A Fault Clearing Overvoltage in A Vacumn Circuit-Breaker with Special Reference to Circuit Parameter Uncertainty

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Abstract

A field test was carried out to investigate a fault clearing overvoltage due to current interruption of a 3-phase to ground fault at the secondary side of a *22/6.6*kV *3*MVA to transformer by a vacumn circuit-breaker. EMTP simulations in comparison with the field test results have made it clear that the capacitance of a CR divider to measure voltages affects significantly *dv/dt* of a transient voltage across the circuit breaker, and the measured results of *dv/dt* using the CR divider are far smaller than the real values of *dv/dt*. Also, it has been found that the leakage inductance of the transformer are rather different from that evaluated from its rating possibly due to the transformer saturation caused by the large fault currents. An interrupted current by a circuit breaker and a magnetizing resistance of a transformer should not be neglected in an EMTP simulation to obtain a satisfactory result.

Keywords : Fault surges, Transient recovery voltage,
Vacumn circuit breaker, EMTP

1. Introduction

Vacumn circuit breakers (VCB) have been widely used in a utility power system, a factory and a large building, because of the high capability of current interruption. On the contrary, the VCB produces a high overvoltage during 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* (voltage rise at the wavefront) across the VCB poles in a spot-network receiving facility./1/ It is possible that the VCB losses its current interruption capability due to the severe *dv/dt*./2/

The present paper investigates a fault clearing overvoltage due to fault current interruption by a VCB. A field test of the overvoltage was carried out. A 3-phase to ground fault was initiated at the secondary (low voltage) side of a *22/6.6*kV *3*MVA transformer, and the fault current was interrupted by a VCB at the primary side of the transformer. Transient voltages at the VCB terminals were measured through a CR divider. The field test is simulated by the Electro-Magnetic Transients Program (EMTP/3/). The simulation results are compared with the field test result to investigate the EMTP simulation accuracy. Then, a parametric analysis is carried out by the EMTP in comparison with the field test to make uncertain circuit parameters clear.

2. 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 *22/6.6*kV *3*MVA 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 "T" at the both terminals of the VCB are measured through a CR divider of which the capacitance to the earth is *500*pF. The first phase to interrupt the fault current is controlled to be either phase "T" or phase "S". A source voltage E_0 is varied from *8*kV to about *20*kV so as to find a critical voltage to cause VCB failure of current interruption.

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

It is observed that the oscillating frequency of the transient voltages in case No. 13 to 15 is $f_1=23.0$kHz, while that in case No. 16 is $f_2=30.8$kHz. For the case No. 13 to 15 are different only in the source voltage, the maximum overvoltages across the VCB are different proportionally to the source voltage. A difference between case No.15 and No.16 is the CR divider which is installed in phase "T". In other words, the capacitance of the CR divider affects the oscillating frequency in case No.15 where phase "T" is interrupted first, while it dose not in case No. 16 where phase "S" is interrupted first.

Put L_t being the transformer inductance, C_t the transformer capacitance and C_p the CR divider capacitance. Then, the oscillating frequencies f_1 in case No. 13 to 15 and f_2 in case No.16 are given in the following equation.

$$f_1 = a\Big/\sqrt{L_t\left(C_t + C_p\right)}, \quad f_2 = a\Big/\sqrt{L_t C_t} \qquad (1)$$

a : constant

The above equation gives the following relation.

$$k = f_2/f_1 = \sqrt{\left(C_t + C_p\right)/C_t} \qquad (2)$$

The capacitances are given in the field test by :

$$C_t \cong 570pF, \ C_p \cong 500pF \qquad (3)$$

Thus, we obtain

$$k=1.37 \qquad (4)$$

From Table 1, the following result is given.

$$k = f_2/f_1 = 30.8/23.0 = 1.34 \qquad (5)$$

The above agrees well with that in eq. (4). Therefore, it is confirmed that the reason why the oscillating frequency is higher in case No. 16 than in case No.13 to 15 is that the *CR* divider capacitance affects the oscillating frequency in case No. 13 to 15.

The above observation has indicated that a measured result of the oscillating frequency of a transient voltage is lower by $\sqrt{C_t/(C_t+C_p)}$ than its actual value. This results in lower dv/dt in the measured result, and may cause a trouble if the measured dv/dt is adopted to a design and application of a VCB.

The above phenomenon is theoretically quite reasonable and may have been well known. It , however , has not been reflected in the standard of a VCB and its testing in Japan.

3. EMTP Simulation

3.1 Model Circuit and Parameters

A digital simulation of the field test explained in the previous chapter is carried out using the EMTP. 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 $C_{gA}=128$, $C_{gB}=134$, $C_{g2}=450$, $C_m=420$, $C_n=15$, $C_n'=4$ [pF]

leakage inductance $L_{t1}=105.3$, $L_{t2}=87.84$ [mH]

resistance of windings $r_b=1.31$, $r_e=0.06$ [Ω]

magnetizing resistance $R_{mag}=159$ [kΩ]

(2) CR divider 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]

In the above, the transformer capacitances are estimated by a numerical calculation of 6 simultaneous equations based on capacitance measurements. The inductances L_{t1} and L_{t2} are determined from measured results of voltages and currents during a 3-phase to ground fault, and after current interruption of the first phase. The magnetizing resistance is estimated from the attenuation constant of a measured transient voltage knowing the inductances.

In an EMTP simulation, a 3-phase to ground fault is set for time $t<0$. At $t=0$, one phase of a VCB interrupts a fault current which is varied from 0 to 3A because the value was unknown in the field test. At the same time ($t=0$), the transformer inductance is changed from L_{t1} for $t<0$ to L_{t2} for $t\geq0$.

3.2 Simulation Result

Table 2 summarizes the simulation conditions and results corresponding to Table 1. Transient voltage waveforms are given in Fig. 4.

It is observed in Table 2 that the calculated result with the interrupted current $I_c=1.5$A agrees best with the field test result for case No. 13. For case No. 14 to 16, the calculated results with I_c =1.0A seem to be the best though dv/dt in the calculated results is greater than that in the filed test result . The interrupted current I_c, which gives a good agreement of a simulation result with a field test result, tends to be proportional to the source voltage E_0. Considering the transient voltage waveforms in Figs. 2 and 4, the optimum value of I_c for a simulation seems to be 0.5 to 1.5A in the cases investigated in the present paper. $I_c=0$ 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 $I_c=0$.

From the above observation, it can be said that an EMTP simulation can give a satisfactory result compared with a field test result as far as circuit parameters in the simulation are appropriate.

3.3 Discussions of Circuit Parameters

(1)Transformer inductance

In a transient simulation, a transformer is represented quite often by its leakage inductance. The test ransformer in Fig. 1 has the following rating.

primary voltage 22kV, secondary 6.6kV

capacity 3MVA, %reactance 8.3%

Based on the above rating, the leakage inductance at a power frequency is given by:

$L_{t1}=128.3$mH

The above inductance is greater by about 20% than that determined from the measured result in Sec. 3.1. The reason for the difference is estimated that:

(a) The transformer is saturated by the large fault current, and thus its inductance becomes smaller than that in a steady state.

(b) The leakage inductance at a high frequency (transient frequency) differs from that at a power frequency.

Simulation results with the inductance are given in Table 3. In this case, the fault current ($t<0$) is smaller by about 20% as expected. The transient voltage are little smaller and the oscillating frequency is little greater in Table 3 than those in Table 2. If an accurate simulation of a fault clearing overvoltage is required, the transformer inductance has to be carefully determined considering its saturation due to the fault current and the transient frequency. If only dv/dt of the transient voltage across a VCB is concerned, the leakage inductance determined from the transformer rating can be used in the transient simulation.

(2) Transformer stray capacitance

As is clear from the model circuit of Fig.3, the transformer stray capacitance are composed of the following 6 components.

$C_{gA}=C_{gC}$, C_{gB}: high-voltage winding to earth for 3 phases

$C_{ga}=C_{gb}=C_{gc}=C_{g2}$: low-voltage winding to earth

C_m: high-voltage to low-voltage windings

$C_{AB}=C_{BC}=C_h$, $C_{AC}=C_h'$

: between 3 phases of high-voltage windings

The above 6 components requires to solve 6 simultaneous equations based on 6 different measurements of the stray capacitances. Conventionally it is assumed that:

$C_{gA}=C_{gB}=C_{gC}=C_{g1}$, $C_h=C_h'=0$

If the above assumption is acceptable, only 3 measured date are required to determine 3 unknown; $Cg1$, $Cg2$ and Cm.

In the present field test, various measurements of the stray capacitances were carried out. Various combinations of 6 simultaneous equations were numerically solved using Newton Raphson method, and it has been found that many sets of the simultaneous equations do not converge, i.e. they do not give a reasonable solution of the 6 unknowns. The date given in Sec. 3.1 are obtained from the converged set of the 6 simultaneous equations.

The above observation indicates that we need a further investigation of a measurment and a model circuit of transformer stray capacitances, and of evaluation of the capacitance values.

(3) Magnetizing resistance

A winding resistance corresponding to the copper loss of a transformer is easily determined and its date is available by a manufacturer. A magnetizing resistance corresponding to the iron loss is, in general, neglected in a transient calculation. In a fault clearing overvoltage, however, the magnetizing resistance becomes a part of a closed circuit in the transformer side of a circuit breaker, when the CB interrupts a fault current as is clear in the model circuit of Fig. 3.

In an EMTP simulation neglecting the resistance, a calculated transient voltage is not damped and the oscillation sustains for long, while the field test results in Fig. 2 show a large attenuation by which the transient voltage is rapidly damped. Considering the fact, the magnetizing resistance $Rmag$ is evaluated from the field test results of the transient voltage in Fig. 2. Supposed that the total capacitance of the closed circuit after current interruption is known, the magnetizing resistance $Rmag$ is evaluated in the following equation.

$$Rmag = 1/3\alpha C$$

where C : total capacitance $C=Cg_A+Cm+Cn+2Cn'+Cp$

α : attenuation constant in a measured waveform

EMTP simulation results including the magnetizing resistance show an well damped waveform as in Fig. 4, and agree satisfactorily with the field test result in Fig. 2.

The above observation clearly indicates that the magnetizing resistance should be considered in a simulation of a transient voltage due to fault current interruption.

4. Actual dv/dt in A Real Circuit

It has been explained in Chap. 2 that a measured result of *dv/dt* of a transient voltage across a circuit breaker is different from its actual value because the capacitance of a CR divider to measure the transient voltage distorts the transient voltage waveform. Therefore, it is impossible to measure the actual *dv/dt* as far as a divider is used for a measurement. In such the case, a computer simulation is the easiest approach to estimate the real *dv/dt*.

Table 4 shows EMTP simulation results of transient voltages and *dv/dt* with no CR divider, and the transient voltage waveforms are given in Fig.5 . The transient voltage waveforms in Fig. 5 are observed to be significantly different from those in Fig. 4 with the CR divider. A comparison of Table 4 (no CR divider) with Table 2 (CR divider) indicates that the maximum transient overvoltage is not much different, but the oscillating frequency is quite different as has been explained in Chap. 2. The latter leads to a significant difference in *dv/dt*. The oscillating frequency with no CR divider is decreased by *20%* to *40%* and correspondingly *dv/dt* is decreased by *20%* to *40%* with existence of the CR divider. In other words, the measured values of *dv/dt* are lower by *20%* to *40%* than the actual *dv/dt*.

5. Conclusions

Based on field test and EMTP simulation results, the following conclusions have been obtained on a transient voltage and its *dv/dt* across a vacumn circuit breaker by which a 3-phase to ground fault current is interrupted.

(1) Measured *dv/dt* is smaller by *20%* to *40%* than the actual *dv/dt* because of the capacitance of a CR divider to measure the transient voltage across a VCB. The decrease corresponds to an increase of the oscillating frequency of the transient voltage. The ratio of the increase is given by $\sqrt{C_t/(C_t+C_p)}$ where Ct is the transformer capacitance and Cp the CR divider capacitance.

(2) An EMTP simulation gives a satisfactory result compared with a field test result if the interrupted current is appropriately set. For the field tests carried out in the paper, the current is set to be in a region of *0.5* to *1.5*A.

(3) The transformer inductance obtained from the field test result differs from that calculated from the transformer rating.The reason for this is estimated due to transformer saturation by a large fault current. It is rather hard to determine the transformer stray capacitance even by a measurement. To obtain an accurate EMTP simulation, the transformer magnetizing resistance has to be considered. The above circuit parameters are desired to be determined theoretically from the transformer rating. This is a problem to be resolved in the near future.

6. References

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(2) N. Kuroda et. al. : " A surge overvoltage measurement of a VCB ", IEE Japan, Res. Meeting Paper, SP-96-50, 1996.10.

(3) W. Scott-Meyer : ATP Rule Book , B.P.A. 1994.2.

Table 1 Test conditions and results

CASE No.	phase	interruption		source voltage (kV)	recovery voltage (kV)	fault current (A)	T R V		
		phase	time (ms)				voltage (kV)	freq. (kHz)	dV/dt (kV/us)
a) 13	R	T	30. 6	18. 24	17. 96	1, 090			
	S			18. 38	18. 24	1, 090			
	T			18. 24	17. 96	1, 080	50. 9	23. 0	2. 341
b) 14	R	T	31. 4	9. 23	9. 09	541			
	S			9. 28	9. 16	542			
	T			9. 22	9. 11	545	23. 4	23. 0	1. 076
c) 15	R	T	30. 8	13. 39	13. 18	797			
	S			13. 48	13. 35	796			
	T			13. 42	13. 18	797	29. 3	23. 0	1. 348
d) 16	R	S	30. 8	13. 46	13. 18	796			
	S			13. 48	13. 35	800			
	T			13. 41	13. 21	794	12. 1	30. 8	0. 557

source freq.=50Hz ,CRdevider on Phase T

Table 2 Simulation conditions and results

CASE No. Ic (A)	interruption		recovery voltage (kV)	load-side voltage (kV)	T R V		
	phase	time (ms)			voltage (kV)	freq. (kHZ)	dV/dt (kV/us)
No.13 0.0	R	4. 584	-17. 97	14. 18	-26. 82	37. 88	2. 235
	S	4. 584	-17. 97	17. 11	26. 46	38. 17	2. 205
	T	39E-3	-18. 63	31. 16	-48. 33	23. 26	2. 301
No.13 1.0	R	4. 581	-17. 97	14. 18	-26. 81	37. 88	2. 275
	S	4. 581	-17. 97	17. 11	26. 46	38. 17	2. 250
	T	37E-3	-18. 63	30. 98	-48. 15	23. 26	2. 210
No.13 1.5	R	4. 580	-17. 97	15. 32	-27. 96	37. 88	2. 511
	S	4. 580	-17. 97	18. 21	27. 58	38. 17	2. 485
	T	36E-3	-18. 63	31. 36	-48. 53	23. 26	2. 341
No.13 2.0	R	4. 579	-17. 97	16. 81	-29. 43	37. 88	2. 991
	S	4. 579	-17. 97	20. 03	28. 99	38. 17	2. 683
	T	35E-3	-18. 63	32. 11	-49. 27	23. 15	2. 579
No.14 0.0	R	4. 584	-8. 803	6. 948	-13. 14	37. 98	1. 095
	S	4. 584	-8. 802	8. 380	12. 96	38. 14	1. 080
	T	39E-3	-9. 128	15. 26	-23. 67	23. 20	1. 127
No.14 1.0	R	4. 579	-8. 803	8. 236	-14. 42	37. 98	1. 466
	S	4. 579	-8. 802	9. 814	14. 20	38. 14	1. 314
	T	35E-3	-9. 128	15. 73	-24. 14	23. 20	1. 264
No.14 2.0	R	4. 575	-8. 803	12. 96	-18. 42	38. 14	2. 085
	S	4. 575	-8. 802	14. 59	18. 06	38. 14	2. 059
	T	30E-3	-9. 132	19. 18	-27. 57	23. 20	1. 702
No.15 1.0	R	4. 581	-12. 60	9. 944	-18. 81	37. 98	1. 596
	S	4. 581	-12. 60	12. 00	18. 56	38. 22	1. 578
	T	36E-3	-13. 07	22. 00	-34. 04	23. 20	1. 642
No.15 1.5	R	4. 579	-12. 60	11. 79	-20. 65	37. 98	2. 099
	S	4. 579	-12. 60	14. 05	20. 33	38. 30	1. 882
	T	34E-3	-13. 07	23. 24	-35. 27	23. 20	1. 889
No.16 1.0	R	4. 581	12. 60	-12. 00	-22. 69		1. 780
	S	36E-3	13. 07	-21. 58	33. 58	31. 25	2. 274
	T	4. 581	12. 60	9. 070	14. 46	32. 03	0. 9800
No.16 1.5	R	4. 579	12. 60	-14. 25	-24. 57		2. 101
	S	34E-3	13. 07	-23. 54	35. 52	31. 25	2. 745
	T	4. 579	12. 60	10. 35	15. 06	32. 03	1. 240

Table 3 Simulations with transformer rating

CASE No. Ic (A)	interruption		recovery voltage (kV)	load-side voltage (kV)	T R V		
	phase	time (ms)			voltage (kV)	freq. (kHZ)	dV/dt (kV/us)
No.13 0.0	R	4. 091	-18. 09	13. 42	-23. 03	38. 46	1. 772
	S	4. 091	19. 08	16. 06	22. 77	38. 76	1. 752
	T	53E-3	-19. 38	29. 53	-45. 84	23. 58	2. 183
No.13 1.0	R	4. 089	-18. 09	13. 75	-23. 35	38. 46	1. 913
	S	4. 089	19. 08	16. 06	23. 09	38. 76	1. 897
	T	50E-3	-19. 38	29. 82	-46. 11	23. 58	2. 302
No.13 1.5	R	4. 088	-18. 09	14. 70	-24. 29	38. 46	2. 312
	S	4. 088	19. 08	17. 14	23. 96	38. 76	2. 088
	T	49E-3	-19. 38	30. 27	-46. 56	23. 58	2. 353
No.14 1.0	R	4. 087	-8. 864	7. 879	-12. 58	38. 62	1. 243
	S	4. 087	9. 346	9. 204	12. 38	38. 79	1. 228
	T	48E-3	-9. 497	15. 16	-23. 14	23. 62	1. 244
No.14 2.0	R	4. 082	-8. 865	12. 39	-17. 07	38. 62	1. 988
	S	4. 082	9. 350	14. 61	16. 73	38. 79	1. 964
	T	42E-3	-9. 501	18. 43	-26. 38	23. 56	1. 629
No.15 1.0	R	4. 088	-12. 69	10. 31	-17. 04	38. 62	1. 622
	S	4. 088	13. 38	12. 02	16. 81	38. 79	1. 465
	T	49E-3	-13. 60	21. 23	-32. 66	23. 62	1. 651
No.15 1.5	R	4. 086	-12. 69	12. 34	-19. 07	38. 62	1. 897
	S	4. 086	13. 38	14. 48	18. 79	38. 79	1. 878
	T	47E-3	-13. 60	22. 28	-33. 70	23. 62	1. 823
No.16 1.0	R	4. 088	-13. 38	-12. 10	-20. 47		1. 647
	S	49E-3	13. 60	-21. 02	32. 41	31. 81	2. 338
	T	4. 088	12. 69	7. 269	13. 06	32. 61	0. 9745
No.16 1.5	R	4. 086	-13. 38	-14. 79	-22. 54		2. 079
	S	47E-3	13. 60	-22. 70	34. 08	31. 81	2. 661
	T	4. 086	12. 69	8. 746	14. 26	32. 61	1. 223

Table 4 Simulations with no CR devider

CASE No. Ic (A)	interruption		recovery voltage (kV)	load-side voltage (kV)	T R V		
	phase	time (ms)			voltage (kV)	freq. (kHZ)	dV/dt (kV/us)
No.13 1.0	R	4. 581	-17. 97	14. 13	-26. 76	38. 17	2. 272
	S	4. 581	-17. 97	17. 11	26. 51	37. 88	2. 254
	T	37E-3	-18. 63	30. 00	-47. 10	31. 85	2. 982
No.13 1.5	R	4. 580	-17. 97	15. 26	-27. 90	38. 17	2. 506
	S	4. 580	-17. 97	18. 21	27. 64	37. 88	2. 490
	T	36E-3	-18. 63	30. 69	-47. 79	31. 85	3. 236
No.14 1.0	R	4. 579	-8. 803	8. 802	-14. 39	38. 17	1. 463
	S	4. 579	-8. 802	9. 814	14. 23	37. 88	1. 317
	T	35E-3	-9. 128	15. 62	-24. 00	31. 65	1. 808
No.14 2.0	R	4. 575	-8. 803	-12. 96	-18. 34	38. 17	2. 075
	S	4. 575	-8. 802	14. 59	18. 13	37. 88	2. 067
	T	30E-3	-9. 132	20. 98	-29. 33	31. 85	2. 553
No.15 1.0	R	4. 581	-12. 60	9. 909	-18. 77	38. 17	1. 593
	S	4. 581	-12. 60	12. 00	18. 59	37. 88	1. 581
	T	36E-3	-13. 07	21. 53	-33. 52	31. 85	2. 270
No.15 1.5	R	4. 579	-12. 60	11. 74	-20. 60	38. 17	2. 094
	S	4. 579	-12. 60	14. 05	20. 38	37. 88	1. 886
	T	34E-3	-13. 07	23. 59	-35. 57	31. 85	2. 746
No.16 1.0	R	4. 581	12. 60	-12. 00	-18. 64		1. 584
	S	36E-3	13. 07	-21. 58	33. 58	31. 25	2. 274
	T	4. 581	12. 60	-9. 832	18. 70	38. 76	1. 587
No.16 1.5	R	4. 579	12. 60	-14. 17	-20. 52		2. 085
	S	34E-3	13. 07	-23. 54	35. 52	31. 25	2. 745
	T	4. 579	12. 60	-11. 73	20. 58	38. 46	2. 089

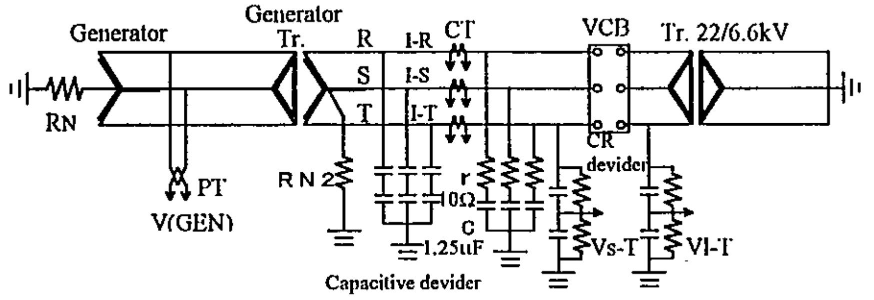
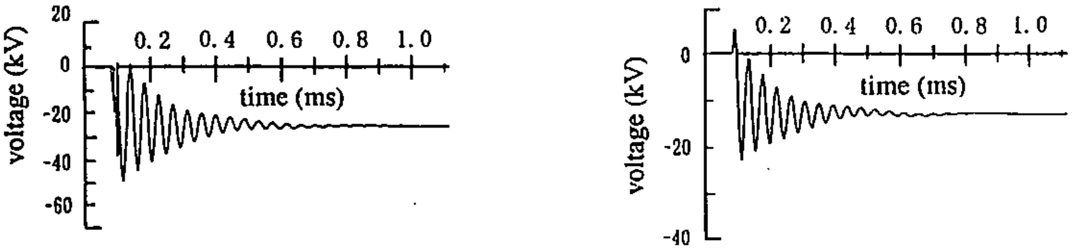
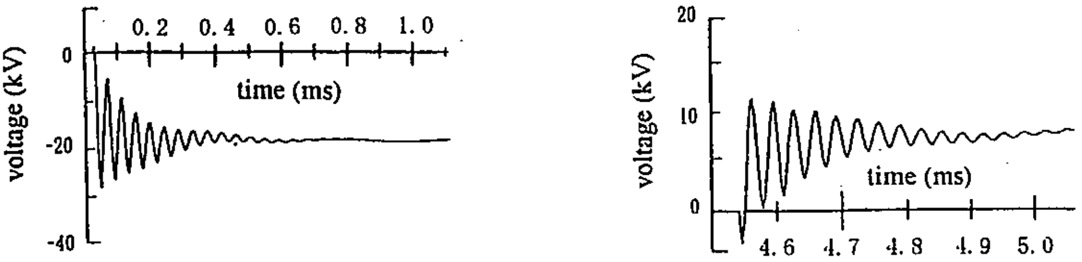


Fig.1 Field test circuit



(a) Case No.13

(b) Case No.14



(c) Case No.15

(d) Case No.16

Fig.2 Transient voltage waveforms across the VCB

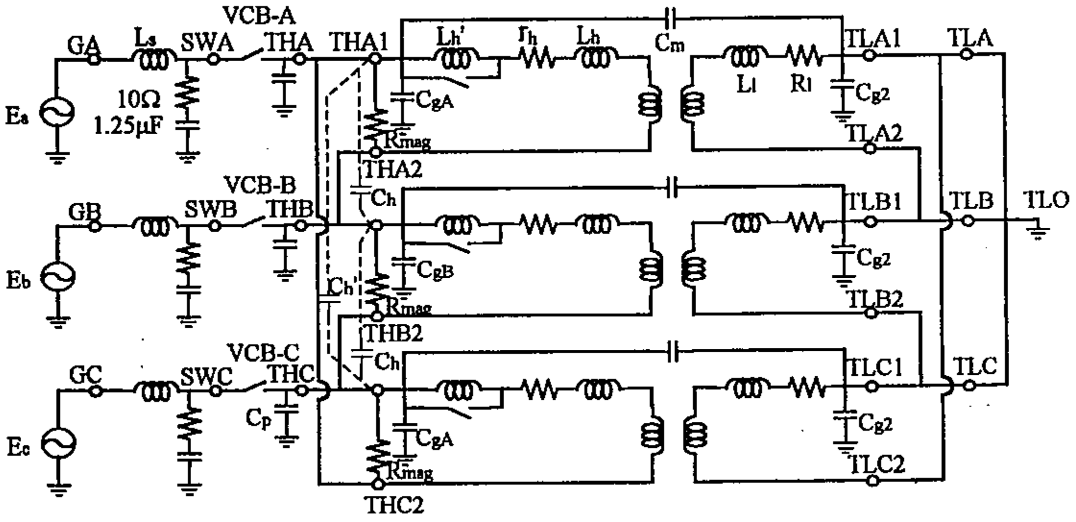
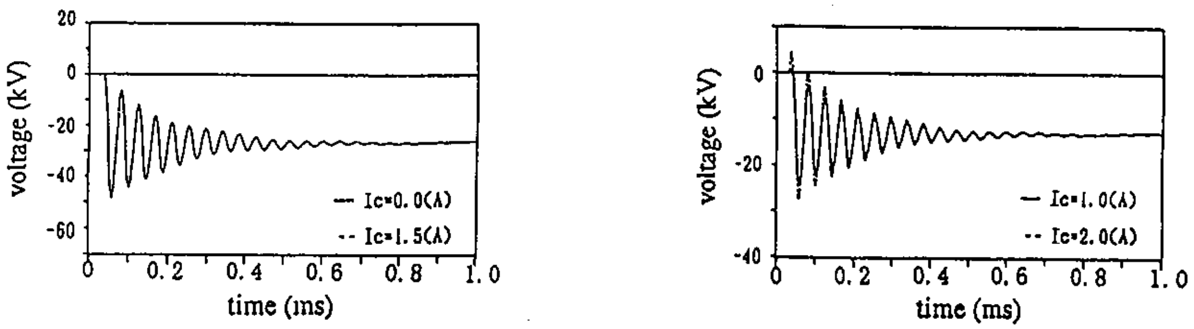
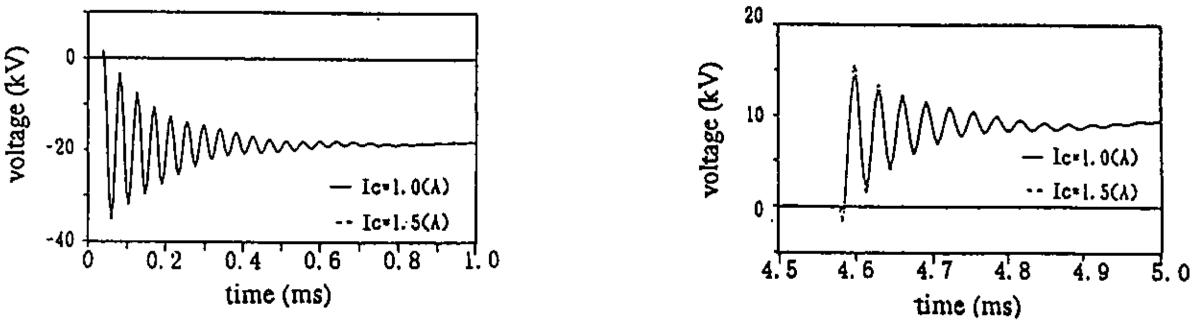


Fig.3 A model circuit



(a) Case No.13

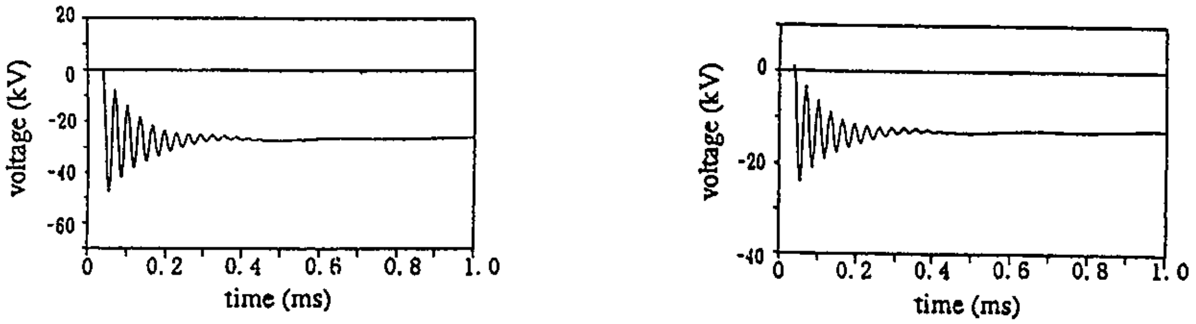
(b) Case No.14



(c) Case No.15

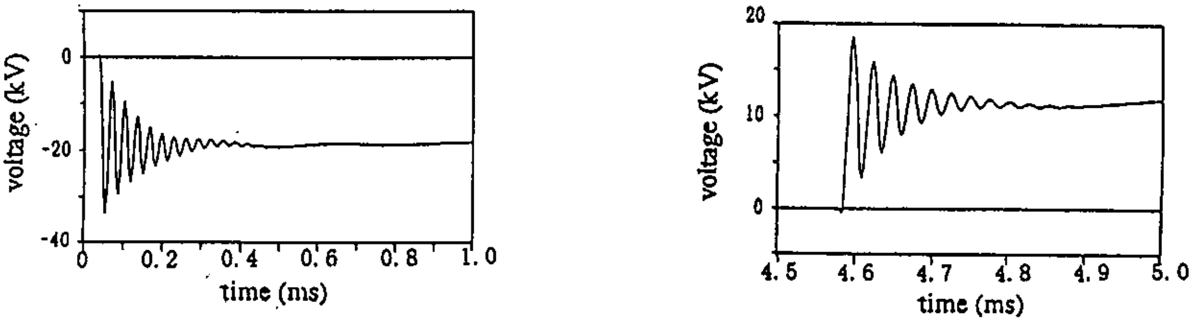
(d) Case No.16

Fig.4 EMTP simulation results



(a) Case No.13 (Ic=1.5A)

(b) Case No.14 (Ic=1.0A)



(c) Case No.15 (Ic=1.0A)

(d) Case No.16 (Ic=1.0A)

Fig.5 EMTP simulation results with no CR devider