Transient recovery voltages when clearing a fault in presence of series limitation reactors

D. Santos, G. Cabriel
Electricité de France
Direction des Etudes et Recherches[1]
(France)

Abstract - **In some EDF high voltage (90 and 63 kV) network configurations, power flow is limited by different impedance seen from the bus bar (underground cables in parallel with overhead lines). This difference imposes a reduced power flow in the overhead line in relation to its capacity, which is due to thermal constraints of the cable. A reactor in series with the underground cable can balance the impedances, thus allowing an accurate adjustment of the power flow.**

To improve power flow, a reactor in series with the underground cable is adequate, instead of increasing the cable section. When using series reactors, transient recovery voltage (TRV) stresses are too severe in almost every case to comply with IEC standards, especially in terms of rate of rise of the recovery voltage (RRRV). This paper presents TRV EMTP simulation studies. Several protection devices are analysed and evaluated with regard to their capability to reduce TRV stresses. A parallel capacitance with the series reactors is adapted to comply with IEC standards for low impedance reactors. A RC parallel circuit is adopted for high impedance reactors. The reactor resonance frequency and impedance mainly determine the severity of TRV, and thus the type of protection device to be used.

I. INTRODUCTION

When clearing faults, circuit breaker contacts are subjected to transient recovery voltage. Excessive TRV can cause reignition across the breaker contacts and lead to breaker failure.

The short circuit current interruption occurs at the zero crossing instant. For a fault after the reactor, the current is limited by the source and reactor impedances, which are mainly inductive. The current zero crossing corresponds to a maximum or minimum voltage. The source voltage is at the interruption moment at its crest value and the circuit breaker reactor side voltage will tend to zero. This difference provokes a transient at the source and at the reactor terminal side of the circuit breaker. Each transient has a frequency and a damping related to its parameters. The source transient oscillates around the kHz and is strongly damped quickly following the source 50 Hz voltage. The reactor side transient oscillates around its resonance frequency between $\pm L w I_{fault}$, with an exponential DC component defining the voltage damping. The transient recovery voltage is the voltage difference at the circuit breaker terminals.

Firstly, this document presents the TRV stresses for different reactors allowing different compensation degrees in two different environments: in single phase laboratory test circuit and in an EDF representative network. The studied reactors have different resonant characteristics as well as inductance. Several sensibility studies are performed with parameters varying as follows: several short circuit source currents, two different service voltages, different types of fault (three phase and single line to ground fault, short line fault), number of parallel lines, reactor resonance frequency and inductance.

Secondly, several protection devices (spark gap, surge arresters, resistance with surge arresters, resistance, capacitance, and RC parallel circuit) are tested and compared from a TRV parameters reduction point of view. System comparisons are performed on those devices in order to determine the most suitable ones. Among the efficient solutions the most reliable ones must be chosen taking into account the global cost of the equipment (reactor and TRV protection device) compared to the alternative solution of increasing the cable section and to the actual important non energy distribution cost.

II. PROBLEM DESCRIPTION

The transient voltage of the source is not of critical importance. The key feature of this particular TRV wave shape is its high frequency oscillations at the reactor side terminal of the circuit breaker. The voltage across the circuit breaker strongly depends on the voltage at this side of the circuit breaker which can be described as follows, if arc and fault impedances are neglected :

$$TRV(t) = U1(t) - U2(t) \qquad (1)$$

whereby :

U1(t) - voltage source side terminal

---

[1] 1, av. Général de Gaulle -92141 CLAMART CEDEX (France)

U2(t) - voltage reactor side terminal

The reactor side transient voltage can be described as follows :

$$U1(t) = U1(t)_{(particular)} + U1(t)_{(homogenous)} \tag{2}$$

The reactor side transient voltage can be described as follows :

$$U2(t) = U2(t)_{(homogenous)} \tag{3}$$

$$U2(t) = K2 \cdot e^{-\alpha r \cdot t} \cdot \cos(wr \cdot t + \delta) \tag{4}$$

with :

$$k2 = w \cdot Lr \cdot Ifault \tag{5}$$

δ - initial phase angle of U2
wr - angular velocity defining the frequency oscillation
αr - exponential coefficient related to the time constant
Lr - reactor inductance
w - angular velocity (AC)

and,

$$Ifaul(rms) = \frac{E/\sqrt{2}}{w \cdot (Ls + Lr)} \tag{6}$$

Ls - source positive inductance
E - Equivalent source voltage

The oscillation frequency of both side transients can be calculated by using the following two equations :

$$ws = \frac{1}{\sqrt{Ls \cdot Cs}} \qquad wr = \frac{1}{\sqrt{Lr \cdot Cr}} \tag{7a.b.}$$

The damping factors are the following :

$$\alpha s = \frac{1}{2 \cdot Rs \cdot Cs} \qquad \alpha r = \frac{Rr}{2 \cdot Lr} \tag{8a.b.}$$

An example of the type of transients involved are showed in figure.1 :

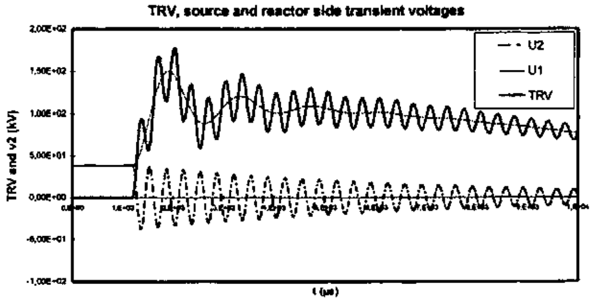

Fig.1 : Voltage stresses at the reactor side (U2) and across the circuit breaker when clearing a three phase fault immediately after the reactor. The voltage at the source side (U1) terminal can be obtained by operating TRV minus reactor side voltage. The resultant TRV may largely exceed IEC standard specifications depending on the reactor impedance and resonance frequency.

III. CALCULATION PROCEDURE

Since neither the required conditions for the reactor installation from the TRV point of view nor the exact reactor characteristics (impedance and resonance frequency) to be installed are known, the most suitable way to proceed is by assessing the material performances in experimental laboratory tests which are directly comparable to simulation results. A convenient method is to use a single phase laboratory test circuit where first pole interruption TRV parameters involved are directly referred to IEC 56 standards. This first analysis is followed by a three phase complete HV network one whereby the second and third pole, as well as short line faults resulting TRV are calculated.

A. Single phase laboratory test circuit

The method consists of three steps :

1. Circuit parameters calculations (Figure 2) ;
2. Variation of upstream circuit and reactor parameters ;
3. TRV data monitoring and analysis ;

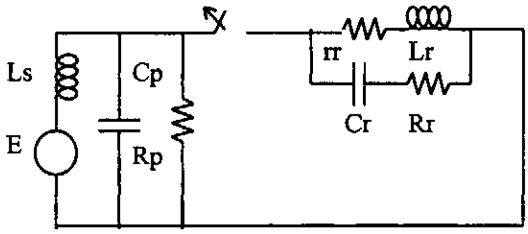

Fig.2 : Single phase laboratory test circuit.

Source parameters (E, Ls, Rp, Cp) : It is assumed that the frequency is kept constant at least until the (occurrence of the) TRV peak. This approximation is acceptable because the electromagnetic time constant is rather small compared to the electromechanical one. The source value is related to the amplitude factor due to the increase of the neutral potential. The amplitude factor is defined as the recovery voltage of the first phase interrupting the current divided by the composed assigned voltage of the system. An amplitude factor of 1,5 was assumed, according to the existing neutral impedances.

$$E = \sqrt{2} \cdot k \cdot \frac{U}{\sqrt{3}} \tag{9}$$

The voltage source and Ls define an equivalent depending on the short circuit current. The branch Rp and Cp relate to the upstream capacities to the ground, they are calculated regarding the method presented in [1]. Depending on the reactor impedance, the source parameters are adjusted regarding the IEC 56 test-duties which are related to the effective short circuit *rms* current value.

Reactor : A two parallel branch model (RrCr//rrLr) was used to model the reactor. The power frequency impedance is defined by the RL branch and the branch RC defines the high frequency one. This second branch was calculated as a function of the assumed reactor resonance frequency. The power frequency quality factor is 30 (wLr/rr) for every case. Equation 10 defines the HF resistance, due to skin effect.

$$Rf2 = Rf1 \cdot \sqrt{\frac{f2}{f1}} \tag{10}$$

with : f2 : high frequency

f1 : 50 Hz

Circuit breaker : A TACS information switch model was developed in order to directly determine the calculated TRV parameters. The thermal and dielectric envelope may be declared as an input of the model such as the desired outputs. To obtain excessive TRV parameters the envelope must be over dimensioned in order to get a simple ideal switch behaviour. This model allows an easy and quick analysis of TRV parameters assessing the success of the opening operation. It allows easy post processing and analysis.

B. Three phase circuit

Three phase and single line to ground faults could be performed using underground cable and overhead line frequency dependent models available in EMTP version 3.0. Different short line (cable) faults were tested considering different conductor sections and fault locations. The performance of the second and third poles could also be analysed. As far as the equivalent source circuit is concerned, the single phase calculated circuit values are easily transposed to a three phase circuit as indicated in [1]. Figure 3 shows the mentioned circuit. The neutral inductive impedance is about j40 Ω. What ever the point in the 90 and 63 kV network is, the zero sequence impedance varies between 10 and 120 Ω and between 10 and 90 Ω, respectively [2]. Considering a large quantity and diversity of substations with very different short circuit currents varying from 10 kA to 31,5 kA, Z0/Zd may vary from 24 to 70 for 90 kV and from 34 to 105 for 63 kV networks.

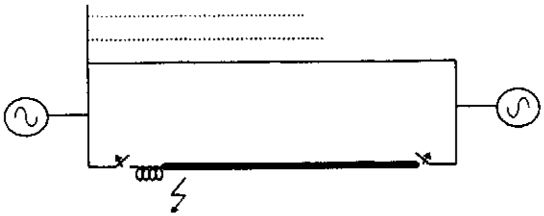

Fig.3 : Three phase circuit.

IV. HYPOTHESIS AND PARAMETERS

A. Hypothesis

The considered hypothesis are :

- Constant frequency equivalent source ;
- Source time constant equals 80 ms (three phase circuit) ;
- Circuit breaker modelling independent of its technology ;
- Short circuit current is interrupted after the asymmetric component is accomplished ;
- TRV IEC 56 standard is used to accept or reject a configuration according to the calculated TRV parameters ;
- EDF 80 % of HV 90 and 63 kV three phase short circuit current is around 16 kA.

B. Parameters

The considered parameters are :

- Short circuit currents : 31.5, 20, 16 and 10 kA.
- Service voltages : 63 and 90 kV.
- Type and location of the fault.
- Parameters of the considered reactors as showed in table 2.
- Average length of 90 kV and 63 kV circuits are 20 km and 15 km, respectively.

V. ANALYSIS AND RESULTS

A. Preliminary sensitivity studies

- TRV are more severe with no asymmetric short circuit current. IEC 56 suggests a less severe envelope for test-duty n°5.
- First pole interruption leads to more severe TRV than second and third pole interruption.
- For the same reactor, the crest TRV value (Uc) is greater if the service voltage is greater with an identical RRRV.
- For the same reactor, the smaller the short circuit current, the smaller RRRV.
- The insertion of a 50 m underground cable between the circuit breaker and the reactor does not reduce significantly the RRRV, because the TRV oscillation frequency is mainly imposed by the reactor resonant frequency.
- Short line (or cable) fault imposes supplementary oscillations to the TRV wave shape, depending on the fault distance to the circuit breaker and on the fault type. We performed three phase and single line to ground faults at different distances from the circuit breaker (5, 10, 15 and 20 km). Due to underground cable and overhead line different L and C per unit length, one can expect different behaviours for TRV wave shapes. For three phase faults, in case of an overhead line for the considered fault locations the short circuit current was not significantly reduced to decrease circuit breaker voltage stresses. In case of an underground cable, no significant reduction on RRRV were found. In fact, the RRRV stresses are already unacceptable for three phase faults after the reactor. As far as single line to ground faults are concerned, no important TRV stresses were found. The short circuit current is rather small due to the reactor, positive source and neutral impedance.
- The number of overhead lines connected to the bus bar may contribute to reduce the RRRV by increasing the capacity to the ground seen from the bus bar. In this case it is recommended to perform TRV simulation studies adapted to any particular configuration.
- **The greater the reactor impedance, the more severe the TRV is (wLI_{fault}).**

- **The greater the resonance reactor frequency, the greater the RRRV is.**

B. Results with no protection device

All simulations showed very severe TRV parameters compared to IEC standards for three phase faults leading to unacceptable RRRV. For 16 kA short circuit current substations, the calculated RRRV among all test-duties vary from 11,0 and 26,5 kV/µs. For 31,5 kA short circuit current substations, the calculated RRRV among all test-duties vary from 14,18 and 33,75 kV/µs. The results are presented in table 3 and 4. The presence of several other overhead lines or underground cables does not guarantee standard IEC TRV.

C. Tested protective devices

In order to reduce TRV parameters the following solutions in parallel with the reactor were considered :

- Air-gap ;
- Surge arrester ;
- Resistance ;
- Capacitance (a) in parallel or (b) to ground;
- RC circuit ;

Air-gap

After the fault inception, the air-gap will flashover and the short circuit current can be easily interrupted by the circuit breaker, with no important stress. The main disadvantage is low reliability due to disturbances (faults, birds, objects...) that may modify the gap distance. This type of equipment easily deteriorates with time.

Surge arrester

The principle of this solution is identical to the previous one. The chosen protection level must be inferior to the voltage across the reactor in a short circuit steady state condition. Significantly good results were obtained in reducing the RRRV. Nevertheless, the choice of the protection level must result from a compromise between the efficiency reducing TRV stresses and surge arrester energy dimensioning $(U_{reactor(short\text{-}circuit)} > P_{rotection}\ L_{evel} > U_{reactor(AC)})$. Unfortunately, energy comsuption is several times the admissible in typical surge arresters. An important over energy dimensioning would be necessary to use this solution. A resistance could be used with the function of energy dissipater during the fault. It should respect the following conditions : the voltage across the resistance must not be greater than the voltage across the reactor during the fault (otherwise no reduction in RRRV is observed) and its value must be important, so that the energy can be dissipated in the resistance and not in the surge arrester. As previously said, these two factors are contradictory. No interesting compromise was found.

Resistance

A parallel resistance dimensioned to obtain an aperiodic critical system could also be a good solution. The critical aperiodic regime eliminates the TRV high frequency oscillations. A great reduction of Uc value is obtained. However, no gain is obtained in RRRV because the voltage at the reactor side decreases abruptly from its maximum to zero. In any case, this solution drawback is the very high AC consumption (losses) during the system life cycle.

Capacitance

(a) Capacitance in parallel - This solution is equivalent to the redefinition of the reactor resonance frequency. It means that reactors to be installed could be designed imposing a reactor resonance frequency reduction. The greater the capacitance is, the lower the resonance frequency, the lower RRRV is, and the higher the Uc value is.

The capacitance value was calculated to reduce RRRV to an acceptable IEC standard, keeping Uc value below IEC 56 specifications. This solution is suitable to reactors comprised between B1 and B7. For higher impedance reactors, no good results were obtained concerning UC value.

(b) Capacitance to ground between the circuit breaker and the reactor - This solution is as efficient as the previous one. The main disadvantage is the specified Basic Insulation Level.

The PFIWL (Power Frequency Insulation Withstand Level) for capacitance (b) equals the simple phase-to-ground voltage. In case of capacitance (a), a significantly lower PFIWL must be specified ($U_{reactor} = wL\ I_{nominal}$). For this reason, the first solution seems to be economically appropriate.

RC circuit

A RC circuit as the advantage of damping TRV wave shape in order to reduce Uc value and RRRV. This solution is quite interesting regarding the high impedance reactors.

The capacitance must be calculated to reduce RRRV according to IEC 56, and it should limit the 50 Hz current in order to avoid energy dissipation in the resistance. The energy dissipation must be negligible during its life cycle. For this reason the resistance must be the smallest possible. The current flowing in this RC branch in normal service (AC) must be approximately of 1/1000 times the nominal charge current. The capacity choice must respect these two conditions. The disadvantages are the small available place in urban substations and its superior cost compared to a simple capacitance.

D. Advantages and disadvantages

The following table sums up the advantages and disadvantages of the analysed protection devices :

protection devices	**Advantages**	**Disadvantages**
air-gap	efficient	adjustment ageing
surge arrester	efficient	energy withstand
resistance	not efficient	losses
capacitance	efficient	-
RC circuit	efficient	available place more expensive

Table 1 : Advantages and disadvantages of the studied protection devices.

E. Examples and analysis

Three calculation examples follow, concerning three reactors : B1 (0,6 Ω), B5 (2,6) and B8 (7,7 Ω).

Figure 4 shows the two calculated TRV wave shapes for the reactor B1 with and without parallel capacitance. The figure shows in addition the IEC 56 standard envelope for test-duty n°4. Without parallel capacitance, the calculated RRRV is 14,3 kV/μs, which is significantly greater than the standard one (2 kV/μs). With a parallel capacitance of 12,5 nF, the calculated RRRV is 2,0 kV/μs.

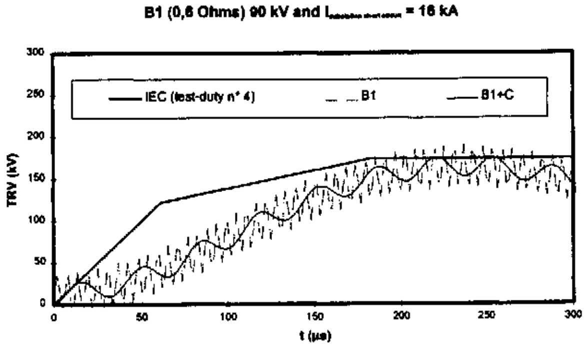

Fig.4 : TRV in presence of B1 with and without protection device.

In the case of 63 kV networks a 72,5 kV circuit breaker is normally used. In this case the required RRRV is 0,75 kV/μs for test-duty n°4 (instead of 2 kV/μs). This is the case in presence of low impedance reactors (B1, B2 and B3). The capacitances needed to obtain the specified RRRV are in the range of 1,3 to 2,8 μF. In fact, it is an EDF current practice to use 100 kV circuit breaker chambers. For this reason, the same capacities used for 90 kV can be used with success.

Figure 5 shows the same type of curves for the reactor B5 with and without parallel capacitance. The figure shows in addition the IEC 56 standard envelope for test-duty n°3 for 72,5 and for 100 kV equipment. Without parallel capacitance, the calculated RRRV is 17,6 kV/μs, which is significantly greater than the standard one (1,85 kV/μs). With a parallel capacitance of 12 nF, the calculated RRRV lower than the IEC specified one for 100 kV equipment. This capacitance is the same obtained with the 90 kV circuit which leads in this case to a RRRV of 2,0 kV/μs.

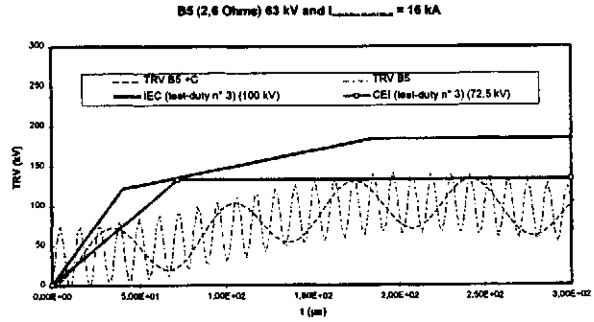

Fig.5 : TRV in presence of B5 with and without protection device.

Figure 6 concerns the reactor B8, and it reveals an identical problem requiring a different solution.

Initially, no protection device is installed, the calculated RRRV is of 16 kV/μs, which is unacceptable compared to 3,0 kV/μs (the standard one for test-duty n°3). With a parallel capacitance of 12,3 nF the standard RRRV was obtained. Unfortunately, standard test-duty n°3 envelope was overtaken after t1, because of the extreme impedance reactor value. It was decided to increase the capacitance value to smooth TRV. A capacitance of 200 nF was tested trying to achieve an acceptable TRV without success. In this circumstances a RC solution is recommended, with no relevant AC energy consumption. Nevertheless, an added resistance of 40 Ω was necessary to avoid the slight overtake of the standard Uc value. This RC circuit is named in figure 6 as RC'. Another successful RC couple was tested and named as RC2, corresponding to 50 nF capacitance and 100 Ω resistance. A variety of RC couples can be successfully used. It was then prudently decided not to adopt any general RC couples for high impedance reactors. In any case, the capacitance must be a 50 Hz very high impedance (some tens of kΩ). In normal conditions, an AC current of less than 1 A flows in the parallel branch, and of less than 10 A for a steady-state three phase fault. These resistances may be space demanding in line with dielectric standard withstand levels (Basic Insulation Levels).

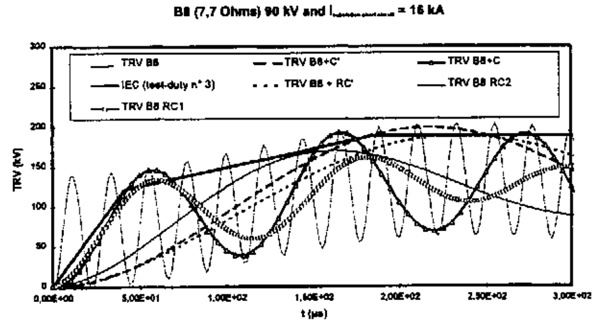

Fig.6 : Several TRV are showed describing different dimensioned protection devices. The curves are : IEC test-duty n°3 envelope ; reactor without any protection device ; reactor with a parallel capacitance (C) of 12,3 nF (TRV overtakes IEC standard) ; reactor with a parallel RC couple (RC1) of 12,3 nF and 300 Ω (TRV slightly overtakes IEC standard) ; reactor with a parallel capacitance (C') of 200 nF (TRV overtakes IEC standard) ; reactor with a parallel RC couple (RC') of 200 nF and 80 Ω (TRV succeeds IEC standard) ; reactor with a parallel RC couple (RC2) of 80 nF and 100 Ω (TRV succeeds IEC standard). It is observed that several RC couples can be used successfully.

F. Synthesis and recommendations

In the conditions of the study, no typical short circuit current interruption in the presence of series reactors succeeds without a TRV protection device. The authors have chosen a parallel capacitance to reduce voltage stresses across the circuit breaker when clearing faults in the range of B1 and B7 reactors. In fact, the equivalent resonance frequency should not exceed 33 kHz (table 5) for a 16 kA substation, and 18 kHz for 31,5 kA substation (table 6).

As showed, for reactor B8 a parallel RC circuit would suit regarding IEC standards. The exposed reasons justify no general proposition in terms of RC values. For higher impedance reactors, other test-duties may be required and as a consequence, simulation studies should be performed to obtain optimal RC couples from the economical and equipment size point of view.

So in this case the recommendations are as follows :

- considering 90 kV substations of 16 kA and of 31,5 kA, a capacitance of 20 nF and of 50 nF are respectively chosen in presence of reactors comprised between B1 and B7.
- for 63 kV networks, the same capacitance values are adopted if 100 kV circuit breaker chambers are used. This is already an EDF common practice.
- For B8 and higher impedance reactors a RC parallel circuit must be envisaged.

The extreme case of a 31,5 kA substations is to be considered as possible but rare.

VI. FUTURE WORK

Laboratory TRV testing of circuit breakers in presence of a reactor prototype with TRV protection device should be scheduled to assess the good fitting and accurately measure the reactor high frequency damping. After choosing the location where the system is to be installed in the HV network, some new studies should be performed for special network configuration or in presence of high impedance reactors.

VII. CONCLUSION

TRV parameters in presence of a series reactor are more severe than IEC 56 specifications, specially in terms of RRRV. A protection device can smooth TRV in order to significantly decrease RRRV. The adopted protection device is a parallel capacitance with the reactor. For high impedance reactors a RC parallel circuit is necessary.

VIII. ACKNOWLADGEMENTS

The authors gratefully acknowledge Mr Bedier and Mr Lachenal from EDF/DEPT/CNIR, J. Michaud, R. Hentschel, J. Sousa and B. Scappaticci, for their valuable contribution during the study.

IX. REFERENCES

[1] GAUTHIER J., BRUMENT Y., "Mesure de la TTR inhérente en basse tension et réglage de la TTR presumée - Application en réseau moyenne tension triphasé", Note Technique : EDF/DER, HM-51/3076, du 12/06/90.

[2] CORROYER C., "Mise à la terre des points neutre des réseaux HT", Report : EDF/Service Transport, D.63/689, du 09/04/81.

[3] IEC International Standard n° 56, "High-voltage alternating-current circuit-breakers", fourth edition, 1987.

[4] HARNER R.H., RODRIGUEZ J., "Transient recovery voltage associated with power-system, three-phase transformer secondary faults", IEEE, pp : 1887-1896, January 1972.

[5] H.W. DOMMEL, "The EMTP" Theory Book, Second Edition. The University of British Columbia, 1994.

[6] "Inventaire des ouvrages du réseau de transport au 31.12.1988", EDF/CERT/Dep. Exploitation.

X. APPENDIX

Reactors	Zr (Ohms)	Lr (mH)	Cr (µF)	fr(kHz)
B1	0,60	1,91	3,32E-04	200
B2	0,85	2,70	2,34E-04	200
B3	1,25	3,98	6,37E-04	100
B4	1,80	5,73	4,42E-04	100
B5	2,60	8,27	3,06E-04	100
B6	3,70	11,77	2,15E-04	100
B7	5,30	16,86	6,01E-04	50
B8	7,70	24,50	4,14E-04	50

Table 2 : List and reactors parameters to be installed.

Icc = 31.5 kA Unet = 63 kV	VATR (kV/µs)	U1 (V)	Uc (V)	t2 (s)
B1	22,71	6,20E+04	1,52E+05	1,94E-04
B2	27,16	7,49E+04	1,55E+05	1,87E-04
B3	17,22	7,79E+04	1,48E+05	1,87E-04
B4	20,54	9,34E+04	1,52E+05	1,86E-04
B5	23,28	1,08E+05	1,54E+05	1,88E-04
B6	25,51	1,19E+05	1,56E+05	1,85E-04
B7	14,18	1,23E+05	1,51E+05	1,90E-04
B8	15,94	1,35E+05	1,55E+05	1,89E-04
Icc = 20. kA				
Unet = 63 kV				
B1	15,48	4,25E+04	1,42E+05	1,94E-04
B2	21,74	5,86E+04	1,51E+05	1,87E-04
B3	12,51	5,73E+04	1,41E+05	1,87E-04
B4	15,59	7,16E+04	1,44E+05	1,86E-04
B5	19,44	8,90E+04	1,50E+05	1,88E-04
B6	23,43	1,06E+05	1,55E+05	1,85E-04
B7	12,22	1,07E+05	1,47E+05	1,90E-04
B8	14,31	1,22E+05	1,52E+05	1,90E-04
Icc = 16. kA				
Unet = 63 kV				
B1	13,33	3,63E+04	1,40E+05	1,94E-04
B2	18,77	5,03E+04	1,48E+05	1,92E-04
B3	10,99	4,98E+04	1,39E+05	1,87E-04
B4	13,99	6,35E+04	1,43E+05	1,86E-04
B5	17,64	8,01E+04	1,48E+05	1,88E-04
B6	22,25	9,86E+04	1,55E+05	1,94E-04
B7	11,00	9,78E+04	1,44E+05	1,91E-04
B8	13,34	1,14E+05	1,50E+05	1,90E-04
Icc = 10. kA				
Unet = 63 kV				
B1	7,53	2,13E+04	1,32E+05	1,94E-04
B2	12,40	3,34E+04	1,39E+05	1,92E-04
B3	7,53	3,44E+04	1,34E+05	1,87E-04
B4	9,60	4,44E+04	1,36E+05	1,96E-04
B5	13,68	6,13E+04	1,43E+05	1,88E-04
B6	16,85	7,54E+04	1,47E+05	1,94E-04
B7	9,28	8,05E+04	1,42E+05	1,90E-04
B8	10,57	9,40E+04	1,43E+05	1,90E-04
Icc = 6.3 kA				
Unet = 63 kV				
B1	5,10	1,43E+04	1,30E+05	1,94E-04
B2	7,11	1,98E+04	1,32E+05	1,87E-04
B3	4,90	2,27E+04	1,30E+05	1,97E-04
B4	7,41	3,30E+04	1,34E+05	1,96E-04
B5	9,56	4,33E+04	1,37E+05	1,88E-04
B6	11,58	5,33E+04	1,39E+05	1,95E-04
B7	7,17	6,23E+04	1,38E+05	1,90E-04
B8	9,00	7,73E+04	1,41E+05	1,90E-04

Table 3 : TRV parameters without protection device (63 kV).

	VATR (kV/µs)	U1 (V)	Uc (V)	t2 (s)
Icc = 31.5 kA Unet = 90 kV				
B1	21,88	6,14E+04	1,96E+05	2,09E-04
B2	32,65	8,84E+04	2,12E+05	2,13E-04
B3	18,06	8,44E+04	1,96E+05	2,18E-04
B4	23,68	1,09E+05	2,04E+05	2,17E-04
B5	26,98	1,27E+05	2,08E+05	2,08E-04
B6	33,75	1,54E+05	2,17E+05	2,05E-04
B7	17,85	1,57E+05	2,08E+05	2,10E-04
B8	20,51	1,76E+05	2,14E+05	2,10E-04
Icc = 20. kA Unet = 90 kV				
B1	16,61	4,54E+04	1,92E+05	2,14E-04
B2	19,58	5,50E+04	1,93E+05	2,08E-04
B3	14,10	6,41E+04	1,91E+05	2,18E-04
B4	18,86	8,47E+04	1,99E+05	2,06E-04
B5	22,86	1,05E+05	2,04E+05	2,08E-04
B6	27,95	1,27E+05	2,10E+05	2,14E-04
B7	15,33	1,34E+05	2,03E+05	2,10E-04
B8	17,56	1,53E+05	2,08E+05	2,10E-04
Icc = 16. kA Unet = 90 kV				
B1	14,26	3,87E+04	1,89E+05	2,14E-04
B2	20,01	5,36E+04	1,97E+05	2,13E-04
B3	11,23	5,21E+04	1,86E+05	2,18E-04
B4	14,84	6,87E+04	1,91E+05	2,17E-04
B5	19,22	8,90E+04	1,98E+05	2,08E-04
B6	26,47	1,17E+05	2,11E+05	2,14E-04
B7	14,49	1,23E+05	2,02E+05	2,10E-04
B8	16,05	1,41E+05	2,04E+05	2,10E-04
Icc = 10. kA Unet = 90 kV				
B1	9,63	2,59E+04	1,84E+05	2,14E-04
B2	11,34	3,15E+04	1,84E+05	2,13E-04
B3	8,41	3,77E+04	1,83E+05	2,18E-04
B4	10,57	4,85E+04	1,86E+05	2,17E-04
B5	14,77	6,68E+04	1,93E+05	2,18E-04
B6	18,78	8,47E+04	1,98E+05	2,14E-04
B7	11,29	9,59E+04	1,95E+05	2,10E-04
B8	13,68	1,17E+05	2,00E+05	2,10E-04
Icc = 6.3 kA Unet = 90 kV				
B1	9,63	2,59E+04	1,84E+05	2,14E-04
B2	11,34	3,15E+04	1,84E+05	2,13E-04
B3	8,41	3,77E+04	1,83E+05	2,18E-04
B4	10,57	4,85E+04	1,86E+05	2,17E-04
B5	14,77	6,68E+04	1,93E+05	2,18E-04
B6	18,78	8,47E+04	1,98E+05	2,14E-04
B7	11,29	9,59E+04	1,95E+05	2,10E-04
B8	13,68	1,17E+05	2,00E+05	2,10E-04

Table 4 : TRV parameters without protection device (90 kV).

Reactors	C (f=Max kHz) (µF)	Equivalent frequency (kHz)
B1	12,5E-3	33
B2	16,7E-3	24
B3	8,5E-3	27
B4	10,3E-3	21
B5	12,0E-3	16
B6	12,5E-3	13
B7	13,4E-3	11

Table 5 : Capacitance values and equivalent frequency of the protected reactor for a 16 kA substation.

Reactors	C (f=Max kHz) (µF)	Equivalent frequency (kHz)
B1	40,0E-3	18
B2	50,0E-3	14
B3	25,0E-3	16
B4	35,0E-3	11
B5	25,0E-3	11
B6	25,0E-3	9
B7	20,0E-3	9

Table 6 : Capacitance values and equivalent frequency of the protected reactor for a 31,5 kA substation.