Taking the chart of the SN ratio into account, we knew that the optimal condition is regarded as $A_2B_3C_3D_3E_3F_3G_2H_2$, and the current condition is $A_2B_2C_2D_2E_2F_2G_2H_2$. On the basis of these two levels, we estimated and confirmed each SN ratio. Table 3 shows that the optimal condition is approximately 7 dB better than the current one. Additionally, the benefits of the estimation and confirmation coincide well. As a reference, we added the response graphs of sensitivity (Figure 7).

Reference

Yoshishige Kanemoto, Naoki Kawada, and Hiroshi Yano, 1998. New evaluation method for electronic circuit. *Quality Engineering*, Vol. 6, No. 3, pp. 57–61.

This case study is contributed by Yoshishige Kanemoto.