TRANSIENT RESPONSE EVALUATION OF HIGH VOLTAGE DIVIDERS FOR IMPULSE MEASUREMENTS

SOUMEK INTHALA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF ENGINEERING IN ELECTRICAL ENGINEERING
SCHOOL OF GRADUATE STUDIES
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG

2006

ISBN 974-15-2287-8

หัวข้อวิทยานิพนธ์	การวิเคราะห์ผลตอบสนองทรานเชี้ยนต์ของตัวลดทอนแรงดันสูง สำหรับการวัดแรงดันอิมพัลส์
นักศึกษา	นายสุเมก อินทะลา
รหัสนักศึกษา	47060229
ปริญญา	วิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชา	วิศวกรรมไฟฟ้า
พ.ศ.	2549
อาจารย์ผู้ควบคุมวิทยานิพนธ์	รศ. ดร. อานันทวัฒน์ คุณากร
อาจารย์ผู้ควบคุมวิทยานิพนธ์ร่วม	ศ. ดร. มาซากิ คันโดะ

บทคัดย่อ

ระบบการวัดแรงดันอิมพัลส์ประกอบด้วย โวลเตจดิไวเดอร์ ระบบสายนำแรงสูง และอุปกณ์วัดหรืออุปกรณ์บันทึกรูปคลื่น ซึ่งอุปกรณ์การวัดจะต้องมีการปรับให้มีความแม่นยำภายใต้มาตรฐานของเครื่องมือวัด โดยการตั้งค่า ซึ่งเกี่ยวกับพารามิเตอร์ของสัญญาณ โดยเฉพาะอย่างยิ่งสำหรับเครื่องมือวัดแรงดันอิมพัลส์ พารามิเตอร์ของผลตอบสนองเวลาสามารถพิจารณาได้โดยการเปรียบเทียบจากระบบการวัดภายใต้การทดสอบ หรือการใช้เครื่องสร้างสัญญาณรูปขั้น วิทยานิพนธ์ฉบับนี้นำเสนอกานการวิเคราะห์ผลตอบสนองรูปขั้นของโวลเตจดิไวเดอร์ หลายชนิด โดยอาศัยโปรแกรม MATLAB/Simulink ช่วยในการคำนวณหาค่าของพารามิเตอร์ต่างๆของผลตอบสนองเวลาของดิไวเดอร์ ดังเช่น จุดเริ่มต้นเสมือนของผนตอบสนองรูบขั้น(O_1), ส่วนพุ่งเกิน(β), เวลาผิดเพี้ยนเริ่มต้น(T_0), เวลาตอบสะนองบางส่วน(T_α), เวลาตอบสนองจากการทดลอง(T_N), และช่วงเวลาเข้าที่(t_s) เพื่อที่จะนำไปตรวจสอบความแม่นยำของซอฟแวร์ ซึ่งในการทดลองจะนำเครื่องสร้างสัญญาณ มาเป็นแหล่งจ่าย จ่ายให้กับโวลเตจดิไวเดอร์ และได้ทำการอธิบายรายละเอียดเกี่ยวกับอัลกอริธึมและความสามารถของซอฟแวร์ด้วย

Thesis Title	Transient Responses Evaluation of High Voltage Dividers for Impulse Voltage Measurements
Student	Mr. Soumek Inthala
Student ID.	47060229
Degree	Master of Engineering
Programme	Electrical Engineering
Year	2006
Thesis Advisor	Assoc. Prof. Dr. Anantawat Kunakorn
Co- Thesis Advisor	Prof. Dr. Massaki Kando (Tokai University of Japan)

ABSTRACT

Impulse voltages are detected using a measuring system consisting of a high voltage divider, a transmission system and recording instruments. These measuring equipments must be calibrated periodically to have an accuracy within permissible limits. This involves the determination of a scale factor, linearity and the validity range with respect to signal parameters; especially for impulse voltage measurements. The time response parameters can be determined by comparing the measuring system under tests with a calibrated reference divider, or by using a unit step generator. In this thesis, structures of various high voltage dividers are presented. A computer aided tool is developed based on MATLAB/SIMULINK to evaluate the divider time response parameters such as a base magnitude, a settling level, a virtual origin (0_1), an overshoot (β), a distortion time (T_0), a partial response time (T_{α}), an experimental response time (T_N), and a settling time(t_s). In order to check the validity of the software tool, the experiments are performed using two unit step generators with different high voltage dividers. The details of the algorithm and capabilities of the software are also discussed.

ACKNOWLEDGEMENTS

This work is carried out at Department of Electrical Engineering, Faculty of Engineering, King Mongkut's of Technology Lardkrabang (KMITL).

Firstly, I would like to express my special gratitude to Assoc. Prof. Dr. Anantawat Kunakorn, my supervisor and examiner, for giving me the opportunity to explore the interesting field of power engineering, and for his encouragement and guidance during the research. I would like to thank Prof. Dr. Masaaki Kando from Department of Electrical and Electronic, Tokai University, Japan, my co-supervisor, for his encouragement.

I would like to thank Mr. Norasage Pattanadech from Department of Electrical Engineering, Faculty of Engineering, KMITL, Thailand, my co-supervisor, for his encouragement and all practical techniques in a high voltage laboratory.

I would like to thank Mr. Atthapol Ngaopitakkul and Mr. Seksun Ngamsritrakul, Doctoral and Master student respectively, for their encouragement.

I would especially like to thank all academic staff from Department of Electrical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang (KMITL), for giving me very useful knowledge and experience.

I would like to tank Mr. Pearawut Yutthagowith from the Center of Excellence in Electrical Power Technology, Faculty of Engineering, Chulalongkorn University, Thailand, for providing some equipments and practical techniques to use in the experimental tests.

I sincerely thank my Thai friends, all staff and colleagues for their help and good cooperation.

The financial support is provided by JICA. This is gratefully acknowledged.

Finally, I would like to thank King Mongkut's Institute of Technology Ladkrabang (KMITL) and AUN/SEE-Net (JICA) for giving me an opportunity to upgrade my knowledge.

Soumek Inthala

TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS (Cont.)

LIST OF TABLE

TABLE PAGE

LIST OF FIGURES

FIGURE PAGE

LIST OF FIGURES (Cont.)

FIGURE PAGE

CHAPTER I

INTRODUCTION

1.1 Background

Disturbances in electric power transmission and distribution systems are frequently caused by two kinds of transient voltages whose amplitude may greatly exceed the peak values of the normal a.c. operating voltage.

The first kind is lightning overvoltages, originated by lightning strikes at the phase wires of overhead lines or the busbars of outdoor substations. These lightning will induce steep rising voltages in the line and set up traveling waves along the line, and may damage the system's insulation. The magnitude of these overvoltages may reach several thousand kilovolts, depending upon the characteristics of the lightning. Measurements and experiences have shown that lightning overvoltages are characterized by short front duration, ranging from a fraction of a microsecond to several tens of microseconds and then slowly decreasing to zero. The standard impulse voltage has been accepted as a periodic impulse that reaches its peak value in 1.2 μsec and then decreases slowly (in about 50 μsec) to haft its peak value [1].

The second kind is caused by switching phenomena. That is a transient overvoltage due to sudden changes in the state of power systems, e.g. switching operation or faults. These are known as switching impulse voltages. It has become, generally, recognized that the switching impulse voltages are usually the dominant factor affecting the design of insulation in H.V. power system rated voltages of about 300 kV and above. Accordingly, the various international standards recommend that equipment designed for voltages above 300 kV be tested for switching impulses. Although the waveshape of switching overvoltages occurring in the system may vary. The recommended switching surge voltage has been designated to have a front time of about 250μsec and half value time of 2500 μsec [1].

Both lightning overvoltages and switching overvoltages are simulated in a laboratory in order to perform an impulse voltage withstand test for electrical equipments.

The quality of high voltage impulse measurements requires adequate dynamic performance of measuring systems with respect to the waveforms to be measured. The qualification of the various impulse measurements is a prerequisite for repeatability and reproducibility of testing results [5]. The variation of measuring system of response parameters can lead to improper conclusions when only conventional examinations of the dynamic behaviour are used.

1.2 Objective of the study

This research work is concerned with the measurement, calculation and analysis of unit step responses. In this research, different methods available to calibrate the high voltage measuring system such as methodology for voltage comparison method and dynamic response method are discussed.

The time response parameters can be determined by comparing the measuring system under tests with calibrated reference divider or by using unit step generators. In this thesis, structures of various high voltage dividers are presented. A computer aided tool is developed based on MATLAB/Simulink to evaluate the divider time response parameters such as a base magnitude, a settling level, a virtual origin (0_1), an overshoot (β), a distortion time (T_0), a partial response time (T_α), an experimental response time (T_N), and a settling time(t_s). In order to verify the validity of the software developed, the experiments are performed using a unit step generator with different high voltage dividers. The details of the algorithm and capabilities of the software are also discussed.

1.3 Problem Statement

An impulse voltage is a transient signal, which usually rises rapidly to a peak value and then falls more slowly to zero. An impulse voltage divider is required to measure the peak value, the time parameters and the overshoot or the oscillation of the impulse waveform. The impulse voltage divider performance must agree the approval procedure according to the international standards such as IEC, ANSI [2, 3] to ensure that the value of measured signal impulse is valid.

The widely-used method in the evaluation of the performances of a high voltage dividers for impulse voltage measurements is the transient responses of the divider due to an injection of unit step waveform. However, the procedure in analyzing the results from unit step tests is normally performed manually, which cause some errors.

It should be useful to develop a computer-aided tool used in calculation processes of the transient responses from the unit step tests so that the procedure can be more convenient, and provide more precise judgment in measurements.

1.4 Proposed Solution

In HV measurement techniques, the step response of an HV impulse divider is often used to characterise the dynamic performances. Although electromagnetic interference, traveling waves due to mismatch and other effects may influence the experimental step response, the step response is still enable for operators to render an overall judgment on the quality of the divider for measuring HV impulse waveforms. To put this judgment on a more quantitative basis, five parameters of the step response are specified in IEC 60 to approve a divider by the "component method" [2].

This method of qualifying impulse dividers by their response parameters has, however, several weak points. None of response parameters is directly related to the error of a divider used to measure the peak value and time parameters of HV impulses.

Furthermore, the uncertainty of determining the response parameters is of comparable magnitude as the specified IEC limiting values. A divider may rejected by the "component method" though it may be accepted by the "comparison method" by which measuring errors of the divider under test can directly determined [7].

This research work presents computer-aided analysis tool for a calculation of transient responses of a high voltage divider. The analysis tools are developed on the basis of MATLAB/Simulink. The results show that the computer–aided analysis tools are able to correctly predict transient parameters of the high voltage divider, and this will be very useful for impulse measurements in a high voltage laboratory

The results obtained for three high voltage dividers with two unit step generators were compared with the values obtained by comparison measurements with a reference divider. The possibility of replacing the response parameters by this technique for qualifying HV impulse dividers is discussed.

1.5 Scope of the research work

This research work is concerned with the evaluation of transient responses of various high voltage dividers. A computer algorithm is developed using MATLAB/Simulink. The computer-aided tool, then, is used in the investigation of transient response parameters for high voltage dividers.

Finally, the compatibility of the high voltage dividers with three types of impulse voltage waveforms: full lightning impulses, tail chopped impulses and switching impulses is considered.

1.6 Outline of the thesis

CHAPTER 2 presents conventional high voltage dividers. In this chapter the various high voltage dividers are used to reduce the high amplitude to a suitable value for a recording device or low voltage meters.

CHAPTER 3 discusses some requirement of high voltage divider by using unit step generator which could define the dynamic behaviour of the impulse dividers.

CHAPTER 4 discusses some simulation and experimental results about transient and unit step response. In this chapter, the simulation results of three study cases were given and explained.

CHAPTER 5 presents the conclusion of the work and some suggestions for the futures are point out in this chapter.

CHAPTER 2

HIGH VOLTAGE DIVIDERS

2.1 Introduction

A voltage divider is an important high voltage device. The divider is employed to reduce the amplitude of a measured signal to a suitable value for a record instrument. The voltage divider consists of high voltage and low voltage units which may be constructed from resistors, capacitors or a combination between resistors and capacitors. Generally, resistor voltage dividers are mostly proper for d.c voltage measurements, and also applicable for a use with a.c voltage measurements with a condition that the power loss is not too much. However an additional error can occur due to the inductance of the resistor and the stray capacitances. As a result, in a.c measuring system, the capacitive divider is normally used for measuring both peak and RMS voltages. For impulse measurements, a capacitive high voltage divider can be employed with a modification to improve response characteristics using a damp resistor. This is called damped capacitive voltage divider [6].

It has been shown by many investigators that a distributed parameter network is probably the best equivalent circuits to simulate the actual high voltage dividers. Generalized distributed parameter network for a voltage divider is shown in Figure 2.1. A voltage divider os formed by a large number (n) of elements or sections [1], and the n impedances $Z_l^{'}$ in series are providing the voltage reduction. An equal number of impedances $Z_q^{'}$ to earth are distributed along this column. The input voltage V is, thus, greatly reduced to the low output voltage V_2. The total impedances are then defined by

$$Z_1 = \sum Z_l^{'} = nZ_l^{'}$$
$$Z_q = (\sum \frac{1}{Z_q^{'}})^{-1} = \frac{Z_q^{'}}{n} \qquad (2.1)$$

The number n is equivalent to the voltage ratio V/V_2 of the divider. The impedance Z_q of the lead may change the ratio of the whole voltage measuring system. The matrix representation of such a network, which is equivalent to a transmission line network, is well known. The normalized transfer function may be determined as [1]:

$$h_t(s) = \frac{nV_2}{V} = \frac{n\sinh\frac{1}{n}\sqrt{Z_l(s)/Z_q(s)}}{\sinh\sqrt{Z_l(s)/Z_q(s)}} \tag{2.2}$$

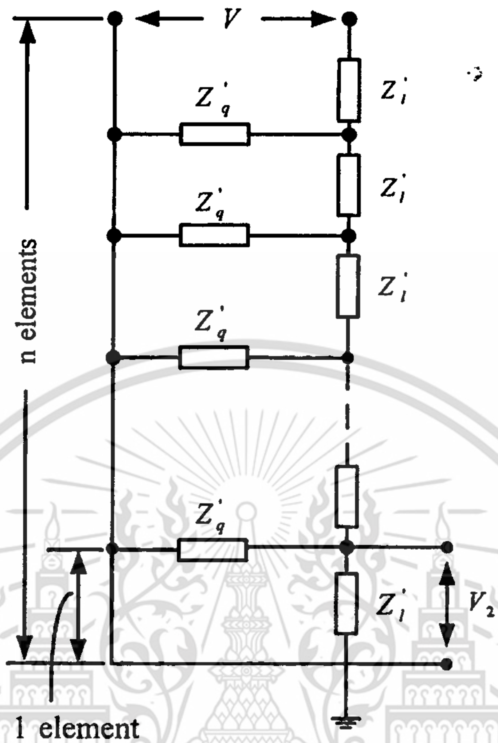


Figure 2.1 Distribution parameter equivalent circuits of voltage dividers [1].

The normalized unit step response is:

$$g_t(t) = L^{-1}[\frac{1}{s}h_t(s)] \tag{2.3}$$

Both quantities can be computed and analyzed for different equivalent circuits, for which the impedances $Z_l^{'}$ and $Z_q^{'}$ are specified. However, $Z_q^{'}$ is always represented by stray capacitances $C_e^{'}$ to earth. This stray capacitance is, thus, assumed to be equally distributed.

There are many types of high voltage dividers employed in industries such as resistive voltage dividers, capacitive dividers, ect. The following sections will detail the configuration and equivalent circuits of widely-used high voltage dividers.

2.2 Resistive Voltage Dividers

The best representation of resistive voltage dividers has to insert inductive components L' of the actual resistor R' in series as well as capacitive elements C'_p in parallel to the resistors (see Figure 2.2). Inductances are inherent with every flow of current due to the magnetic field, and the parallel capacitors C'_p are occurred by the construction of the resistors.

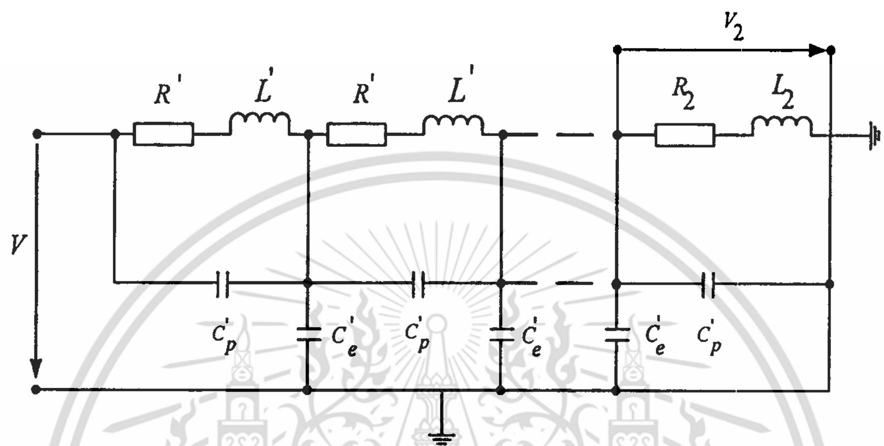


Figure 2.2 Equivalent circuit for resistor voltage dividers. $R = nR'$; $L = nL'$; $C_e = nC'_e$; $C'_p = C'_p/n$; $R_2 = R'$; $L_2 = L'$; $R_1 = (n-1)R'$ [1].

The normalized transfer function is easily found from equation (2.2) as:

$$h_t(s) = n\frac{\sinh\frac{1}{n}\sqrt{\frac{(R+sL)sC_e}{1+(R+sL)sC_p}}}{\sinh\sqrt{\frac{(R+sL)sC_e}{1+(R+sL)sC_p}}} \tag{2.4}$$

The normalized unit step response is:

$$g_t(t) = 1 + 2e^{-at}\sum_{k=1}^{\infty}(-1)^k\frac{\cosh(b_k t)+\frac{a}{b_k}\sinh(b_k t)}{1+\frac{C_p}{C_e}k^2\pi^2}; \tag{2.5}$$

where a = R/2L;

$$b_k = \sqrt{a^2 - \frac{k^2\pi^2}{LC_e[1+(C_p/C_e)k^2\pi^2}};$$

k = 1, 2, 3... ∞

It is clear that resistor dividers are ideal for d.c. voltage measurements. The transfer function $h_t(s)$ for high R values and accordingly small value of L / R increases steadily with a decrease of the frequency. For $s \to 0$, $h_t(s) \cong 1$ and therefore

$$V_2 = \frac{V}{n} = V\frac{R_2}{R_1 + R_2}$$

The ability to measure a.c. voltages as well as the ripple inherent in d.c. voltages depend upon the decrease of $h_t(s)$ with frequencies. Since, for all constructions of high ohmic resistor dividers, the L/R values are lower than about 0.1 μs, and also $C_p << C_e$, the controlling factor of the transfer function is given by the product RC_e. Neglecting L and C_p in equation (2.4) as well as in equation (2.5), the transfer function and the unit step response become:

$$h_t(s) \approx n\frac{\sinh\frac{1}{n}\sqrt{sRC_e}}{\sinh\sqrt{sRC_e}} \qquad (2.6)$$

$$g_t(t) = 1 + 2\sum_{k=1}^{\infty}(-1)^k \exp(-\frac{k^2\pi^2}{RC_e}t) \qquad (2.7)$$

where $k = 1, 2, 3...\infty$

The response time T_N can be computed as:

$$T_N = \frac{RC_e}{6} \qquad (2.6)$$

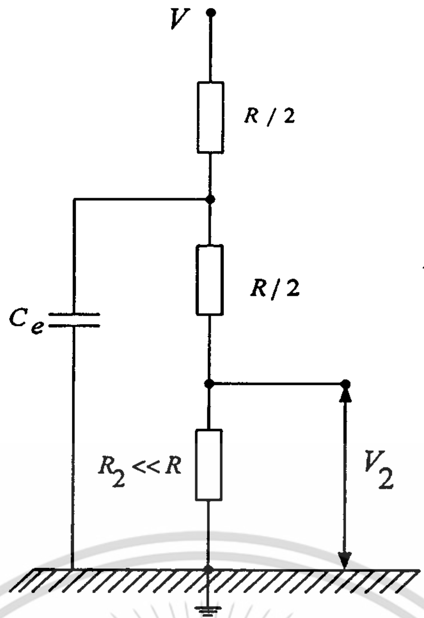


Figure 2.3 Common equivalent circuit representing approximately the distributed parameter circuit of Figure 2.2 [1].

2.3 Capacitive Voltage Dividers

A treatment of capacitor voltage dividers with stacked capacitor unit is thus justified. The distributed parameter network is able to simulate the transfer properties. Figure 2.4 shows such a network, which may encounter all possible circuit elements. The actual stacked capacitors are now simulated by the capacitance units C', and L' taking into account the inherent inductance. The series resistance R' may be used to simulate either only small losses within the capacitor units C', or even real resistors in series with these units. The small values of stray capacitances are inserted in parallel to the stacked columns C'_p and to ground C'_e.

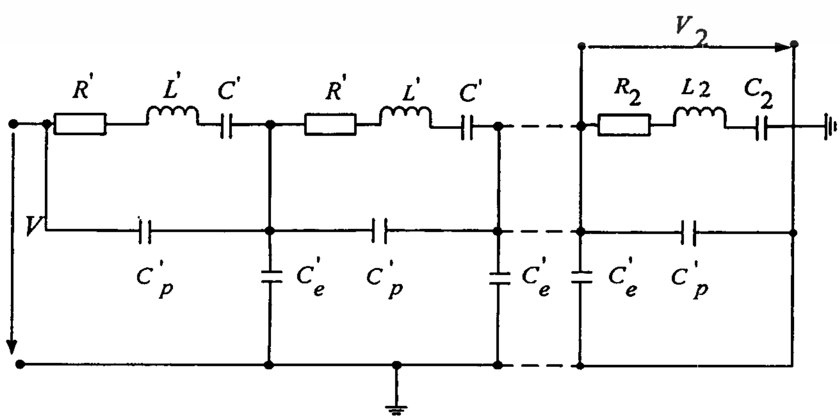


Figure 2.4 Equivalent circuit for capacitor voltage dividers, $R = nR'$; $L = nL'$; $C_e = nC'_e$; $C = C'/n$; $C_p = C'_p/n$; $R_2 = R'$; $L_2 = L'$; $C_2 = C'$ [1].

The normalized unit step response is:

$$g_t(t) = 1 - \frac{C_e}{6(C+C_p)} + 2\exp(-at)\sum_{k=1}^{\infty}(-1)^k \frac{\cosh(b_k t) + \frac{a}{b_k}\sinh(b_k t)}{AB}; \qquad (2.8)$$

where $A = \left(1 + \frac{C_p}{C} + \frac{C_e}{Ck^2\pi^2}\right)$; $a = \frac{R}{2L}$

$B = \left(1 + \frac{C_p k^2 \pi^2}{C_e}\right)$; $\qquad b_k = \sqrt{a^2 - \frac{k^2\pi^2 A}{LC_e B}}$

Pure capacitor voltage dividers are therefore sensitive to input voltages with short rise times, and the oscillation may occur at the output voltages. Such a capacitance divider within a whole measuring circuit, i.e. with leads connected to its input, will form a series resonant, and thus the whole measuring circuit will oscillate.

It is obvious that pure capacitor dividers are not adequate to measure impulse voltages with a steep front (front chopped lightning impulse voltages) or any highly transient phenomena (voltage during chopping). Switching impulse voltages or even full lightning impulse voltages, however, can be properly recorded, if the transient phenomena during the front of the impulse have disappeared.

2.4 Damped Capacitive Voltage Divider

Damped capacitive voltage dividers have serial connected resistors, so that the internal self-oscillations can be reduced. In order to reach an optimal transmission behaviour all components of the voltage divider have to fulfill the following adjustment condition: $R_2C_2 = R' C_p'$.

The possible improvement of pure capacitor voltage dividers is achieved by inserting real resistor unit in series with capacitor as shown the equivalent circuit in Figure 2.4, and the same normalized unit step response of this voltage divider is likely to equation (2.8).

Figure 2.5 shows the equivalent of the parallel-mix resistor and capacitor voltage divider.

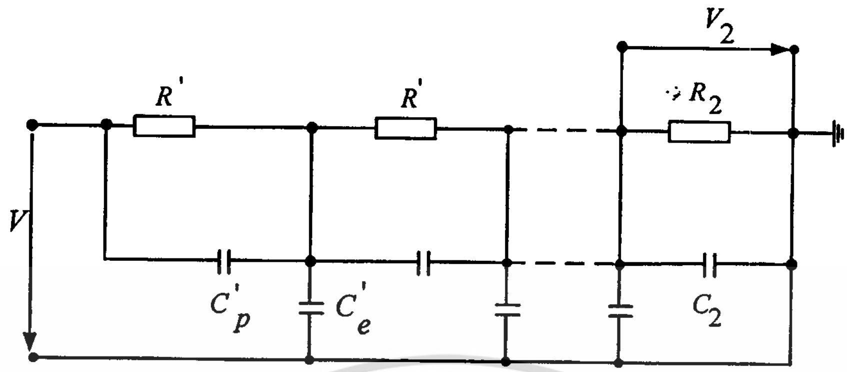


Figure 2.5 Simplified equivalent circuits for parallel - mixed resistor-capacitor dividers.

$R = nR; C_p = C'_p / n; C_e = nC'_e; R_2 = R'; C_2 = C'_p$ [1].

The normalized transfer function of the equivalent circuit is:

$$h_t(s) = n\frac{\sinh \frac{1}{n}\sqrt{\frac{sRC_e}{1+sRC_p}}}{\sinh \sqrt{\frac{sRC_e}{1+sRC_p}}} \tag{2.9}$$

The normalized unit step response is:

$$g(t) = 1 + 2\sum_{k=1}^{\infty}(-1)^k \frac{ex(-a_k t)}{1+k^2\pi^2 C_p / C_e} \tag{2.10}$$

where $a_k = \dfrac{k^2\pi^2}{RC_e(1+k^2\pi^2 C_p / C_e)}$

$k = 1, 2, 3\ldots$

2.5 The low voltage (LV) Arm of the Measuring System

The low voltage arm is an integral part of the high voltage divider and that impedances of this arm are not different from those of a unit of the HV arm. However, if the ratio or scale factors of HV dividers are large and the dimensions of any low voltage arms are relatively big, the construction of low voltage arms is somewhat difficult. Therefore, some addition problems are finally treated concerning adequate construction and layout of the LV of a measuring system. Many distortions in the response can be related to this part of the system [8].

For voltage dividers used in DC and AC voltage measurements, the design of LV arm is not critical, if only steady state voltages have to be recorded. However, if any fast transients have to be transmitted from the voltage divider to the recording instrument, the LV arm of the divider itself may introduce large disturbances to the response. As a result the adequate impedance matching is necessary to transmit impulse voltages from the divider to the recording instrument.

In Figure 2.6, the simplified equivalent circuits for the matching procedures for various types of dividers are sketched. The signal cable is mainly treated as losses, so that the surge impedance $Z_k = \sqrt{L_k / C_k}$ becomes independent of the frequency, and the travel time of $\tau_k = \sqrt{L_k C_k}$. For resistor dividers as shown in Figure 2.6(a), the cable matching is simply done by a non-inductive resistor $R = Z_k$ at the end of the signal cable. The transmission line theory provides the well known background for this procedure, the reflection coefficient be come zero and any step voltage appearing across R_2 is transmitted without any distortion by the cable. As the input impedance of the signal cable is $R = Z_k$, this resistance is in parallel to R_2 and forms an integral part of the dividers l.v. arm.

For parallel-mixed resistor-capacitor-voltage dividers the same procedure for cable matching as shown in Figure 2.6 (a), can be used. A matching resistor R, coaxially designed to meet the high – frequency requirements, will not reflect energy.

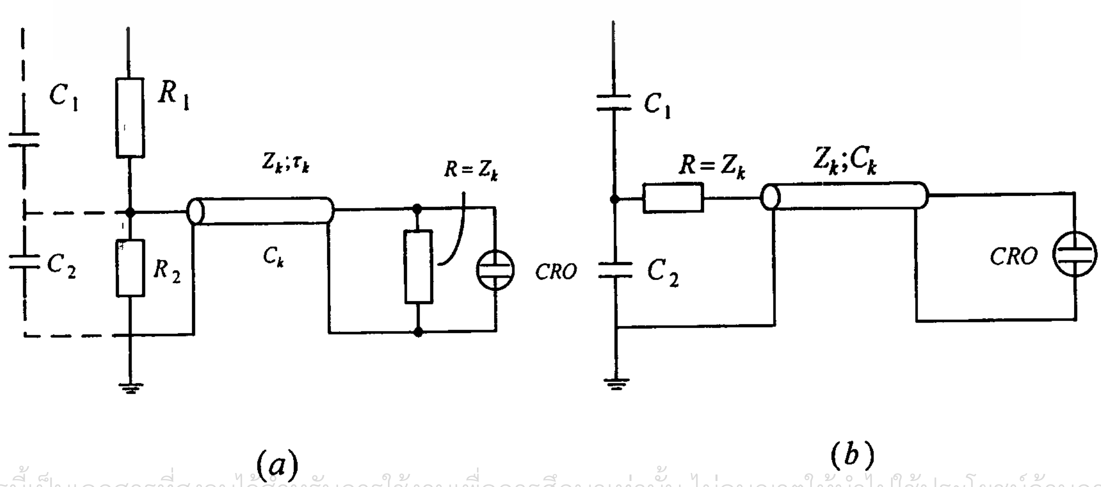
For capacitor voltage dividers as Figure 2.6 (b) or Figure 2.6 (c), the signal cable can not be matched at its end. A low ohmic resistor in parallel to C_2 would load the l.v. arm of the divider too heavily and decrease the output voltage with time. To avoid the traveling wave oscillations, the cable can be terminated at its input end. A voltage step of constant amplitude at C_2 will be halved by $R = Z_k$ at the cable input end. This halved voltage travels to the open end and is doubled by reflection. Thus the original amplitude of the voltage across C_2 appears at the input of the recording instrument. The reflected wave charges the cable to its final voltage amplitude, and is absorbed by R, as the capacitor C_2 forms a short circuit.

In reality, C_2 is of finite value and is therefore discharged during these transient events. The computation shows that the discharge period is very close to twice the travel time. After this time, the cable capacitance is charged to the final voltage, and from this can be obtained two ratios of the voltage divider, namely:

$$n_0 = \frac{C_1 + C_2}{C_1} \qquad \text{for } t = 0;$$

$$n_e = \frac{C_1 + C_2 + C_k}{C_1} \qquad \text{for } t \geq 2\tau_k;$$

The signal cable, therefore, introduces an initial overshoot of the voltage of $\Delta V = (n_e / n_0) - 1 = C_k / (C_1 + C_2)$, which may well be neglected for short or medium cable length, and high value of C_2, i.e. high ratios of the voltage dividers. Capacitor dividers are often used for field testing of transient voltages, and longer cables thus are often necessary. The step response can be improved by transferring part of the l.v. capacitor C_2 to the cable end and connecting it in series with a resistor, as shown in Figure 2.6 (c). This system, first treated by Burch [4], offers some opportunities to decrease the overshoot effect. Burch proposed to make both matching resistances equal and $R_3 = R_4 = Z_k$. If then the condition $C_1+C_2 = C_3+C_4$ is satisfied, the initial and the infinite time value of the voltage become the same, and the original overshoot of about $C_k/(C_1+C_2)$ is reduced to about 1/6. There are, however, further opportunities to improve the response as recently demonstrated by Zaengl [4]. For damped capacitor dividers, the resistors R_1 and R_2 necessary within the l.v. arm, shown in Figure 2.6 (d). As R_2 is very small in comparison to R_1, the value of this matching resistor must only be reduced by the small value of R_2. The methods of Figure 2.6 (c) can be also applied.



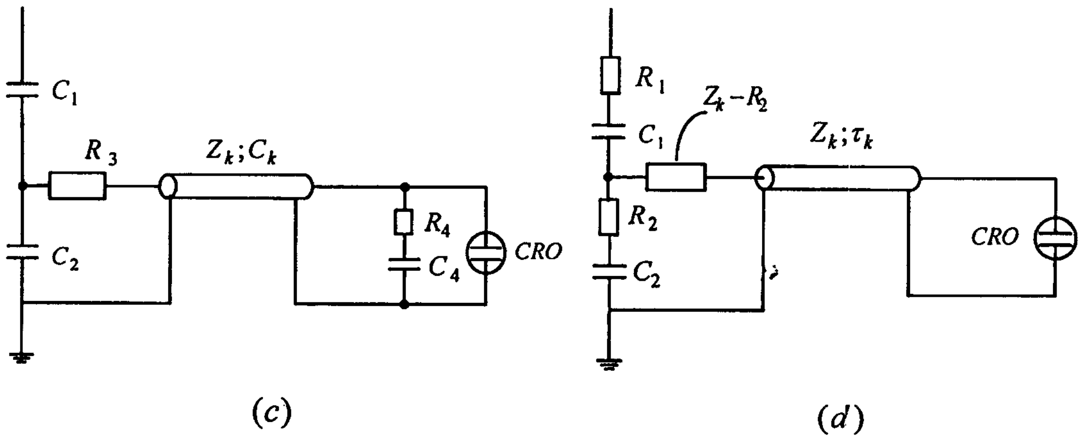


Figure 2.6 Circuits for signal cable matching. (a) Resistor or parallel-mixed capacitor-dividers. (b) Capacitor dividers, simple matching. (c) Capacitor dividers with compensated matching. (d) Damped capacitor divider, simple matching [1].

2.6 H.V. Divider in Measurement System

Basically, an impulse voltage measuring system [1, 4] consists of an impulse voltage generator which is connected to a test object via a lead. These three elements are included in the voltage generating system as shown in Figure 2.10 the voltage generating system is integrated with the voltage measuring systems which are composed of a voltage divider, a lead cable between the test object and the divider, a measuring cable, and a recording instrument. In addition the measuring system must have an appropriate ground return.

Two important parameters, which are used to evaluate impulse measuring system characteristics, are scale factors and transient behaviors. According to IEC [2] the scale factors of the converting device and the transmission system are not varied by more than ± 1% for the ranges of the ambient temperature and given clearance. The transient behaviors must be adequate for the measuring of the peak voltage and time parameters over the range of waveforms.

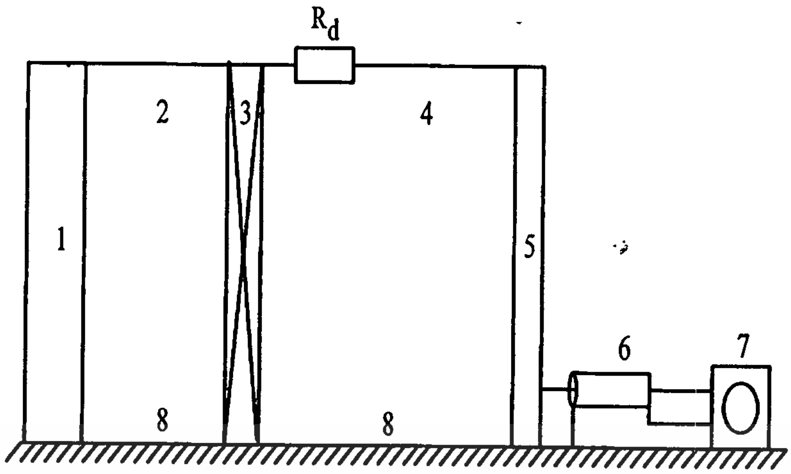


Figure 2.7 Basic voltage measuring system. (1) Impulse generator. (2) Lead cable to the test object. (3) Test object. (4) Lead cable to the voltage divider. (5) Voltage divider. (6) Measuring cable. (7) Recording instrument. (8) Ground return [1].

CHAPTER 3

UNIT STEP RESPONSES OF HIGH VOLTAGE DIVIDERS

3.1 Introduction

High voltage signals are measured using a measuring system consisting of high Voltage divider, transmission system and recording instruments. These measuring equipment are to be calibrated periodically to have accuracy within permissible limits. It involves determination of scale factor, linearity and its validity range with respect to signal parameters like frequency, amplitude, and time parameters especially for impulse measuring systems [6]. The time parameters can be determined by comparing the measuring system under test with another calibrated reference divider or by using a unit step generator.

In a high – voltage impulse voltage measuring system, unit step response (USR) has played an important role in evaluating dynamic characteristics of the system. It would be vary useful if USR of a system can be reasonably analyzed before performing an actual test.

3.2 Unit Step Responses

In the step response method, the voltage or current step is applied to the primary of measuring system and output is measured across the secondary using a digital or analog oscilloscope. From the output the relevant parameters of the step response like partial response time (T_α), response time (T_N), overshoot (β), initial response time (T_0) and the settling time (t_s) are measured. These parameters shall meet the requirement given in the relevant standard [2,3].

Step response is the output of a measuring system, which a function of time when the input is a step function. All response parameters under discussion are derived from the step response.

The circuit arrangements are as shown in Figure 3.1a, 3.1 b and 3.1 c

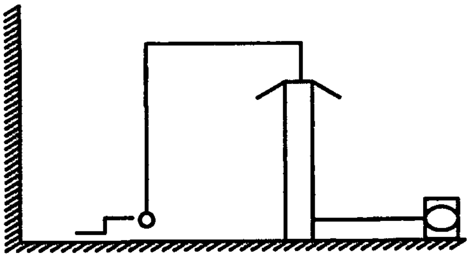


Figure 3.1a

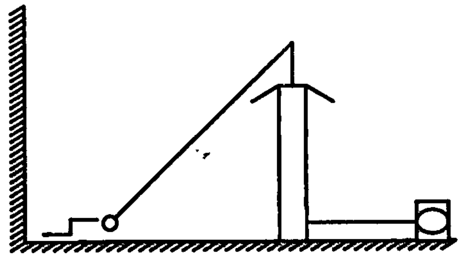


Figure 3.1b

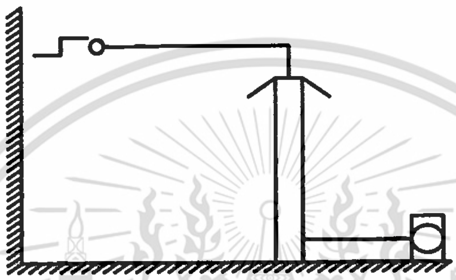


Figure 3.1c

Figure 3.1 Step response measurements for impulse voltage measurement systems

1. The lead is taken vertically and then horizontally to the divider forming a square loop. In this method the step generator is kept at the ground level as shown in Figure 3.1a.

2. Divider lead is taken diagonally towards ground level where step input is applied and thus forming a triangular loop on Figure 3.1b.

3. The step generator is kept approximately at the height, which is same as that of the divider and lead is taken horizontally to the divider as shown in Figure 3.1c. The metal strip is connected between the divider and step generator forming a square loop acting as a return path.

The IEC and IEEE standards recommend that the normal divider lead is drawn horizontally and provided with a vertical extension to the ground level where the step generator is placed.

A voltage divider is constructed from passive components, and can be represented by two port network as show in Figure 3.1 [10]. The following parts will be mathematical analysis for such a network [4].

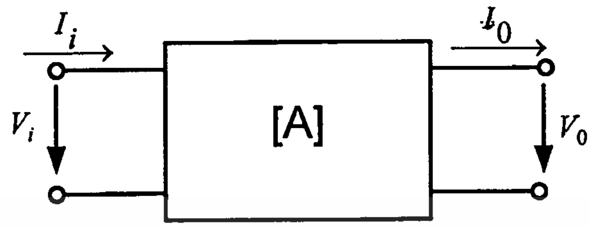


Figure 3.2 A two port network for a voltage divider

This network has relations between input and output waveform accordance with the matrix equation (3.1)

$$\begin{bmatrix} V_i(s) \\ I_i(s) \end{bmatrix} = \begin{bmatrix} A_{11}(s) & A_{12}(s) \\ A_{21}(s) & A_{22}(s) \end{bmatrix} \bullet \begin{bmatrix} V_0(s) \\ I_0(s) \end{bmatrix} = [A] \begin{bmatrix} V_0(s) \\ I_0(s) \end{bmatrix} \tag{3.1}$$

where [A] is the network matrix of the system defined by this equation.

The measuring system will load the generating system and those the input impedance of the measuring system is some time necessary. As the output current I_0 for a voltage dividing system of HV ratio can not influence the input, the condition $I_0 = 0$ can always be assumed. From Equation (3.1) then the input impedance is:

$$z_i(s) = \frac{V_i(s)}{I_i(s)} = \frac{A_{11}(s)}{A_{21}(s)} \tag{3.2}$$

The most important quantity is the voltage transfer function. For $I_0 = 0$, this function becomes:

$$H(s) = \frac{V_0(s)}{V_i(s)} = \frac{1}{A_{11}(s)} \tag{3.3}$$

It contains the ratio N of voltage dividing system. This ratio is a constant quantity for low frequencies only and hence we may derive this ratio by

$$N = \lim_{s\to 0}\left[\frac{V_i(s)}{V_0(s)}\right] = \lim_{s\to 0}[A_{11}(s)] = A_{11}(0) \tag{3.4}$$

The voltage transfer function, equation (3.3), is conveniently normalized by N. Denoting the normalization by h(s), we obtain

$$h(s) = NH(s) = \frac{A_{11}(0)}{A_{11}(s)} \tag{3.5}$$

When the input is a unit step and a unit step response output is g(t), the Laplace transform of g(t) and a transfer function are written as equations (3.3-3.5).

$$G(t) = L^{-1}[\frac{1}{s}H(s)] = L^{-1}[\frac{1}{sA_{11}(s)}] \tag{3.6}$$

From equation (3.5), the Laplace transform of $v_0(t)$ and $v_i(t)$ are calculated as shown in equation (3.7).

$$\begin{aligned} v_0(t) = L^{-1}[V_0(s)] &= L^{-1}[sG(s)V_i(s)] \\ &= \frac{d}{dt}(\mathrm{L}^{-1}[G(s)V_i(s)]) \\ &= \frac{d(g(t)*v_i(t))}{dt} \end{aligned} \tag{3.7}$$

The response time, then, can be obtained from

$$T_N = \lim_{s\to 0}[\frac{1-h(s)}{s}] \tag{3.8}$$

Transfer functions and unit step responses due to:

1) Resistive dividers

2) Capacitive dividers

3) Damped capacitive dividers

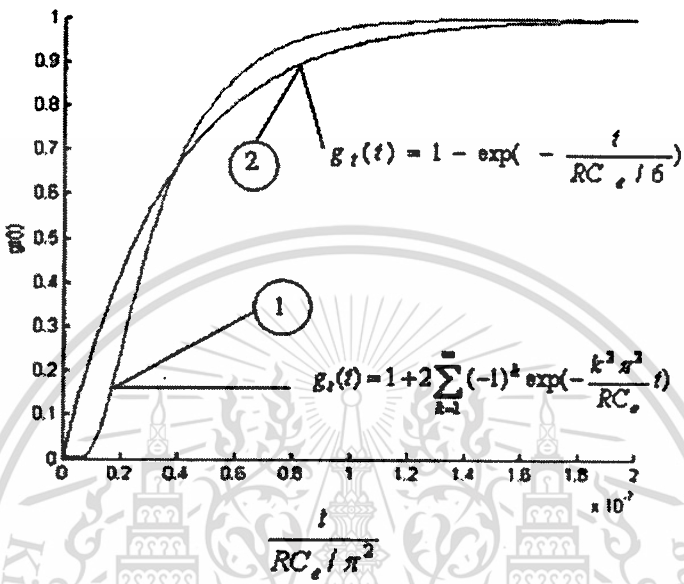


Figure 3.3 Comparison of the unit step responses with equal response time. (1) For equivalent circuit Figure 2.2 with equation (2.5). (2) For equivalent circuit Figure 2.3 with equation (2.7).

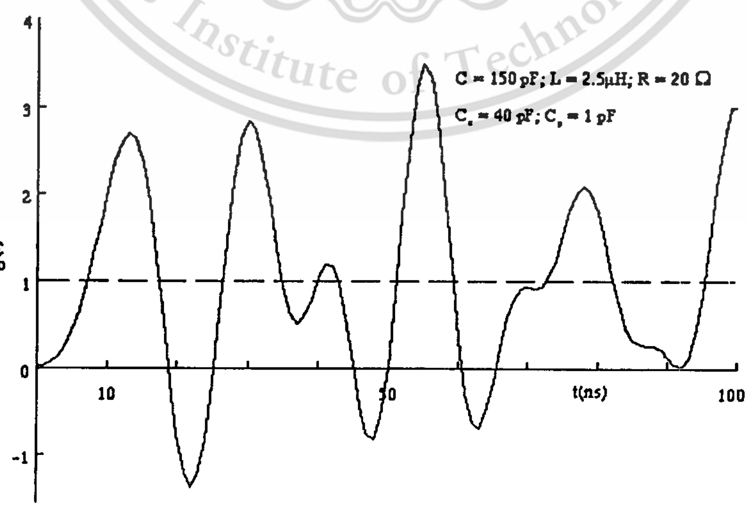


Figure 3.4 Calculated unit step response for a capacitor voltage divider; equivalent circuit see Figure 2.4, $R = 20\Omega$; $L = 2.5\ \mu H$; $C = 150$ pF; $C_e = 40$ pF; $C_p = 1$ pF.

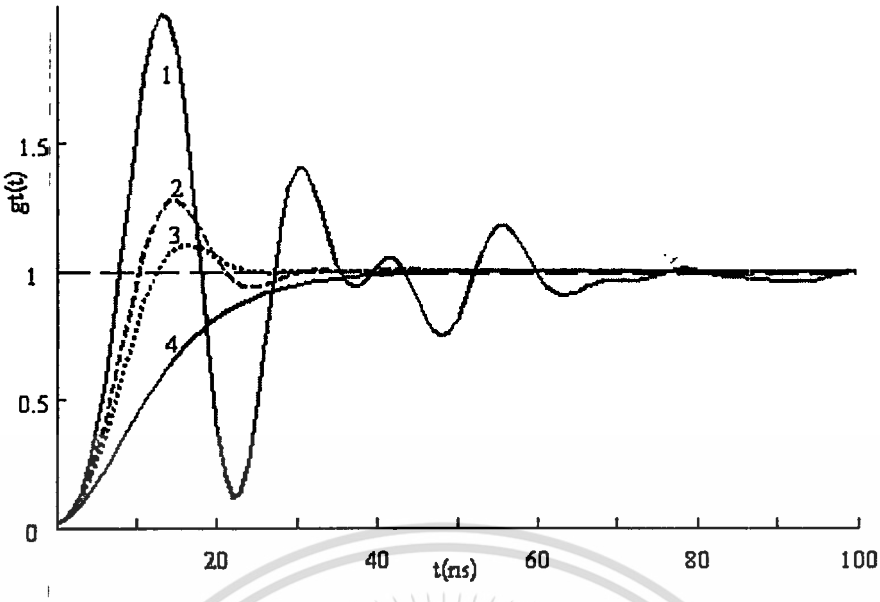


Figure 3.5 Computed unit step response $G_t(t)$ for damped capacitive dividers according to equivalent circuit Figure 2.4.

<table>
<tr><td>C =150 pF;</td><td>L = 2.5 µH;</td><td>C_e = 40 pF;</td><td>C_p = 1 pF</td></tr>
<tr><td>(1) R = 250 Ω</td><td colspan="3" rowspan="4">$\sqrt[4]{\frac{L}{C_e}} = 1000\Omega$</td></tr>
<tr><td>(2) R = 750 Ω</td></tr>
<tr><td>(3) R= 1000 Ω</td></tr>
<tr><td>(4) R = 2000 Ω</td></tr>
</table>

Figure 3.6 Shows the idealized unit step response g(t) of oscillating system. Whereas the step response of a low voltage circuit with small dimensions can be easily measured, this is difficult for HV impulse dividers which are up to 10 m in height and which are unshielded. The experimental procedure for measuring the step response of a divider is described in [2,3]. In a square loop arrangement, the divider is connected to the step generator via a horizontal and a vertical lead, each as long as the height of the divider. But the "experimental step response" so obtained is, in general, not equal to the step response of the divider in the actual H.V. test circuit, which is quite different from the step response measurement arrangement.

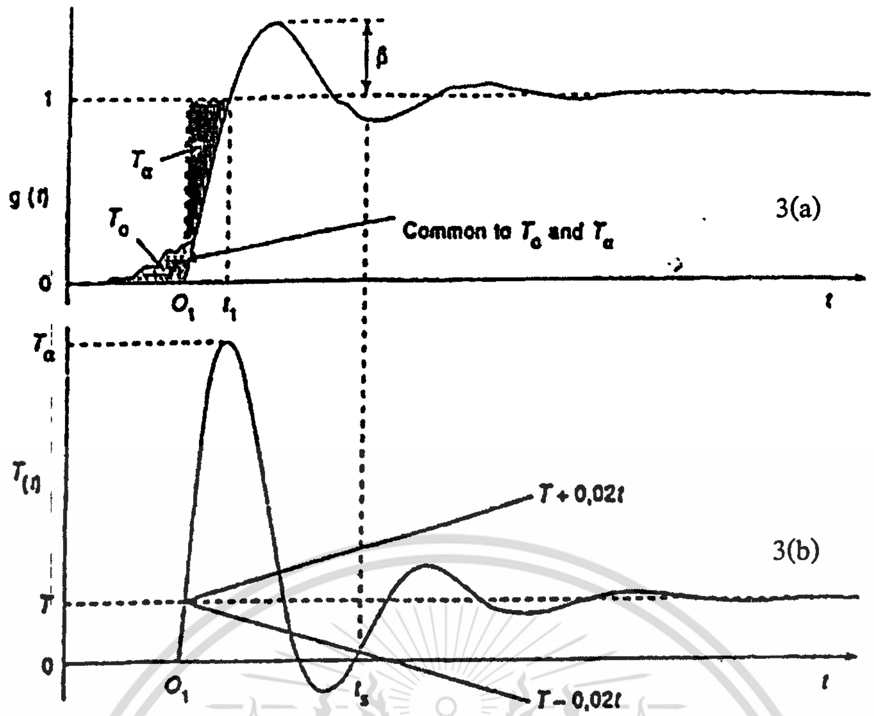


Figure 3.6 Normalized step response and its Integral

a) Normalized step response g(t)

b) Response time T as function of t

Furthermore, as the divider is unshielded it is susceptible to electromagnetic interference. This may lead to bumps or oscillations superimposed on g (t) at the beginning. In order to eliminate this interference, the present standard [2,3] defines a virtual starting point 0_1 by the intersect of the time axis and a straight line drawn as tangent to the steepest portion of the front of the experimental step response in Figure. 3.2. This definition somewhat arbitrary, and significant information about g(t) may be lost by replacing its original shape by a straight line.

The impulse voltage divider can measure full and tail – chopped impulses with a front time T_1 if the overshoot β and the partial response time T_α of the tested impulse voltage divider should be such that β and T_α / T_1 are within the shaded of Figure 3.7.

For measuring impulses hopped on the front in the range of chopping time T_C to be considered. The following conditions should be met:

- the settling should be such that:

$$t_s \leq T_C$$

- the experimental response time T_N and partial response time T_α should be such that:

$$T_\alpha - 0.03\ T_C \leq T_N \leq 0.03\ T_C$$

- and the initial distortion time T_0 should be small so that:

$$T_0 \leq 0.005\ T_C$$

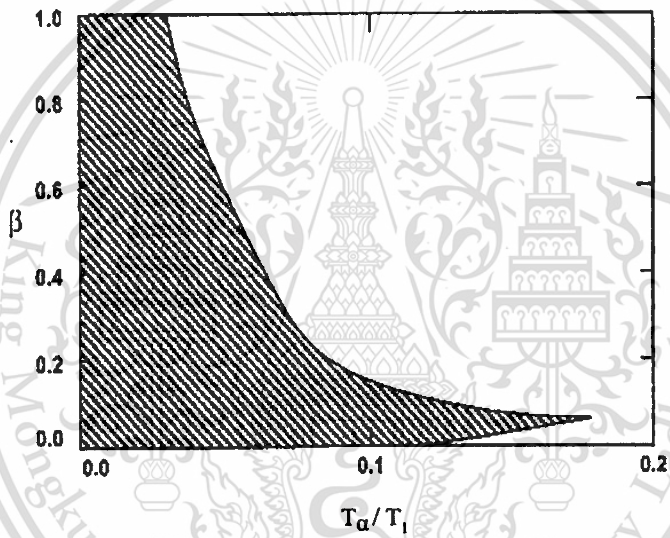


Figure 3.7 Overshoot β as a function of the related partial response time T_α / T_1

3.3 Transient Response Parameters

The response parameters to be evaluated from the step response of the divider are [11]:

- Virtual origin (O_1)
- Experimental time response time (T_N)
- Partial response time (T_α)
- Settling time(t_s)
- Initial distortion time (T_0)
- Overshoot (β)

The initial response time (To) is the area bounded by zero line, the normalized step response g(t) and the straight line used to determine O_1. The overshoot (β) is the ratio of the maximum value of the normalized step response to unit value.

The partial response time (T_α) is evaluated by finding out the area under the curve from virtual origin to the settling level at the first peak.

$$T_\alpha = \int_0^{t_1} (1 - g(t))dt \tag{3.9}$$

The step response integral T(t) can be found by integrating one minus normalized step response over the period of virtual origin to settling level

$$T(t) = \int_0^{T} (1 - g(\tau))d\tau \tag{3.10}$$

Experimental response time T_N is the value of the step response integral at t_{Max}

$T_N = T(t_{Max})$

Where t_{MAx} is the maximum of the relevant time parameter of the impulse for which the measuring system has to be approved. The relevant time parameters are taken over nominal epoch T_N. For the impulse measurement it is applicable only for the front part T_1= 0.8 μs to T_2=1.2 μs. The experimental response time is taken at $T(t_{Max})$

Two slopes with the tolerance limit of T + 0.2t and T - 0.2t are drawn from T. The time t where the last point of the slope intersects with the unit step integral is the settling time t_s.

The requirements for reference measuring systems accordance to the IEC [2] are:

An overall uncertainty of less than ± 1 % for the measurement of the peak value and less than ± 5% for the measurement of the time parameters of full and tail chopped lightning impulse voltages, switching impulse voltages or impulse current.

An overall uncertainty of less than ± 3 % for measurement of the peak value and less than ± 5 % for measurement of the time parameters of front – chopped impulse voltage.

The satisfactory performance of reference measuring system shall be shown by comparative measurement at high voltage or current against a measuring system which is itself traceable through national or international comparisons. The scale factor shall be established with an uncertainty within ± 0.5 %

Alternatively the performance of a reference measuring system can be shown by the measurement of the scale factor with an uncertainty of ± 5 % and the measurement of the unit step response. The response parameters should satisfy the following requirements as shown in Table 3.1.

Table 3.1 The response parameters for reference measuring system

Parameters	Full and tail chopped lightning impulses	Front-chopped lightning impulses	Switching impulses	Current impulses
Experimental response time T_N	≤ 15 ns	≤ 10 ns	---	---
Settling time t_s	≤ 200 ns	≤ 150 ns	≤ 10 μs	---
Partial response time T_α	≤ 30 ns	≤ 20 ns	---	0.1 T_1
Initial distortion time T_0	---	≤ 2.5 ns	---	---

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 Introduction

In this chapter, the evaluation of transient response behaviours of impulse voltage dividers, the analysis tools are developed on the basis of MATLAB/Simulink, which employs Wavelet transform to reduce noise signals of the measured impulse voltage, before computing the unknown parameters with an algorithm based on MATLAB as show in Figure 4.1, and Daubechies 20 is selected as a mother wavelet for a filter process [6].

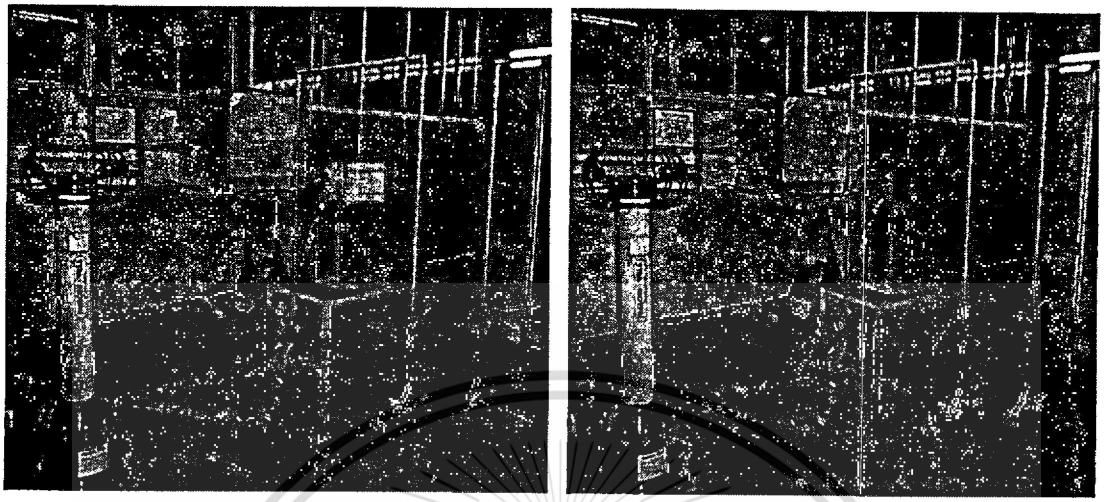
The results show that the computer–aided analysis tools are able to correctly predict transient parameters of the high voltage divider, and this will be very useful for impulse measurements in a high voltage laboratory, by comparing the measurements which were carried out proved that the calculated values of the response characteristics lie very closely to the reference measuring systems.

4.2 Measurements of Transient Response Parameters for High Voltage Dividers

An impulse voltage measuring system consists of a high voltage divider, a unit step generator and a lead line as shown in Figures 4.1-4.3. Three high voltage dividers are employed in the investigation. USG is a unit step generator or a pulse generator (PG) having a zero output impedance. Occasionally, a damping resistor (R_d), which is not indicated in Figures 4.1-4.3, is inserted between lead and the unit step generator. The lead line is a band wire to reduce inductance in a HV lead, and the grounding of the step voltage generator and the ground plane is connected by a vertical metal sheet of 2 m width as shown in Figures 4.1-4.3.

In this research, the computer program is used to calculate the unit step response parameters and verify three measuring systems using two unit step generators (USG), which produced by two companies: as Dr. Strauss's USG that having a rise time less 10 ns and other one came from Heafely's produced which having a rise time 3 ns. Two USG are used in this thesis to evaluate the response parameters of impulse voltage dividers, and then compare the results with the reference measuring system as mentioned in the national standard [2].

There are three models for measurements of unit step response of high voltage dividers as shown in the Figures below:

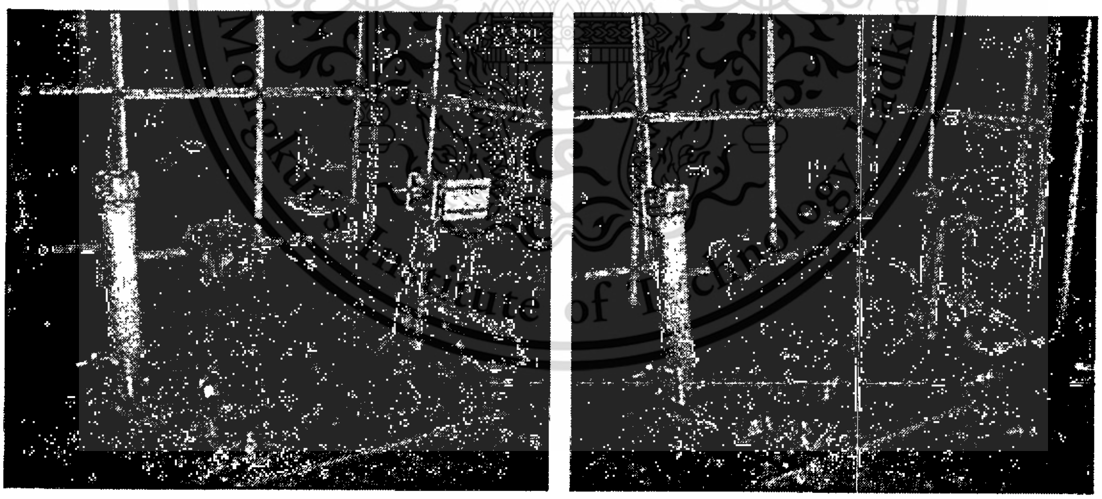


(a) (b)

Figure 4.1 Test circuit arrangements for divider A with difference USGs

(a) Model A with Dr. Strause USG

(b) Model A with Haefely USG

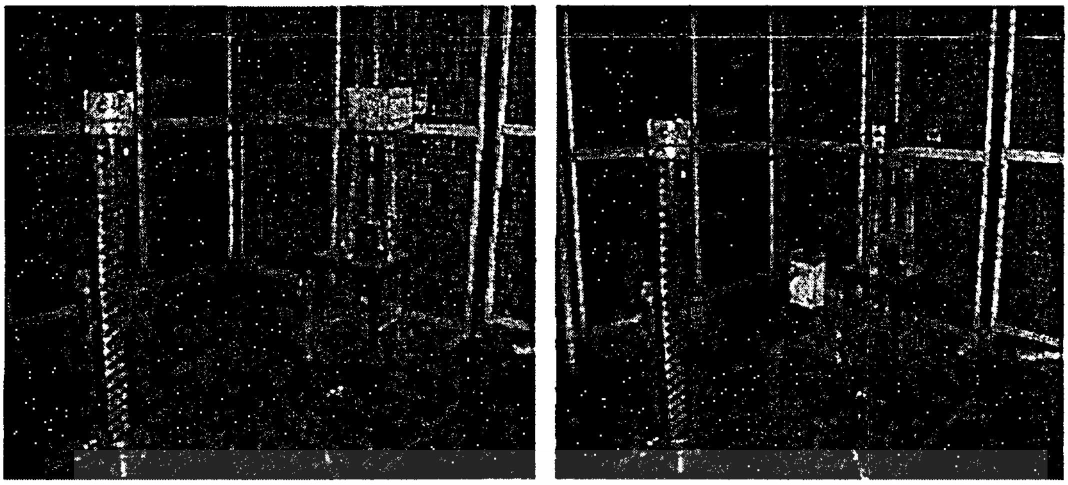


(a) (b)

Figure 4.2 Test circuit arrangements for divider B with difference USGs

(c) Model B with Dr. Strause USG

(d) Model B with Haefely USG



(a) (b)

Figure 4.3 Test circuit arrangements for divider C with difference USGs

(e) Model C with Dr. Strause USG

(f) Model C with Haefely USG

Divider A is a shielded capacitive voltage divider (Figure 4.1) with 4200 pF which is a reference divider at KMITL high voltage laboratory. The divider has a rated voltage of 200 kV for standard lightning impulse.

Divider B is a 100 kV capacitive divider (Figure 4.2) with 420 pF for high voltage arm and without shielding ring at the top of high voltage electrode; used in the high voltage laboratory at Chulalongkorn University.

Divider C is a 200 kV damped capacitive voltage divider (Figure 4.3) with 420 pF and 176 Ω for high voltage arm and without shielding ring at high voltage electrode; used in the high voltage laboratory at Chulalongkorn University.

4.3 Transient Response Parameters Calculation

The computer-aided analysis tool for a calculation of transient responses of high voltage dividers is constructed for this research. The analysis tool is developed on the basis of MATLAB/Simulink, the Wavelet transform is applied to get rid of needless noises super-imposed on the step response waveforms. The approximation signals on scale 5, 8, 9 are normalized for a lead resistance 0, 30, 100 and 120 Ohms respectively, and all transient parameters, then, are analyzed.

Signals such as image and speech have different characteristics at different time or space, i.e., they are non-stationary. Most of the biological signals too, such as, Electrocardiogram, Electromyography, etc., are non-stationary. To analyze these signals, both frequency and time information are needed simultaneously, i.e., a time-frequency representation of the signal is needed. To solve this problem, The Wavelet Transform, which was developed in the last two decades, provides a better time-frequency representation of the signal than any other existing transform. Wavelets provide convenient sets of basis functions for function spaces, like the Fourier basis consisting of sine and cosine functions. Wavelets also oscillate and their curves yield zero net area. But they are "small waves" as they are localized in time. The wavelets are better suited to represent functions that are localized both in time and frequency (it requires fewer terms than the Fourier analysis).

The developed program function is shown as a flow chart in Figure 4.4. The unit step responses measured using a digital oscilloscope are employed as and input for the computer aided tool.

The response parameters to be evaluated from the step response of the high voltage dividers are: a virtual origin (O_1), an initial distortion time (T_0), a partial response time (T_α), an experimental response time (T_N), an overshoot (β) and a settling time (t_s). Firstly, the data file of unit step response are imported from DSO or a disk drive and then, performing a normalization of the step response waveform at level zero to one unit or (per unit level). The Wavelet transform is used as a filter, and then starting to evaluate unit step response waveform using interpolation equations.

As defined in the standards [2, 3], the virtual origin O_1 of the step response is the intersection with the time axis of a straight line drawn as a tangent to the steepest portion of the front of the step response. In the case of a response with oscillations in the front, a mean curve is drawn through the oscillations and this mean curve is used to determine the tangent line. Any initial distortion is neglected when drawing a tangent line.

The steepest portion is found by finding out the slope between two consecutive points. After finding out the steepest portion, a tangent is drawn to the curve at the steepest point and is extended to intersect the base level. The point of intersection is taken as virtual origin (0_1).

The initial distortion time (T_0) is the area bounded by zero line, the normalized step response g(t) and the straight line used to determine (O_1). The overshoot (β) is the ratio of the maximum value of the normalized step response to unit value.

The partial response time (T_α) is evaluated by finding out the area under curve from virtual origin to the setting level at the first peak. The experimental response time (T_N) is the value of the step response integral at t_{MAX}. Two slopes with the tolerance limit of T + 0.2t and

T - 0.2t are drawn from T. The time t where the last point of the slope intersects with the unit step integral is the settling time t_s. Finally all parameters of the unit step responses are displayed.

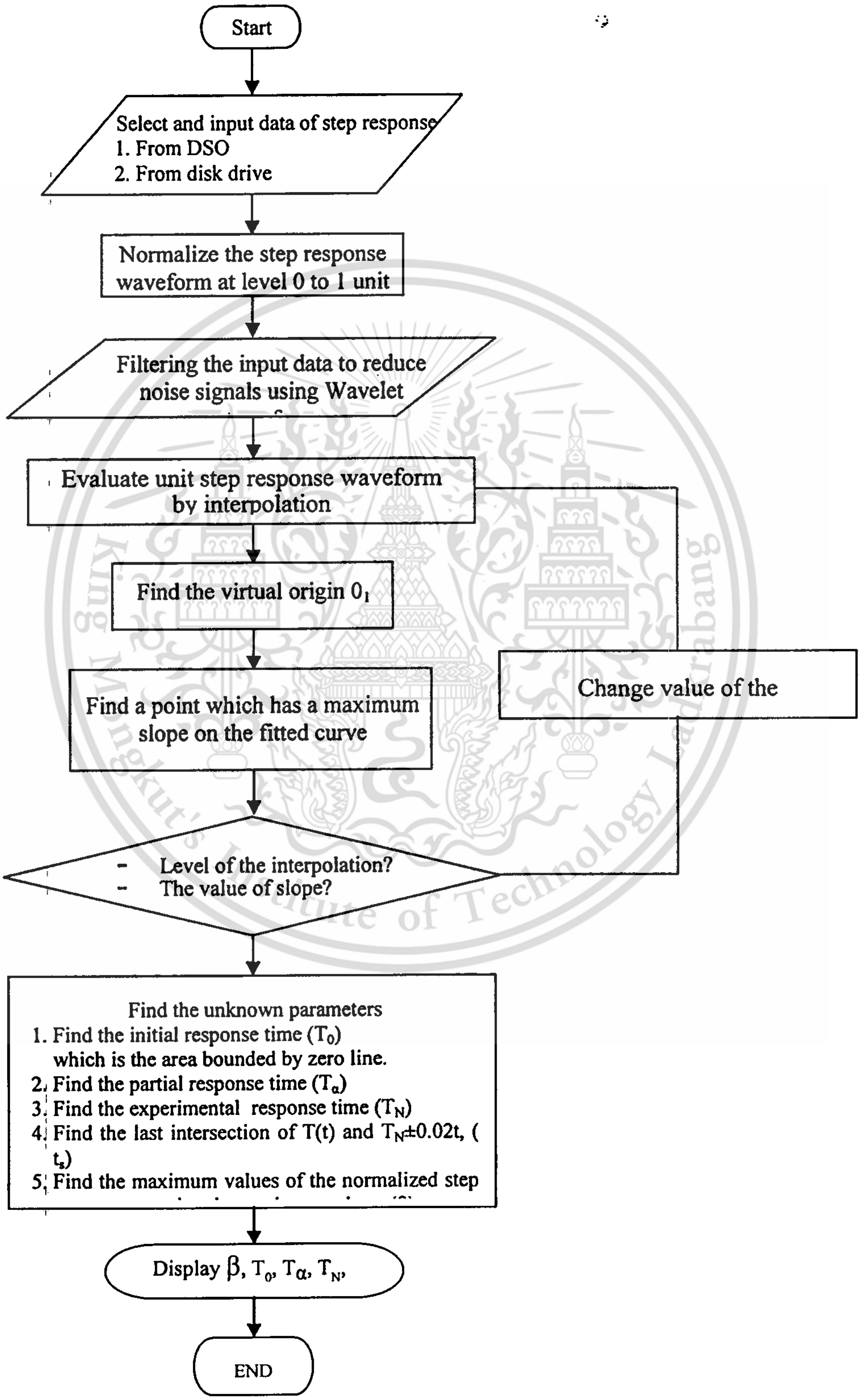


Figure 4.4 Flow chart of the developed program using MATLAB/Simulink

The oscillations can be partly related to the travel time $\tau = \sqrt{LC_e}$, as a unit step voltage applied to the input end of such a ladder network can travel along the column. If the voltage amplitude is not reduced to zero value when the earthed l.v. part is reached, this will be reflected exciting oscillations across the last column element, the l.v. part [1].

Pure capacitor voltage dividers are therefore sensitive to input voltage with short rise times and the output voltage may oscillate with non-oscillating input voltages. Such a capacitance divider within a whole measuring circuit, i.e. with lead connected to its input, will form a series resonant circuit and thus the whole measuring circuit will oscillate. Thus it is obvious that pure capacitor dividers are not adequate to measure impulse voltages with a steep front (front chopped lightning impulse voltages) or any high transient phenomena (voltage during chopping).

The unit step responses of the divider A with and without damping resistors are shown in Figures 4.5-4.10. The two unit step generators are used in the experiments for a comparison. While Figures 4.11-4.18 illustrate results obtained from dividers model B and model C.

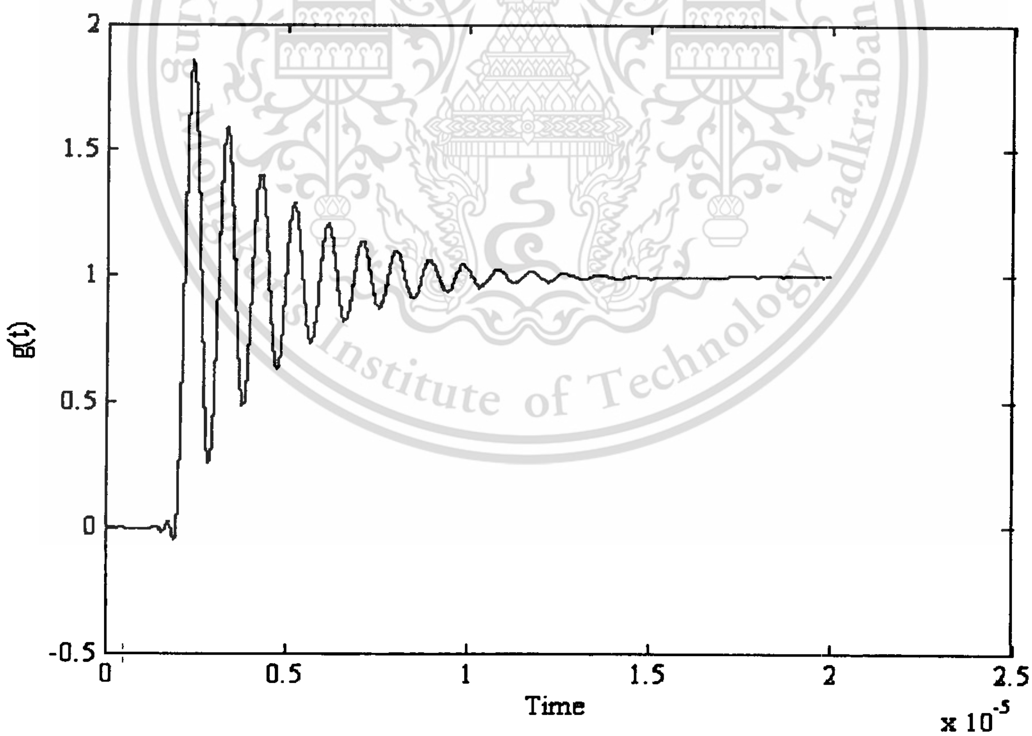


Figure 4.5 Measurement USR waveform of divider A with Dr. Strauss USG in Figure 4.1, for R_d=0

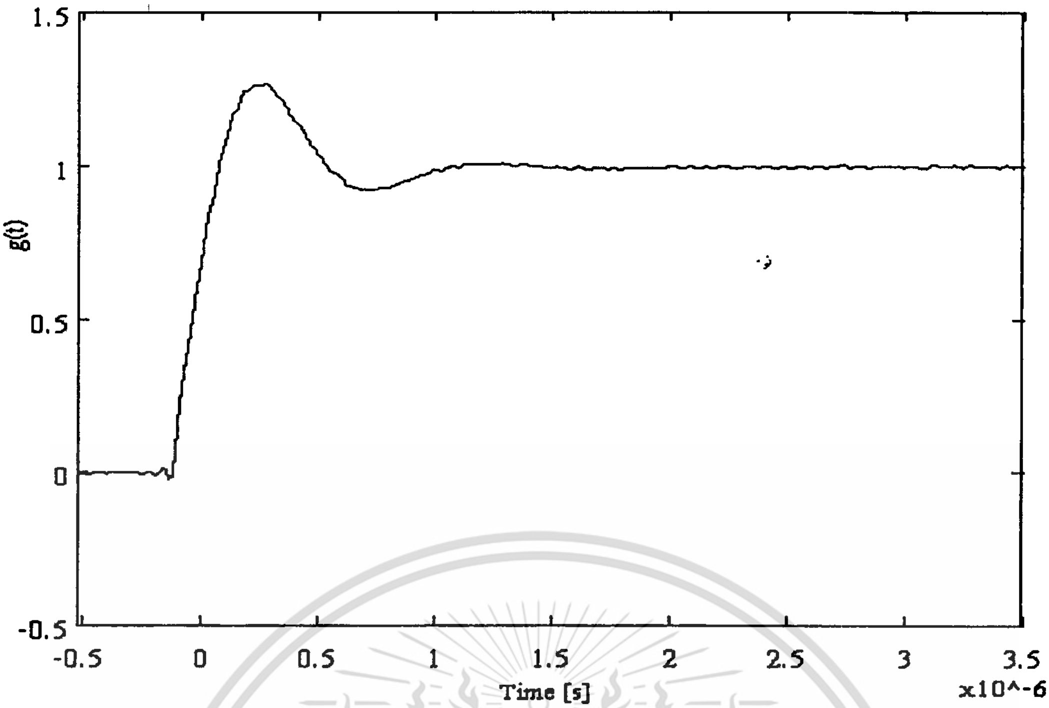


Figure 4.6 Measurement USR waveform of divider A with Dr. Strauss USG in Figure 4.1, for R_d=30 Ohm

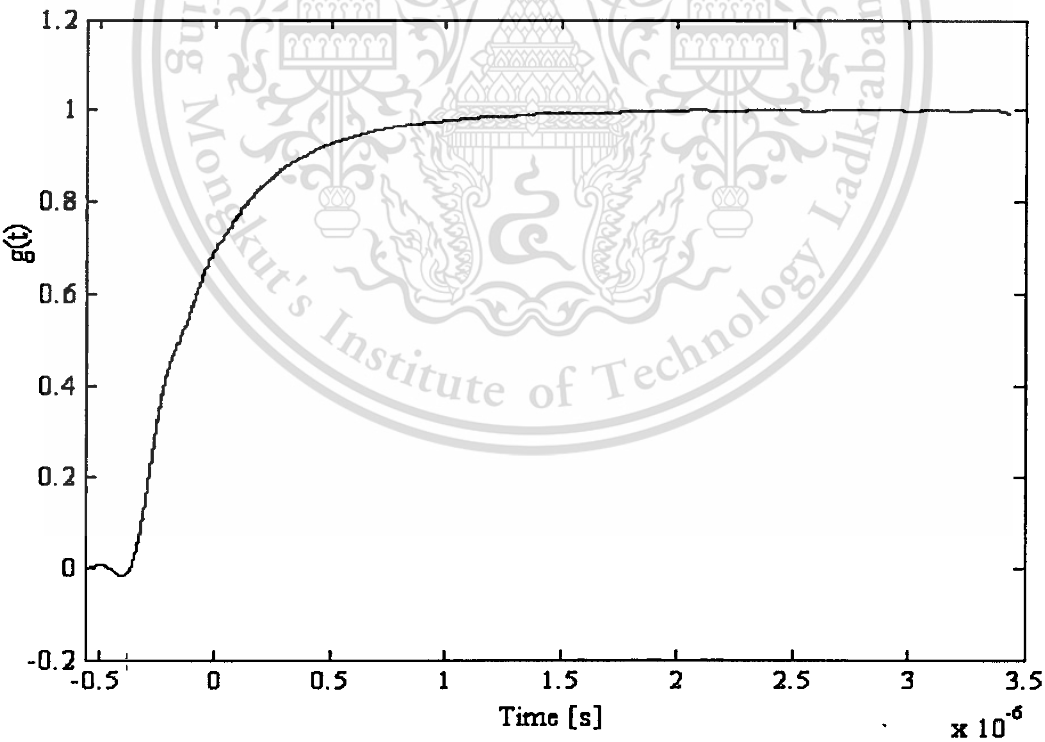


Figure 4.7 Measurement USR waveform of divider A with Dr. Strauss USG in Figure 4.1, for R_d=100 Ohm

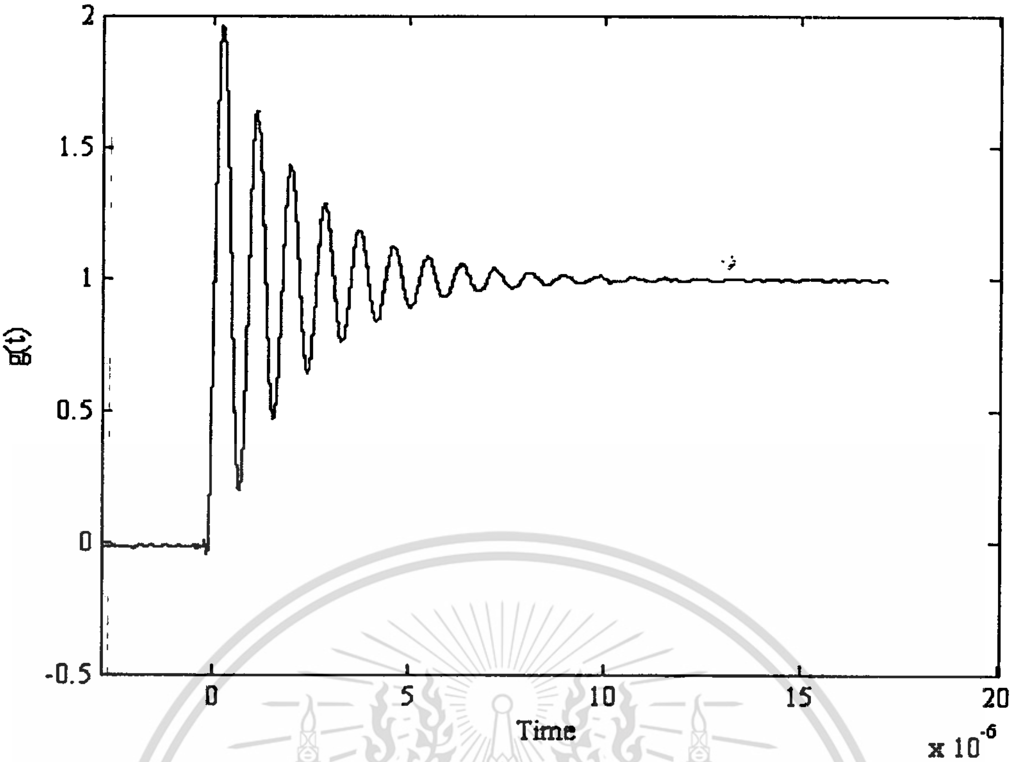


Figure 4.8 Measurement USR waveform of divider A with Haefely USG in Figure 4.1, for R_d=0

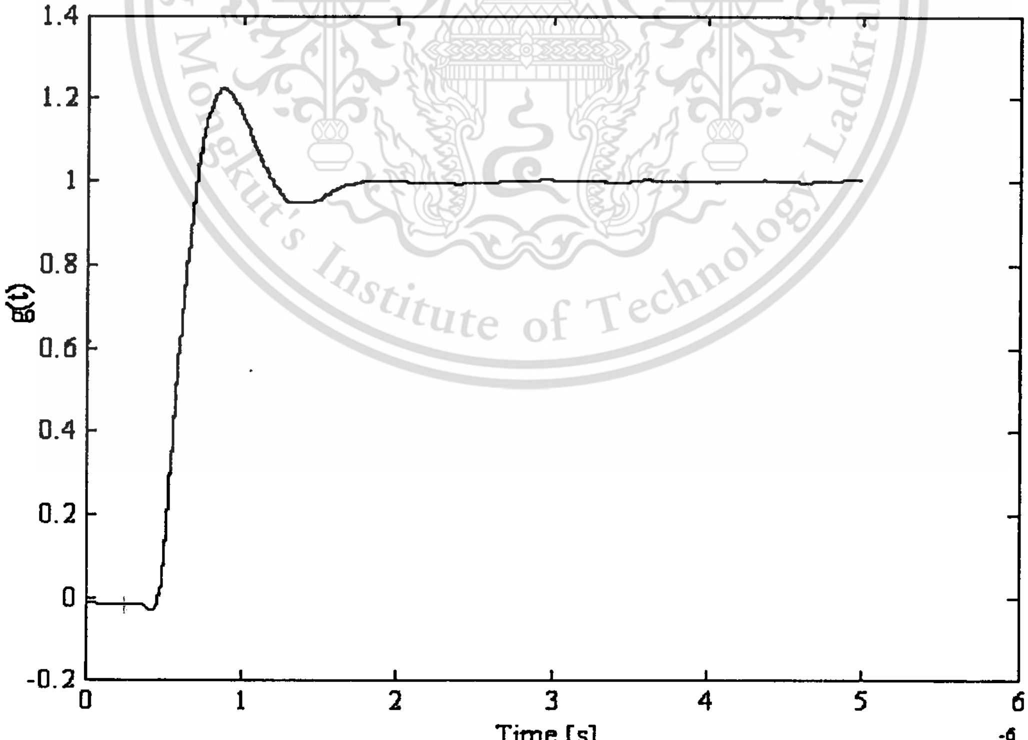


Figure 4.9 Measurement USR waveform of divider A with Haefely USG in Figure 4.1, for R_d=30 Ohm

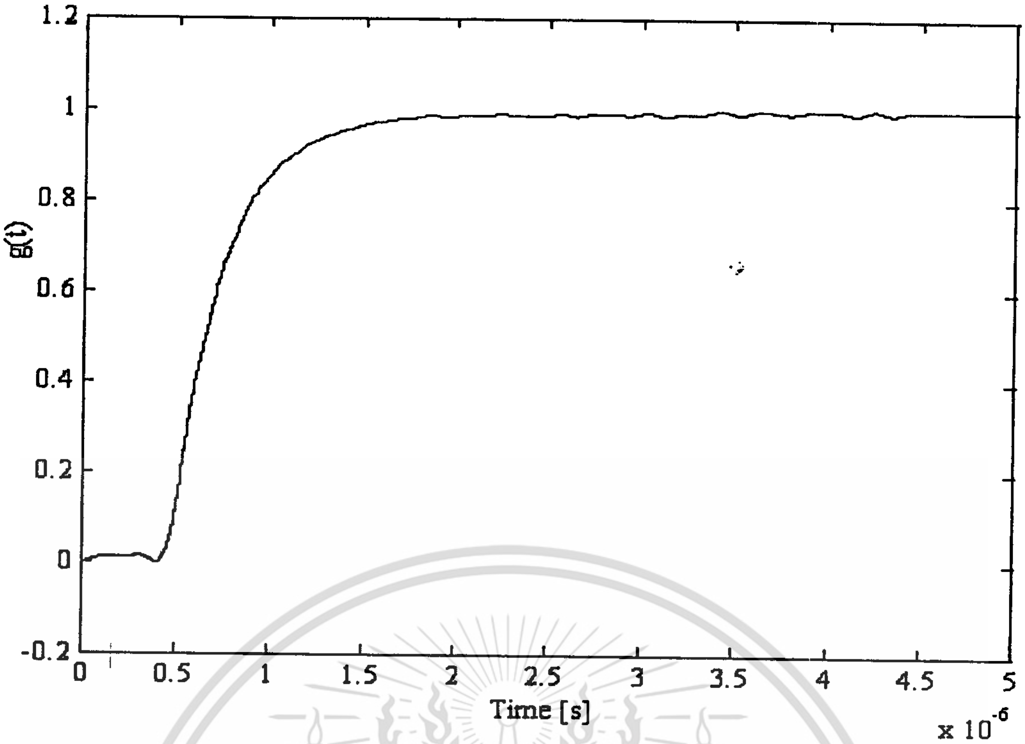


Figure 4.10 Measurement USR waveform of divider A with Haefely USG in Figure 4.1, for R_d=100 Ohm

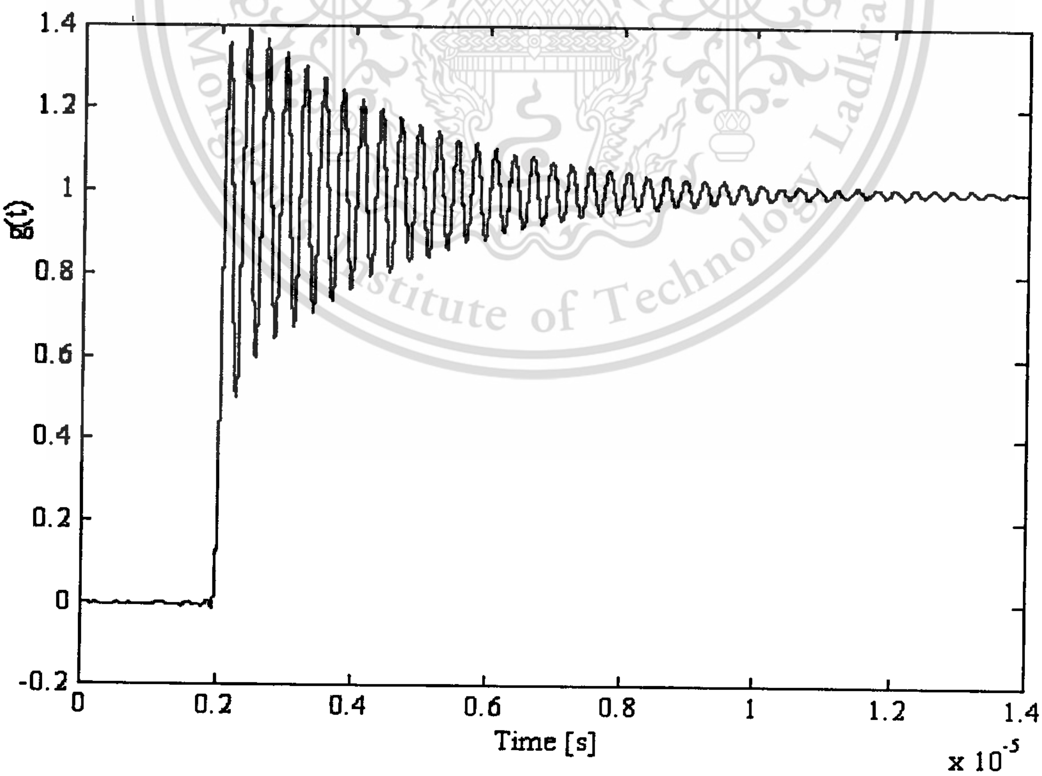


Figure 4.11 Measurement USR waveform of divider B with Dr. Strauss USG in Figure 4.2, for R_d= 0 Ohm

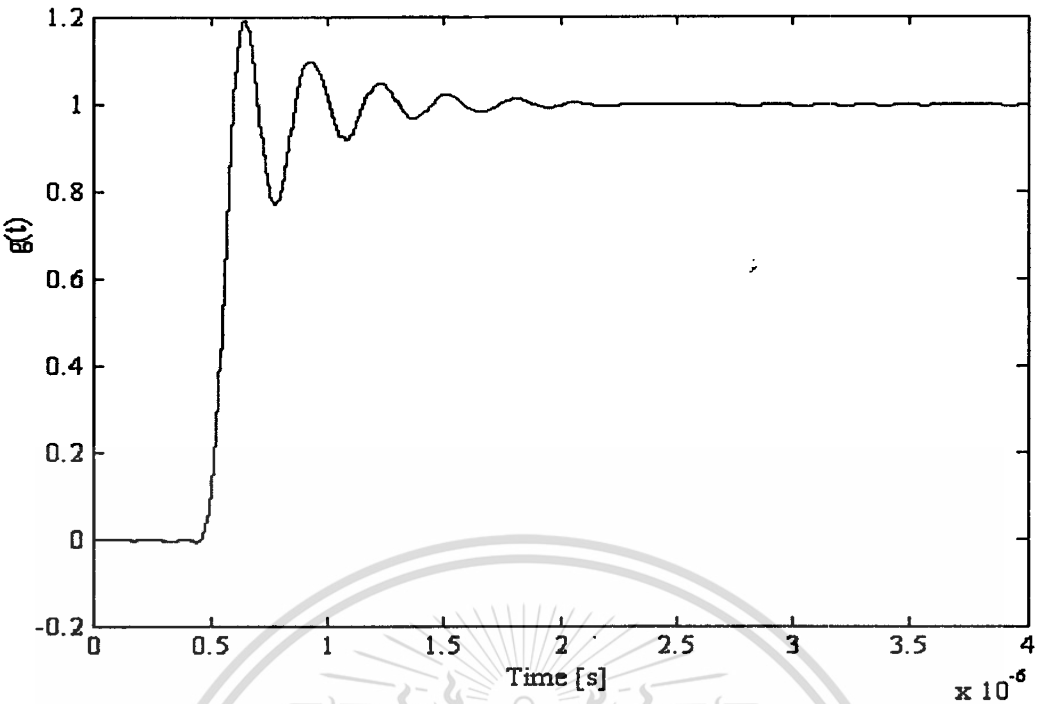


Figure 4.12 Measurement USR waveform of divider B with Dr. Strauss USG in Figure 4.2, for R_d= 30 Ohm

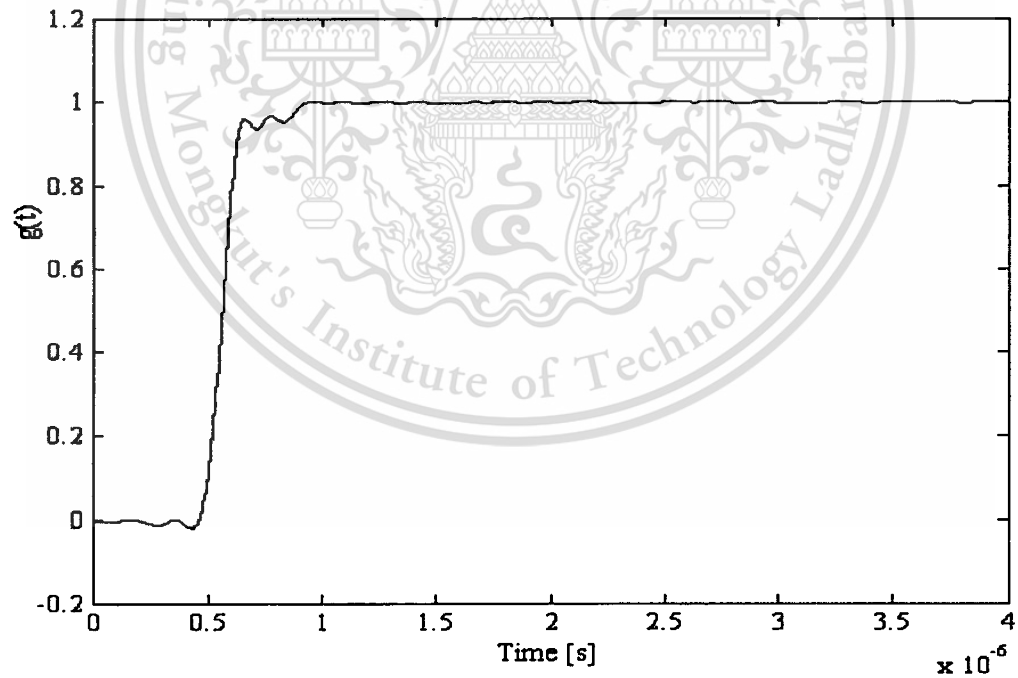


Figure 4.13 Measurement USR waveform of divider B with Dr. Strauss USG in Figure 4.2, for R_d= 120 Ohm

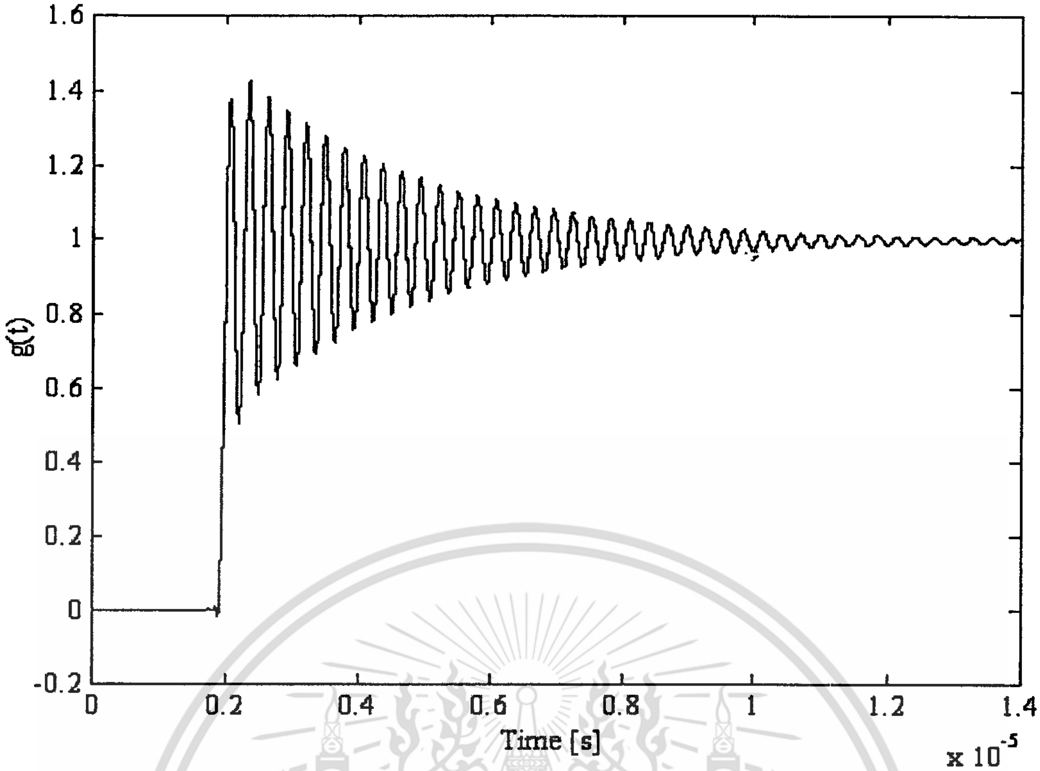


Figure 4.14 Measurement USR waveform of divider B with Haefely USG in Figure 4.2, for R_d= 0 Ohm

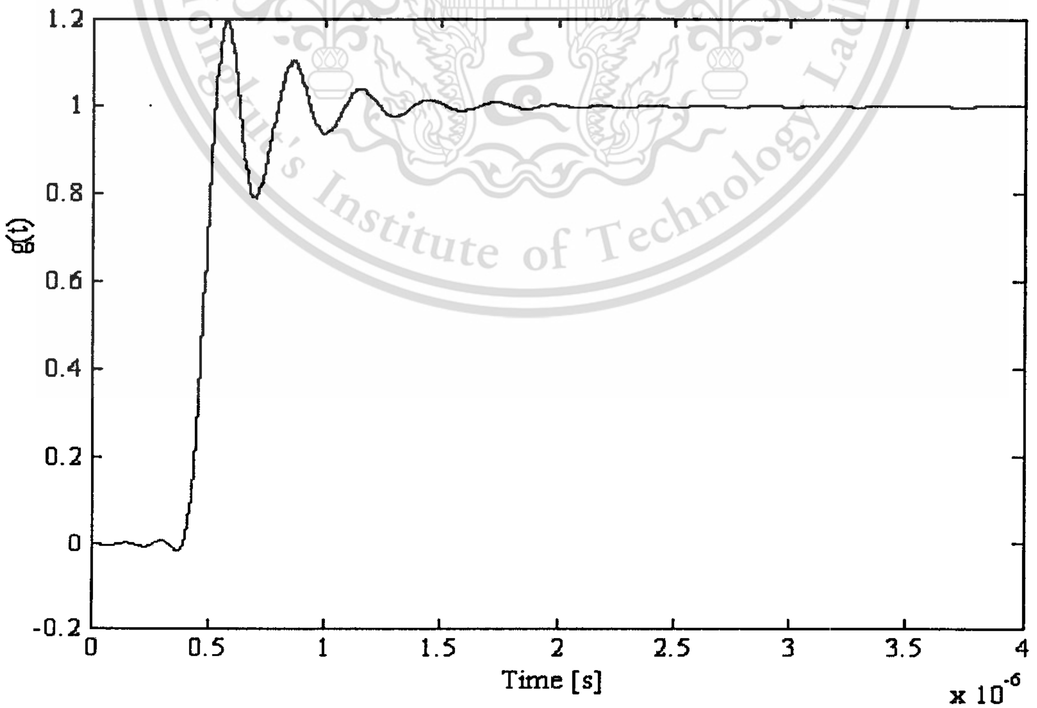


Figure 4.15 Measurement USR waveform of divider B with Haefely USG in Figure 4.2, for R_d= 30 Ohm

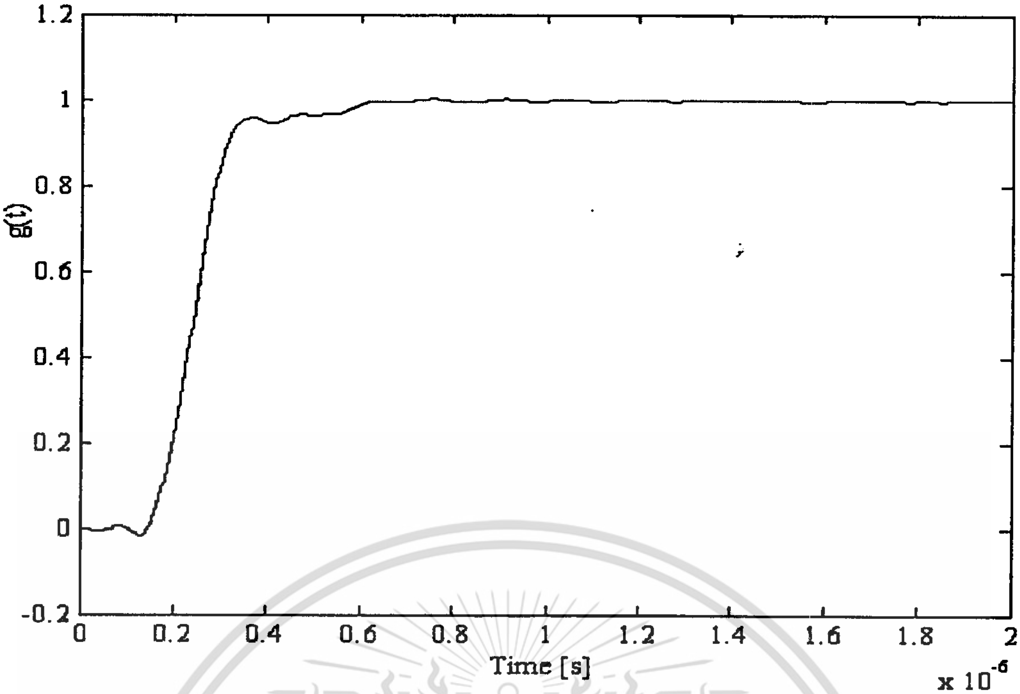


Figure 4.16 Measurement USR waveform of divider B with Haefely USG in Figure 4.2, for R_d= 120 Ohm

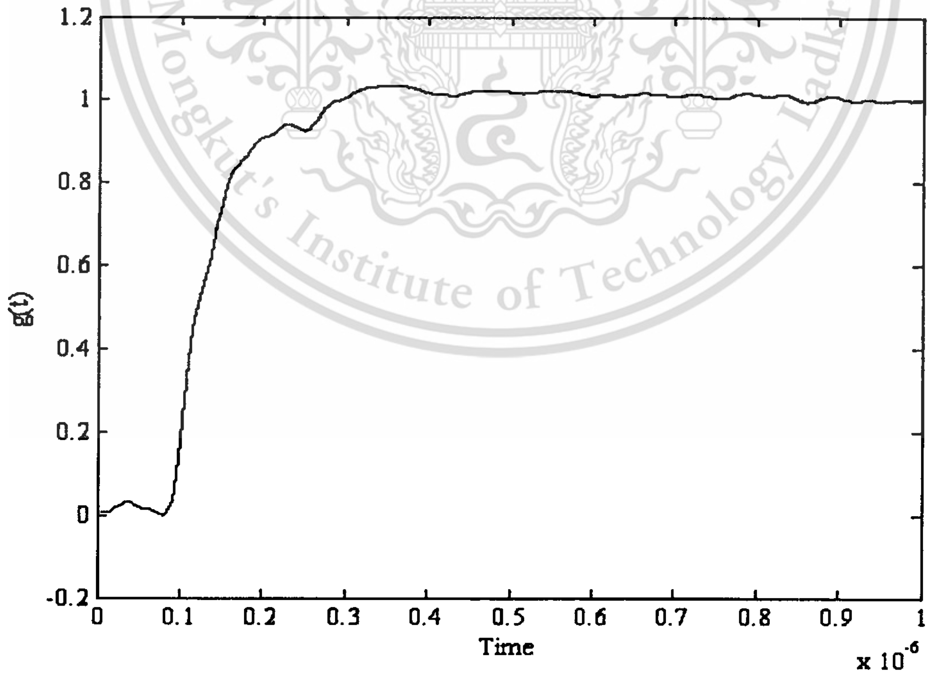


Figure 4.17 Measurement USR waveform of divider C with Dr. Strauss USG in Figure 4.3, for R_d= 0 Ohm

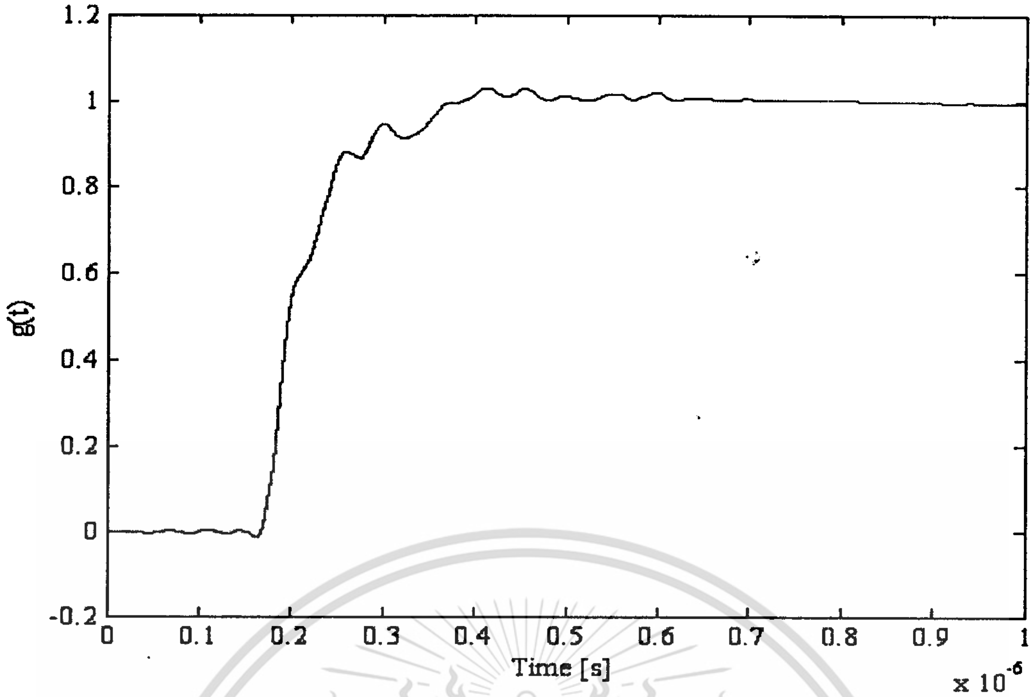


Figure 4.18 Measurement USR waveform of divider C with Haefely USG in Figure 4.3, for R_d= 0 Ohm

From unit step responses of three dividers shown in Figures 4.5-4.18. USR parameters which are T_α (partial response time), T_N (experimental response time), t_s (settling time), and β (overshoot), are calculated summarized in Tables 4.1-4.3. There are slight differences between USR parameters, which obtained from Dr. Strauss unit step generator and Heafely unit step generator as shown in Tables 4.1-4.3.

Table 4.1 Calculated USR parameters for divider A

Parameters	Dr. Straus USG			Haefely USG		
	$R_d = 0\Omega$	$R_d = 30\Omega$	$R_d = 100\Omega$	$R_d = 0\Omega$	$R_d = 30\Omega$	$R_d = 100\Omega$
T_0 [ns]	0.635	4.28	2.11	1.59	3.7	1.05
T_α [ns]	67.891	90.22	283.67	63.53	90.93	334.84
T_N [ns]	-59.379	33.345	282.87	-72.57	43.16	334.57
T_S [μs]	3.61	0.898	1.01	2.38	0.865	1.05
β [%]	84.6748	33.51	0.4604	95.74	26.58	0.143

Table 4.2 Calculated USR parameters for divider B

Parameters	Dr. Straus USG			Haefely USG		
	$R_d = 0\Omega$	$R_d = 30\Omega$	$R_d = 120\Omega$	$R_d = 0\Omega$	$R_d = 30\Omega$	$R_d = 120\Omega$
T_0 [ns]	7.10	7.77	3.84	7.60	7.78	8.69
T_α [ns]	36.50	46.90	88.40	36.90	48.80	86.70
T_N [ns]	-55.24	50.30	86.60	-70.30	52.10	86.70
T_S [μs]	991.40	270.50	228.10	1672.50	276.30	249.01
β [%]	38.83	20.28	0.61	41.92	19.46	0.17

Table 4.3 Calculated USR parameters for divider C

Parameters	Dr. Straus USG (system E) Rd =0 Ohm	Haefely USG (system D) Rd = 0 Ohm
T_0 [ns]	2.99	2.65
T_α [ns]	42.33	46.50
T_N [ns]	37.53	39.90
t_S [μs]	237.00	263.20
β [%]	3.05	2.99

The results from Tables 4.1-4.3, can be compared the response parameters with the reference measuring systems which can be obtained the results as shown in Tables 4.4-4.6, which accordance to the IEC recommendation [2]. For measuring full lightning and tail chopped impulses with a front time T_1. The overshoot β and the partial response time T_α should be such that β and T_α / T_1 are within the shaded area of the Figure 4.19 and for measuring switching impulse the settling time t_s should be less than 10 μs.

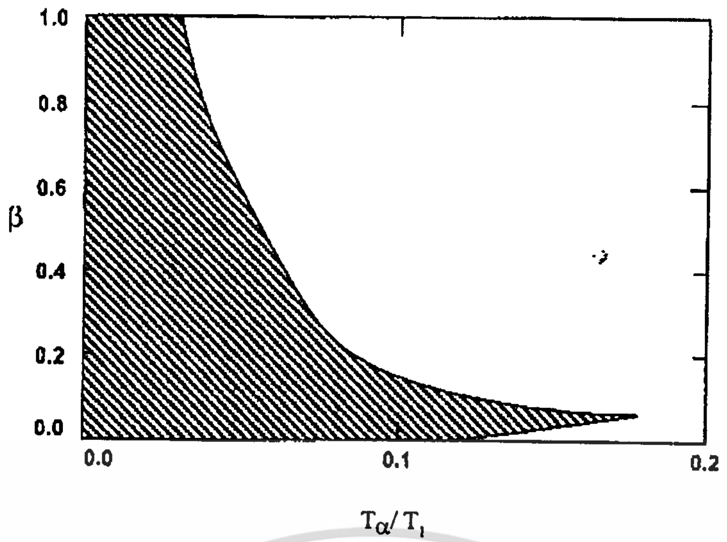


Figure 4.19 Overshoot (β) as function of T_α / T_1

Table 4.4 Comparative USR parameters for divider A with two unit step response generators

$R_d[\Omega]$	Results from Haefely USG for divider A		Types of waveforms to be measured			Results from Dr. Strauss USG for divider A	
	T_α/T_1	β[per unit]				T_α/T_1	β[per unit]
0	0.0566	0.8468	×	Full lightning impulse	×	0.053	0.957
	0.0113	0.8468	√	Tail-chopped impulse	√	0.011	0.957
	$t_s < 10\mu s$		√	Switching impulse	√	$t_s < 10\mu s$	
30	0.0752	0.3351	×	Full lightning impulse	√	0.076	0.266
	0.0150	0.3351	√	Tail-chopped impulse	√	0.015	0.266
	$t_s < 10\mu s$		√	Switching impulse	√	$t_s < 10\mu s$	
100	0.2364	0.0046	×	Full lightning impulse	×	0.279	0.001
	0.0473	0.0046	√	Tail-chopped impulse	√	0.056	0.001
	$t_s < 10\mu s$		√	Switching impulse	√	$t_s < 10\mu s$	

√ = The accepted value of a comparison

× = The unaccepted value of a comparison

Table 4.5 Comparative USR parameters for divider B with two unit step response generators

$R_d[\Omega]$	Results from Haefely USG for divider B		Types of waveforms to be measured			Results from Dr. Strauss USG for divider B	
	T_α/T_1	β[per unit]				T_α/T_1	β[per unit]
0	0.03042	0.38800	√	Full lightning impulse	√	0.03075	0.41917
	0.00608	0.38800	√	Tail-chopped impulse	√	0.00615	0.41917
	$t_s < 10\mu s$		√	Switching impulse	√	$t_s < 10\mu s$	
30	0.03908	0.20280	√	Full lightning impulse	√	0.04067	0.19460
	0.00782	0.20280	√	Tail-chopped impulse	√	0.00813	0.19460
	$t_s < 10\mu s$		√	Switching impulse	√	$t_s < 10\mu s$	
120	0.07367	0.00610	√	Full lightning impulse	√	0.07225	0.00171
	0.01473	0.00610	√	Tail-chopped impulse	√	0.01445	0.00171
	$t_s < 10\mu s$		√	Switching impulse	√	$t_s < 10\mu s$	

Table 4.6 Comparative USR parameters for divider C with two unit step response generators

$R_d[\Omega]$	Results from Haefely USG for divider C		Types of waveforms to be measured			Results from Dr. Strauss USG for divider C	
	T_α/T_1	β[per unit]				T_α/T_1	β[per unit]
0	0.03528	0.02990	√	Full lightning impulse	√	0.03872	0.02986
	0.00706	0.02990	√	Tail-chopped impulse	√	0.00774	0.02986
	$t_s < 10\mu s$		√	Switching impulse	√	$t_s < 10\mu s$	

In Tables 4.3-4.5, it is found that a good damping resistor for divider A, B and C for each models are: 30Ω and 120Ω for dividers A and B. In addition, there is no damping resistor for divider C because the influence from high voltage leads and electromagnetic builds surrounding the divider can be neglected.

CHAPTER 5

CONCLUSION AND FURTHER WORK

The measurement of high voltage transients requires a means of reducing the high voltage signal to levels which are compatible with data recording equipment. The measurement devices which accomplish this reduction are known generically as voltage dividers and ideally they should scale the signal to a smaller value without distortion. These dividers, however, invariably introduce some distortion of the input signal, due to inadequate bandwidth or aberrations such as overshoot. This distortion may be negligible or totally unacceptable, depending on the allowable error associated with the particular measurement requirement.

A method is proposed for determining the correct settling level of the step response by which the great uncertainty in the evaluation of five parameters such as the experimental response time T_N, the partial response time T_α, the initial distortion time T_0, the over shoot β and the settling time t_S can be reduced to tolerable values. The method has been shown to be effective for resistive, capacitive and damped capacitive dividers.

The computer-aided analysis tools for an evaluation of transient responses of high voltage divider have been proposed. The unit step responses of three high voltage dividers are used as an input for this computer-aided tool. The analysis algorithm on the basic of MATLAB/Simulink has been developed to predict T_0, T_α, T_N, T_s and β of the high voltage divider. Wavelet transform has been used in order to get rid of needless noises from the measured signals. The results obtained from this computer-aided tool can be used as an indicator to decide whether the high voltage divider under consideration are appropriate for impulse measurement when considering β and the ratio of T_α/T_x with a standard recommendation.

The results of investigations in this thesis may be useful in the evaluation of the transient response parameters. However, apart from the theoretical significance of any parameters in characterizing the divider transfer error, the difficulties and uncertainties when evaluating the response parameters from experimental data must also be considered. In addition, other alternatives for predicting the performance of high voltage dividers in impulse voltage measurements, such as a frequency responses or convolution methods should be taken into consideration in the further work.

REFERENCES

[1] E.Kuffel, W.S. Zaengl and J. Kuffel, **High Voltage Engineering Fundamentals**. 1st ED. Wheaton & Co. Ltd., 1984.

[2] IEC 60-2:1994: **High–voltage test techniques Part 2**: Measuring system. 2nd ED.

[3] IEEE Std 4-1995: **IEEE Standard Techniques for High Voltage testing**

[4] Dieter Kind and Kurt Feser, **High–Voltage Test Techniques**. 2nd ED., 1999.

[5] Zdenek Matyas and Martti Aro, **"HV Impulse Measuring Systems Analysis and Qualification by Estimation of Measuring Erros via FFT, Convolution, and IFFT,"** IEEE Trans. on Instrumnets and Measurements, Vol. 54, No. 5, pp. 2013-2019, October 2005.

[6] S. Inthala, P. Yuthagowit, A.Ngaopitakkul, A.Kunakorn, N. Pattanadech and M. Kando, **"Computer-aided Analysis Tools for Step Response Parameters of High Voltage Dividers,"** ECTI-CON 2005, pp.153-156, May 2005.

[7] M. Glinka and K. Schon, **"Numerical Convolution Technique for Qualifying HV impulse Dividers,"** International High Voltage Engineering Symposium, pp. 71-74, August 1997.

[8] Walter S. Zeangl, **"Theory and Application of Voltage Dividers for High and Very High DC, AC and Impulse Voltages,"** [Lecture Notes]. ETH, pp.1-33, January 1999.

[9] Nils Hyltén-Cavallius, **High Voltage Laboratory Planing**. Haefely & Co. Ltd., 1986.

[10] J. Rungis and K. Schon, **"The Evalution of Impulse Divider Response Parameters,"** IEEE Trans. on Instruments and Measurement, Vol. 39, No. 2, pp. 346-352, April 1990.

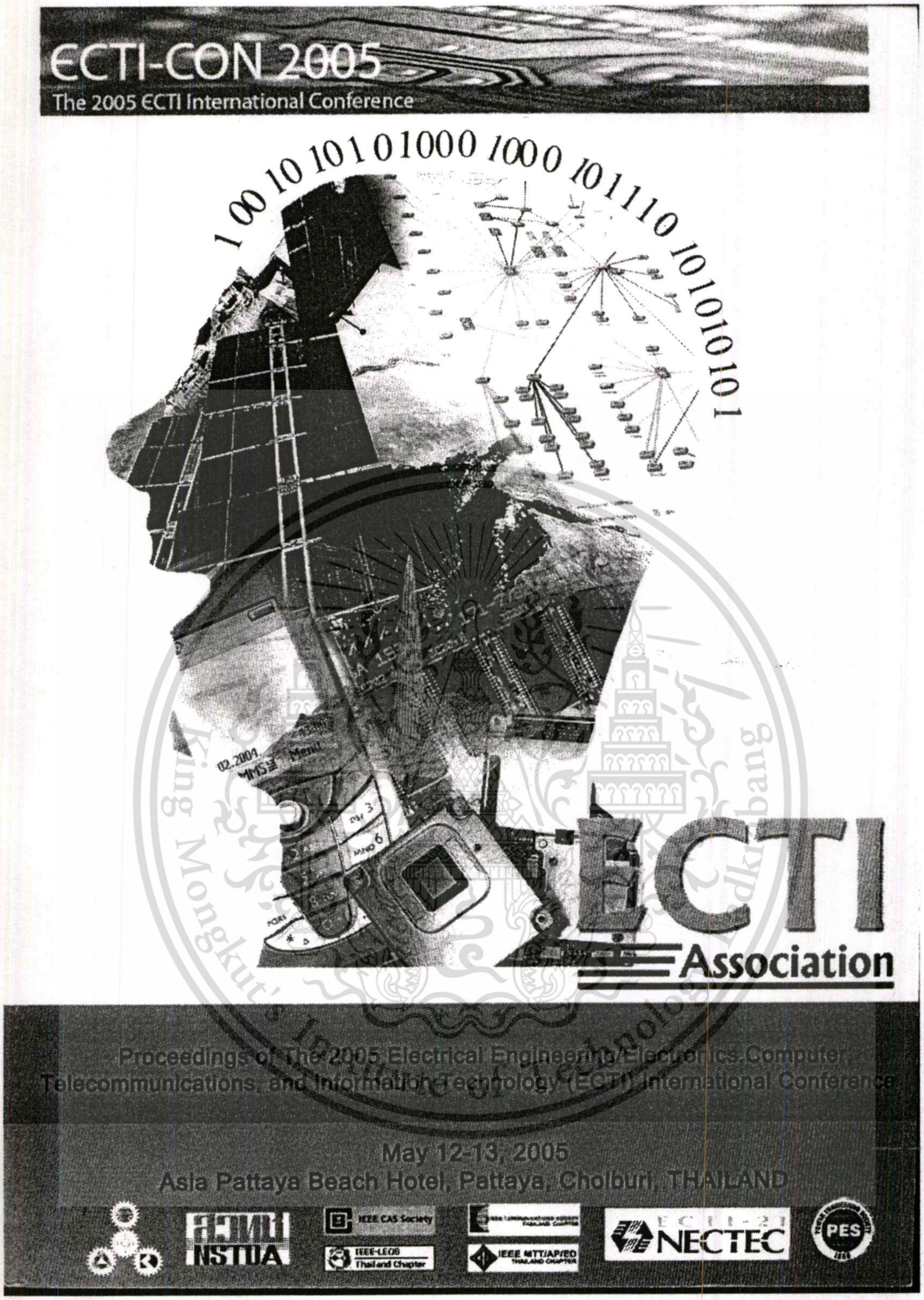
[11] O. Rajesh Kumar, M.Kanyakumari, N.K. Kini, S.Priya, P.V.V Nambudiri and K.N. Sirinivasan, **"Software Evaluation of Step Responses of High Voltage Dividers,"** International High Voltage Engineering Symposium, No. 467, pp. 1.242.P4-1.245. P4, August 1999.

Appendices

Appendix A

The Publication

S. Inthala, P. Yuthagowit, A.Ngaopitakkul A.Kunakorn, N. Pattanadech and M. Kando, **"Computer-aided Analysis Tools for Step Response Parameters of High Voltage Dividers,"** International Conferenc on Electrical Engineering/Electronics, Computer, Telecommunications, and Information Technology (ECTI' 2005), pp. 153-156, Pattaya, Thailand, May 12-13, 2005.


ECTI-CON 2005
The 2005 ECTI International Conference
ECTI
Association
Proceedings of The 2005 Electrical Engineering/Electronics, Computer, Telecommunications, and Information Technology (ECTI) International Conference
May 12-13, 2005
Asia Pattaya Beach Hotel, Pattaya, Cholburi, THAILAND
NSTDA
IEEE CAS Society
IEEE-LEOS Thailand Chapter
IEEE MTT/AP/ED Thailand Chapter
NECTEC
PES

Computer-aided Analysis Tools for Step Response Parameters of High Voltage Dividers

S. Inthala*, P. Yuthagowit, A.Ngaopitakkul* A.Kunakorn*, N. Pattanadech* and M. Kando*****

*Department of Electrical Engineering, Faculty of Engineering, KingMongkut's Institute of Technology Ladkrabang, Thailand. E-mail: soumek1@yahoo.com,
**Center of Excellence in Electrical Power Technology, Faculty of Engineering, Chulalongkorn University, Thailand
***Department of Electrical & Electronic Engineering, Tokai University, Japan. E-mail:

ABSTRACT

This paper presents two computer-aided analysis tools for a calculation of transient responses of a high voltage divider. The analysis tools are developed on the basis of Labview and MATLAB. The results show that both computer-aided analysis tools are able to correctly predict transient parameters of the high voltage divider, and this will be very useful for impulse measurements in a high voltage laboratory.

Keywords: Step response, High voltage dividers

1. INTRODUCTION

A voltage divider is an important high voltage device. The divider is employed to reduce the amplitude of a measured signal to a suitable value for a record instrument. The voltage divider consists of high voltage and low voltage units which may be constructed from resistors, capacitors or a combination between resistors and capacitors. Generally, resistor voltage dividers are mostly proper for d.c voltage measurements, and also applicable for a use with a.c voltage measurements with a condition that the power loss is not too much. However an additional error can occur due to the inductance of the resistor and the stray capacitances. As a result, in a.c measuring system, the capacitive divider is normally used for measuring both peak and RMS voltages. For impulse measurements, a capacitive high voltage divider can be employed with a modification to improve response characteristics using a damp resistor. This is called damped capacitive voltage divider [1, 2, 3, 4].

2. IMPULSE VOLTAGE MEASUREMENTS

An impulse voltage is a transient signal, which usually rises rapidly to a peak value and then falls more slowly to zero. An impulse voltage divider is required to measure the peak value, the time parameters and the overshoot or the oscillation of the impulse waveform. The impulse voltage divider performance must agree the approval procedure according to the international standards such as IEC [2], ANSI [3] to ensure that the value of measured signal impulse is valid.

Basically, an impulse voltage measuring system [1, 4] consists of an impulse voltage generator which is connected to a test object via a lead. These three elements are included in the voltage generating system as shown in Fig. 1. The voltage generating system is integrated with the voltage measuring systems which are composed of a voltage divider, a lead cable between the test object and the divider, a measuring cable, and a recording instrument. In addition the measuring system must have an appropriate ground return.

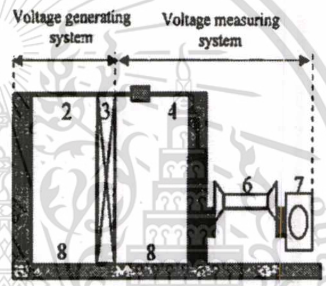


Fig. 1: Basic voltage measuring system [4].
(1) Impulse generator. (2) Lead cable to the test object. (3) Test object. (4) Lead cable to the voltage divider. (5) Voltage divider. (6) Measuring cable. (7) Recording instrument. (8) Ground return.

Two important parameters, which are used to evaluate impulse measuring system characteristics, are scale factors and transient behaviors. According to IEC [2] the scale factors of the converting device and the transmission system are not varied by more than ± 1% for the ranges of the ambient temperature and given clearance. The transient behaviors must be adequate for the measuring of the peak voltage and time parameters over the range of waveforms. Usually, the transient behavior can be evaluated from the parameters obtained from unit step responses. IEC provides a recommendation on the test circuit for determining the unit step response as shown in Fig 2.

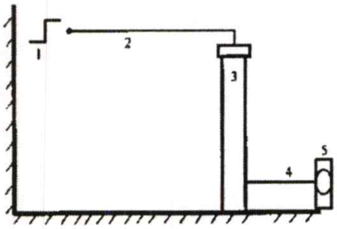


Fig. 2: Step response measurement for voltage measurement systems. [2]
(1) Unit step function (2) Lead (3) Tested impulse voltage divider (4) Measuring cable (5) Recording instrument.

The required parameters of the step response which are evaluated, consist of the experimental response time T_N, the partial response time $T\alpha$, the initial distortion time T_0, the over shoot β and the settling time t_S. The definition of the parameters is described in IEC [2]. These parameters from the step response g(t) are examined as illustrated in Fig 3.

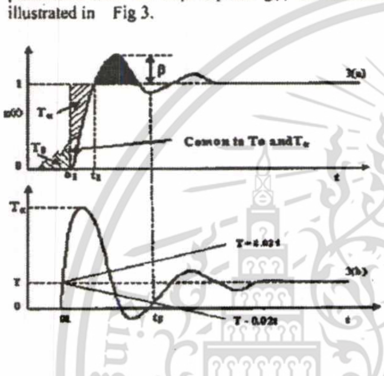


Fig. 3: Parameters of the unit step response.
a) Normalized step response g(t)
b) Response time T as function of t

The response time T_N is give by the following equations: [2]

$$T_N = \int_0^\infty (1 - g(t))dt \qquad (1)$$

With g(t) as a function of the measured signal.

For other parameters, the calculation can be performed manually with the output response provided from the tests. Generally, a voltage divider can measure full and tail–chopped impulses with a front time of T_x if the overshoot β and the ratio of $T\alpha/T_x$ the tested impulse voltage divider are within the shaded area as shown in Fig 4.

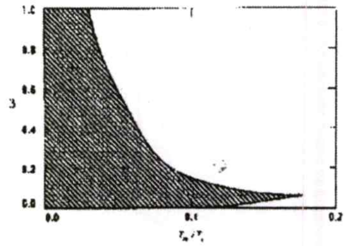


Fig. 4: Overshoot β as a function of the related partial response time $T\alpha/T_x$

3. COMPUTER AIDED TOOLS AND RESULTS

To evaluate the transient behaviors of the impulse voltage divider, two computer-aided tools are developed. The first tool employs the capability of the toolboxes of Labview program to evaluate all parameters, whereas the second one employs Wavelet transform to reduce noise signals of the measured impulse voltage, before computing the unknown parameters with an algorithm based on MATLAB. Daubechies 20 is selected as a mother wavelet for a filter process.

The input for these two analysis tools are obtained from capturing a unit step response of a commercial high voltage divider. The arrangement of test circuit is detailed in Fig 5.

Fig. 5: Test circuit arrangement
(1) Unit step generator (2) A high voltage divider (3) Lead with adjustable resistor

The unit step signals were applied to the measuring system with a lead resistance 0, 30 and 100 Ohms respectively. The output at the low voltage arm of the high voltage divider as a response due to the unit step input was measured. Fig 6 shows output responses due to several lead resistances.

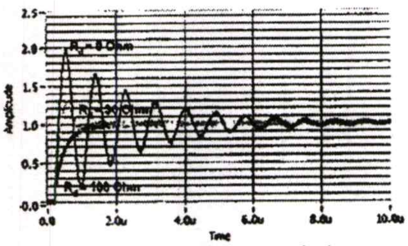
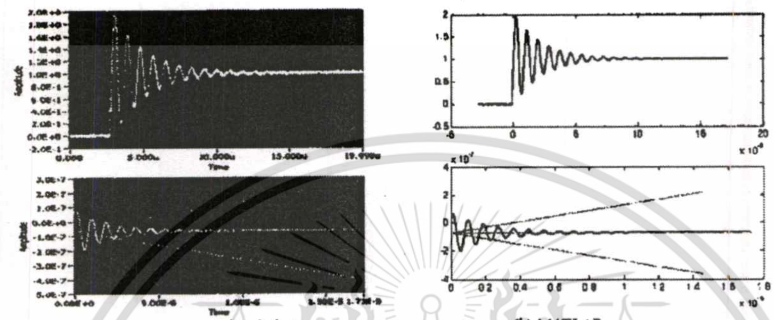


Fig. 6: Step response signal at various lead resistance values.

The unit step response of high voltage divider, then, were imported as input files for the two computer-aided analysis tools. For the Labview-based tool, the input files are normalized and all transient parameters are analyzed using an algorithm developed on the basic of toolboxes provided by Labview package.

For the MATLAB-based tool, the Wavelet transform is applied to get rid of needless noises superimposed on the step response waveforms. The approximation signals on scale 5, 8, 9 are normalized for a lead resistance 0, 30 and 100 Ohms respectively, and all transient parameters, then, are analyzed.

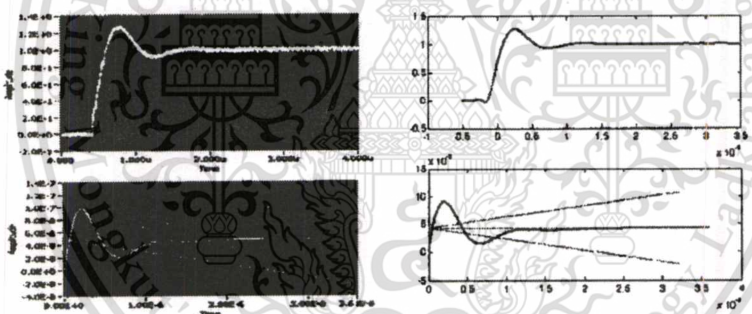


(a) *Labview* *(b) MATLAB*

Fig. 7: The evaluated step response parameters at the lead resistance value of 0 Ohm.

(a) Step response parameters determination on Labview

(b) Step response parameters determination on MATLAB

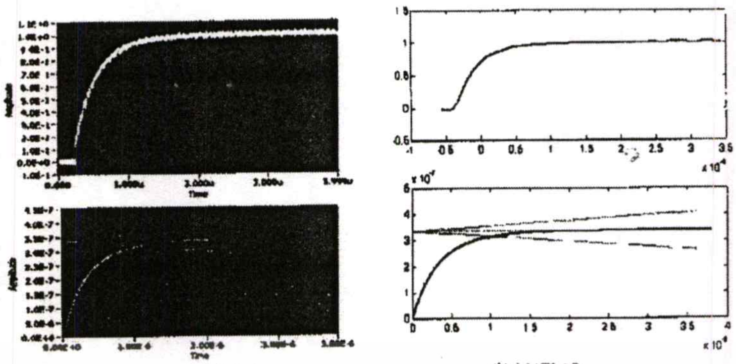


(a) Labview *(b) MATLAB*

Fig. 8: The evaluated step response parameters at the lead resistance value of 30 Ohm.

(a) Step response parameters determination on Labview

(b) Step response parameters determination on MATLAB



(a) Labview (b) MATLAB

Fig. 9: The evaluated step response parameters at the lead resistance value of 100 Ohm.
(a) Step response parameters determination on Labview
(b) Step response parameters determination on MATLAB

Table1: Step response parameters compared between two computer-aided tools

Parameters	Labview			MATLAB		
	$R_d = 0\Omega$	$R_d = 30\Omega$	$R_d = 100\Omega$	$R_d = 0\Omega$	$R_d = 30\Omega$	$R_d = 100\Omega$
T_o [ns]	3.23	-0.593	-5.59	1.59	3.7	1.05
T_α [ns]	68.30	97.18	338.29	63.53	90.93	334.84
T_N [ns]	-63.91	49.22	337.87	-72.57	43.16	334.57
T_s [μs]	2.39	0.866	1.05	2.38	0.865	1.05
β[%]	96.30	29.54	4.35	95.74	26.58	0.143

The results obtained from the proposed computer -aided analysis are summarized in Table 1. There are slightly different values of two tools such as, the initial distortion time T_o and the overshoot β. This due to that there is a noise reduction process for MATLAB algorithm before starting calculations while such a process is not included in Labview applications. It can be seen that all these transient responses of a high voltage divider under investigations give the ratio of $T\alpha/T_x$ within the applicable range for standard impulse measurements in both lightning impulses (1.2/50μs) and switching impulses (250/2500μs)

4. CONCLUSIONS

The two computer-aided analysis tools for an evaluation of transient responses of high voltage divider have been proposed. The unit step responses of a high voltage divider are used as an input for these two computer-aided tools. The analysis algorithm on the basic of Labview and MATLAB have been developed to predict T_O, T_α, T_N, T_s and β of the high voltage divider. Wavelet transform has been used in order to get rid of needless noises from the measured signals. The results obtained from the computer-aided tools can be used as an indicator to decide whether the high voltage divider under consideration is appropriate for impulse measurement when considering β and the ratio of $T\alpha/T_x$ with a standard recommendation.

5. ACKNOWLEDGMENT

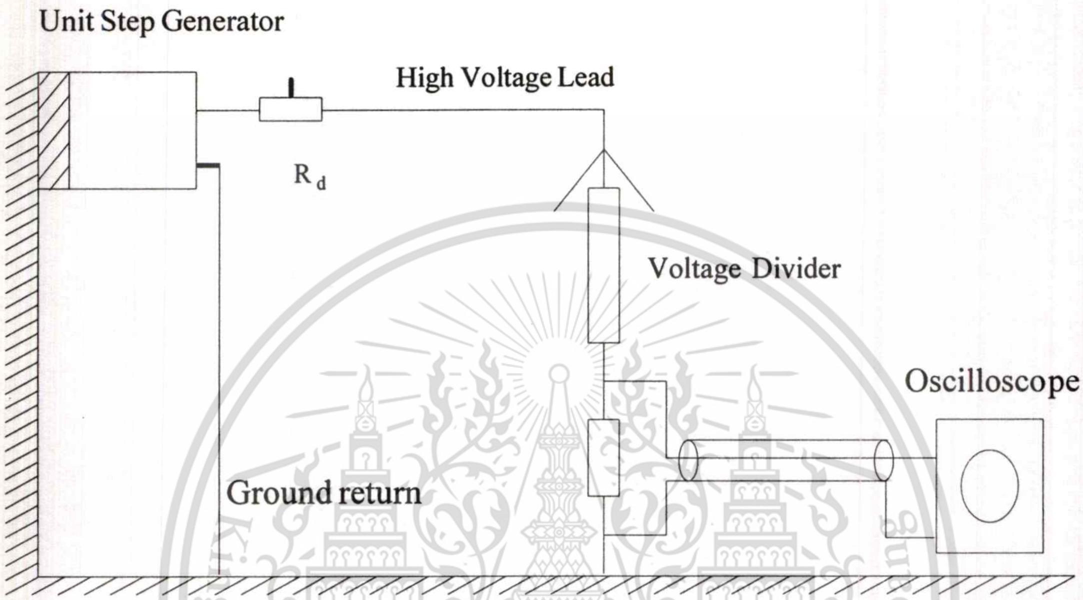
The Authors would like to give a special recognition to AUN/SEED-net, JICA for the financial support on this project.

REFERENCES

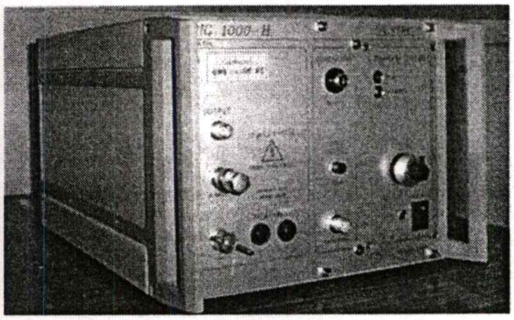
[1] Dieter Kind, Kurt Feser "High-Voltage Test Techniques", Second Edition, 1999
[2] IEC 60-2 High-voltage test techniques Part 2: Measuring system, Second edition, 1994
[3] IEEE Standard Techniques for High Voltage testing, 1995
[4] E.Kuffel, W.S. Zaengl and J. Kuffel. "High Voltage Engineering Fundamentals", Second Edition, 2000
[5] C. H. Kim and R. Aggarwal, "Wavelet transforms in power systems: Part. 1 General introduction to the wavelet transform", IEE Power Engineering Journal, April 2000, pp 81-87

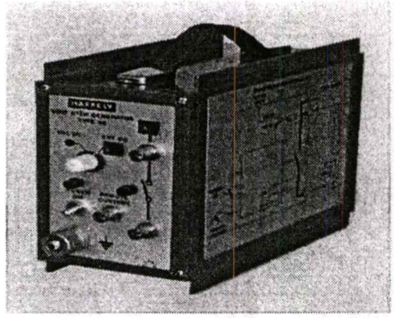
Apendix B

Circuit diagram and equipments used in a high voltage loboratory



Circuit arrangement for the experimental test

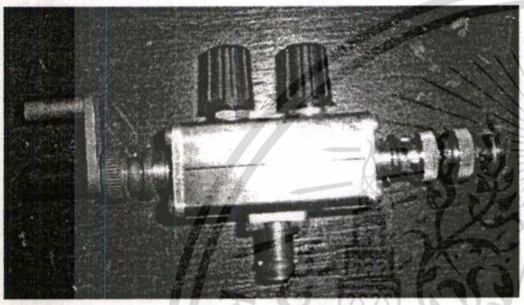


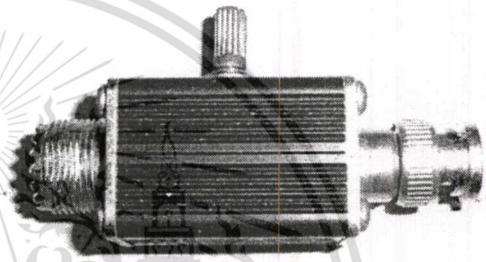


Dr. Strauss unit step generator

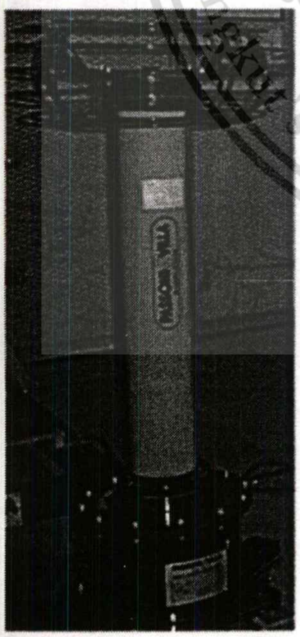
Haefely unit step generator

Two unit step generators to enject step pulse in to high voltage divider



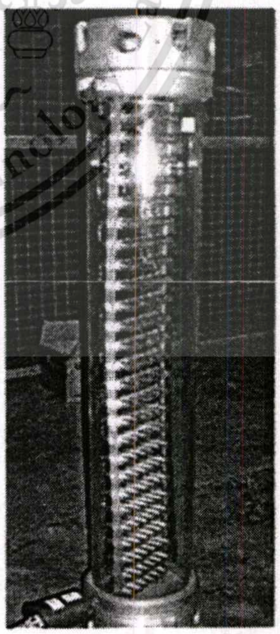


Damping resistor used for reducing the oscillation signal



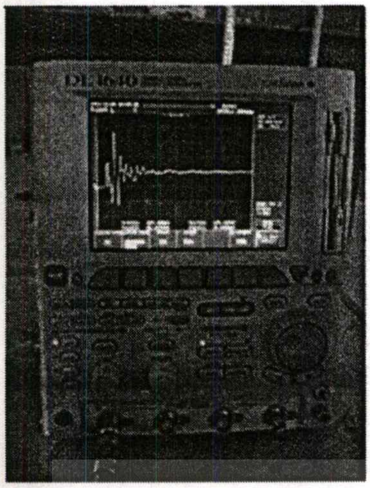
200 kV, Capacitive divider

100 kV, Capacitive divider

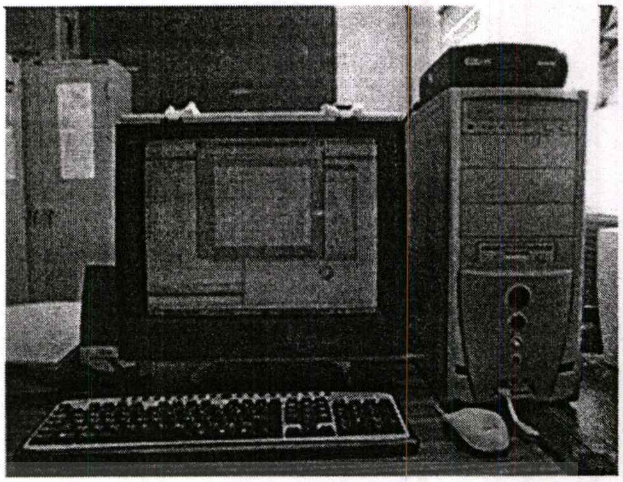


200 kV, RC divider

Three High Voltage Dividers used in this research



YOKOGAWA
DL1640(200MS/s, 200 MHz)
Digital Oscilloscope



PC computer used for evaluating data from
Digital Oscilloscope

Appendix C

MATLAB Program for Evaluation of Unit Step Response Parameters of High Voltage Dividers

```
%%%%%%55 for test00.txt%55555555
signal = input ('Please enter a network:');
Length = size (signal);
scale =  input ('Please enter a scale wavelet:');
 time = signal(:,1);
 temp_ampitude = signal (:,2);
 [aa bb] = size (time);
 delta_time = (time (aa)-time (1))/aa;
 %time= time1+delta_time;
% nor_ampitude=temp_ampitude;
% nor_ampitude=(temp_ampitude/temp_ampitude(aa));
temp_avg = mean (temp_ampitude (9000:10000));
nor_ampitude = (temp_ampitude/temp_avg);
 temp_min = nor_ampitude (1);
 %[temp_min round_min] = min(nor_ampitude);
 if temp_min > = 0
    up_ampitude = nor_ampitude-temp_min;
 elseif temp_min  < 0
    up_ampitude = nor_ampitude + abs (temp_min);
 end
 ampitude = up_ampitude / (1+abs(temp_min));
% amplitude=nor_ampitude
 %ampitude=(nor_ampitude/nor_ampitude(aa));
% save ampitude.txt  ampitude -ascii
```

```
%figure(1)
%plot(time,ampitude)
%  %original signal
y0=0.00;
y30=0.3;
y90=0.9;
y98=0.98;
y100=1;
y102=1.02;
%%%%%%%%%%%%%%%%%%%%%%  Wavelet transform %%%%%%%%%%%%%%%%%%%%%%
ss = ampitude;
mother = 'db20';
m = 10; %scale = 4;
[c,l] = wavedec (ss, m, mother);
 for j = 1:m
   LF_signal(:,j) = (wrcoef('a',c,l,mother,j));
 end
 y = LF_signal (:,scale);
% figure(1)
 %plot(time,y),grid;
    save output.txt  y -ascii
 count0 = 0; count30 = 0; count90 = 0; count100 = 0;
 Ref_time0 = 0; Ref_time30 = 0; Ref_time90 = 0; Ref_time100 = 0;
 count_j = 0;
 countdown0 = 0;  countdown90 = 0; countdown30 = 0; countdown100 = 0;
 for j = 1:(length(time)-1)
    x1 = time(j);  x2 = time(j+1) ;
    y1 = LF_signal(j,scale) ; y2 = LF_signal(j+1,scale);
   %    y1= ampitude(j) ; y2=ampitude(j+1);
   count_j=count_j+1;
```

```
%%%%%%%%%%%%%%%% find 0 percent of unit step by interpolation%%%%%%%
  if ((y1 < = y0) & (y2  > = y0))
    x0 = x1+(((y0-y1) / (y2-y1)) * (x2-x1));
    Ref_time0 = Ref_time0+1;
    count0 = count0+1;
    rec_time0 (Ref_time0) = x0;
    round_x0 (Ref_time0) = count_j;
  elseif  ((y1> = y0) & (y2  < = y0))
  xdown0 = x1+ (((y0 - y1)/(y2 - y1)) * (x2 - x1));
   Ref_time0 = Ref_time0 + 1;
    countdown0 = countdown0+1;
     rec_time0 (Ref_time0) = xdown0;
     round_x0 (Ref_time0) = count_j;
%%%%%%%%%%%%%%%%  find 100 percent of unit step by interpolation%%%%%%%
 elseif  ((y1 < = y100) & (y2  > = y100))
   x100 = x1+(((y100 - y1) / (y2 - y1)) * (x2 - x1));
    Ref_time100 = Ref_time100 + 1;
     count100 = count100 + 1;
      rec_time100 (Ref_time100) = x100;
      round_x100 (Ref_time100) = count_j;
  elseif  ((y1 > = y100) & (y2  < = y100))
   xdown100 = x1+ (((y100 - y1) / (y2 - y1)) * (x2 - x1));
    % Ref_time90 = 1;
     Ref_time100 = Ref_time100 + 1;
     countdown100 = countdown100 + 1;
      rec_time100 (Ref_time100) = xdown100;
      round_x100 (Ref_time100) = count_j;
  end
end
```

```
rec_time0;
rec_time100;
round_x0;
round_x100;
%%%%%%%%%%%%%%%% find virtual origin of a step response %%%%%%%%%
Ref_origin = 0; count_j = 0;
for j = round_x0(1) : round_x100(1) + 1
  temp_ox1 = time (j); temp_ox2 = time (j + 1);
  temp_oy1 = LF_signal (j, scale); temp_oy2 = LF_signal (j + 1, scale);
  temp_down1 = y0; temp_up = y100;
   count_j = count_j + 1;
  diff_ox = abs (temp_ox2 - temp_ox1);
  diff_oy = abs (temp_oy2 - temp_oy1);
  slop = (diff_oy / diff_ox);
   Ref_origin = Ref_origin + 1;
        rec_slop (Ref_origin) = slop;
  round_origin (Ref_origin) = count_j;
end
  [max_slop row_slop] = max (rec_slop);
 round_slop = row_slop+round_x0 (1) - 1;
 max_slop_oy = y (round_slop);
 max_slop_ox = time (round_slop);
  diff_oynew = (max_slop_oy - y0);
  o1 = max_slop_ox - (diff_oynew / max_slop);
 round_o1 = round_slop-round ((max_slop_ox - o1) / diff_ox);
newtime = time(round_o1 : round_slop);
 y_line1 = y0; Ref_line = 0; count_j = 0;
 for j = round_o1-1:round_slop
    x_line1 = time (j); x_line2 =t ime (j+1);
    diff_linex = abs (x_line2-x_line1);
```

```
    y_line1 = y_line1 + (max_slop * diff_linex);
    count_j = count_j + 1;
    Ref_line = Ref_line + 1;
      y_new (Ref_line) = y_line1;
      round_line (count_j) = count_j;
   end
figure (2)
% cct=time(round_x0:aa)-time(round_o1);
% cct2=time((round_o1-1):round_slop)-time(round_o1-1);
%                                   subplot(2,1,1);plot(time(round_x0:aa),y(round_x0:aa),time((round_o1-
1):round_slop),y_new)
% subplot(2,1,1);plot(cct,y(round_x0:aa),cct2,y_new)
     subplot (2,1,1); plot(time(1:aa), y(1:aa), time((round_o1-1):round_slop), y_new)
       start_to = 0;
     for  j = round_x0(1):(round_o1-1)
        temp_xto1 = time (j); temp_xto2 = time (j+1);
    temp_yto1 = LF_signal (j, scale); temp_yto2 = LF_signal (j+1, scale);
   temp_down1 = y0; %temp_up = y100;
    diff_wto1 = abs (temp_xto2 - temp_xto1);
    diff_lto1 = abs (temp_down1 - temp_yto1);
  diff_lto2 = abs (temp_down1 - temp_yto2);
  diff_lto = diff_lto1 + diff_lto2;
   area_to1 = 0.5 * diff_wto1 * diff_lto;
   start_to = start_to + area_to1;
 end
 start_to; count_j = 0;
  for j = (round_o1 - 1) : round_slop - 1
     count_j = count_j + 1;
     temp_xto3 = time (j); temp_xto4 = time (j + 1);
    temp_yto3 = LF_signal (j, scale); temp_yto4 = LF_signal (j + 1, scale);
```

```
    temp_down2 = y_new (count_j); temp_up = y_new (count_j + 1);
     diff_wto2 = abs (temp_xto2 - temp_xto1);
     diff_lto3 = abs (temp_down2 - temp_yto3);
   diff_lto4 = abs (temp_up - temp_yto4);
   diff_lto5 = diff_lto3 + diff_lto4;
    area_to2 = 0.5 * diff_wto2 * diff_lto5;
    start_to = start_to + area_to2;
 end
 total_to = start_to;   % the initial distortion time.
      %%%%%%%%%%% find area up and down 100 percent unit step %%%%%%%%%%%
  sum_area = zeros (size (rec_time100));
 for  jj = 1:(length(rec_time100) - 1)
    for j = round_x100(jj) : round_x100(jj + 1)
     temp_w1=time (j); temp_w2=time (j+1);
     temp_l1=LF_signal (j, scale); temp_l2=LF_signal (j+1, scale);
    temp_down1= y100; temp_up = y100;
     diff_w1 = abs (temp_w2-temp_w1);
     diff_l1 = abs (temp_down1- temp_l1);
   diff_l2 = abs (temp_down1- temp_l2);
   diff_l = diff_l1 + diff_l2;
    area = 0.5 * diff_w1 * diff_l;
    sum_area(jj) = sum_area(jj)+area;
 end
end
tri_area = 0;
%for j = round_x0 (1):round_x100 (1)
 for  j = round_o1:round_x100(1)
     temp_w1 = time (j);  temp_w2 = time (j+1) ;
     temp_l1 = LF_signal (j, scale) ; temp_l2 = LF_signal(j+1, scale);
    temp_down1= y100;  temp_up = y100;
```

```
diff_w1 = abs (temp_w2 - temp_w1);
diff_l1 = abs (temp_down1- temp_l1);
diff_l2 = abs (temp_down1- temp_l2);
diff_l = diff_l1 + diff_l2;
area_tri = 0.5 * diff_w1 * diff_l;
tri_area = tri_area+area_tri;
end
total_area=tri_area;   % The partial response time T alpha
sum_area;
for i = 1:length(sum_area)
  round_ch = rem (i,2);
  if round_ch = 1
    total_area = total_area - sum_area (i);
  elseif round_ch =0
    total_area = total_area + sum_area(i);
  end
end
total_area;      % Experimental response time
%%%%%%%%%%%%%%%% find setting time %%%%%%%%%%%%%%%%
Ref_ts = 0; ts_area = 0; count_j = 0;
for j = round_o1:(length(time)-1)
  temp_xts1 = time (j); temp_xts2 = time (j+1);
  temp_yts1 = LF_signal (j,scale) ; temp_yts2 = LF_signal(j+1,scale);
  temp_down = y0;  temp_up = y100;
  diff_xts = abs (temp_xts2-temp_xts1);
  diff_yts1 = abs (temp_up-temp_yts1);
  diff_yts2 = abs (temp_up-temp_yts2);
  diff_yts = diff_yts1+diff_yts2;
  area_ts = 0.5 * diff_xts * diff_yts;
  count_j = count_j + 1;
```

```
 if ((temp_down <= temp_yts1) & (temp_up >= temp_yts1))
  ts_area = ts_area+area_ts;
 Ref_ts = Ref_ts+1;
 rec_ts_area (Ref_ts) = ts_area;
 round_ts(Ref_ts) = count_j;
elseif  ((temp_down <= temp_yts1) & (temp_up <= temp_yts1))
 ts_area = ts_area-area_ts;
 Ref_ts = Ref_ts+1;
 rec_ts_area (Ref_ts) = ts_area;
 round_ts (Ref_ts) = count_j;
end
 end
%%%%%% find linear ts 0.02 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ref_ts2 = 1; count_ts = 0; ttt = rec_ts_area;

  for j =  round_o1(1) + 1:(length(ttt) - 1)
        temp_xts5 = time (j);  temp_yts5 = total_area(1);
        % temp_yts5=rec_ts_area(1);
            Ref_ts2=Ref_ts2 + 1;
                count_ts=count_ts + 1;
                 temp_lts (1) = time (round_o1);
                   temp_lts (Ref_ts2) = temp_xts5;
   y_ts_positive = temp_yts5 + ((0.02 * temp_lts (Ref_ts2)) - 0.02 * temp_lts (1));
   y_ts_neg = temp_yts5 - ((0.02 * temp_lts (Ref_ts2)) - 0.02 * temp_lts (1));
                 rec_lts_positive (1) = temp_yts5;
                  rec_lts_neg (1) = temp_yts5;
                 rec_lts_positive (Ref_ts2) = y_ts_positive;
                 rec_lts_neg (Ref_ts2) = y_ts_neg;
                 round_lts (Ref_ts2) = count_ts;
  end
```

```
%%%%%%%%%%%%%% find ts %%%%%%%%%%%%%555
x_ts = time (round_o: (length (time) - 1));
x_lts = time (round_o1 (1) (length(ttt) - 1));
data_area_ts=rec_ts_area;  %%%%% y-axis %%%%%%%%
data_time_area_ts=x_ts;    %%%%% x-axis %%%%%%%%
round_time_area_ts=round_o1; %%%%% row start of x-axis %%%%%%%
data_linear_ts_pos=rec_lts_positive';  %%%% data of linear positive or y-axis %%%%
time_linear_ts_pos=x_lts;  %%%%%%%%%%% time start of linear positive or x-axis %%%%
round_time_linear_ts_pos=round_o1(1); %%% row start of linear positive or x-axis %%%%
data_linear_ts_neg = rec_lts_neg';      %%%%%data of linear negative or y-axis %%%%%
time_linear_ts_negs = x_lts;       %%%%% time start of linear negative or x-axis %%%%%
round_time_linear_ts_neg = round_o1(1);     %% row start of linear negative or x-axis %%
chk_ts = 0; chk_area = 0; count_j = 0;  i= 0;
for j = round_o1(1) + 1:(length(ttt)-1)
i = i+1;
time_xts = time (j); time_next_xts = time (j+1);
curve_impulse = data_area_ts (j); curve_next_impulse=data_area_ts (j+1);
curve_linear_pos = data_linear_ts_pos (i);
%curve_next_linear_pos=data_linear_ts_pos(i+1);
curve_linear_neg = data_linear_ts_neg (i);
%curve_next_linear_neg=data_linear_ts_neg(i+1);
time_new (i) = time_xts-(time(round_o1+1));
count_j = count_j+1;
diff_curve_up = abs (curve_impulse - curve_linear_pos);
diff_curve_down = abs (curve_impulse - curve_linear_neg);
diff_up (i) = diff_curve_up;
diff_down (i) = diff_curve_down;
if diff_up(i) > diff_down(i)
diff(i) = diff_down(i);
```

```
else diff(i) = diff_up(i);
end
   if i =1
        temp_aa = diff (i);
        temp_bb = time_new (i) ;
   elseif temp_aa > diff(i)
         temp_aa = diff (i);
          temp_bb=time_new (i);
end
% setting_time = temp_bb-time (round_o1); %%%%%% setting time %%%%%%%5555
  setting_time = temp_bb;
end
   %%%%%%%%%%%%%%%%%%%%%  find overshoot %%%%%%%%%%%%
temp_B = max(y);
B = ((temp_B - y100)/y100) * 100;
 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%  show Output %%%%%%%%%%
 B          %%%%%% overshoot %%%%%%%%%
setting_time   %%%%%%%%% setting time %%%%%
 total_area   %%%%%% TN %%%%%%%%%%%%
 total_to    %%%%%%%%% To %%%%%%%%%%
  tri_area %%%%%%%%% T-Alfa %%%%%%%%%%%%%
   o1  %%%%%%%%%%%%%% virtual origin %%%%%%%%%%5
   x_ts = time (round_o1 :( length (time)-1))-time (round_o1);
   temp_lts = time (round_o1 (1) :( length (ttt)-1))-time (round_o1);
    subplot(2,1,2);
plot(x_ts,rec_ts_area,x_ts,total_area,temp_lts,rec_lts_positive,temp_lts,rec_lts_neg);
 tsemp = rec_ts_area';
```

BIOGRAPHY

Mr. **Soumek Inthala** was born in May 10, 1977 at Vientiane municipality, Laos. He received B. Eng in Electrical Engineering department, Faculty of Engineering, National University of Laos, 2001. Since then, he has been a Lecturer in the Electriacl Department, National University of Laos. He is a postgraduate student of KMITL, Thailand under the AUN/SEED-Net programme.