Theoretical Formulation of a Transient Recovery Voltage when Clearing a Transformer Secondary Fault

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Abstract: An analytical formula of a transient recovery voltage and its *dv/dt* across a circuit breaker has been derived for the case of a transformer secondary fault. A comparison of the calculated results with field test and EMTP simulation results has proved its satisfactory accuracy. Applying the formula, the effect of various circuit parameters on the transient recovery voltage and its *dv/dt* have been made clear. The *dv/dt*, defined conventionally as the ratio of the crest value and the time to the crest, is found to be about 2/3 of the maximum value of the *dv/dt* given as a function of the time. Also, a formula has been developed to give critical circuit parameters by which the *dv/dt* across a vacumn circuit breaker reaches the critical condition i.e. the circuit breaker fails to interrupt a fault current.

Keywords: TRV, fault clearing overvoltage, VCB, measurement, simulation, analytical formula

1. INTRODUCTION

A vacumn circuit breaker (VCB) has been widely used in a utility power system, a factory and a large building, because of its high capability of current interruption. On the contrary, the VCB produces a high transient recovery voltage (TRV) due to the current interruption. When a fault current at the secondary side of a transformer is interrupted by the VCB at the primary side, it produces a severe *dv/dt* (rate of voltage rise at the wavefront) across the VCB poles in a spot-network power receiving facility [1, 2]. It is possible that the VCB loses its current interruption capability due to the severe *dv/dt*.

A field test is, in theory, the most accurate approach. It, however, is not always possible to carry, and is time and money consuming. Also, a field test result often involves an error due to the measuring system, and its correction is, in general, not straightforward. It was pointed out in reference (3) that the measured frequency of a TRV was more than 30% lower than the real value because of the capacitance of a CR divider used to measure voltages. A numerical simulation nowadays is a quite powerful and convenient approach to investigate a power system phenomenon, because a very sophisticated and generalized computer program, such as EMTP, SPICE, MATLAB and etc, has been developed. The numerical simulation, however, is not always efficient when carrying a parametric analysis, and not accurate enough when the parameters being not certain. Also, it often makes a user to lose a physical insight of the phenomenon.

The present paper develops an analytical formula of a TRV. Calculated results by the formula are compared with a field test of the TRV and a simulation result by the ATP-EMTP [4]. A parametric analysis of the TRV is carried out by the formula in comparison with the EMTP simulation. The formula is applied to find a critical condition of a VCB failure of current interruption.

2. FIELD TEST AND EMTP SIMULATION

The detail of a field test and an EMTP simulation was reported in the IPST '97 as reference (3). The result is summarized here.

A. Field test

Fig. 1 illustrates a field test circuit of a fault clearing overvoltage due to current interruption by a VCB. A 3-phase to ground fault is initiated at the secondary (low voltage) side of a 22/6.6kV 3MVA transformer, and the fault current is interrupted by a VCB at the primary (high voltage) side of the transformer. Transient voltages to the earth on phase "C" at the both terminals of the VCB are measured through a CR devider.

Table 1 summarizes the test conditions and results. Fig. 2 shows phase "C" transient voltage waveforms across the VCB. (a) to (c), case No. 13 to 15, are the case that phase "C" is the first phase to be interrupted, and (d), case No. 16, the case of the phase "B" being the first phase.

B. EMTP simulation

Fig. 3 illustrates a model circuit of the EMTP simulation corresponding to the field test circuit in Fig. 1. The circuit parameters are:

1) transformer stray capacitance $C_{gA}=128$, $C_{gB}=134$, $C_{g2}=450$, $C_m=420$, $C_h=15$, $C_h'=4$ [pF]
leakage inductance $L_{t1}=105.3$, $L_{t2}=87.84$ [mH]
resistance of windings $r_h=1.31$, $r_c=0.06$ [Ω]
magnetizing circuit resistance $R_m=159$ [kΩ]
2) CR devider capacitance $C_p=500$ [pF]
3) source inductance $L_s=1.96$ [mH]
4) source voltage E_0 case No. 13: $E_0=17.96$,
No. 14: $E_0=8.80$, No. 15 and 16: $E_0=12.60$ [kV]

Table 2 summarizes the simulation conditions and results corresponding to Table 1. Transient voltage waveforms are

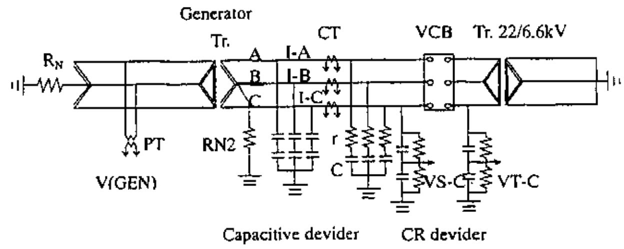


Fig. 1 Field test circuit

given in Fig. 4. It is observed in Table 2 that the calculated result with the interrupted current I_{co}=2.0A agrees best with the field test result for case No. 13. I_{co}=0 is not realistic because a spike voltage just after t=0 (current interruption) in the field test result does not appear in the simulation result with I_c=0. The interrupted current of the VCB was informed to be 1.8 to 2.5A.

The above observation makes it clear that an EMTP simulation gives a satisfactory result compared with a field test result.

3. DERIVATION OF ANALYTICAL FORMULA

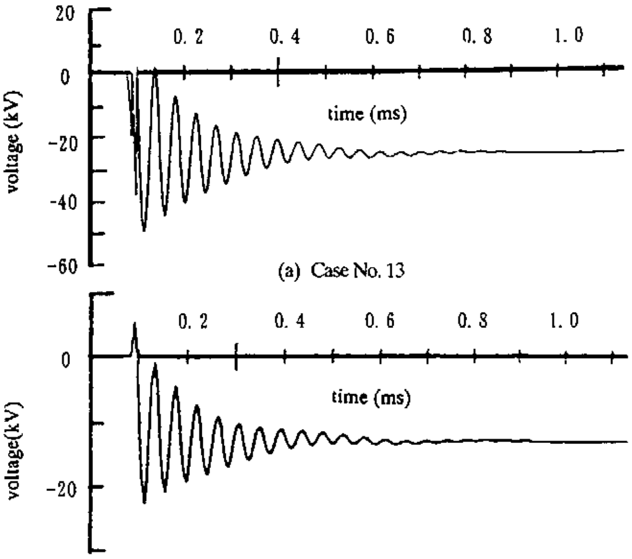
A. Model circuit

Fig. 5 illustrates a model circuit of an analytical

Table 1 Test conditions and results

Case No.	phase	interruption phase	interruption time (ms)	source voltage (kV)	recovery voltage (kV)	fault current (A)	TRV voltage (kV)	TRV freq. (kHz)	TRV dv/dt (kV/us)
13	C	C	30.6	18.2	18.0	1080	50.9	23.0	2.34
14	C	C	31.4	9.22	9.11	545	23.4	23.0	1.08
15	C	C	30.8	13.4	13.2	797	29.3	23.0	1.35
16	B	B	30.8	13.5	13.4	800			
	C			13.4	13.2	794	12.1	30.8	0.745

source freq.=50Hz , CR devider on phase C



(a) Case No. 13

(b) Case No. 14

Fig. 2 Test results of voltage waveforms across VCB

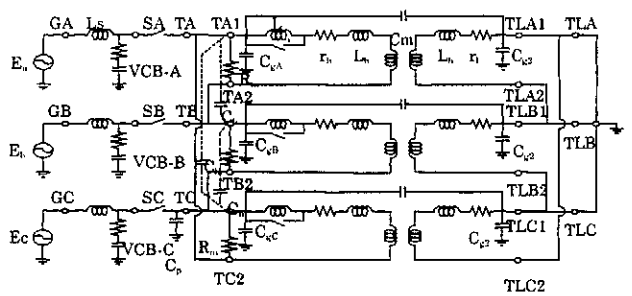


Fig. 3 Model circuit

formulation of a TRV due to current interruption of a 3-phase to ground fault at a transformer secondary side by a VCB. Although a transformer is, in general, Δ-Δ connected in medium and low voltage systems, the transformer in Fig. 5 is made to be Y-Y connection with isolated neutral by applying Δ-Y transformation. A 3-phase symmetrical AC voltage is taken as a source in Fig. 5.

$$E_a(t) = E_o\sin(\omega t + \theta)$$
$$E_b(t) = E_o\sin(\omega t + \theta - 2\pi/3) \qquad (1)$$
$$E_c(t) = E_o\sin(\omega t + \theta - 4\pi/3)$$

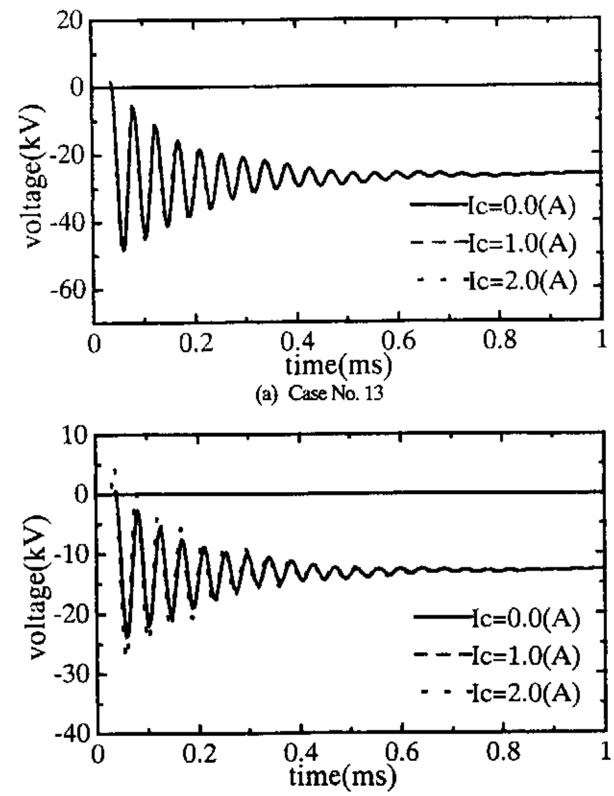
The 3-phase fault currents are interrupted in the sequence of phase "C" and the phases "A" and "B".

B. Derivation of an analytical formula

An equivalent circuit to Fig. 5, when the first phase being interrupted at t=0 with its peak (θ=-π/6), is shown in Fig. 6 (a). The voltage of the remaining phases "A" and "B" are

Table 2 Simulation conditions and results

case No. /Ico(A)	interruption phase	interruption time (μs)	recovery voltage (kV)	load-side voltage (kV)	TRV voltage (kV)	TRV freq. (kHz)	TRV dv/dt (kV/us)
13/0.0	C	39.0	-18.6	31.2	-48.3	23.3	2.25
13/1.0	C	37.0	-18.6	31.0	-48.2	23.3	2.24
13/2.0	C	35.0	-18.6	32.1	-49.3	23.2	2.35
14/1.0	C	35.0	-9.13	15.7	-24.1	23.2	1.15
15/1.0	C	36.0	-13.1	22.0	-34.0	23.2	1.60
16/1.0	B	36.0	13.1	-21.6	33.6	31.3	2.14
	C	4581	12.6	9.07	14.5	32.0	0.946



(a) Case No. 13

(b) Case No. 14

Fig. 4 Simulation results of voltage waveforms across VCB given by:

$$E_a(t=0)=E_b(t=0)=-E_o/2 \quad (2)$$

For an interesting time period is some 10 μs at most, the voltage source in Fig. 6 (a) is assumed to be a dc voltage. Thus, L_s and C_t in Fig. 6 (a) cause no effect on the transient. Neglecting the resistance r_t and considering the initial values, an equivalent circuit with Laplace operator "s" is drawn as Fig. 6 (b), where the following relation of the initial value is given.

$$V_{co}=V_c(t=0)=E_o\,,\; I_{bo}=I_b(t=0)=-I_a(t=0)=I_{ao} \quad (3)$$

I_{co} = interrupted current of the first phase

Considering the above, Fig. 6 (b) is further simplified as Fig. 6 (c), where the load-side voltage $V_c(s)$ of the phase "C" VCB is given by:

$$V_c(s)=Eo/s-\left(3Eo/2s+L_tI_{co}\right)/\left(1+s^2/\omega_1^2\right) \quad (4)$$

$$\text{where}\quad \omega_1^2=2/3L_tC_c\,,\; C_c=C_{gA}+C_h+2C_h'+C_m+C_p \quad (5)$$

Laplace inverse transform of (4) results in :

$$v_c(t)=-Eo/2+V_o\cos(\omega_1 t-\phi) \quad (6)$$

$$\text{where}\quad V_o=(3/2)\sqrt{E_o^2+E_1^2}\,,\; \phi=\tan^{-1}(-E_1/E_o) \quad (7)$$

$$E_1=(4/9)Z_oI_{co}\,,\; Z_o=\sqrt{3L_t/2C_c}$$

The voltage across the phase "C" VCB is then given by:

$$v_{CB}(t)=3E_o/2-V_o\cos(\omega_1 t-\phi) \quad (8)$$

The above formulation has neglected the damping oscillation of transient voltages. The damping has been found to come mostly from the resistance R_m of the transformer magnetizing circuit in Fig. 3 because it becomes a part of a closed circuit in the load-side circuit after the phase "C" VCB open circuited. When taking R_m into account, an equivalent circuit to Fig. 5 is given as Fig. 7 in s-domain. From the figure, $V_c(s)$ is obtained and its Laplace inverse transform gives the following time solution.

$$v_c(t)=-Eo/2$$
$$-\left\{(3\alpha Eo+2I_{co}/3C_c)\sin(\beta t)+(3\omega_1 Eo/2)\sin(\beta t+\varphi)\right\}\exp(-\alpha t)/\beta \quad (9)$$

where

$$\varphi=\tan^{-1}\left(\sqrt{\omega_1^2-\alpha^2}/\alpha\right),\quad \alpha=1/3R_mC_c,\; \beta=\sqrt{\omega_1^2-\alpha^2}$$

Applying the following approximation:

$$\beta=\sqrt{2/3L_tC_c-1/4R_m^2C_c^2}\cong\sqrt{2/3L_tC_c}=\omega_1$$
$$\varphi\cong\tan^{-1}(\omega_1/\alpha)=\tan^{-1}\left(\sqrt{6}R_m/Z_o\right)\cong\pi/2 \quad (10)$$

(9) is simplified as:

$$v_c(t)=-Eo/2-\left\{V_o\cos(\omega_1 t-\phi)-(Z_oE_o/R_m)\sin(\omega_1 t)\right\}$$
$$\cdot\exp(-\alpha t) \quad (11)$$

The voltage across the phase "C" VCB is given in the following equation.

$$v_{CB}(t)=-1.5E_o-\left\{V_o\cos(\omega_1 t-\phi)-(Z_oE_o/R_m)\sin(\omega_1 t)\right\}$$
$$\cdot\exp(-\alpha t) \quad (12)$$

It should be clear that the above equation becomes the same as (6) with R_m reaching infinite.

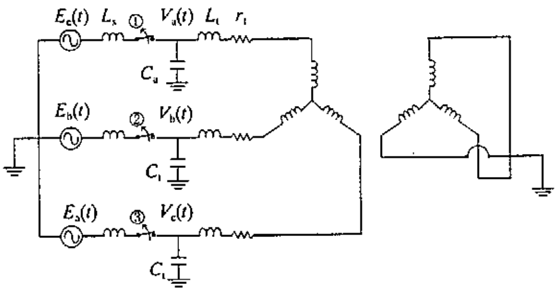
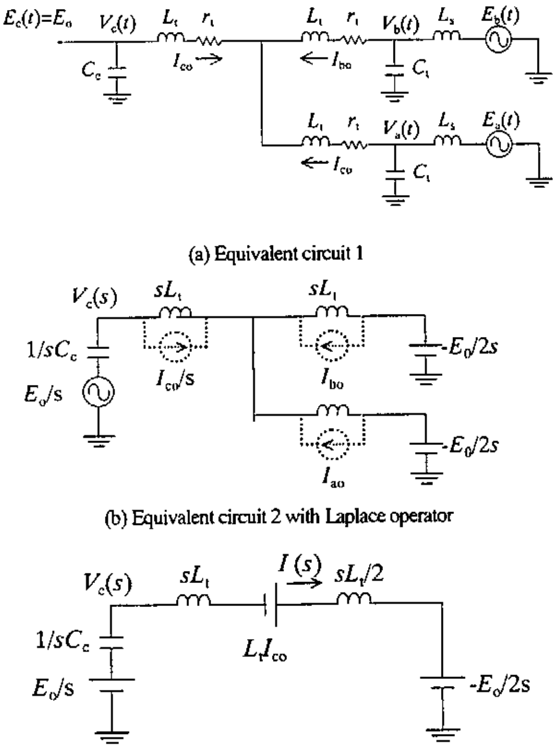


Fig. 5 A model circuit of an analytical formulation



(a) Equivalent circuit 1

(b) Equivalent circuit 2 with Laplace operator

(c) Equivalent circuit 3

Fig. 6 Equivalent circuit to Fig. 5

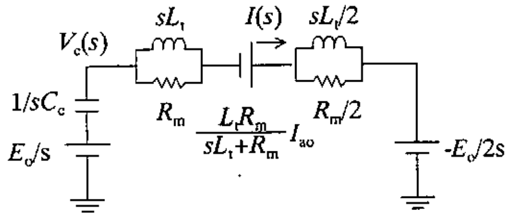


Fig. 7 An equivalent circuit to Fig. 5 considering Rm

In the same manner as the above, the remaining phase voltage, when it is interrupted, are derived. For example, the phase "a" voltage at the load-side is given by:

$$v_a(t) = \frac{1}{2}(E_{ao} + E_{bo}) - \left[\frac{1}{2}(E_{bo} - E_{ao})\{\cos(\omega_2 t') - \alpha_2/\omega_2 \sin(\omega_2 t')\}\right.$$
$$\left. + \frac{I_{co}}{\omega_2 C_a}\sin(\omega_2 t')\right]\exp(-\alpha_2 t') \qquad (13)$$

where $\alpha_2 = 1/2C_a R_m,\ C_a = C_m + C_{gA} + C_h + 2C_h',$

$\omega_2 = \sqrt{1/L_t C_a - \alpha_2^2},\ t' = t - T_a,$

T_a: time when phase "A" interrupted

$E_{ao} = E_o \sin(\omega T_a + \theta),\ E_{bo} = E_o \sin(\omega T_a + \theta - 2\pi/3)$

C. Analytical formula of dv/dt and maximum values

Rate of rise (dv/dt) of the VCB voltage is given by replacing E_o with $E_a(t)$ of (1).

1) Neglecting R_m

$$dv_{CB}(t)/dt = (3\omega Eo/2)\cos(\omega_1 t + \theta) + \omega_1 V_o \sin(\omega_1 t - \phi) \qquad (14)$$

2) Considering R_m

$$dv_{CB}(t)/dt = (3\omega Eo/2)\cos(\omega_1 t + \theta) + \sqrt{\omega_1^2 + \alpha^2}\exp(-\alpha t)$$
$$\cdot\{V_o \sin(\omega_1 t - \phi + \varphi_1) + Z_o E_o / R_m \cos(\omega_1 t - \varphi_2)\} \qquad (15)$$

where $\varphi_1 = \tan^{-1}(\alpha/\omega_1),\ \varphi_2 = \tan^{-1}(-\alpha/\omega_1) = -\varphi_1$

Applying the following approximation:

$$\sqrt{\omega_1^2 + \alpha^2} \cong \omega_1,\ \varphi_1 = -\varphi_2 \cong 0 \qquad (16)$$

(15) is simplified as:

$$dv_{CB}(t)/dt = (3\omega Eo/2)\cos(\omega_1 t + \theta)$$
$$+ \{\omega_1 V_o \sin(\omega_1 t - \phi) + 3\alpha E_o \cos(\omega_1 t)\}\exp(-\alpha t) \qquad (17)$$

The maximum voltage of $v_{CB}(t)$ and $dv_{CB}(t)/dt$, and the natural resonance frequency are given by:

1) Neglecting R_m

$$v_{CBmax} = 1.5Eo + V_o \quad at\ t = t_1 = (\pi + \phi)/\omega_1$$
$$dv_{CB}(t)/dt|_{max} = \omega_1 V_o \quad at\ t = t_2 = (\pi/2 + \phi)/\omega_1 \qquad (18)$$

$$f_1 = 1/T_1 = 1/\pi\sqrt{6L_t C_c} \qquad (18')$$

2) Considering R_m

$$v_{CBmax} = 1.5Eo + (V_o + 1.5Z_o E_o E_1/R_m V_o)\exp\{-(\pi + \phi)/2R_m Z_o\}$$
$$dv_{CB}(t)/dt|_{max} \cong (\omega_1 V_o - 9\alpha E_o E_1/2V_o)\exp\{-(\pi/2 + \phi)/2R_m Z_o\} \qquad (19)$$

Conventionally dv_{CB}/dt is defined using the maximum value v_{CBmax} and time to v_{CBmax}.

$$dv/dt = |v_{CBmax}|/(t_{max} - t_o) = |v_{CBmax}|/(T/2) \qquad (20)$$

where $T = 1/f_1$: oscillating period

It should be noticed that the above definition differs from $dv_{CB}/dt|_{max}$ in (18) and (19), i.e. (20) is an averaged rate of rise per half the period of the oscillating waveform and is smaller than those in (18) and (19).

D. Calculated results

Test cases in Table 1 are calculated using the formulas in the previous sections. It should be noted that the transformer in the field test was delta-delta connected as in Fig. 1, while the transformer was assumed star-star connected in the derivation of the analytical formula. Thus, the values of the leakage inductance L_t and the resistance R_m is transformed from the delta to the star winding in the evaluation. Calculated results are summarized in Table 3. Also, transient voltage waveforms across the VCB by the proposed formula are shown in Fig. 8.

A comparison of Table 3 with Tables 1 and 2 shows that the analytical result of the oscillating frequency agrees quite well with the field test and EMTP simulation results. The analytical results of the maximum voltage and the transient waveforms agree satisfactorily with the EMTP simulation results. The maximum error of the proposed formula compared with the EMTP simulation is observed to be 12% for v_{CBmax}. Also, waveforms in Fig. 8 agree well. From the observation, the proposed analytical formula is said to be reasonably accurate. If a transient voltage waveform is not concerned, the formula neglecting R_m, i.e. (8), (14) and (18) are good enough as observed in Table 3.

4. APPLICATION OF THE PROPOSED FORMULA

A. Rate of rise of a transient voltage across a VCB

The rate of rise of a transient voltage across a VCB is conventionally defined as in (20). It is clear that the definition gives an averaged rate of rise which is lower than the rate of rise given by (18) and (19). Table 4 shows the rate of rise as a function of time evaluated by (18). It is observed that dv_{CB}/dt becomes maximum at t=6.835 μ s corresponding to t_2 in (18) and minimum at t=17.61s corresponding to the time t_1 at which v_{CB} becomes maximum. The variation of dv_{CB}/dt as a function of time may be significant to a detailed investigation of current interruption capability of a VCB in conjunction with time variation of its dielectric strength. In such the case, the analytical formula is expected to be very useful.

B. Effect of circuit conditions

1) Interrupted current I_{co}

It is evident in (7) that a contribution of interrupted current I_{co} to a transient voltage is given by E_1=(4/9)$Z_o I_{co}$. Table 5 shows variation of v_{CB} and dv_{CB}/dt as a function of I_{co}. It is clear from the table that the maximum voltage and rate of rise increase as the interrupted current increases via the increase of E_1.

2) capacitance C_c

(18) indicates that v_{CBmax} increases as Z_o increases and, $dv_{CB}/dt|_{max}$ increases as $\omega_1 Z_o = 1/C_c$ increases. This is clearly observed from a comparison of cases No.15 and 16 in Table 3. The both cases are in the same conditions except C_c=1071pF in case No.15 while C_c=571pF in case No.16. Effectiveness of a surge capacitor or a CR surge suppressor is evident from the above.

Table 3 Analytical results by the proposed formula

Case	phase	E_0 (kV)	I_{co} (A)	R_m	E_1 (Kv)	V_0 (kV)	Z_0 (Ω)	f_1 (kHz)	T_1 (μs)	v_{CBmax} (kV)	time (μs)	$dv_{CB}/dt\|_{max}$ (kV/μs)	time (μs)	dv/dt (kV/μs)
13	C	18.0	2.0	NO	5.69	28.3	6404	23.2	43.1	55.2	19.4	4.12	8.67	2.56
				YES	5.69	28.3	6404	23.2	43.1	55.9	19.4	4.03	8.67	2.59
14	C	8.8	1.0	NO	2.85	13.9	6404	23.2	43.1	27.1	19.4	2.02	8.63	1.26
				YES	2.85	13.9	6404	23.2	43.1	27.4	19.4	1.98	8.63	1.27
15	C	12.6	1.0	NO	2.85	19.4	6404	23.2	43.1	38.3	20.0	2.83	9.25	1.78
				YES	2.85	19.4	6404	23.2	43.1	38.6	20.0	2.78	9.25	1.79
16	B	12.6	1.0	NO	3.90	19.8	8770	31.8	31.4	38.7	14.2	3.95	6.36	2.46
				YES	3.90	19.8	8770	31.8	31.4	39.3	14.2	3.83	6.36	2.50

3) Inductance L_t

The oscillating frequency f_1 decreases and the surge impedance Z_0 increases as the inductance L_t increases in (18). The increase of Z_0 results in an increase of v_{CBmax}. $dv_{CB}/dt|_{max}$ decreases because the decrease of f_1 is relatively greater than the increase of Z_0.

4) Resistance R_m

A comparison of (8) and (12) shows clearly that the resistance R_m damps an oscillating voltage by the term of exp(- α t). If only the first few cycle of the oscillation concerns, R_m causes no effect because of very small "t". Therefore, R_m can be neglected to evaluate the maximum voltage and rate of rise. It is very difficult to measure the value of R_m. In this paper, it is determined from the measured waveform of an oscillating voltage. In general, R_m can be taken as some 10kΩ.

C. Effect of CR divider

It has been known that a measuring system affects a measured result especially in a transient overvoltage. In the field test explained in Sec. 2. A, the transient voltage was measured by a CR divider as a common practice, and it was found that the measured voltage and its rate of rise were significantly different from those with no CR divider [4, 5]. This will be investigated by applying the proposed formula.

Table 6 shows the effect of a CR divider evaluated by the proposed formula. It is obvious that the CR divider reduces v_{CB} by 1 to 2 kV (1 to 7%) and the oscillating frequency f_1 by 8.5kHz (37%). The rate of rise of v_{CB} is decreased by 35 to 45% depending mainly on the decrease of f_1, which is analytically defined by:

$$k = \sqrt{C_p/(C_p + C_t)} \tag{21}$$

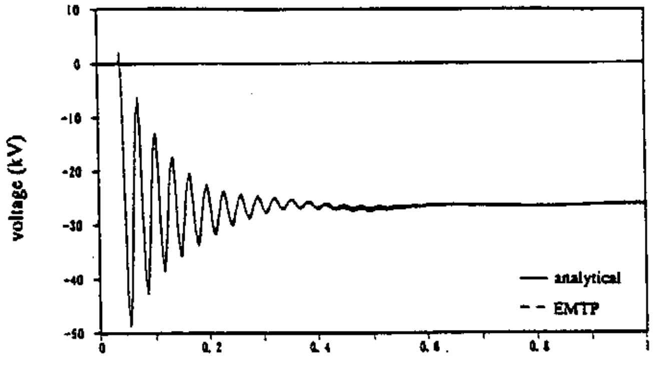
In the field test, C_p=500pF and C_t=571pF give the above value as k=0.683. The value explains the decrease of f_1 in Table 6 and the difference of f_1 in cases No.13 to 15 and case No. 16 where no CR divider was installed in phase B.

D. Characteristic of current interruption overvoltage

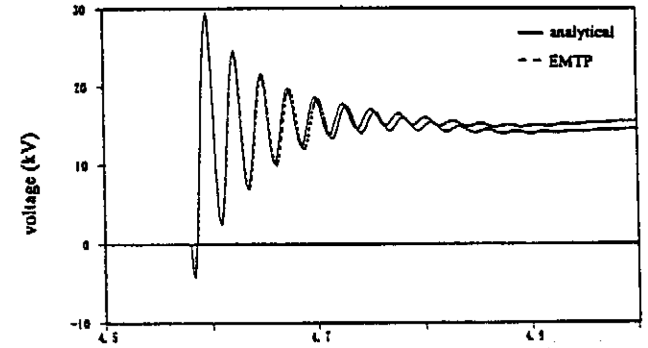
1) Voltage across a VCB and its rate of rise

If the condition $E_0^2 >> E_1^2$ is satisfied, V_0 in (7) is simplified using the approximation $\sqrt{1+x} \cong 1+x/2$ for $1 >> x$.

$$V_o = 1.5E_o(1+8m/81),\ m = (Z_o I_{co}/E_o)^2 \tag{22}$$



(a) Phase C—first interrupted phase



(b) Phase B—second interrupted phase

Fig. 8 Analytical results of voltage waveforms across VCB for case No.13

Table 4 Rate of rise as a function of time by (18) for case No. 14 (I_{co}=2A)

time (μs)	1	2	5	6.835	8	10	12	15	17.61
dv_{CB}/dt (kV/μs)	1.484	1.746	2.210	2.292	2.259	2.052	1.672	0.203	0

Table 5 Effect fo interrupted current Ico for case No.14

I_{co} (A)	0	1	2	3	5
E_1 (kV)	0	2.846	5.692	8.538	14.23
V_0 (kV)	13.2	13.87	15.72	18.39	25.10
v_{CBmax} (kV)	26.4	27.07	28.92	31.59	28.30
$dv_{CB}/dt\|_{max}$ (kV/μs)	1.925	2.022	2.292	2.681	3.715
dv/dt (kV/μs)	1.225	1.256	1.342	1.466	1.778

In the field test in Sec. 2. A, the condition $E_0^2 >> E_1^2$ is satisfied as is clear from Table 3, and the parameters in (22) are in the following range.

Z_0=6 to 9 [kΩ], I_{co}=2 to 1 [A], E_0=9 to 18 [kV]

Then the value of m ranges in the following region.

$$m = 0.25 \text{ to } 2 \qquad (23)$$

Rewriting (18) and (20) by using m,

$$v_{CBmax} = 3E_o(1+4m/81) \cong 3E_o(1+0.05m)$$
$$dv_{CB}/dt|_{max} = (3/2)\omega_1 E_o(1+8m/81) \cong (3/2)\omega_1 E_o(1+0.1m) \qquad (24)$$
$$dv/dt = (6E_o/T_1)(1+4m/81) \cong (3/\pi)\omega_1 E_o(1+0.05m)$$

The following observations are made from (24) considering (23).

a) The maximum voltage (v_{CBmax}) across a VCB is about 3 times of the initial steady-state voltage E_0 at the VCB terminal. A contribution of a transient component E_1 given by the product of the interrupted current I_{co} and the apparent surge impedance Z_o is 10% of E_0 at most, i.e. an influence of the circuit parameters is less than 10%.

b) An average rate of rise of v_{CB} is given approximately by $1.5\omega_1 E_o$, and a contribution of the transient component E_1 is less than 10%.

c) The maximum rate of rise ($dv_{CB}/dt|_{max}$) is more than 1.5 times of dv/dt, and a contribution of the transient component reaches 20% at most. It should be noticed that the second term of the rate rise in (24) is affected mainly by $1/C_c$.

2) Critical condition of *dv/dt*

A VCB becomes not able to interrupt a fault current when *dv/dt* exceeds a certain value g_o. If circuit parameters corresponding to $dv/dt < g_o$ can be found, it is very useful to an installation and design of a VCB. The critical condition is derived from (24).

$$(3/\pi)\omega_1 E_o(1+4m/81) < g_o$$

Considering that $1+4m/81<1.1$, let's approximate $1+4m/81=1.1$. Then,

$$\omega_1 < \pi g_o / 3.3E_o$$

Substitution of L_t and C_c into ω_1,

$$L_t C_c > 0.74(E_o/g_o)^2 \qquad (25)$$

The above equation is rewritten by:

$$C_c > 0.74(E_o/g_o)^2/L_t, \quad L_t > 0.74(E_o/g_o)^2/C_c$$
$$\text{or } E_o < 1.17 g_o\sqrt{L_t C_c} \qquad (26)$$

From the above equation, the critical condition, C_c for example, is estimated by given parameters E_0, L_t and g_o.

In the field test, the following parameters are known. g_o=2.8kV/μs, L_t=29.28mH, C_c=1071pF for cases No. 13 to 15. Under the above condition, the critical source voltage E_o that the VCB being able to interrupt a fault current is given from the third equation of (26) by: E_o<18.3kV

In fact, the VCB failed to interrupt a fault current when the source voltage exceeded 18kV due to restriking in the field test. This might be a typical example to prove a usefulness of (26).

Table 6 Effect of CR divider

Case No.	I_{co} (A)	CR divider	v_{CBmax} (kV)	dv/dt (kV/μs)	f_1 (kHz)
13	1.5	YES	54.64	2.536	23.2
		NO	55.28	3.514	31.8
14	2.0	YES	28.92	1.342	23.2
		NO	30.83	1.960	31.8
15	1.5	YES	38.86	1.787	23.2
		NO	39.74	2.526	31.8

5. CONCLUSIONS

The paper has derived an analytical formula of a transient recovery voltage and its rate of rise across a vacumn circuit breaker (VCB) when the VCB interrupts a fault current due to a three-phase to ground fault at a transformer secondary side . Results evaluated by the formula are compared with those of a field test and EMTP simulation, and its accuracy has been confirmed to be reasonable.

Applying the proposed analytical formula, a characteristic of a transient voltage due to current interruption is investigated and the following remarks have been obtained.

1) The conventional definition of *dv/dt* is an averaged value of a time function *dv(t)/dt*, and is about 2/3 of the maximum value of the time function.

2) A capacitance C_p of a CR divider to measure the transient voltage reduces the maximum voltage by 1 to 7%, and the oscillating frequency by more than 35%. dv/dt is decreased by 35 to 45% depending mainly on the decrease of the oscillating frequency given by $\sqrt{C_p/(C_p+C_c)}$ where C_t the transformer capacitance.

3) The maximum voltage across a VCB is about 3 times of the initial steady-state voltage at the VCB terminal and a contribution of the circuit parameters to the maximum voltage is less than 10%.

4) A critical condition by which a VCB fails current interruption has been analytically derived. The formula can determine a critical circuit condition such as a total capacitance of the circuit and a source voltage.

The analytical formula developed in the paper is expected to be very useful to an installation and design of a VCB.

6. REFERENCES

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