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Procedural Perfection in Impulse Shape Generation for Indoor Type Impulse Test of Power Transformers

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Abstract **- In this paper we are to demonstrate the high voltage impulse test performed to testify the withstand capability of power transformer. Then the problems associated in practical wave generation will be stated which solutions are to be improved by the proposed method using PC tools. Then a simulation result will be presented for use in our practical lab test and the range of desired parameters should be compared.**

Key words: Impulse test, Surge protection, Power transformer indoor test, Mathematical modeling.

I. INTRODUCTION

The outdoor power transformers are highly at risk to receive heavy voltage surge from lightening. As to design the insulating capability a similar or even severe impulse wave, shaped with a defined rise/front time and tail time is applied in indoor to the leads of it [1]. Now to get the exact scenario, the correct type of wave shape generation is must which seems to be trial and error to get in practice. So a mathematical representation of the instrument with load effect and stray capacitances under concern, an automatic generation of the parameters (R, C, air gap) can be achieved to apply for some predefined wave shapes necessary for different kV level test and get the result in 1st try. For the preceding sections we are to do this with a simulated model as well as with the mathematical tools like Laplace.

II. PRINCIPLE OF OPERATION OF MARX-TYPE IMPULSE GENERATOR

A Marx-type impulse generator has the schematics like fig-1 which is commonly applied to the test.

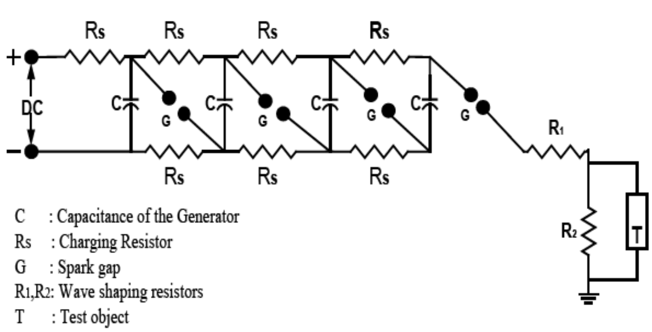

Fig 1: Marx type impulse voltage generators

The mainly generated impulse voltage waveform represents the following common incidents:

1) Standard lightening impulse waveform
2) Standard switching impulse waveform
3) Other special switching or uncontrolled impulses.

At the beginning of the operation a DC generator is used to charge the staged capacitors to its peak value. Normally the peaks of individual capacitors lie in 20 kV. Now when to test an insulator string (i.e) the air gap is made to break down by triggering the lowest air gap. The impulse capacitor is charged via a high charging resistance (R_o) to the direct voltage U_o and then discharged by ignition of the switching gap F (fig. 3). During this charging and discharging period, the desired impulse voltage U(t) appears across the load capacitor Cy.

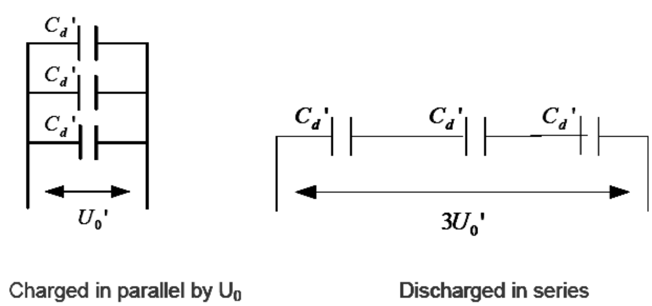

Fig 2: Capacitor orientation for charging/discharging phase

The discharging path then made the impulse to appear across the test object, as shown in the fig. 3.

Fig 3: A 3 staged b type IG s discharging

Now the waveform, generated has 3 major components to define before applied to [4]. These are:
1) Amplitude or % of amplitude 2) Wave front time,T_C
3) Wave trail time, T_S.
An acceptable Impulse [4] which can represent a lightening like waveform is defined by T_C, T_S & U_{max} and has the shape like fig. 4:

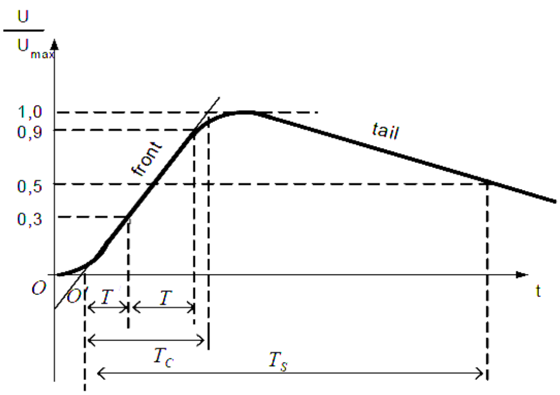

Fig 4: An ideal impulse wave's properties

Now we are going to create a signal which should be automatically generated with the given parameters of R, C, U_o and should fulfill the necessary T_C, T_S & U_{max}. For that we are to create a coding and simulate it in SPICE in the preceding sections. Then we are to apply it in a practical test, to get the real data and to verify its use in 1st time accurate try in impulse test.

III. SIMULATION AND ANALYSIS

1) *Spice simulation and no load analysis*

In this segment we have simulated the IG in spice (fig-5) with no transformer as load.

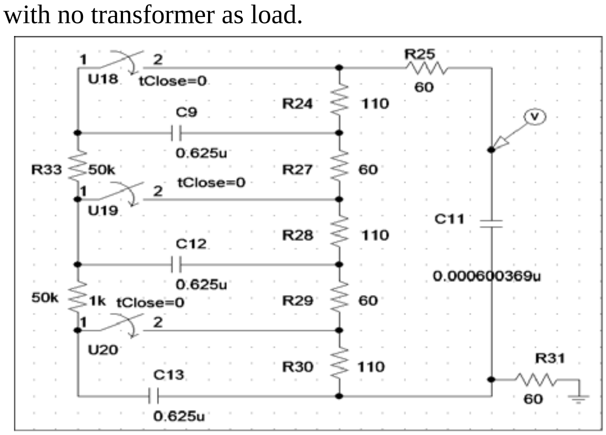

Fig 5: Spice schematic representing IG main circuit

The simulated waveform for the specific parameters appears as fig. 6 which has reported dissimilarities with our practical findings.

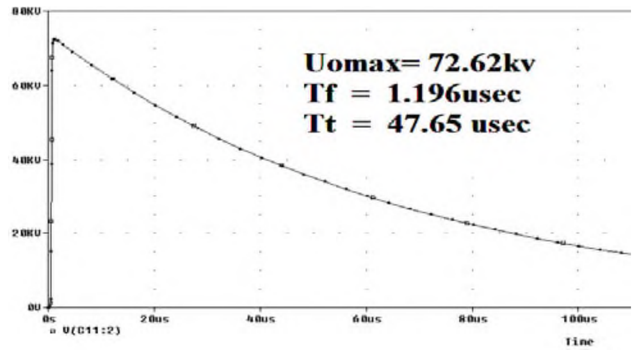

Fig 6: simulation result, V (C11) of the ckt of fig.5.

The granted wave shape in our Impulse lab appeared as fig.7 (which is made by trial and error basis): [1],[2],[4]

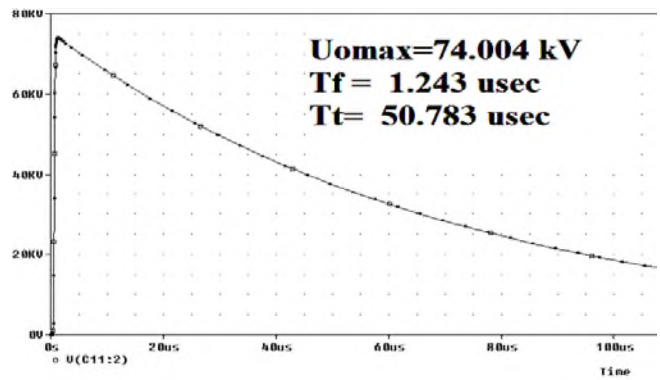

Fig 7: An industry granted impulse shape

Hence we are going to mathematically represent the system where, for the same value of front and tail resistor a multistage IG can be reduced to a single stage by using Laplace transform and it's inverse. As shown in fig. 8 the single stage is:

8: Single stage (reduced) equivalent of multistage IG during discharging phase

Then by using KCL, KVL and inverse Laplace we obtain the output parameter U(t) in time domain. We are here to present the equations, derived along with the constants only, where the detailed is given in appendix.
The output voltage in time domain is found as:
$U(t) = k\,[e^{s1t} - e^{s2t}]$
Here,
$k = A / (s1-s2)$ $\quad s1, s2 = -b \pm \sqrt{(b2-4ac)}/2a$

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$a=1,\ b = \frac{1}{Rf*Cd} + \frac{1}{Rt*Cd} + \frac{1}{Rf*Cy},\quad c = \frac{1}{(Rf*Cy*Rt*Cd)}$

$A = \frac{Uo}{Rf*Cy}$

The single staged parameters are defined for multistage as:
U_0 = n* per stage voltage of capacitor
R_f = n* per stage resistance of front resistor
R_t = n * per stage resistance of tail resistor
C_y = capacitance of divider/load capacitor
C_d = (1/n) * per stage capacitance of capacitor

Now, we have used MatLab coding to plot U(t). In practice we had to do the iterative process in fixing the suitable resistance and capacitance values for a defined waveform. By using the above equations and coding we can bring a more proximate waveform in a quicker and easier way which reduced the time, labor of handling weighty elements and chance, to decrease the durability of the transformer insulation.

3.2 Spice simulation with load and analysis

In this portion we have tested the spice model with a capacitive load representing a real equivalent transformer. But as found the tail time deviates from the practical test data for a 200KVA transformer. Moreover now in the schematics, we have added the stray capacitances which are inherited in the system. This caused a visible improvement in proximity with real test wave shape which is given in part IV of this paper.

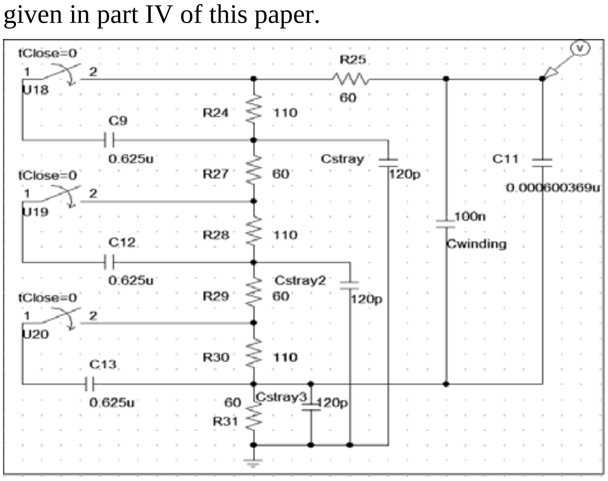


Fig 9: Spice schematic of IG main circuit with transformer model as load.

The generated wave shape across the capacitor divider can be found as fig. 10 which shows some definite deviation:

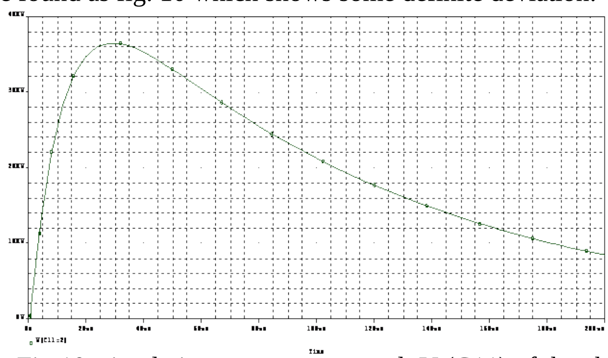


Fig 10: simulation result V (C11) of the ckt of fig. 9.

The main sources of this deviation are the non-calculated distributed capacitances that an original transformer winding has. If we can calculate it then we can measure the loading to use it in simulation and hence to produce the testable wave shape. [3], [5], [6].

For the exact R_f, R_t and U_o to find, we must then to have a calculated mathematical model which can represent a transformer's equivalent capacitance. For the tested circular disk wound transformer we have developed the total capacitance of a winding as: [5],[6],[7].

$C_{winding} = C_{turn-turn} + C_{disk-disk}$
$\quad = C_{tt} + (C_{dd\ due\ to\ key\ spacer} + C_{dd\ due\ to\ insulating\ oil})$

C_{tt} exists as for the turns on a disk have paper insulation in between them and C_{dd} exists as for key spacer in some portion and insulating oil for the rest of the portion in between the disks consisting the turns. As shown in the

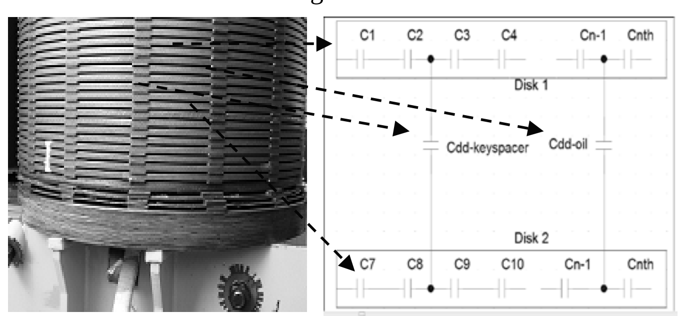


fig. 11 the two portions can be visualized clearly.

Fig 11: Two types of capacitances in a winding.

For the disk type transformer we have the developed equations. These are: [6], [7].

The turn-turn capacitance C_{tt} :

$$C_{tt} = \varepsilon_0 \varepsilon_p * 2 * \pi * R_{ave} * \frac{(h + 2\tau p)}{\tau p}$$

Where, R_{ave} = Average radius of the disk
h = Bare copper or conductor height
($h + 2\tau p$ = taking fringing effect into account)
ε_0 =Permittivity of air (vacuum)
ε_p= Relative permittivity of paper
R_{ave} = Average distance of the ring from center.

Now the disks are positioned one upon one using Key spacer which is paper or plastic type materials, in some portion. The rest of the gaps are filled with oil as insulating as well cooling media. So the disk-disk capacitance is expressed as: [6], [7].

$$C_{dd} = \varepsilon_0 \pi * (R_{out}^2 - R_{in}^2) * \left[\frac{f_{ks}}{\frac{\tau_p}{\varepsilon_p} + \frac{\tau_{ks}}{\varepsilon_{ks}}} + \frac{(1 - f_{ks})}{\frac{\tau_p}{\varepsilon_p} + \frac{\tau_p}{\varepsilon_{oil}}} \right]$$

Here, f_{ks} = Key spacer fraction (usually 1/3 in value)

Then we have the apprx. total capacitance of transformer as K:

$$K = \frac{27.8 * D}{N} \left[\frac{\varepsilon_p (h + 2\tau_p)}{2 * n * \tau_p} + \frac{4}{3} * \frac{r + \tau_{ks}}{\frac{2\tau_p}{\varepsilon_p} + \frac{\tau_{ks}}{\varepsilon_{ks}}} \right] * 10^{-12} \text{ F}$$

Here, K = Apprx. total capacitance of transformer. [8]
D = Mean winding diameter
N = No of discs in winding
n = No of turns per disc
τ_p = Thickness of paper insulation
τ_{ks} = Thickness of key spacer

The tabulated data we had for our tested 28MVA, 33/11Dyn 11outdoor type transformer are given below: [1],[4].

Table 1: Tested transformer's properties to be concerned

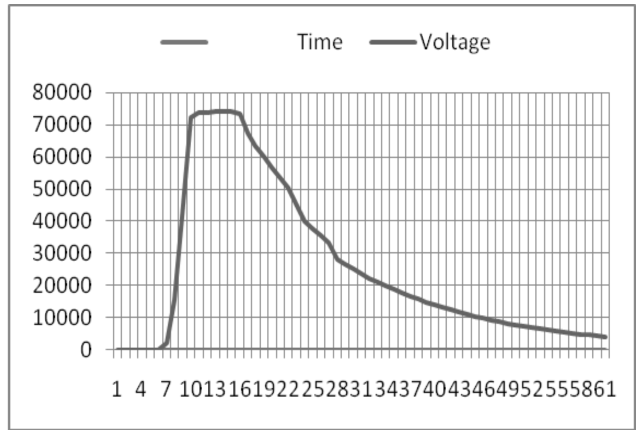
Parameter	Value	Parameter	Value
R_{out}	453 mm	τ_p , τ_{ks}	0.5 mm,4.2mm
R_{in}	365 mm	h	12.2 mm
f_{ks}	1/3	ε_p	3.5
n	8	ε_{oil} , ε_{ks}	2.2, 4.5

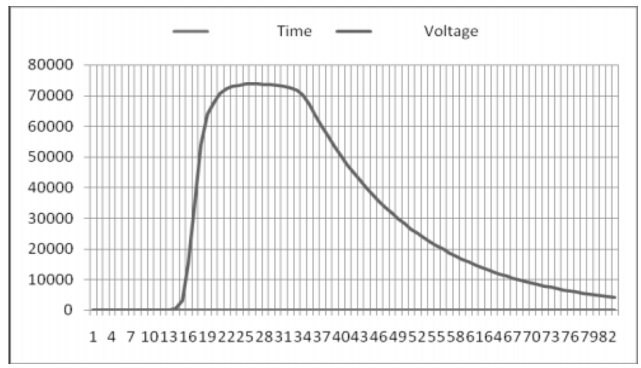
With these data we have calculated the approximate total capacitance of the transformer, K which is found as 33.7 e^{-12} Farad. Then we again use this value as $C_{winding}$ to find the desired impulse.

IV. Real Time Instrument & Experimentation

We are to apply the stated method in a practical impulse test. The Impulse Generator is made by HUAGAO H.V. which has the rated voltage of 1600kv and rated energy storage of 100kJ. In our lab there are up to 7 stages of capacitor bank that can be used. As similar in spice model we have used 3 stages and take the various data over the monitoring system. By taking the all sampled data over the electronic monitoring panel, we have plotted them in excel worksheet. Then the parameters and design data are tabulated and the findings in wave shape in 1st try are compared. The findings are given here serially along with the referred part number.

1. IG output wave at lab for no load using R_f, R_t generated from simulation of fig.5 (reff. to part 3.1):
2. IG output wave found with stray capacitances included in order to get a generalized model for the IG itself (reff. to part 3.2):

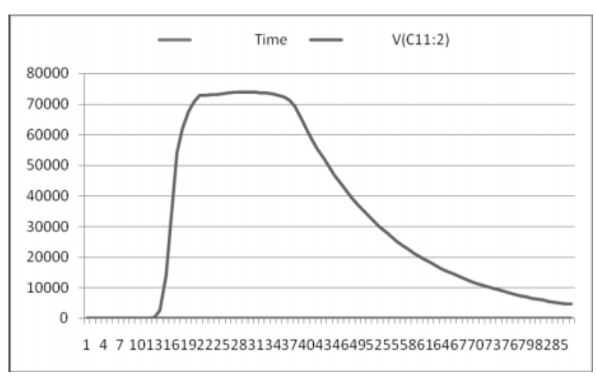




6) IG wave found in lab using R_f, R_t obtained from the simulation of both Spice and MatLab where stray capacitance and transformer winding's equivalent model are included (reff. to part 3.2):

Table 2: Front and Tail time found from simulated model, with load and stray capacitances included for comparing the characteristics of impulse

Lab found		Determined from simulation of part 3.2		Input parameters found from MatLab coding		Simulation model parameters	
T_f	T_t	T_f	T_t	R_f	R_t	C_{stray}	C_{load}
1.31 usec	49.89 usec	1.26 usec	50.97 usec	59	114	50pf	33.7 pf



In comparing between the values listed as in fig. 7 and lab result listed in table 2, here we see that we have gotten an acceptable wave shape in lab to test the insulation level effectively in first try.

V. CONCLUSION AND FUTURE WORKING PLAN

In our present work we have obtained a procedure where from a defined desired output we can calculate the value needed for the parameters to be set. For impulse test then we can get the test result in a quicker and safer way. This can reduce the error as well the durability of various precious equipments. In future we are going to work on low tension side. At low tension terminal as the voltage level is low, so the inductance plays a big role in creating required wave shape. The resultant wave has overshoots as well some high frequency transients. So we are planning to make a detailed model for LT IG test. From which, by means of software we should be able to get the correct wave shape at an instant at both side.

VI. APPENDIX

Reduction of 'n' stage impulse circuitry to a single stage and derivation of U(t) with constants:

The reduction can be made as:
Now in s domain analysis the represented ckt is:

Here, in loop 1:

$$\frac{Uo}{s} = I1\left(\frac{1}{sCd} + Rt\right) - I2*Rt \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

In loop 2:

$$I2\left(Rt + Rf + \frac{1}{sCy}\right) = I1*Rt \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In outer loop:

$$U(s) = I2*\frac{1}{sCy} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

We need to compute U(s) by putting I2.

(2)⇒

$$I1 = \frac{I2\left(Rt + Rf + \frac{1}{sCy}\right)}{Rt} = I2 + I2*\frac{Rf}{Rd} + I2*\frac{1}{sRtCy} \quad \ldots (4)$$

Putting (4) in (1) implies:

$$\frac{Uo}{s} = \{I_2 + I_2\left(\frac{R_f}{R_t}\right) + I_2*\left(\frac{1}{s(R_t C_y)}\right)\}\{\frac{1}{sC_d} + R_t\} - I_2*R_d$$

$$= I_2\left[\frac{1}{sC_d} + \frac{R_f}{s(C_d R_t} + \frac{1}{s^2(R_t C_d C_y)} + R_f - \frac{1}{sC_y}\right]$$

$$I_2 = \left(\frac{Uo}{s}\right)*\left[\frac{1}{\frac{1}{sC_d} + \frac{R_f}{s(C_d R_t)} + \frac{1}{s^2(R_t C_d C_y)} + R_f + \frac{1}{sC_y}}\right]$$

$$= \left(\frac{Uo}{sR_f}\right)*\left[\frac{1}{1 + \frac{1}{s}\left(\frac{1}{R_f C_d} + \frac{1}{R_t C_d} + \frac{1}{R_f C_y}\right) + \frac{1}{s^2(R_f R_t C_d C_y}}\right]$$

$$\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Putting (5) in (3) implies:

$$U(s) = I_2*\left(\frac{1}{sC_y}\right)$$

$$= \left[\frac{Uo}{sR_f}*\frac{1}{1 + \frac{1}{s}\left(\frac{1}{R_f C_d} + \frac{1}{R_t C_d} + \frac{1}{R_f C_y}\right) + \frac{1}{s^2}*\left(\frac{1}{R_f R_t C_d C_y}\right)}\right]*\left[\frac{1}{sC_y}\right]$$

$$= \frac{Uo}{R_f C_y}*\left[\frac{1}{s^2 + s\left(\frac{1}{R_f C_d} + \frac{1}{R_t C_d} + \frac{1}{R_f C_y}\right) + \frac{1}{R_f C_y}*\frac{1}{R_t C_d}}\right]$$

$$\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Now we are to solve Eq[n] (6) by taking the constants A,b and c

$$A = \frac{Uo}{R_f C_y}, b = \left(\frac{1}{R_f C_d} + \frac{1}{R_t C_d} - \frac{1}{R_f C_y}\right), c = \left(\frac{1}{R_f C_y}*\frac{1}{R_t C_d}\right)$$

$$U(s) = A*\frac{1}{s^2 + bs + c} = \frac{A}{(s - s_1)(s - s_2)} = \frac{A}{(s_1 - s_2)}\left[\frac{1}{(s - s_1)} - \frac{1}{(s - s_2)}\right]$$

$$s_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Then, we shall apply inverse Laplace transform on U(s) to get U(t).

$$U(s) = \frac{A}{(s_1 - s_2)}\left[\frac{1}{(s - s_1)} - \frac{1}{(s - s_2)}\right]$$

$$= k*\left[\frac{1}{(s - s_1)} - \frac{1}{(s - s_2)}\right]$$

So,

$$U(t) = k[e^{s_1 t} - e^{s_2 t}]$$

Here,

$$k = \frac{A}{(s_1 - s_2)}, s_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a},$$

$$s_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

$$a = 1,$$

$$b = \frac{1}{R_f C_d} + \frac{1}{R_t C_d} - \frac{1}{R_f C_y}, c = \frac{1}{R_f R_t C_d C_y}$$

$$A = \frac{Uo}{R \; C \; y}$$

. VII. ACKNOWLEDGMENT

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