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인덕티브 센서 응용을 위한 시간 영역 리드아웃 회로

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Time-Domain Read-Out Circuit for Inductive Sensor Applications

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요 약

본 논문에서는 IoT 응용에서 사용되는 인덕티브한 센서의 인덕턴스를 측정할 수 있는 회로를 제안하였다. RL 저역 통과 필터 회로, 비교기, 전류 제어 스위치, 커패시터의 특성을 이용하여 회로를 구성하였으며, RL 저역 통과 필터 회로의 출력 전압이 기준 전압보다 큰 duration time을 통해 1nH-1H 범위 내의 인덕턴스 값을 도출 할 수 있다.

ABSTRACT

This paper propose a circuit that can measure the inductance of an inductive sensor used in IOT applications. The circuit was constructed using the characteristics of an RL low-pass filter circuit, comparator, current control switch, and capacitor, and the inductance value within the range $1[nH] < L \leq 1[H]$ can be derived through the duration time during the output voltage of the RL low-pass filter circuit is greater than the reference voltage.

Keywords

Inductance Measurement, Read-Out Circuit, Sensor, Time-Domain

Ⅰ. Introduction

IoT(Internet of Things) technology, which deals with information exchanged between objects connected by the internet while minimizing human intervention, is positioned as a core technology in various industries of the 4th Industrial Revolution[1].

The main goal of IoT technology is to connect devices, objects, and sensors to the internet so that data can be collected, exchanged, and processed in real time[2]. Among such devices, the sensor plays a role in recognizing and collecting various information and data required by the IoT system[3]. The data collected by the sensor in the IoT system is used for control, and through the data collected by the sensor, the IoT system can automate various processes. Therefore, the sensor system composed of sensors and circuits is a core component in IoT technology, and the quality and accuracy of data collected by the sensor play a crucial role in determining the efficiency of IoT technology[4-5]. In addition, to improve the quality

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and accuracy of the data collected by the sensor, accurate measurement of the sensor capacity is required. If the sensor's capacity measurement is incorrect, erroneous data can be transmitted to the device, and this can have a significant influence on the IoT system. Therefore, if the error can be reduced in the measurement of sensor capacity, more accurate and reliable data can be provided to the IoT system so that it can perform more effectively.

In this paper, among various sensors used in IoT technology, we present a circuit that can process the capacity of inductive sensors using inductance change. In general, circuits to measure inductance of inductive sensor has used to measure inductance according to the output voltage value of the circuit. However, in this paper, we composed a circuit that uses the mathematical expression of the duration time in the time domain in an RL low-pass filter circuit. The aim of our research is to measure the capacity of an inductive sensor more accurately and briefly to improve the quality of data provided by the sensor.

In this paper, the range of inductance to be measured is restricted to 1nH to 1H. The contents of the paper are as follows. Section Ⅱ shows a mathematical expression derived for the duration time based on the characteristics of the output voltage over time for the fundamental diagram of the RL low-pass filter circuit and provides verification of mathematical expression by using Pspice simulation. Section Ⅲ describes the circuit that can process the inductive sensor based on details from Section Ⅱ. Section Ⅳ is for result and discussion of this paper. For the results, we described the method to derive inductance L by using the circuit suggested in this paper and tables of the result by using Pspice simulation has suggested. Moreover, several considerations has presented for measuring inductance of the inductive sensor using the circuit and the method suggested in this paper. Section V deals with the conclusion of this paper.

Ⅱ. Equation of duration time in RL low-pass filter circuit

2.1 Equation of duration time

When a pulse wave as the red line in Figure 1 applied in the RL low-pass filter circuit, the output voltage has a periodic property in the section after the first low level as seen in the green line in Figure 1. Therefore, if the function of the output voltage for the high level at the second cycle is obtained, using the periodic property, we can define a range of duration times in which the value of the output voltage is higher or lower than an arbitrary voltage x[V] existing within a specific range. For the high level at the second cycle of the pulse wave, the function of the output voltage will be similar to the form of Equation (1) which indicates the function of the output voltage over time for the high level in the first cycle of the pulse wave applied to the RL low-pass filter circuit; in this equation, V_{high} is corresponding to the high level of the pulse wave applied to the circuit.

$$V_{out} = V_{high}(1-e^{-\frac{R}{L}t}) \quad \cdots (1)$$

However, in this case, voltage increases from the minimum value of the output voltage at the low level of the previous cycle, which is not 0, and must be shown as a form of parallel shift in line with the period of the pulse wave τ. Therefore, the function of the output voltage at the high level of the second cycle can be expressed as Equation (2).

$$V_{out} = V_{high}(1-e^{-\frac{R}{L}(t-\tau+t')}) \quad \cdots (2)$$

t' in Equation (2) is a result derived from considering the initial value of the output voltage at the second high level of the pulse wave; to determine the equation of t', we have to determine the equation of the output voltage for the first cycle of the pulse wave applied to the RL low-pass filter circuit at first. Since the function of the output voltage in this section appears in decreasing form from the value $V_{high}(1-e^{-\frac{R}{L}D\tau})$ for pulse wave with duty cycle $D\times 100\%$ for $0 < D < 1$, it can be expressed as follows.

$$V_{out} = V_{high}(1-e^{-\frac{R}{L}D\tau})\times e^{-\frac{R}{L}(t-D\tau)} \quad \cdots (3)$$

Considering Equation (3), t' can be expressed as follows.

$$V_{high}(1-e^{-\frac{R}{L}t'}) = V_{high}(1-e^{-\frac{R}{L}D\tau})\times e^{-\frac{R}{L}(1-D)\tau}$$

$$\therefore t' = -\frac{L}{R}ln\left\{1-e^{-\frac{R}{L}(1-D)\tau}+e^{-\frac{R}{L}\tau}\right\} \quad \cdots (4)$$

To obtain a duration time higher or lower than an arbitrary voltage x[V], it is necessary to obtain time t, where the function of the output voltage represents an arbitrary voltage x in the first low level and the second high level section. If we set the time representing x in the first low level and second high level sections of the pulse wave as t_1 and t_2, using Equation (2) and (3), t_1 and t_2 can be expressed as follows.

$$t_1 = \frac{L}{R}ln\left(\frac{V_{high}(1-e^{-\frac{R}{L}D\tau})}{x}\right)+D\tau \quad \cdots (5)$$

$$t_2 = \frac{L}{R}ln\left(\frac{V_{high}}{V_{high}-x}\right)+\tau-t'' \quad \cdots (6)$$

First, the duration time d_1 of the output voltage, which in a range smaller than an arbitrary voltage x, can be obtained using (t_2-t_1), and is shown as follows.

$$d_1 = \frac{L}{R}ln\left(\frac{x}{(V_{high}-x)(1-e^{-\frac{R}{L}D\tau})}\right)+(1-D)\tau-t' \cdots (7)$$

The duration time d_2 of the output voltage, which is in a range larger than the arbitrary voltage x, can be obtained using (t_3-t_2). Moreover, considering the periodic property of the output voltage, the sum of d_1 and d_2 is equal to one cycle of the pulse wave. Therefore, since $d_1+d_2=\tau=\frac{1}{f}$, d_2 can be expressed as follows.

$$d_2 = \frac{L}{R}ln\left(\frac{(V_{high}-x)(1-e^{-\frac{R}{L}D\tau})}{x}\right)+D\tau+t' \cdots (8)$$

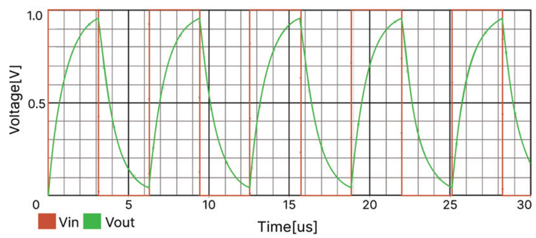

그림 1. 입출력 전압의 파형

Fig. 1 Waveform of the input and output voltage

2.2 Frequency of the pulse wave

Since Section Ⅱ deals with the RL low-pass filter circuit, it is necessary to set the frequency f of the pulse wave applied to the circuit at not more than the cut-off frequency. Since the cut-off frequency is $f_c = \frac{R}{2\pi L}$ for the known resistance R, the inductance L can be expressed as $L=\frac{R}{2\pi f_c}$. Therefore, if we preset the range of inductance to be measured, the range for the frequency of the pulse wave can be set using this range. If the range of inductance to be measured is set at $L_{\min} < L \le L_{\max}$, the range for the cut-off frequency will be $\frac{R}{2\pi L_{\max}} \le f_c$. In addition, since $f \le f_c$ must be satisfied, it can be considered that if a value that is equal to or less than the minimum value of the cut-off frequency is set as the frequency of pulse wave, it will satisfy all values of inductance in the range of $L_{\min} < L \le L_{\max}$. However, since the aim of this paper is to measure the inductance using the characteristic of the output voltage over time, it is necessary to indicate the frequency f of the pulse wave to the circuit as a mathematical expression. In this paper, the frequency of the pulse wave is set to $f=\frac{R}{2\pi L_{\max}}$ for the range $L_{\min}<L\leq L_{\max}$ of the inductance to be measured.

2.3 Range of an arbitrary voltage x

To obtain values of each duration time d_1 and d_2, by using Equation (7) and Equation (8), it is necessary to define the range of an arbitrary voltage x. Considering that the waveform of the output voltage and the periodic characteristic after the first low level section when a pulse wave with a frequency not more than cut-off frequency is applied, it can be seen that the output voltage reaches a minimum value when t equals τ and a maximum value when t equals $(1+D)\tau$. Since the value of voltage x must be between the minimum and maximum values of the output voltage, using Equation (2) and Equation (3), the range of x can be expressed as follows.

$$(e^{-\frac{R}{L}(1-D)\tau}-e^{-\frac{R}{L}\tau})<\frac{x}{V_{high}}<(1-e^{-\frac{R}{L}(D\tau+t^{''})})\quad\cdots(9)$$

However, to obtain the range of x in Equation (9), there is a problem that the resistance R and inductance L must be considered. The process of deriving the equation for the duration time in Section 2.1 is a process for obtaining the inductance L, so L is an unknown value while R is a known value. Furthermore, it is necessary to define the range that satisfies all values of the range of inductance to be measured. Therefore, the inductance L in Equation (9) must be expressed as a constant, and it can be expressed using details described in Section 2.2.

In Section 2.2, the frequency f of a pulse wave that satisfies $f\leq f_c$ was set to $f=\frac{R}{2\pi L_{\max}}$ for all inductances L within the range $L_{\min}<L\leq L_{\max}$. Since frequency f is a fixed value, if $L\rightarrow 0$, the transfer function of RL low-pass filter circuit converges to 1. This means that when the frequency f is fixed at a constant value, the waveform of the output voltage approaches the shape of the applied pulse wave as the inductance value decreases. That is, as the inductance L increases in Equation (9), the value of $(1-e^{-\frac{R}{L}(D\tau+t^{''})})$ decreases and the value of $(e^{-\frac{R}{L}(1-D)\tau}-e^{-\frac{R}{L}\tau})$ increases. Therefore, if $L_{\max}$ is substituted for the L term in Equation (9), all inductance value L within the range $L_{\min}<L\leq L_{\max}$ can be satisfied, and the range for an arbitrary voltage x can be expressed as follows.

$$(e^{-\frac{R}{L_{\max}}(1-D)\tau}-e^{-\frac{R}{L_{\max}}\tau})<\frac{x}{V_{high}}<(1-e^{-\frac{R}{L_{\max}}(D\tau+t^{''})})\quad\cdots$$

(10)

In Equation (10), τ equals $\frac{2\pi L_{\max}}{R}$ as the reciprocal of the frequency f of the applied pulse wave.

2.4 Verification of equation

In Section 2.4, Pspice simulation was used to verify that Equation (7) and Equation (8) for duration time d_1 and d_2 hold. In the Tables in Section 2.4, the theoretical values are expressed using Equation (7) and Equation (8) for each d_1 and d_2, and the experimental values are expressed using Pspice simulation. In addition, the error rate is expressed using $\left|\frac{d_{th}-d_{\exp}}{d_{th}}\right|\times 100\%$. Table 1, 3, 5, and 6 show that Equation (7) and Equation (8) hold according to changes in each variable of those Equations when the frequency equals the cut-off frequency. If two equations hold for the cut-off frequency, it can be shown that they hold for the ranges set in Section 2.2 and Section 2.3.

Table 1 shows that equations for the duration time hold according to the change of inductance. We set the resistance to $1kohm$ and the duty cycle and V_{high} of the applied pulse wave to 50% and 1V. In addition, the cut-off frequency according to the value of each inductance is shown in Table 2.

표 1. 인덕턴스 변화에 따른 duration time
Table 1. Duration time according to inductance change

L	d	x[V]	Theoretical value	Experimental value	percent error
1uH	d_1	0.3	2.295ns	2.294ns	0.04%
		0.4	2.736ns	2.735ns	0.04%
		0.5	3.140ns	3.141ns	0.03%
	d_2	0.3	3.987ns	3.985ns	0.05%
		0.4	3.545ns	3.551ns	0.17%
		0.5	3.140ns	3.140ns	-
10uH	d_1	0.3	22.930ns	22.950ns	0.09%
		0.4	27.350ns	27.370ns	0.07%
		0.5	31.400ns	31.420ns	0.06%
	d_2	0.3	39.870ns	39.860ns	0.03%
		0.4	35.450ns	35.450ns	-
		0.5	31.400ns	31.400ns	-
100uH	d_1	0.3	0.299㎲	0.229㎲	-
		0.4	0.274㎲	0.274㎲	-
		0.5	0.314㎲	0.314㎲	-
	d_2	0.3	0.399㎲	0.399㎲	-
		0.4	0.355㎲	0.354㎲	0.28%
		0.5	0.314㎲	0.314㎲	-
1mH	d_1	0.3	2.293㎲	2.294㎲	0.04%
		0.4	2.735㎲	2.731㎲	0.15%
		0.5	3.140㎲	3.141㎲	0.03%
	d_2	0.3	3.987㎲	3.985㎲	0.05%
		0.4	3.545㎲	3.551㎲	0.17%
		0.5	3.140㎲	3.140㎲	-

표 2. 각 인덕턴스 값에 사용된 주파수
Table 2. Frequency used for each inductance value

L[H]	$f_c[Hz]$
1uH	159.15MHz
10uH	15.915MHz
100uH	1.592MHz
1mH	159.15KHz

Table 3 shows that the equations for the duration time hold even when the resistance changes to a value other than $1kohm$ In Table 3, except that the inductance is 1mH, all other values of pulse wave are set the same as in Table 1. In addition, the cut-off frequency according to the value of each resistance is shown in Table 4.

표 3. 저항 변화에 따른 duration time
Table 3. Duration time according to resistance change

R	d	x[V]	Theoretical value	Experimental value	percent error
100 Ω	d_1	0.3	22.950v	22.940㎲	0.04%
		0.4	27.360㎲	27.370㎲	0.04%
		0.5	31.420㎲	31.420㎲	-
	d_2	0.3	39.850㎲	39.860㎲	0.03%
		0.4	35.440㎲	35.410㎲	0.05%
		0.5	31.380㎲	31.390㎲	0.03%
300 Ω	d_1	0.3	7.652㎲	7.650㎲	0.03%
		0.4	9.124㎲	9.120㎲	0.04%
		0.5	10.480㎲	10.470㎲	0.10%
	d_2	0.3	13.290㎲	13.290㎲	-
		0.4	11.820㎲	11.830㎲	0.08%
		0.5	10.460㎲	10.470㎲	0.10%
500 Ω	d_1	0.3	4.592㎲	4.596㎲	0.09%
		0.4	5.476㎲	5.471㎲	0.09%
		0.5	6.287㎲	6.287㎲	-
	d_2	0.3	7.974㎲	7.970㎲	0.05%
		0.4	7.090㎲	7.100㎲	0.14%
		0.5	6.279㎲	6.280㎲	0.02%

표 4. 각 저항 값에 사용된 주파수
Table 4. Frequency used for each resistance value

R[ohm]	f_c[Hz]
100Ω	15.92 kHz
300Ω	47.75 kHz
500Ω	79.58 kHz

Table 5 shows that the equations for the duration time hold even when V_{high} of the pulse wave changes to a value other than 1V. We set the resistance and inductance to $1kohm$ and 1mH, and the duty cycle of the pulse wave to 50%.

표 5. V_{high} 변화에 따른 duration time
Table 5. Duration time according to V_{high} change

V_{high}	d	x[V]	Theoretical value	Experimental value	percent error
3V	d_1	1	2.449μs	2.448μs	0.04%
		1.5	3.142μs	3.141μs	0.03%
		2	3.835μs	3.834μs	0.03%
	d_2	1	3.831μs	3.836μs	0.13%
		1.5	3.138μs	3.169μs	0.99%
		2	2.445μs	2.448μs	0.12%
5V	d_1	2	2.736μs	2.735μs	0.04%
		3	3.547μs	3.546μs	0.03%
		4	4.528μs	4.528μs	-
	d_2	2	3.544μs	3.551μs	0.20%
		3	2.733μs	2.736μs	0.11%
		4	1.752μs	1.754μs	0.11%
7V	d_1	2	2.226μs	2.225μs	0.04%
		4	3.430μs	3.428μs	0.06%
		6	4.934μs	4.932μs	0.04%
	d_2	2	4.054μs	4.055μs	0.02%
		4	2.850μs	2.854μs	0.14%
		6	1.346μs	1.349μs	0.22%

Table 6 shows that the equations hold even when the duty cycle of the pulse wave changes to a value other than 50% in the range of $0 < D < 1$ for $D \times 100\%$. Resistance and inductance were set to be the same as in Table 5.

표 6. Duty cycle 변화에 따른 duration time
Table 6. Duration time according to duty cycle change

D	d	x [V]	Theoretical value	Experimental value	percent error
0.1	d_1	0.2	5.027μs	5.025μs	0.04%
		0.3	5.566μs	5.564μs	0.04%
		0.4	6.008μs	6.006μs	0.03%
	d_2	0.2	1.253μs	1.258μs	0.40%
		0.3	0.714μs	0.718μs	0.56%
		0.4	0.272μs	0.276μs	1.47%
0.3	d_1	0.3	3.703μs	3.702μs	0.03%
		0.4	4.145μs	4.144μs	0.02%
		0.5	4.550μs	4.549μs	0.02%
	d_2	0.3	2.577μs	2.580μs	0.12%
		0.4	2.135μs	2.138μs	0.14%
		0.5	1.730μs	1.733μs	0.17%
0.7	d_1	0.3	0.886μs	0.884μs	0.23%
		0.4	1.328μs	1.328μs	-
		0.5	1.734μs	1.733μs	0.06%
	d_2	0.3	5.394μs	5.396μs	0.04%
		0.4	4.952μs	4.951μs	0.02%
		0.5	4.546μs	4.549μs	0.07%
0.9	d_1	0.6	0.278μs	0.276μs	0.79%
		0.7	0.720μs	0.718μs	0.28%
		0.8	1.259μs	1.257μs	0.16%
	d_2	0.6	6.002μs	6.003μs	0.02%
		0.7	5.560μs	5.565μs	0.09%
		0.8	5.021μs	5.030μs	0.18%

표 7. 주파수 변화에 따른 duration time
Table 7. Duration time according to frequency change

f	d	x [V]	Theoretical value	Experimental value	percent error
1 kHz	d_1	0.3	0.499ms	0.498ms	0.20%
		0.4	0.500ms	0.499ms	0.20%
		0.5	0.500ms	0.499ms	0.20%
	d_2	0.3	0.501ms	0.502ms	0.20%
		0.4	0.500ms	0.501ms	0.20%
		0.5	0,500ms	0.501ms	0.18%
10 kHz	d_1	0.3	49.153μs	49.151μs	0.004 %
		0.4	49.594μs	49.593μs	0.002 %
		0.5	50.000μs	49.999μs	0.002 %
	d_2	0.3	50.847μs	50.848μs	0.002 %
		0.4	50.406μs	50.407μs	0.002 %
		0.5	50.000μs	50.001μs	0.002 %

100 kHz	d_1	0.3	4.153㎲	4.151㎲	0.05%
		0.4	4.595㎲	4.599㎲	0.09%
		0.5	5.000㎲	5.002㎲	0.04%
	d_2	0.3	5.847㎲	5.850㎲	0.05%
		0.4	5.405㎲	5.400㎲	0.09%
		0.5	5.000㎲	5.000㎲	-

In conclusion, the range of inductance to be measured can be set to $L_{\min} < L \leq L_{\max}$. When a pulse wave with duty cycle $D \times 100\%$ for range $0 < D < 1$ is applied to the RL low-pass filter circuit, if the frequency of the pulse wave is set to $f = \frac{R}{2\pi L_{\max}}$ for known resistance value R, $f \leq f_c$ will be satisfied. Therefore, Equation (7) and Equation (8) will hold; the range of x that holds for all inductance values in the range $L_{\min} < L \leq L_{\max}$ is expressed as Equation (10). Based on these results, we will deal with a circuit that can measure the inductance of an inductive sensor with Equation (7) and Equation (8).

Ⅲ. Circuit to measure inductance

3.1 The diagram of the circuit

The diagram of the circuit to measure the inductance of an inductive sensor is shown in Figure 2. Section Ⅲ uses the characteristics of comparator, current control switch, and capacitor to utilize the duration time.

First, if the output voltage of the RL low-pass filter and the reference voltage x are applied to each V_+ and $V_-$of the comparator, the waveform of the output voltage V_{amp} of the comparator will depend on the duration times d_1 and d_2. Considering an ideal amplifier, since $V_{amp} = (V_+ - V_-) \times \infty$, if the voltage applied to the V_+ terminal is greater than the voltage applied to the V_- terminal, $V_{amp} = \infty$, which is the same as the amplifier's amplification. On the other hand, if the voltage applied to V_+ is less than the voltage applied to V_-, $V_{amp} = -\infty$, which can be thought of as the minimum voltage in the circuit(the voltage set at GND), 0V. Therefore, V_{amp} is in the form of a pulse wave in which a high level and low level are repeated for each $V_{out} > x$ section and $V_{out} < x$ section. Thus, for one period of the pulse wave, the duration of the high level and low level will appear as d_2 and d_1.

Second, the current control switch used in the circuit of Figure 2 is an ideal switch in the Pspice simulation. If current is applied to the left area of the switch, the switch will turn on and current will flow to the right area of the switch. Otherwise, if current is not applied to the left area of the switch, the switch will turn off and current will not flow to the right area. To utilize a current control switch, it is necessary to convert the output voltage through the comparator into current. If V_{amp} in the form of V-pulse passes through the resistance R_2, it can be considered that it will be converted into the form of an I-pulse, and the current value I of the I-pulse will satisfy $I = \frac{V_{amp}}{R_2}$ according to Ohm's law. This can be thought as a current source. Therefore, when current is applied to the current control switch, the high level section and the low level section will appear repeatedly in the I-pulse, and the switch will operate in the form of repeating on and off.

Finally, if current is applied to the capacitor through the switch that repeats on and off, it can be thought of as applying an AC current repeating high and low levels in the form of an I-pulse to the capacitor. In Figure 2, the capacitor C is connected in parallel with the resistor R_3, and this can be thought of as a circuit that current source connected in series to a structure in which C and R_3 are connected in parallel. This is done to prevent a floating error from occurring when only a capacitor is connected in series with a current source in the Pspice simulation, and the resistance R_3 is a virtual resistor that does not actually exist. Therefore, one hypothesis is needed to ignore the value of resistance. If the constant current in the high level section of the I-pulse is I_{high}, the current I_C flowing through the capacitor when the switch is turned on can be expressed as $I_c = \frac{R_3}{X_c + R_3} I_{high}$, using the current distribution law. If the resistance R_3 is set to a much greater value than the reactance X_c of the capacitor, the value of R_3 can be thought of as ∞ compared to X_c, so it can be considered that I_C equals I_{high}. Moreover, if the value of R_3 is very large compared to X_c, the total impedance $Z = \left(\frac{1}{X_c} + \frac{1}{R_3}\right)^{-1}$ of the parallel circuit composed of C and R_3 can be considered to equal X_c when the switch turned on. Therefore, if Ohm's law is used for I_C, the voltage V_f applied to the circuit composed of C and R_3 can be expressed as $V_f = \frac{I_c}{X_c} = \frac{I_{high}}{X_c} = \frac{I_{high}}{Z} = V_c$ for the voltage V_c, which is applied to the capacitor C. In addition, if the voltage V_c formed across the capacitor is not saturated within 1 cycle of the I-pulse applied to the capacitor, the amount of charge formed on the electrode plate of the capacitor when the switch is turned on can be expressed as follows.

$$Q = \int_{t_0}^{t_0 + d_2} I_{high} \, d\tau = I_{high} d_2 \qquad \cdots (11)$$

Since $Q = CV_c$, substituting this equation into Equation (11) leads to Equation (12) for duration time d_2; this illustrates the section in which the output voltage V_{out} of the RL low-pass filter is higher than the reference voltage x[6].

$$d_2 = \frac{CV_c}{I_{high}} = \frac{CV_f}{I_{high}} = \frac{CR_2 V_f}{V_{amp}} \qquad \cdots (12)$$

Therefore, the duration time d_2 can be obtained using Equation (12), and the inductance of inductive sensor can be obtained by applying the value of d_2 to Equation (8).

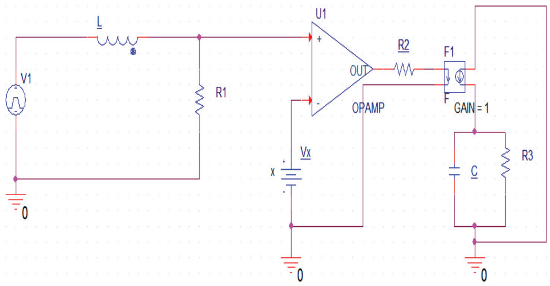

그림 2. 인덕턴스를 측정하기 위한 회로 구성
Fig. 2 Diagram of circuit to measure inductance

3.2 Equation to derive inductance L

In the circuit shown in Figure 2, by using the characteristics of the capacitor, the duration time d_2 in the range larger than the reference voltage x can be obtained, and the value of the inductance L can be obtained by using the value of d_2. Equation (13) is used to find the value of inductance L.

$$\begin{aligned} R(d_2 - D\tau) &= L\left\{ \ln\left(\frac{V_{high} - x}{x}\right) + \ln\left(1 - e^{-\frac{R}{L}D\tau}\right) - \ln\left(1 - e^{-\frac{R}{L}(1-D)\tau} + e^{-\frac{R}{L}\tau}\right) \right\} \\ &= L \ln\left\{ \frac{(V_{high} - x)\left(1 - e^{-\frac{R}{L}D\tau}\right)}{x\left(1 - e^{-\frac{R}{L}(1-D)\tau} + e^{-\frac{R}{L}\tau}\right)} \right\} \end{aligned} \qquad \cdots (13)$$

However, using Equation (18) in a general way, there is a problem in deriving the value of inductance L. Even though the above equation can be expressed more simply by substituting complex common terms, it is impossible to find the solution to Equation (13) in a general way. Therefore, to derive the value of inductance L, using Equation (13), it is necessary to approximate the right-hand side of the above equation with another equation. Since $\tau = \frac{2\pi L_{\max}}{R}$, $(1 - e^{-\frac{R}{L}D\tau})$ on the right-hand side can be expressed as $(1-e^{-\frac{2D\tau L_{\max}}{L}})$, which indicates a value close to 1. Therefore, $\ln(1-e^{-\frac{R}{L}D\tau})$ can be approximated to zero, and in the case of $\ln(1-e^{-\frac{R}{L}(1-D)\tau}+e^{-\frac{R}{L}\tau})$, it also can be approximated as $\ln(1-e^{-\frac{R}{L}(1-D)\tau}+e^{-\frac{R}{L}\tau})\simeq 0$. By substituting this approximation into Equation (13), the inductance L can be expressed as follows.

$$L=\frac{R_1(d_2-D\tau)}{\ln\left(\frac{V_{high}-x}{x}\right)} \quad \cdots (14)$$

In addition, by substituting d_2 of Equation (12) into Equation (14), the relational expression between the voltage V_f through the capacitor and the inductance L can be expressed as follows.

$$L=\frac{R_1(\frac{CR_2V_f}{V_{amp}}-D\tau)}{\ln\left(\frac{V_{high}-x}{x}\right)} \quad \cdots (15)$$

3.3 Consideration of capacitance C

To find the inductance L using the above description, it is necessary to consider the capacitance C because the voltage V_c formed across the capacitor must not be saturated for a duration time d_2. In Section 3.3, we set a range of capacitance in which saturation does not occur. Capacitance means the ability of a capacitor to charge an electric charge; the unit is the Farad. The definition of 1 Farad is the capacitance at which the voltage potential becomes 1V when a charge of 1 coulomb is applied, and the range of capacitance can be set using this. If saturation does not occur, it can be expressed as $\frac{1}{V_c}>\frac{1}{V_{amp}}$ because it is $V_c<V_{amp}$. When a constant current I flows through the capacitor for time Δt, it can be expressed as $V_c=\frac{I\Delta t}{C}$ because $Q=CV_c$; using this, the capacitance can be expressed as follows[6].

$$C>\frac{I\Delta t}{V_{amp}}=\frac{\Delta t}{R_2} \quad \cdots (16)$$

However, since this paper deals with the process to measure inductance L, the values of inductance L and duration time Δt cannot be defined in advance. Therefore, a hypothesis is needed to set the range of capacitance C. Above all, the value for duration time to be used in this paper will necessarily represent a value smaller than the period τ of the pulse wave applied to the RL low-pass filter circuit. Therefore, if saturation does not occur even after a time much longer than the period τ, saturation will not necessarily occur during the duration time. Thus, if it is assumed that $\Delta t=\tau\times(1\times 10^3)$, Δt can be regarded as a time much longer than the duration time; when this value is substituted into Equation (16), saturation will not necessarily occur for the capacitance that satisfies the condition of Equation (16). Therefore, assuming $\Delta t=\tau\times(1\times 10^3)$, Equation (16) can be expressed as follows.

$$C>\frac{\tau\times(1\times 10^3)}{R_2} \quad \cdots (17)$$

If saturation does not occur for the voltage V_c formed across the capacitance, the waveform of V_c is as shown in Figure 3. As can be seen in Figure 3, when the switch is on, V_c increases linearly and reaches a peak value at the moment that the switch is switched from on to off. Furthermore, for the section in which the switch is off, this peak value stays constant. This can be considered a phenomenon that occurs because sufficient time has not passed for saturation with respect to V_c, and the value of V_c can be easily measured using this property. In this paper, the first peak value will be measured for the waveform of V_c. Even though the duration time from the first low level was measured in Section 2, some values approximated as 0 in Section 3.2 are values related to the translation of time t, so even if the inductance L was calculated for the first peak value of V_c, it does not matter. Thus, this paper deals with the first cycle of the pulse wave applied to measure the voltage V_c formed in the capacitor during time d_2; the voltage measured at time τ will be same as the first peak value of V_c.

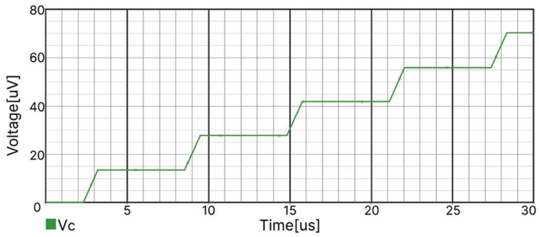

그림 3. 포화가 일어나지 않을 때 V_c의 파형

Fig. 3 Waveform of V_c when saturation does not occur

3.4 Method to derive inductance L

In section 2.2, when the range of inductance L to be measured was set to $L_{\min} < L \leq L_{\max}$, the frequency f of the pulse wave applied to the RL low-pass filter circuit was set to $f = \dfrac{R}{2\pi L_{\max}}$. However, if the same frequency is applied to all inductances within the range of $1[nH] < L \leq 1[H]$ to be measured in this paper, the value of inductance L can calculated incorrectly using Equation (15). Considering the characteristic of the RL low-pass filter circuit, the gain value converges to 1 when the frequency of the pulse wave applied to the circuit is very small below the cut-off frequency. When the value of the actual inductance L is very small compared to $L_{\max}$ and the gain converges to 1, regardless of the value of the actual inductance L and the reference voltage x, the value of the duration time will appear to be almost same as the $D\tau$ of the applied pulse wave. Furthermore, when the value of the actual inductance L is much greater than $L_{\max}$, the cut-off frequency for the actual inductance will decrease as the value of the inductance increases. That is, in these cases, the inductance L of the inductive sensor cannot be correctly obtained. Therefore, in Section 3.3, to solve this problem, a method of subdividing and measuring the range of $1[nH] < L \leq 1[H]$ is presented. Each subdivided range and measurement sequence are shown in Table 8, and the measurement method is shown in a flowchart in Figure 4. However, in the process of finding the value of inductance L using the flowchart in Figure 4, there is one consideration for the reference voltage x. In order to obtain the inductance L as accurately as possible, the reference voltage x should be set ass large as possible. It is because that if the value of actual inductance L is very small compared to $L_{\min}$, the output voltage of RL circuit will show a waveform that increases very quickly during the high level section of the pulse wave, and as it increases in a range greater than $L_{\max}$, the first peak value of the output voltage will gradually decreases. In section 3.2, the range for the reference voltage x was expressed as in Equation (15). Since the period τ of the pulse wave is $\tau = \dfrac{2\pi L_{\max}}{R}$, if it substituted into the right hand side of Equation (15), the condition of reference voltage x can be expressed as follows.

$$\frac{x}{V_{high}} < 1 - e^{-2D\pi + \ln\left(1 - e^{-2D\pi} + e^{-2\pi}\right)} \qquad \cdots (18)$$

표 8. 측정 순서

Table 8. Order of measurement

Order of measurement	Range of L
1	$10[mH] \leq L \leq 1[H]$
2	$100[uH] \leq L \leq 10[mH]$
3	$1[uH] \leq L \leq 100[uH]$
4	$10[nH] \leq L \leq 1[uH]$
5	$1[nH] \leq L \leq 10[nH]$

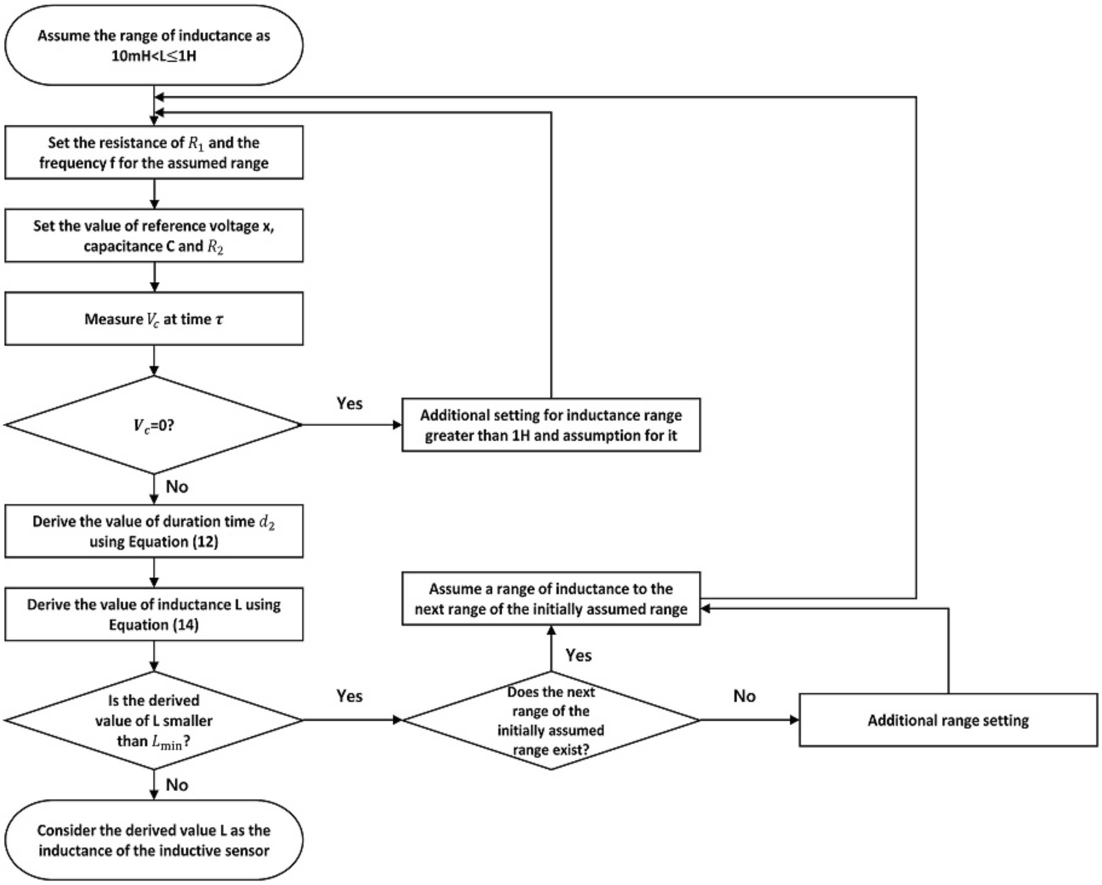

그림 4. 인덕턴스를 측정하는 방법에 대한 순서도
Fig. 4 Flowchart of measuring inductance

The value of x to consider the above mentioned contents could be set using the condition of Equation (18). For instance, when the duty cycle of the pulse wave applied to the RL circuit is 50%, the right hand side of Equation (18) is approximately 0.958. Therefore, according to the condition of Equation (18), we could set $x = 0.95\,V_{high}$ as the reference voltage x in this case. First, as shown in the flowchart of Figure 4, of the value of the actual inductance L is sufficiently large than the maximum value 1H of inductance range which covered in paper, the value of V_c will represent 0. Therefore, it will be possible to derive the inductance L for setting additional range of it. Moreover, if the value of inductance L does not satisfy $L > L_{\min}$ through all the ranges presented in Table 8, it also can be obtained by setting an additional range.

Ⅳ. Results and discussion

4.1 Method to derive inductance L

Experiment proceeded using Pspice simulation, which was performed to confirm whether the inductance L of the inductive sensor can be measured through Equation (15). This was done to measure the inductance L within the range $1[nH] \le L \le 1[H]$; the measurement method is the same as the method presented in Section 3.4. However, to proceed with the simulation using this method, it is necessary to indicate values of resistance as fixed for each range in Table 8; values of resistance in each range used in the simulation are shown in Table 9. These resistance values were set so that the frequency of the pulse wave applied to the RL low-pass filter circuit had a value between 100kHz and 200MHz; the value of the resistance can be set according to the environmental conditions of the designer.

표 9. 각 범위에서 사용된 저항 및 주파수
Table 9. Resistance and frequency used for each range

	Range of L	R_1	f
1	$10[mH] < L \le 1[H]$	1MΩ	159kHz
2	$100[uH] < L \le 10[mH]$	10kΩ	159kHz
3	$1[uH] < L \le 100[uH]$	100Ω	159kHz
4	$10[nH] < L \le 1[uH]$	100Ω	15.9MHz
5	$1[nH] \le L \le 10[nH]$	10Ω	159MHz

In addition, to apply the condition of Equation (17), it is necessary to determine the value of resistance R_2. In this paper, it was set $R_2 = 1Mohm$ However, as can be seen Table 9, the frequency of the pulse wave was set differently for each range. As the value of the frequency f increased, the value of the τ of the pulse wave decreased. Therefore, if a value of capacitance that satisfies the condition of Equation (17) was set for the case of $f = 159kHz$, saturation will not occur for all ranges shown in Table 9. Therefore, substituting it into Equation (17), the condition of capacitance that prevents saturation is $C > 6.28[nF]$. Saturation will not occur for all capacitance values that satisfy this condition; however, to apply the current distribution law as described in Section 4.1, it is necessary to set the resistance R_3 much greater than capacitance C. Therefore, it is necessary to set the value of capacitance considering both cases. In this paper, resistance and capacitance was set to $R_3 = 100Mohm, C = 1uF$, and the duty cycle of the pulse wave applied to the RL circuit was set to 50% to simplify the calculation. Moreover, to consider some considerations in Section 3.4, the reference voltage x has set to $x = 0.95\,V_{high}$ to reduce the error between the actual inductance value and the measured inductance value as much as possible. Since $\ln(\frac{V_{high} - x}{x}) = -\ln(19)$ in this case, Equation (15) is not affected by the value of V_{high}; in Section 4.1, V_{high} was set to $V_{high} = 1\,V$ for simulation.

Above all, as described in Section 3.3, Table 10 shows that the peak value in the period during which the switch is on stayed constant until time τ, when the voltage V_c formed across the capacitor was set not to be saturated. For cases in which the value of inductance L were $100mH$ and $10nH$, the voltage from 0 to τ is shown with the time interval to be $\frac{1}{8}\tau$. Table 10 shows that the value of inductance L can be derived using the voltage measured at time τ.

표 10. 0 - τ까지의 커패시터에 형성되는 전압
Table 10. Voltage through the capacitor from 0 to τ

L	t[sec]	V_c
100 mH	0.785㎲	7.278μV
	1.570㎲	19.053μV
	2.355㎲	30.828μV
	3.140㎲	42.603μV
	3.925㎲	42.703μV
	4.710㎲	42.703μV
	5.495㎲	42.703μV
	6.280㎲	42.703μV
10	0.785ns	0V

nH	1.570ns	0V
	2.355ns	0V
	3.140ns	2.150V
	3.925ns	2.280V
	4.710ns	2.280V
	5.495ns	2.280V
	6.280ns	2.280V

Second, Tables 11, 12, 13, 14 and 15 show that Equation (15) holds for each range of inductance L from Table 9. Ranges of each table is represented as $L_{\min} < L \le L_{\max}$. Moreover, it can be confirmed that the inductance L within the range $1[nH] \le L \le 1[H]$ can be obtained using the method described in Section 3.3 through the measured value for $L = L_{\min}$ in a specific range and the measured value for $L = L_{\max}$ in the next range.

표 11. $10[mH] < L \le 1[H]$ 범위 내의 인덕턴스 L
Table 11. Inductance L within range $10[mH] < L \le 1[H]$

L_{actual}	$L_{measure}$	percent error
1H	1.015H	1.50%
500mH	500.310mH	0.06%
100mH	99.555mH	0.45%
30mH	29.864mH	0.45%
10mH	9.826mH	

표 12. $100[uH] < L \le 10[mH]$ 범위 내의 인덕턴스 L
Table 12. Inductance L within range $100[uH] < L \le 10[mH]$

L_{actual}	$L_{measure}$	percent error
10mH	10.146mH	1.46%
5mH	5.003mH	0.06%
1mH	0.996mH	0.40%
500µH	496.076µH	0.78%
100µH	98.264µH	

표 13. $1[uH] < L \le 100[uH]$ 범위 내의 인덕턴스 L
Table 13. Inductance L within range $1[uH] < L \le 100[uH]$

L_{actual}	$L_{measure}$	percent error
100µH	101.463µH	1.46%
80µH	80.498µH	0.62%
40µH	39.978µH	0.06%
7µH	6.965µH	0.50%
1µH	9.826µH	

표 14. $10[nH] < L \le 1[uH]$ 범위 내의 인덕턴스 L
Table 14. Inductance L within range $10[nH] < L \le 1[uH]$

L_{actual}	$L_{measure}$	percent error
1µH	1.015µH	1.50%
500nH	500.308nH	0.06%
100nH	99.985nH	1.02%
30nH	29.991nH	0.03%
10nH	9.978nH	

표 15. $1[nH] \le L \le 10[nH]$ 범위 내의 인덕턴스 L
Table 15. Inductance L within range $1[nH] \le L \le 10[nH]$

L_{actual}	$L_{measure}$	percent error
10nH	10.148nH	1.48%
8nH	8.051nH	0.64%
5nH	5.001nH	0.02%
3nH	2.998nH	0.07%
1nH	0.998nH	

Finally, Figure 5 shows the waveform of V_c when the actual inductance is 1.1H for the first range presented in Table 8. This shows that the value of the voltage V_c formed through the capacitor equals zero when it is greater than the maximum value 1H for the inductance range $1[nH] \le L \le 1[H]$ set in this paper. Therefore, if the value of actual inductance is sufficiently larger than 1H, it should be measured by setting an additional range for inductance, as shown in the flowchart in Figure 4.

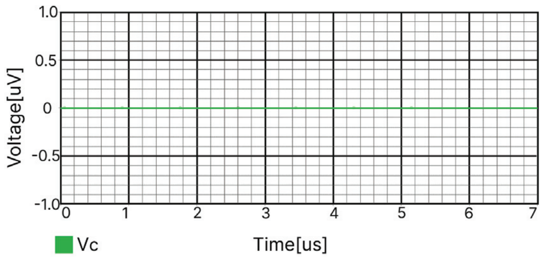

그림 5. 인덕턴스가 1.1H인 경우
Fig. 5 Case of the inductance is 1.1H

4.2 Discussion

Through the results of Section 4.1, it was shown that the inductance of an inductive sensor can be measured by configuring a circuit as shown in Figure 2. To solve certain problems caused, methods for setting certain values have been described and, as can be seen in the results of Section 5.1, the measured values for the aforementioned settings are very close to the actual inductance value L, and the error rate is below 1.5%. However, since some of these settings were arbitrarily determined in this paper, an explanation will provided in this section. First, in Section 3.2, Equation (13) cannot be solved in a general way, so it was solved by approximating some values to zero. Equation (13) can be solved using a method such as numerical substitution in addition to the method suggested in Section 3.2. However, it may takes a lot of time to solve Equation (13), and a slight error will occur with the actual inductance L even during the process of obtaining the value of inductance L using this method. Furthermore, since some values that converged to zero in Section 3.2 are values related to the translation of the t-axis in the function of the output voltage of the RL circuit, the first peak value was measured using the voltage V_c formed across the capacitor. However, if Equation (13) was solved using the numerical substitution method, since the duration time d_2 is defined for the second cycle of the pulse wave applied to the RL circuit, it should be measured as the second peak value, not the first peak value. Second, in Section 3.3, the condition of Equation (16) was used so that the voltage V_c formed in the capacitor did not saturate, and the capacity of the capacitor C was determined by setting $\triangle t = \tau \times (1 \times 10^3)$. The assumption for $\triangle t$ can be arbitrarily set by the designer, but if $\triangle t$ has not been set to a sufficiently long time compared to the duration time d_2, saturation may occur for V_c before the switch is switched from on to off; designer will have to pay attention to this while using this circuit. Finally, in this paper, an ideal current switch with a gain of 1 for current applied to it was used to measure the inductance L using the characteristics of the comparator and capacitor. However, when implementing a circuit and measuring inductance, it will be necessary to consider the characteristics of the switch element used. For instance, if a MOSFET element is used instead of the switch element used in Figure 2, the drain current flowing in the channel formed when the MOSFET is turned on must be considered to measure the voltage V_c through the capacitor[7].

Ⅴ. Conclusion

In this paper, a circuit was constructed to measure the inductance of an inductive sensor; the characteristics of the RL low-pass filter circuit, comparator, current control switch, and capacitor were used. First, a method of setting the frequency of the applied pulse wave to be below the cut-off frequency for all inductance L within the assumed range $L_{\min} < L \le L_{\max}$ was presented using the characteristic that the RL low-pass filter outputs signals well in the band below the cut-off frequency; also, a solution to the problem that inductance cannot be measured correctly when the transfer function for the value of inductance L converges to 1 was been suggested. In addition, to utilize a duration time in which the output voltage of the RL circuit is greater than the reference voltage x, the output voltage of the RL circuit and reference voltage x were applied to both V_+ and V_- of the comparator. Accordingly, to prevent saturation of the voltage formed across the capacitor when the switch turns on, the definition of a farad(the unit of the capacitor) was used to present the conditions for the capacitance in which saturation does not occur, and it was confirmed throrugh Pspice simulation that the value of inductance L appeared close to the value of the actual inductance L for these settings. Therefore, the inductance of the inductive sensor can be measured relatively accurately using the circuit presented in this paper, and this circuit will greatly contribute to improving the quality of data provided by the inductive sensor used in IoT systems.

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