Investigation on current transformers for measuring of electron beam pulse current

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Abstract. The radio-frequency (RF) linear accelerator (linac) system of the PBP-CMU Electron Linac Laboratory at the Plasma and Beam Physics Research Facility is used as an injector system for future mid-infrared and terahertz free-electron lasers. The properties of electron beams produced from the linac must be controlled appropriately to produce high-quality radiation. One of the most important properties is the electron pulse current that can be measured using a current transformer. A copper wire with proper insulator is wound around the ferrite-core forming a secondary coil of the current transformer. The electron beam passing through the transformer acts as the current in the primary coil and it induces an electromotive force in the secondary coil. Therefore, the output signal from the secondary coil can be measured and analyzed to be a pulse current of electron beam. The measured current pulse shape and value strongly depend on the characteristics of the current transformer. This study focuses on testing and calibrating of existing current transformers installed in the linac system. In the experiments, the pulse generator was used to generate the input pulse current with various pulse lengths. The output pulses were then sampled with a digital oscilloscope. The experimental results showed that the output pulses from the current transformers have distort shape compared with the input pulses. Consequently, the correction was conducted to provide more accuracy of the measuring value of the electron pulse current. The results of this research can be used as a valuable database for the existing current transformers and to develop the new ones that can provide more accurate results.

1. Introduction
One of the most important electron beam diagnostic instruments for any accelerator is a current transformer, which is very widely used for measuring the electron beam pulse current and its pulse length. In principle, the current transformer is a non-destructive instrument because the electron beam can pass through it without losing its properties. With this instrument, we consider the electron beam to be a primary coil with a current $I_b$ and a secondary coil of $N$ turns wound around the ferrite core. The secondary coil is used to measure the output current signal $I_s$. The sketch of the current transformer is shown in figure 1. When the electron beam with the current $I_b$ passing through the secondary coil,
the magnetic field generated by the beam current induces the current \( I_s \) in the secondary coil. Since the electron beam is treated as a single primary coil, the electron beam current can be calculated as [1]

\[
I_b = NI_s. \tag{1}
\]

![Figure 1. Sketch of the current transformer.](image)

For the ideal current transformer, the electron beam current \( I_b \), which is calculated with equation (1), should be equal to the input current. However, the output signal from the real current transformer may distort due to the resistance \( R \) of the secondary coil, the inductance \( L \) of the winding, and the stray capacitance \( C \) in the gap between the windings. Therefore, we can consider the real current transformer as an RLC parallel circuit. From calculation of this circuit, the output current pulse from the test pulse and beam input pulse are presented in figure 2.

![Figure 2. Input (primary) and output (secondary) pulses from the real current transformer [2].](image)

From figure 2, there are two differences between input and output signal. First, the rise at the beginning of the output signal. It depends on the inductance \( L \) and the capacitance \( C \) of the current transformer. From RLC parallel circuit, we can calculate the rise time defined from the time that an amplitude of the signal increase from 10% to 90% [3] as

\[
t_{\text{rise}} = 2.2\sqrt{LC}. \tag{2}
\]

Another difference is the exponential droop of the output signal. It depends on the inductance \( L \) and the resistance \( R \) of the current transformer. We can also calculate the droop time defined from the time that an amplitude of the signal decrease from 90% to 10% [3] as

\[
t_{\text{droop}} = 2.2 \frac{L}{R}. \tag{3}
\]

From the droop, the output signal distorts compared with the input signal. Hence, improvement of the output signal using a correction is necessary. This research focuses on testing of the current transformers installed in the linac system of the PBP-CMU Electron Linac Laboratory and investigating on the correction to measure the electron beam pulse current accurately.
2. Testing of the current transformers
There are five current transformers (CT1-CT5) installed in the linac system of the PBP-CMU Electron Linac Laboratory as shown in figure 3. The pulse generator was used to generate the input pulse current 0.5 A with a pulse length between 4 to 10 μs. The input pulses were fed to pass through each current transformer. The output pulses were then sampled with a digital oscilloscope. The results in figure 4 show that the output pulses had distort shape compared with the input pulses for all pulse lengths and all current transformers, especially the output pulses from CT4 and CT5, where CT2 had the least distortion.

CT1  CT2  CT3  CT4  CT5

Figure 3. Current transformers installed in the linac system of the PBP-CMU Electron Linac Laboratory.

(a)  (b)  (c)  (d)

Figure 4. Input and output pulses from current transformers with pulse lengths of (a) 4 μs, (b) 6 μs, (c) 8 μs and (d) 10 μs.
3. Correction of the output pulses from current transformers

Since the output pulse decreases exponentially compared with the input pulse, we can describe the output pulse \( I_{\text{output}}(t) \) as the linear combination of exponential functions \([4]\) as

\[
I_{\text{output}}(t) = A_0 + A_1 e^{-t/k_1} + A_2 e^{-t/k_2} + A_3 e^{-t/k_3} + \ldots
\]

where the coefficients \( A_i \) and \( k_i \) can be found by using the total least-squares curve fitting. Assume that the initial distortion time is \( t_0 \), we can rewrite equation (4) as

\[
I_{\text{output}}(t) = I_{\text{output}}(t_0 + \Delta t) = A_0 + A_1 e^{-(t_0 + \Delta t)/k_1} + A_2 e^{-(t_0 + \Delta t)/k_2} + A_3 e^{-(t_0 + \Delta t)/k_3} + \ldots
\]

where \( t = t_0 + \Delta t \). We can then calculate the correction term of the output current \( \Delta I \) from

\[
\Delta I = I_{\text{output}}(t_0) - I_{\text{output}}(t) = I_{\text{output}}(t_0) - I_{\text{output}}(t_0 + \Delta t)
\]

Thus,

\[
\Delta I = A_1 \left( e^{-t_0/k_1} - e^{-(t_0 + \Delta t)/k_1} \right) + A_2 \left( e^{-t_0/k_2} - e^{-(t_0 + \Delta t)/k_2} \right) + A_3 \left( e^{-t_0/k_3} - e^{-(t_0 + \Delta t)/k_3} \right) + \ldots
\]

The correction term in equation (7) is used to correct the output pulse from distortion. For accuracy, we used three correction terms for fitting in this study. From the total least-squares curve fitting of the output pulse data with pulse length 10 \( \mu \)s, which is almost the same pulse length as the longest RF pulse obtained from our machine, in each current transformer. The parameters from fitting are presented in table 1. The current \( I_{\text{output}} \) and \( t \) are in the units of A and \( \mu \)s, respectively.

Table 1. Parameters of equation (2) fitted to the output pulse data of each current transformer for the input pulse current of 0.5 A using the total least-squares curve fitting.

| Parameter | CT1       | CT2       | CT3       | CT4       | CT5       |
|-----------|-----------|-----------|-----------|-----------|-----------|
| \( A_0 \) | 2.61111\times10^{-3} | 2.87122\times10^{-3} | -8.69624\times10^{-2} | 5.61004\times10^{-5} | -6.58854\times10^{-4} |
| \( A_1 \) | 3.18310\times10^{-1} | 2.23529\times10^{-1} | 2.41231\times10^{-1} | 2.83968\times10^{-1} | 2.35438\times10^{-1} |
| \( A_2 \) | 9.66691\times10^{-2} | 1.50267\times10^{-1} | 2.27739\times10^{-1} | 1.83598\times10^{-1} | 1.87040\times10^{-1} |
| \( A_3 \) | 8.06788\times10^{-2} | 1.18451\times10^{-1} | 1.31212\times10^{-1} | 8.15918\times10^{-2} | 1.27571\times10^{-1} |
| \( k_1 \) | 47.76519 | 55.28469 | 26.76910 | 8.63714 | 8.98058 |
| \( k_2 \) | 16.43807 | 53.76355 | 26.38201 | 8.61006 | 9.00477 |
| \( k_3 \) | 23.38116 | 55.91555 | 23.51585 | 8.83888 | 9.02324 |

When we applied these corrections to the output pulse data with pulse lengths between 4-10 \( \mu \)s, the corrected output pulses are similar to the input pulse for all pulse lengths and all current transformers. The examples of results in figure 5 show the input pulses, output pulses and corrected output pulses from the current transformer CT1 with pulse lengths of 4-10 \( \mu \)s. However, this correction can be used for the input pulse current of 0.5 A only. For the different input pulse current, we have to scale the correction term appropriately.
4. Conclusion

Current transformer is a non-destructive instrument to measure the electron beam pulse current and its pulse length. From the measuring results of five current transformers (CT1-CT5), the output pulses had different distortion compared with the input pulses. After applying the correction, the corrected output pulses are similar to the input pulse for all pulse lengths. We can use the results of this research as a database for the existing current transformers in our facility. In addition, the new current transformer can be developed from the characteristics of the current transformer achieved from this research, such as a number of wounding turns of the secondary coil and a resistance value of the external resistor, especially the characteristics of CT2, which have the least distortion.

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