2. Current interruption transients

For circuit breakers or other switching facilities, transient voltages just after the current interruptions are of great concern with successful current breakings, as the phenomena relate to the competition between the insulation recoveries and transient voltages across the contacts. The transient voltage is called as "Transient recovery voltage, (TRV)." For some typical cases in power systems, calculation principles are shown in this chapter.

2.1 Short circuit current breakings

For circuit breakers short circuit current breaking is the most important performance to fulfil. Just after the interruption of high current the insulation across the contacts is to withstand against TRV of relatively or even very rapid recovery. Applying EMTP, TRVs can be straightforwardly calculated. Nevertheless, for calculating TRVs in large power systems, simplified and effective calculation processes are wished. For the purpose, to bear current injection principle in mind is strongly recommended. The principle is shown in Fig. 2.1.

As shown in the upper figure, the inverse polarity of current (-I) is superimposed to the originally



In current breaking

(-I) is superimposed to the originally flowing short circuit current (I) from the switch terminals. Then the total current is to be zero, corresponding to current interruption. The phenomenon is represented by (a), (b) and (c), i.e. the total phenomenon is (a), which can be replaced by (b) + (c) by superimposing principle. (b) corresponds to short circuited as up to the time, so no TRV appears. TRV is produced only in (c). Therefore, we are to calculate for (c) to obtain TRV. The feature of this method is :

- As for source, only the breaking current is to be considered and some sources in the system are eliminated.
- Only the circuit parameters seen from the switching facility terminals are to be considered. Therefore, parameters remote from the terminals seem to be not so, so important.
- In (c), any initial condition is excluded, so we can apply only dead circuit and injecting current to calculate TRV, thus simplified and easier consideration is applicable.
- In the calculation, ramp current instead of sinusoidal one is mostly applicable due to relatively short time interval of TRV duration time interval, compared to a loop of power frequency current.

As a whole, the method suggests possibility of simplification in TRV calculation. Accurate parameters are necessary only circuit locations close to the switching device concerned.

Great care is to be taken the principle is applicable only for TRV across the switching facility terminals. For other variables, e.g. voltages to ground, the original process ((a) in Fig. 2.1) is to be taken.



Fig. 2.2 Some circuit elements to represent systems



Fig. 2.3 Voltages by injecting ramp currents to circuit elements in Fig. 2.2

Actual complicated systems are composed of simple elements, so firstly to study responses by simple circuit elements seems, hopefully, to be useful and beneficial. In Fig. 2.2 some circuit elements frequently applied to represent actual systems are shown.

(6) ---- (9) are often used in practical short circuit test plant circuits. In Fig. 2.3 ATP-EMTP calculation results injecting ramp currents to the elements (1) ---- (9) are shown. As for actual numerical values of the parameters applied, see the attached data file.

The followings are noted :

 In digital calculations finite values are to be applied, even for the initial part

of the ramp current, yielding astonishing results for cases (2) and (4). Small capacitances are to be connected in parallel to the inductances.

- (6) and (7), also (8) and (9) yield similar results respectively, see Fig. 2.3.(b). But in the enlargements of the very initial parts, significant differences are found in Fig. 2.3 (c). The differences are often of certain importance in actual short circuit test circuits. The differences are originated by capacitances directly connected to the switching facility terminals.
- Hand calculations (analytical) are not so, so difficult, so the reader is strongly recommended to try, at least once, for better understanding these phenomena.

Then, actual application to calculate power system TRVs will be shown next.

Let's introduce Fig. 2.4 (single-phase circuit diagram) as an example. For three phase circuits, basic principle will be shown later.

In Fig. 2.4, a 300kV system around a sub-station is shown. Transformer's another side system is simply represented by voltage source via inductance equivalent to transformer and the system short circuit reactance. Applying what are mentioned before, transmission lines near the circuit breaker are relatively accurately



Fig. 2.4 One line diagram around 300 kV sub-station to calculate TRVs in short circuit clearings



Fig. 2.5 Fault current breaking, fault at F3 in Fig. 2.4

represented by distributed parameter lines, while; remote systems are simply represented by lump elements such as capacitors and inductors. For the details of the parameters applied, see the attached data file. The short circuit capacity at the bus bar is approx. 50kA, representing a sub-station in a relatively high capacity of system. "X" is the connection bus bar relating to ITRV, to be shown later.

Fault points are F1 ----F4. F1 is so called terminal fault, and F2 ---- F4 are line faults. Especially, fault at F2 is called short line fault (SLF), which, due to relatively high breaking current and very high rate of rise of TRV, is of importance for certain type of circuitbreakers.

EMTP calculation result as for F3 fault current breaking in Fig. 2.4 is shown in Fig. 2.5. In (a) overall phenomena are shown. Before current interruption, a portion of voltage exists at the bus corresponding to the distribution along the line (10km). After interruption, bus side voltage recovers to the source value with some transients. Line side one goes to zero also with some transients. The details are clear in (b) as the zooming expression around the current interruption. Note:

- Breaking means overall phenomena

including initiation of movement of circuit- breaker, contact separation, arcing, quenching of arc and current interruption, TRV appearing, withstanding against TRV and power frequency recovery voltage. While interruption means just end of arcing current.

Applying current injection principle before mentioned, TRVs in line fault breakings are understood as:

- Current injections from the circuit breaker are to be --- one current to the bus direction and the other of opposite polarity to the line direction, value of which correspond to F3 fault current.
- Line side TRV follows the principle (8) in Fig. 2.2 and Fig. 2.3
- Bus side TRV, at the first step before the reflection waves coming, follows (3) in Fig. 2.2 and 2.3, as overall surge impedance Z, which is equivalent to resistance Z before the reflection coming, and Inductance corresponding to Transformer, etc. are connected in parallel. Then afterwards, arrivings of reflection waves in some lines, overall voltage change is such like as (5), (6) or (7) in Fig. 2.2 and 2.3. These phenomena are well explained in ANSI C37.06.
- TRV across the terminals of the circuit breaker is the difference of the two TRVs, as shown in Fig. 2.5 (b).
- Be aware, as written before, current injection is valid for across terminals TRV. By each side current injection, only voltage change appears.

Applying current injection principle, for example, dv/dt (rate of rise of recovery voltage, RRRV) and reflection time are easily obtained as [di/dt times surge impedance] and [line length divided travelling speed respectively, thus overall conception of TRV is easily obtained. "X" in Fig. 2.4 corresponds to a connection line between the circuit breaker and the bus, the length of which is in the order of several ten meters. The connection line yields TRV similar to the line side one (SLF), but due to shorter length, of lower amplitude. This is called Initial Transient Recovery Voltage (ITRV). This may be of importance for certain type of circuit breakers, especially breaking higher current such as F1 or F2 fault in Fig. 2.4. A distributed parameter line of the relevant length models the connection line.

For calculation TRV introducing very short connection line by EMTP, very short step time is required by EMTP. In EMTP step time of calculation shall be shorter than the minimum travelling time of the distributed parameter line in the relevant circuit. Therefore, huge number of steps is necessary, as usually several ten ms of calculation time interval is necessary for calculating breaking phenomena, mainly due to initialisation technique in EMTP. On the other hands, time interval of ITRV concerned is very short, such as, several microseconds. Introducing current injection principle in also EMTP calculation, efficient calculation is possible. An example is shown in the attached data file, where 50m of connection line and 0.1 microsecond of step time are introduced, while the total calculation time interval is 20 microseconds.

Three-phase circuit

Like a single-phase circuit, current injection principle is applicable to also a three-phase circuit in a power system. The main concept of current injection in TRV calculation is:

TRV = [Injection current] times [Impedance looked through circuit breaker terminal] For three phase circuits, the following equations are introduced. :

$\begin{bmatrix} e_0 \\ e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} i_0 Z_0 \\ i_1 Z_1 \\ i_2 Z_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} e \\ e \\ e \\ e \end{bmatrix}$	$\begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 \\ 1 & a \\ 1 & a^2 \end{bmatrix}$	$\begin{bmatrix} 1\\a^2\\a \end{bmatrix} \qquad a = \frac{1}{2} \left(-1 + j\sqrt{3} \right)$
----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------------------------------------------------------------------------	------------------------------------------------------------------------------------------------

where Z_0 , Z_1 , and Z_2 are respective sequence impedances looked through circuit breaker terminals, and e_0 , e_1 and e_2 are voltages appearing across the terminals of the circuit breaker. Notations u, v, and w relate to phases. In most cases in power transmission systems, $Z_1 = Z_2$.

Such equations, based on symmetrical component principle, were originally introduced for phenomena in power frequency domain. But introducing Fourier series spectrums for some voltage/current wave shapes, equations are thought to be valid for any voltage/current wave shape including transient one.

Fist example is to calculate first pole to clear impedance for three-phase fault. In the case, assuming phase "u" is the first pole to clear, then, $e_v = e_w = 0$. From the equations shown before, :

$$\frac{1}{3} \begin{bmatrix} e_u \\ e_u \\ e_u \end{bmatrix} = \frac{1}{3} \begin{bmatrix} Z_0 i_u & Z_0 i_v & Z_0 i_w \\ Z_1 i_u & a Z_1 i_v & a^2 Z_1 i_w \\ Z_1 i_u & a^2 Z_1 i_v & a Z_1 i_w \end{bmatrix}$$

For phase "u", (e_u / i_u) is thought to be the equivalent impedance for first pole to clear. From the equation above, :

$$i_{u} = \begin{bmatrix} e_{u} & Z_{0} & Z_{0} \\ e_{u} & aZ_{1} & a^{2}Z_{1} \\ e_{u} & a^{2}Z_{1} & aZ_{1} \end{bmatrix}$$

Then, for first pole to clear, the equivalent impedance is :

$$e_u / i_u = 3Z_0 Z_1 / (2Z_0 + Z_1)$$

Likewise for second and third pole to clear, the followings are introduced respectively. :

$$e_v / i_v = (2Z_0 Z_1 + Z_1^2) / (Z_0 + 2Z_1)$$
 $e_w / i_w = (Z_0 + 2Z_1) / 3$

Also for three phase circuits, TRVs are conceptually considered as products of injection currents and equivalent impedances. Therefore from these impedance values, TRVs in three phase circuits could be guessed, at least for relative values or qualitatively. For quantitatively accurate values, of cause, EMTP calculations are inevitable.

Note:

- Modelings of power system elements such as transformers, overhead transmission lines, under ground cables, etc. will be explained in the following chapters. Care should be taken that the models depend on the frequency of the relevant phenomena. The best way is models for power frequency are applied up to the current interruption, and ones for the frequency of the transient phenomena are applied for the following phenomena. In actual cases compromise is to be necessary.

2.2 Capacitive current switchings



Fig. 2.6 Capacitive current breaking - most simplified representation -

Switchings of capacitive circuits such as no-load overhead transmission lines, under ground cables, or shunt capacitor banks are relatively frequent service of circuit breakers. In breaking capacitive current the maximum recovery voltage across terminals of switching device is higher than twice of the source voltage, see Fig. 2.6. Generally it last longer time, so re-strike (sustained discharge between contacts) could occur. By re-strike, significant over voltage and greate shock due to the impulse discharging current are created in the circuit. So, for modern sophisticated power systems with reduced insulation revel, re-strike free is an earnest requirement.



b) Delaying in 2nd pole to clear
 Fig. 2.7 No-load overhead line
 Capacitive current breaking



In Fig. 2.7, 550kV no-load overhead line's capacitive charging current breaking is shown in simplified manner. The line is represented in symmetrically transposed condition, 150km of length. The source side is much simplified; still general trend is well represented. Details are shown in the attached data file and a).

b) shows voltage changes in normal breaking, i.e. currents in three phases are interrupted in order at each current zero. c) shows delaying of current interruption in the second pole to clear. Due to the electro-static coupling, the first pole's line side voltage is much influenced, so the recovery voltage of the pole is enhanced much. If the scattering of the contact separation timing is more than one 6th of one cycle time interval (2.7ms for 60Hz and 3.3ms for 50Hz), such possibility exists.

More accurate line and system modelling will be explained in the following chapters. In most overhead transmission line systems, so called "Rapid auto-re-closing" is applied. In the sound phase during the operation, the circuit pole may close against the residual voltage of the inverse polarity of the source voltage. The most severe case's result of circuit diagram in Fig. 2.7 is shown in Fig. 2.8 a), where each pole closed at each maximum voltage timing. The highest over voltage at line end terminal is approx. 4 p.u. of the system voltage. Pre-insertion resistor's effect is significant as shown in b), where 1000 ohm of resistors are inserted approx. 10ms in three poles. For details of the system and operation sequence parameters, see the attached data files.



Fig. 2.8 Rapid re-closing with and without resistor insertion

Note :

- In calculating re-closing over voltages, accurate transmission line modelling is necessitated due to the wide range of frequency voltage components included. Damping of the line that is dominant for over voltage value is dependent on the frequency. See the following chapters.
- In the case above shown solidly earthed neutral source circuit is applied. For non-solidly earthed conditions, some examples will be shown in the following as mainly for a cable system.



Fig. 2.9 shows capacitive current breaking in a cable system. The cable is modelled as screened one, i.e. each phase core is surrounded by earthed screen so that no electrical static coupling exists between phase cores, corresponding to equal zero and positive sequence capacitance values. The supply side is modelled as non-earthed neutral condition. Note:

 In EMTP, one-terminal-grounded source is mandatory, so representing non-earthed source, combination of current source and impedance can be applied. Alternatively, (semi) ideal transformer or "No. 18 ungrounded source" can also be applied, see the following.

The result b) is usually specified case for non-solidly earthed neutral system and due to the enhancement (shifting up) of the supply side neutral voltage, the maximum recovery voltage reached up to 2.5 p.u. of the source phase voltage. In c), as more general cases, significant values of capacitances to ground such as cables are connected to the supply side bus bar. Then due to less enhancement of the neutral voltage in the supply side, the maximum recovery voltage is approx. 2.0 p.u., so much re-

duction is expected. Also see the attached data files as for the sys-

As another example, breaking shunt capacitor bank capacitive

current, with 66kV and 50MVA rating, is shown in Fig. 2.10. The supply circuit neutral is high ohmic

resistor grounded. In the calcula-

tion, No. 18 ungrounded source in

EMTP menu is applied, see the attached data file for the details.

The capacitors have series con-

nected reactors, the purpose of which is to suppress harmonics

tem parameter details.



Fig. 2.10 Shunt capacitor bank capacitive current breaking 66kV, 50MVA bank

(higher than 3rd stage) and back-to-back inrush making currents. In Japan, as standard procedure, the reactor reactance is 6% of the capacitor's capacitive reactance. The voltage charged on the capacitor is enhanced due to the inverse polarity of voltage on the series connected reactor, so the recovery voltage is also enhanced by the value. Moreover, due to the voltage oscillation on the reactor, high frequency component is involved at the initial part of the recovery voltage. Occasionally the high frequency component of the recovery voltage elongates the minimum arcing time, i.e. the current is interrupted by relatively longer contact gap, the reactor may bring suitable effect on re-strike free break-

ing. Note:

- As relatively high frequency of oscillation is created by the series connected reactor, in calculation by ATP-EMTP, sufficiently low value of step time is to be used.

2.3 Inductive current breakings



a) Circuit diagram

b) Voltage changes when SHR current breaking

Fig. 2.11 300kV, 150MVA shunt reactor breaking

Inductive current means shunt reactor (SHR), no-load transformer magnetizing or stalled motor energizing current. Due to low current value, the interruption itself is of little problem. While breaking by usual circuit breakers such as air blast, SF₆ or vacuum ones, the current tends to be chopped (forced interruption) before its prospective (natural) current zero. Note:

- Physical chopping phenomena by circuit breaker arc with negative v-i characteristic in conjunction with circuit parameters will be explained in the following chapter.

Fortunately, in ATP-EMTP, current chopping (forced current interruption before current zero) is easily introduced by time controlled usual switch. As an example, 300kV, 150MVA shunt reactor current breaking is explained in Fig. 2.11. "a)" shows one phase of the circuit diagram in simplified modelling. The connection bus inductances are to be introduced adjacent to the circuit breaker. "b)" shows voltage changes around current interruption.

Note:

For details of the circuit parameters in a), see the attached data file, where, for the purpose of calculation stabilizing, several additional elements such as series connected resistors are introduced. Also, "chopping --- re-ignition --- re-interruption" are represented by three switches, which shall not directly be connected forming a ring. Small resistors are to be introduced in between.

At t1, the current is interrupted with chopping (by 5A). When chopping, as for the energy in the reactor (magnetic) and capacitor connected in parallel, the next equation is introduced:

$$\frac{1}{2}CV^{2} = \frac{1}{2}Li_{c}^{2} + \frac{1}{2}CV_{0}^{2}$$

where: V: Maximum voltage across reactor terminals after chopping, when all energy is transferred to C

ic: Chopped current revel

- Vo: Source voltage peak (approx. equal to the voltage at the chopping)
- L: Reactor's inductance

C: Reactor's capacitance

Then the maximum voltages across the reactor terminals and circuit breaker are easily calculated. In Fig. 2.11 b), after t1, the SHR terminal voltage goes to the maximum, and then goes down with the across circuit breaker voltage recovers (B-SHR).At t2, the circuit breaker re-ignites and very high frequency of voltage change at the SHR terminal appears together with high frequency and amplitude (up to a few thousand A) of re-ignition current flowing. The current is re-interrupted after approx. 0.05ms and re-establishment of TRV (B-SHR) appears. What is to be noted, after the second interruption, due to higher trapped magnetic energy in the SHR winding, the voltage recovery is steeper than the first one. So, also the second re-ignition might occur. Such is called as "Multiple re-ignitions" which may corresponds to extremely severe over voltage condition to the reactor insulation. Note:

- The second current interruption mostly occurs at current zero of the circuit breaker, where the current is composed with initially very high but then mostly damped re-ignition high frequency current through capacitances adjacent to the circuit breaker (so called second parallel oscillation circuit) and combined with the AC current in the SHR winding.
- What is most serious as in inductive current breaking for shunt reactor is, very rapid change of voltage at winding terminals by re-ignition. Voltage stress of the winding, especially at the entrance part, is generally very severe by high frequency of voltage stress. Some will be explained in the following chapter.

Attached data files for this chapter:

- Data2-01.dat Current injection to 9 circuit elements
- Data2-02.dat 300kV system TRV calculation in simplified circuit representation
- Data2-03.dat ITRV calculation applying current injection
- Data2-11.dat 550kV overhead transmission line capacitive current breaking
- Data2-12.dat Ditto, but delaying 2nd pole to clear interruption
- Data2-13.dat Ditto, calculating rapid re-closing over-voltages
- Data2-14.dat Ditto, calculating re-closing over-voltages with resistor insertion.
- Data2-15.dat Cable charging capacitive current breaking by isolated neutral source circuit, no significant value of capacitance to earth is connected in the source circuit.
- Data2-16.dat Ditto, but significant value of capacitance (cable) exists in the source circuit.
- Data2-17.dat 66kV, 50MVA shunt capacitor bank capacitive current breaking, No. 18 non-grounded source circuits applied.
- Data2-18.dat 300kV, 150MVA shunt reactor inductive current breaking, chopping ---- re-ignition ---- re-interruption
- Data2-21.dat 4-armed shunt reactor compensated line dropping
- Data2-22.dat Ditto, secondary arc current calculation

Appendix 2.1: TRV with parallel capacitance in SLF breaking

Appendix 2.2: 4-armed shunt reactor for suppressing secondary arc in single pole rapid re-closing **Appendix 2.3:** Switching 4-armed shunt reactor compensated transmission line

Appendix 2.1 TRV with parallel capacitance in SLF breaking

For some kinds of calculations, mathematic process seems to be even easier and simplified. The example is to calculate the change in SLF breaking TRV wave shape by circuit parameter modification, where the original wave shape has been known.

The short-line fault TRV from an idealised distributed parameter line is known as a triangular wave shape. In the Laplace domain, this can be written as follows as for one cycle:

$$TRV(s) = \frac{\omega IZ}{s^2} (1 - 2e^{-t_L s}) \tag{1}$$

where

tL: time to peak without capacitance

 $\boldsymbol{\omega}$ angular frequency of the breaking current

- I: breaking current peak
- Z: surge impedance

S: Laplace operator

The equation is valid for $0 \delta t \delta 2t_{L}$. If the TRV for $t > 2t_{L}$ is required, the equation (1) is to be replaced by the following:

$$TRV(s) = \frac{\omega IZ}{s^2} \left(1 - 2e^{-t_L s} + 2e^{-2t_L s} + \dots \right)$$
(1*a*)

In order to introduce damping of the wave, the term $2e^{-t_L s}$ in equation (1) should be replaced

by, $2ke^{-t_L s}$, where k < 1,0.

The TRV can be represented by the product of the breaking (= injection) current and the impedance, also in the Laplace domain. The injection current in the Laplace domain can be approximated such as (due to very short time interval concerned):

$$\frac{\omega I}{s^2}$$

(corresponding to the current = $\omega I t$ in the time domain)

Then the impedance of the distributed parameter line in Laplace domain is: (for t < $2t_L$)

 $Z(1 - 2e^{-t_L s})$ (2)

The lumped capacitance impedance in the Laplace domain is represented by:

$$\frac{1}{Cs}$$
 (3), where C = capacitance

The capacitance value includes both the lumped capacitance at the circuit-breaker terminal side producing the inherent t_{dL} of the line and the additional capacitance, if any.

Connecting the two impedances represented by (2) and (3) in parallel, the following equation is obtained for the total impedance in the Laplace domain:

$$\frac{Z(1-2e^{-t_Ls})}{Cs(\frac{1}{Cs}+Z-2Ze^{-t_Ls})} = \frac{Z(1-2e^{-t_Ls})}{(1+t_{dL}s)-2t_{dL}se^{-t_Ls}}$$
(4)

where $t_{dL} = ZC$

 $t_{dL} \ is also \ applicable \ for \ conditions \ with \ additional \ parallel \ capacitances.$

The product of the injection current $(\frac{\omega I}{s^2})$ and the impedance (4) is the TRV with parallel capacitance in the Laplace domain:

$$\omega IZ \times \frac{1}{s^2} \times \frac{(1 - 2e^{-t_L s})}{(1 + t_{dL} s) - 2t_{dL} s e^{-t_L s}}$$

$$= \omega IZ \left[\frac{1}{s^2} \times \frac{1}{1 + t_{dL} s} - \frac{1}{s^2} \cdot \frac{2e^{-t_L s}}{(1 + t_{dL} s)^2} + \dots \right]$$

$$= \omega IZ \left[\frac{1}{s^2} - \frac{t_{dL}}{s} + \frac{t_{dL}^2}{1 + t_{dL} s} - 2e^{-t_L s} \left(\frac{1}{s^2} - \frac{2t_{dL}}{s} + \frac{2t_{dL}^2}{1 + t_{dL} s} + \frac{t_{dL}^2}{(1 + t_{dL} s)^2} \right) \right]$$
(5)

The second part of the equation (5) is valid for $t \ \delta t \ \delta 2t$ only.

By reversal Laplace transformation process, SLF TRV with parallel capacitance in time domain is calculated as follows:

For $0 \delta t \delta t$.

$$TRV_1(t) = \omega IZ \left[t + t_{dL} \left(e^{-\frac{t}{t_{dL}}} - 1 \right) \right]$$
(6)

for $t \llcorner \delta t \delta 2t \llcorner$

$$TRV_{2}(t) = TRV_{1}(t) - 2\omega IZ \left[t' \left(e^{-\frac{t'}{t_{dL}}} + 1 \right) + 2t_{dL} \left(e^{-\frac{t'}{t_{dL}}} - 1 \right) \right]$$
(7)

with $t' = t - t_{\perp}$

Using equations (6) and (7), the correct wave shapes of SLF TRVs with line inherent t_{dL} and for conditions with additional parallel capacitance can be calculated.

For cases t > 2t_L, (1a) instead of (1) should be applied. When damping is introduced, $2ke^{-t_Ls}$ should be used instead of $2e^{-t_Ls}$ in equation (1) as mentioned before. The total calculation process is then slightly modified.

For every case, with or without parallel capacitance, the peak value of the TRV is quasi equal to ωIZt_L , i.e. no significant damping to the peak value is introduced. Dividing equations (6) and (7) by ωIZt_L , gives the following equations.

$$TRV(10) = \frac{t_{dL}}{t_L} \left[\frac{t}{t_{dL}} + \left(e^{-\frac{t}{t_{dL}}} - 1 \right) \right]$$
(6a)

$$TRV(20) = TRV(10) - \frac{2t_{dL}}{t_L} \left[\frac{t'}{t_{dL}} \left(e^{\frac{-t'}{t_{dL}}} + 1 \right) + 2 \left(e^{\frac{-t'}{t_{dL}}} - 1 \right) \right]$$
(7a)

The TRV wave shape given by equations (6a) and (7a) can be normalised such that the peak value is unity and time unit is in tdL. The parameter is tL/tdL. Fig. 2A.1 shows the results of a calculation for tL/tdL = 1.0 --- 15. Multiplying the Y-axis value by ωIZt_L and X-axis value by tdL, the actual wave shape is obtained. The peak



Fig. 2A.1 SLF-TRV with parallel capacitance

values are not significantly damped.

Appendix 2.2 4-armed shunt reactor for suppressing secondary arc in single pole rapid re-closing

As the first step of studying switching phenomena in systems with 4-armed shunt reactors, mathematic study seems to be beneficial to grasp the outline. In single pole rapid re-closing, where only the faulted phase of a transmission line is opened, the faulting arc is to quench during the re-closing time interval. By electro static coupling with the sound phases, a certain level of arc current tends to continue without quenching. As higher the system voltage is and as longer the transmission line is, the tendency increases.

For eliminating the arc current (secondary arc current) aiming successful re-closing, 4-armed shunt reactor where the neutral is earthed by means of another reactor is applicable. Fig.2A.2 shows the circuit layout.



Fig. 2A.2 4-armed shunt reactor arrangement

"a)" shows system layout during one phase line to ground faulting, where both ends of the phase are open. Secondary arc may exist. "b)" shows the equivalent circuit at the faulting point, where, assuming voltages along the phase v and w lines are quasi uniform, voltages are applied from the point, instead of both ends, i.e. $e_u=0$ (faulting), e_v and e_w . "iu" is the secondary arc current. Z₀, Z₁ and Z₂ are sequence component reactances of the line section (capacitances and inductances of 4-armed shunt reactor shown in "c)" connected in parallel). The following equations are obtained. :

$$\begin{bmatrix} e_0 \\ e_1 \\ e_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} 0 \\ e_v \\ e_w \end{bmatrix} \qquad \begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} e_0 / Z_0 \\ e_1 / Z_1 \\ e_2 / Z_2 \end{bmatrix} \qquad where \quad a = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$

Except for rotating machines, in transmission systems, $Z_1 = Z_2$. In a transmission line with 4-armed shunt reactor, parameters other than neutral reactor's are fixed by the relevant system condition. So, adjusting the neutral reactor reactance value, we can have:

 $Z_0 = Z_1 = Z_2$

Introducing this condition, then we can have $i_u = 0$ applying the above shown equations, i.e. the secondary arc current can be suppressed.

- Note:
- During switching of such transmission line, due to the non-linearity of the reactors as usually iron cores are used, certain value of transient voltages appear at the neutral point and some insulation failures have been reported. For sophisticated insulation design especially around the neutral point, accurate analysis introducing every detailed parameters of the system including the non-linear characteristics of iron cores is recommended.

Appendix 2.3 Switching 4-armed shunt reactor compensated transmission line

During switching a transmission line with 4-armed shunt reactor compensation, the purpose of which is to suppress secondary arc current when single-phase re-closing, due to unbalanced saturations of the shunt reactor arms, over-voltages appear at the neutral point, the voltage of which point is zero in steady state condition. Following is the most simplified example as for the phenomena.



Fig. 2A.3 400kV overhead line compensated by 4-armed shunt reactor



Fig. 2A.4 Voltages at line entrance and neutral point

precise as possible modelling is necessary for the actual case evaluation.

As shown in Fig. 2A.3, 400kV 300km of overhead transmission line with general parameters is compensated by 4-armed shunt reactor, the compensation ratio of which is 60%. The no-load line is energized from the left end and then dropped.

Such reactor is generally gapped core type, so the saturation characteristic is assumed as shown in the Figure. Some non-linear elements dominate the phenomena, so digital calculation seems to be best applicable.

As for the details of the modelled parameters, see the attached data file

ATP-EMTP calculation result as for the shunt-reactor terminal and neutral voltages when the line is dropped is shown in Fig. 2A.4. In the case, significantly high voltage appears at the neutral point of the reactor after the line dropping, which may be very important for the reactor insulation design.

Care should be taken, as the phenomena much depends on the relevant system parameters, i.e. details of the transmission line parameters, shunt reactor compensation rate, shunt reactor saturation characteristics, etc. as