ANALYSIS OF ELECTROMAGNETIC TRANSIENTS IN CROSS-BONDED CABLE SYSTEMS USING FREQUENCY DEPENDENT CABLE MODELS

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ABSTRACT

This paper describes the selection and use of EMTP frequency dependent cable models in the design of cross-bonded High Voltage underground cable transmission systems. Several types of studies are described, from frequency scans for harmonic analysis to very fast transients due to cable energization and reactor switching. Cable sheath grounding, protection, and design alternatives are discussed, as well as the impact of accurate modelling in this type of studies. The advantages and disadvantages of the models used in a given type of study are discussed, and general recommendations are provided.

Keywords: EMTP, Cables, Frequency dependence

1. INTRODUCTION

In recent years there has been a considerable amount of interest in the modelling of underground cables using transient analysis programs such as the EMTP. High capital costs, non-self-restoring insulation, and high replacement costs in the event of insulation failure are strong incentives to simulate underground cables with very high accuracy. In North America, underground cables are generally viewed as the solution to very specialized situations where the use of overhead lines is either impractical, or environmentally and aesthetically objectionable. In some parts of the world, however, high voltage underground cable transmission is more the norm than the exception.

The EMTP has a fair number of cable models, and their relative merits have been discussed and examined elsewhere [e.g., 1-2]. However, practical experience with the more advanced models available is just beginning to accumulate in a significant way.

This paper describes some of the "basic" transient studies carried out at Ontario Hydro for the design of HV cable systems. Examples based on the simulation of a relatively large 400 kV transmission system with over 250 km of underground cross-bonded cable circuits are shown for illustration purposes. The model selection criteria used in each type of transient simulation is discussed, and some practical guidelines and recommendations are provided.

2. CABLE MODELS IN THE EMTP

The cable models available in the DCG/EPRI version of the EMTP used at Ontario Hydro can be classified as follows:

Lumped-parameter models:
- Nominal π
- Cross-bonded uniform π
- Exact-π

Distributed-parameter models:
- Distributed constant-parameter (CP)
- Frequency dependent "line" model (FD)
- Frequency Dependent Q (FDQ) "cable" model

Lumped-parameter models.
Lumped or concentrated parameter models consist of multiphase coupled π-circuits, where R, L, and C are calculated at a given frequency (normally power frequency). The distributed nature of the cable parameters can be approximated to some extent by cascading a number of these π-sections. The main drawback of this type of model is the poor frequency response beyond the frequency at which the parameters are evaluated. The most commonly-used types of lumped parameter models are:

a) Nominal π-circuit.
The series branch of the nominal π-circuit is the series impedance of the cable, and the shunt branches consist of half of shunt capacitance of the cable.

b) Cross-bonded uniform-π cable model.
This model is also known as the Ametani cross-bonded cable model, and it is probably one of the first dedicated cable models in the EMTP [3]. It represents a major section of a cross-bonded cable by combining three nominal π-circuits, where the coupling of the sheaths to the main conductors is averaged, and the sheaths themselves are bundled into a single conductor..

c) Exact-π.
The exact-π model, is the exact frequency-domain representation of a cable calculated at a given frequency. It is not a time domain model and can only be used during single-frequency steady-state and frequency scan calculations.

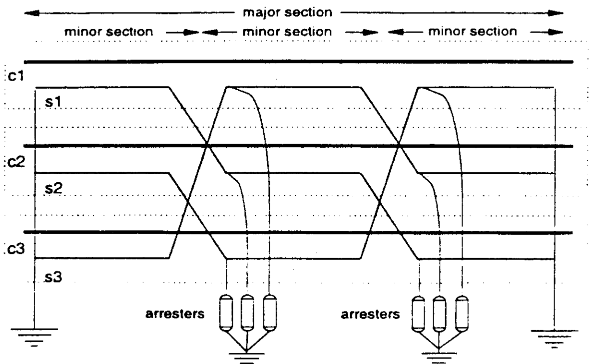

Fig. 1: *Major section of a cross-bonded cable.*

2) Distributed parameter models
Distributed-parameter models take into account the distributed nature of the cable parameters, and they are based on travelling wave theory. In the time-step loop of the EMTP, the differential equations that describe the behaviour of an n-conductor cable system in normal "phase quantities" are first decoupled into n separate differential equations by means of a linear transformation. The resulting decoupled system of equations is solved in "modal quantities". The same linear transformation is then used to convert the modal solution back to phase quantities. This linear transformation generally takes the form of a "modal transformation matrix" Q which relates phase voltages and currents to modal voltages and currents, with the relationships

$$V_{mode} = Q^{t} \cdot V_{phase}$$

$$I_{mode} = Q^{-1} \cdot I_{phase}$$

The distributed parameter models most commonly used in the EMTP are:

a) Distributed constant-parameter (CP) model.
This model is sometimes referred to as the Dommel line model. Parameters R, L, and C are assumed to be constant, and the shunt conductance G is ignored. The modal transformation matrix Q is assumed to be constant and real. R, L, and Q are normally calculated at 1 kHz. Since this model is based on a lossless line representation, only L and C are distributed, and R is lumped in three places. This model is computationally fast because it produces sparse contributions to the nodal admittance matrix of the system, and it is more accurate than concentrated-parameter π-circuit representations. Because Q is assumed to be constant and real, it is not possible to obtain accurate answers at both high and low frequencies. This model can be quite useful to simulate secondary cables and for other specialized applications [4].

b) Frequency Dependent line (FD line) model
This model is also known as the JMARTI overhead line model. The frequency dependence and distributed nature of the parameters are well approximated as long as the modal transformation matrix can be assumed to be constant and real [5]. While this is probably the most accurate model presently available to simulate overhead lines, it can run into problems in the case of underground cables, because the elements of the modal transformation matrix Q can change quite drastically with frequency, as shown in Figure 2.

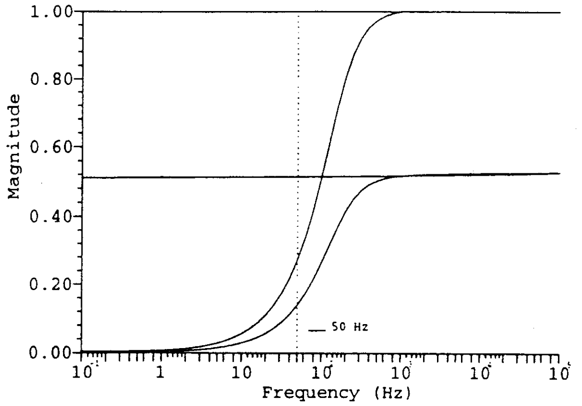

Fig. 2: *Magnitude of column 3 of Q for a three-phase cable (6 curves).*

c) Frequency Dependent Q (FDQ) cable model
This model is also known as the LMARTI cable model. It takes into account the frequency dependence of the cable parameters, as well as the frequency dependence of the modal transformation matrix Q [6]. It is the most accurate cable model presently implemented in the EMTP, and unlike other distributed parameter models, it can accurately reproduce high and low frequency phenomena in the same simulation. The FDQ model requires more resources in terms of storage, but in most cases it is only 30% slower than a comparable FD model.

3 MATCHING THE MODEL TO THE SIMULATION

When performing system studies with the EMTP, a number of factors should be considered in the selection of cable model: accuracy, computational speed and suitability for the type of simulation.

To model a cross-bonded cable with the highest accuracy and detail possible, each major section should be modelled explicitly, using three six-conductor FDQ models to represent each minor section. For example, to model a 25 km cable with 400 m minor sections, a total of 43 six-conductor FDQ models would be required, and the time step of the transient simulation would have to be at least smaller than the travel time the fastest mode of a 400 m minor section (e.g., $\tau = 2.3$ μs). The strain on computational resources due to the small time step would be very large if several such cables have to be modelled, and/or statistical studies are needed to study energization transients.

Computational savings in the order of 30% could be achieved if an FD model with constant Q were used to model each minor section. However, the FD model is unsuitable for the evaluation of sheath voltages and currents [2], as illustrated in the frequency scan of a line-to-ground fault termination of a 10 km cable shown in Figure 3.

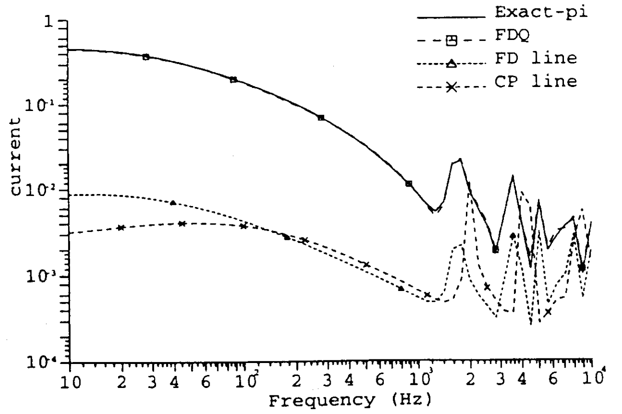

Fig. 3: *Magnitude of sheath currents.*

The detailed representation of each minor section is not necessary in all types of system studies. In simulations where it is not necessary to monitor sheath voltages and currents (e.g., energization transients, reactor switching, etc.), it is possible to make some simplifications. The effect of sheath cross-bonding on core conductors can be approximated by averaging the core-sheath and sheath-sheath terms of the impedance and admittance matrices. Also, the effect of grounding the sheaths at the ends of each major section can be approximated by assuming that the sheaths are continuously grounded (i.e., at zero potential throughout the entire cable length) so that they can be eliminated. With these approximations, a three-conductor equivalent of a cross-bonded cable can be obtained and modelled with an FD model. The main advantage of this continuously cross-bonded model is that it does not limit the simulation time step to a fraction of the travel time of a minor section, thus allowing significant savings in computational time.

The suitability and validity of the three-conductor FD representation have been examined in considerable detail at Ontario Hydro for use in large system studies, both using frequency scan comparisons with detailed exact-π representations, and with time domain simulations using the FDQ model as reference solutions. Figure 4 shows the conductor voltage of an unfaulted phase of a cross-bonded cable under line-to-ground fault termination. The total length of the cable is 25.2 km. The solid trace is the reference response calculated using 21 major sections modelled explicitly with exact-π models for each 400 m minor section, and the dashed trace shows the response of the continuously cross-bonded three-conductor FD model. For the FD model, Q is assumed to be constant and real, and it is evaluated at 1 kHz. Figure 5 shows the currents in the faulted conductor. These results illustrate that the continuously cross-bonded 3-conductor FD model is sufficiently accurate for transient simulations not involving the study of sheath overvoltages

4. SYSTEM STUDIES

In the design of an underground cable sub-system, a number of transient studies should be carried out to calculate transient and temporary overvoltages in order to establish insulation and protective equipment specifications for major system components such as transformers, reactors and generators. From a modelling point of view, three basic types of studies can be considered:

- Frequency scan analysis studies to determine possible resonant conditions
- Sheath protection studies to determine the specifications of the arresters used to limit sheath overvoltages at cross-bonding points.
- Switching transients studies for a number of system design purposes, such as switching and impulse insulation strength levels, arrester specification and circuit breaker specification, to name a few.

From a modelling point of view we will include temporary overvoltage studies in the same general category as switching transient studies. The simulation of temporary overvoltages often involves slow as well as fast transients, because temporary overvoltages usually follow some kind of switching activity during which fast transients may be involved. However, there is no need to make a modelling distinction when FDQ or three-conductor FD models are used since given they are accurate over a wide frequency range.

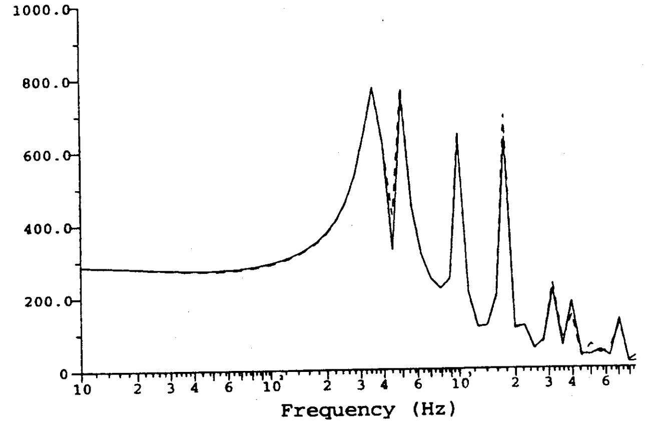

Fig 4: *Frequency scan of l-t-g voltages, 21 major sections. Solid = exact-π, Dashed = FD.*

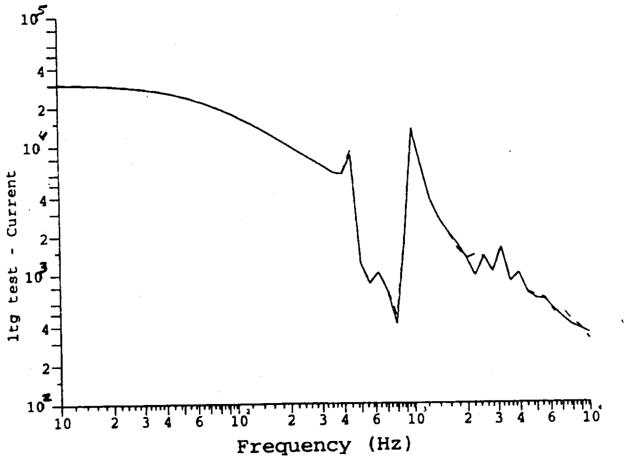

Fig 5: *Frequency scan l-t-g fault current, 21 major sections. Solid = exact-π, Dashed = FD.*

4.1 Frequency Scan Studies

Conceptually, a frequency scan study of system resonances consists of two parts. First, the frequencies at which series and parallel resonances take place are identified by means of driving point impedance calculations at various points in the system. Second, it must be assessed if there is a source that will provide the energy to drive the system into a resonance situation. For example, if a frequency scan identifies a series resonance at 150 Hz, it is necessary to assess if there is a legitimate way to obtain a "sustained" 150 Hz energy source. This 150 Hz energy source can be created by a temporary equipment configuration or contingency situation. However, unless there is a 150 Hz source of energy for the duration of the contingency, there will not be any serious consequences or equipment damage.

The most accurate way to perform harmonic analysis studies in the EMTP is using exact-π models. Since there are no approximations or modal transformations involved, the exact-π model is an ideal tool for model validation and harmonic analysis. For frequency scan calculations, these π-circuits evaluated at each of the scan frequencies are stored in a file and read as they are needed for each steady-state solution of the frequency scan. Frequency scan studies can, for example, show that grounding a transformer neutral through a reactor can be an effective way to limit line-to-ground fault currents in an overhead system, but can lead into resonant conditions in a cable system.

4.2 Sheath Protection Studies

For relatively long cables the preferred sheath bonding method is cross-bonding. The cable is subdivided into minor and major sections, where the length of a minor section is usually determined by practical limitations such as reel size. The sheaths of each minor section are transposed or "cross-bonded", and grounded at the ends of each major section (see Figure 1).

Under balanced steady-state operation, the sheath currents induced on each minor section are 120 degrees apart, and the net sum over a major section is zero. This means that power frequency losses due to sheath currents are essentially eliminated, except for slight unbalances due to cable layout. Even these unbalances can be minimized by also transposing the main conductors at each minor section as the cable is laid. Under switching and unbalanced fault conditions, a change in the physical location of the sheaths at each cross-bonding point represents an electrical discontinuity. Therefore, travelling waves will be reflected, and relatively high transient sheath overvoltages will occur at the sheath cross-bonding points. These overvoltages are normally controlled by means of metal oxide surge arresters or MOVs.

The basic design criterium for the selection of sheath protection MOVs is to keep sheath overvoltages as low as practical. Within this general constraint, the MOV protective level should be high enough to allow the survivability of the surge arresters under normal switching operations (e.g., cable energizations), including switching associated with a fault external to the cable circuit.

The impulse withstand level of sheath insulation can be expected to be lower than factory specifications after the cable is laid. Furthermore, ageing, humidity and other environmental factors contribute to lowering the effective impulse withstand level over the lifetime of the cable. It is not possible to obtain generic figures regarding the impulse withstand capabilities after the above factors are taken into consideration. Therefore, from a practical point of view, it is necessary that the cable manufacturer explicitly guarantees the long-term sheath insulation impulse withstand capability based on the MOV protective level selected.

All studies for the determination of sheath protection specification should be carried out using 6-conductor FDQ cable models (3 cores and 3 sheaths), in order to obtain an accurate, full-spectrum representation of the cable. The length of each minor section is usually determined by the length of cable that will fit on a reel (e.g., 400 m for a 400 kV cable is more or less typical). In the EMTP, each cross-bonding point should be modelled explicitly, and sheath protection MOVs should be modelled as ZnO arresters. It is not necessary to model each MOV at every cross-bonding point along the cable. MOV energy absorption drops sharply after the first two major sections, and including arrester models in more than three major sections into the cable (at sending and receiving ends) is probably unnecessary.

The rest of the system probably does not need to be modelled in great detail, but it is often a convenient (and conservative approach) to re-use the same system representation used in other transients studies (e.g., using three-conductor) FD models. Compared to the resources needed to model the cable being studied in detail, the computational savings that could be achieved using simpler models on other cables in the system is not justifiable.

The energy absorbed by the sheath MOVs during cable energization transients depend on the length of the cable, the number of cables connected at the sending end, and the rating of the MOVs. During the energization of a cable, the arresters closest to the sending end of will absorb the highest energy. As the number of cables connected to the sending end increases, the energy MOV absorption also increases (the effect is similar to that of back-to-back capacitor bank energization). Arrester energy absorption drops rapidly after the first major section. For example, in the energization of a 25 km cable, the energy absorbed by 6 kV MOVs in the first cross-bonding point of the first major section was 7 kJ, whereas in the first cross-bonding point of the second major section energy absorption dropped to 4.5 kJ.

The MOV duty due to a line-to-ground fault external to the cable depends on several factors:

1) Number of cable circuits connected to the faulted bus
2) Relative length of the cables contributing current to the fault
3) System fault level
4) Grounding resistance

The energy duty of sheath protection MOVs depends strongly on the core currents during a line-to-ground fault. The larger the fault current, the higher the energy absorbed by the arresters.

The number of cable circuits connected to the bus affects the magnitude of the initial high frequency transient after the occurrence of a line-to-ground fault. The larger the number of circuits leaving the bus, the higher the initial current peak. On the other hand, as the number of cables connected to the bus increases, the contribution of each cable to the fault current will be lower. The net result is that the dominating factor is the magnitude of the core currents; therefore, fewer cables at the faulted bus mean higher arrester duty. The worst contingency would be if there were only one cable feeding the fault. In such a case, the entire fault level contribution (minus fault current contribution from local generation) would be carried by one cable. This worst case scenario is very similar to an "internal" cable fault; that is, a fault that occurs somewhere along the cable (but not at the terminals). Note that it is not practical or feasible to specify MOVs that will withstand such extreme contingencies.

The grounding resistance at the sectionalizing and cross-bonding points also affects, albeit to a lesser extent, the energy absorbed by the MOVs under fault conditions. The relationship is not straightforward. A very high grounding resistance increases sheath overvoltages, while a very low resistance increases sheath currents. Studies carried out at Ontario Hydro suggest that a grounding resistance in the order of 2 to 4 ohms results in the lowest energy absorption levels for 6 kV rated MOVs. Beyond the first two major sections, grounding requirements are not as important, and special grounding arrangements beyond those required for safety regulations are probably not necessary.

Depending on the fault level of the system, the overriding factor in the specification of sheath protection MOVs can be the energy absorption requirements during external line-to-ground fault conditions. Under such conditions, energy requirements due to cable energization tend to be a relatively small and well-defined factor and they are simply be added to the energy requirements due to line-to-ground faults. Note however, that energization transients produce higher and faster transient overvoltages than line-to-ground faults. Therefore, energization transients must be taken into account in the specification of the protective level of the selected MOVs.

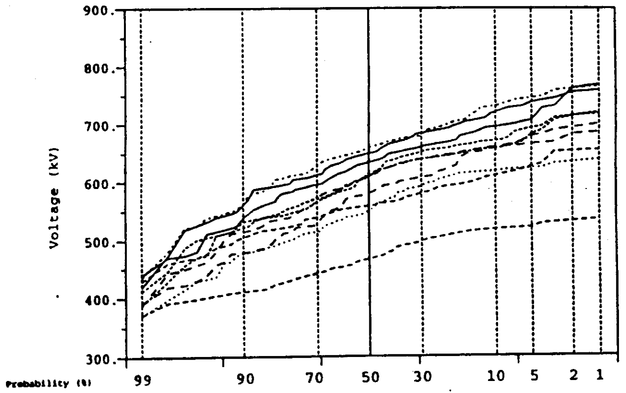

Fig. 5: *Probability distribution of peak energization voltages for 10 buses.*

4.3 Switching Transients Studies

It is probably unnecessary to use different cable models in transient simulations where the cable sheaths do not have to be modelled explicitly. Therefore, we will only discuss two types of switching surge studies, and consider them representative examples from a cable modelling point of view.

4.3.1 Energization Studies

In energization transients studies, cross-bonded cables should be modelled using FD models. The main reasons for this choice are:

- For the cables under consideration, the three-conductor FD model reproduced core voltages and currents in the mid- to high frequency ranges very accurately.

- The use of the three-conductor FD model allowed the use of a larger Δt than it would have been necessary if each 400 m minor section and each cross-bonding point had been modelled explicitly.

- Given the large number of simulations required in statistical studies, the three-phase FD model provided an advantage in terms of computational speed, without any practical loss of accuracy, when compared to an equivalent three-conductor FDQ model.

- Monitoring of sheath voltages and currents is not necessary in this type of simulation.

For modern SF6 breakers, the contact spread can be assumed to have a normal distribution, and contact spread values can be less than 2 ms 90% of the time (which results in a standard deviation σ=1.556 ms). As in the case of overhead line energization studies, EMTP "Statistics" should be made, with 100 independent energizations for each study. The 100 case peaks (highest voltage reached on any of the three phases for each case) are retained, and plotted on a (normal) probability scale (see Figure 5). The truncation level, which is a best estimate of the maximum overvoltage which can be produced by the system, can be calculated from the determined 2% level assuming a Weibull probability distribution. On the few occasions where the EMTP actually calculates a slightly higher maximum value, the higher EMTP value should be used.

4.3.2 Reactor Switching

In the case of long cables, it is often necessary to connect shunt reactors for the purpose of voltage control. These shunt reactors can be switchable for short term voltage control, or can be placed on a more or less permanent basis at the ends of the HV cable itself. Switchable

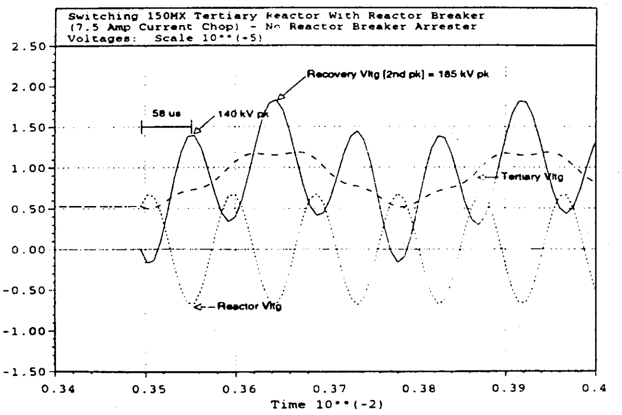

Fig. 6: *Shunt reactor switching. Reactor breaker voltages. No surge arresters.*

reactors are usually installed on the tertiary winding of step-down transformers, to take advantage of low voltage switchgear. Switching out a reactor produces high frequency transients which may result in arc re-ignition and re-ignition overvoltages.

When a reactor is switched out of service, the voltage across the reactor oscillates at very high frequency and eventually decays as the energy stored in the reactor is dissipated via reactor losses. The frequency of oscillation depends on the size of the reactor, and the stray capacitances across the reactor (and breaker bushings). The magnitude of the transient voltage across the reactor also depends on the magnitude of the current chopped, which in turn, depends of the type of breaker and voltage level. The magnitude of the voltage across the breaker depends on the voltage across the reactor as well as the voltage on the "source side". The reactor and source-side voltages oscillate at different frequencies, therefore, the magnitude of the transient recovery voltage across the breaker is generally the sum of the magnitudes of source-side and reactor voltages.

Consider, for example, switching out a 150 MVA shunt reactor connected to the 66 kV winding of a 400/230/66 kV autotransformer bank, with cables connected to the 400 kV and 230 kV buses. Figure 6 shows the Transient Recovery Voltage (TRV) across the breaker terminals, as well as the reactor and source side voltages. The assumed current chopping level is 7.5 A. The cable was modelled assuming the sheaths are continuously cross-bonded and grounded. This simulation indicates that TRV voltages in the order of 185 kV peak or 3.4 pu can be produced. If no action is taken to control the recovery voltage across the breaker, the magnitude and fast rate-of-rise of the TRV, would result in breaker re-strike.

Surge arresters at both the shunt reactor and at source side of the breaker (tertiary terminals of the autotransformer) would limit overvoltages at the reactor terminals, but would not be sufficient to limit the voltages across the breaker terminals. On the other hand, connecting 54 kV surge arresters across the contacts of the circuit breaker terminals would limit the recovery voltage to 86 kV or 1.6 pu, and it would eliminate the risk of re-ignition.

4. CONCLUSIONS

When using the EMTP to carry out system studies, it is desirable to have very high accuracy within reasonable limits imposed by computer resources. It is also desirable to have as few modelling choices as possible, because the design engineer should be more concerned with the studies being conducted than with EMTP-specific modelling details and idiosyncrasies.

For underground cross-bonded cables, three models and/or modelling techniques can cover most of the transient simulations used in transients system studies:

1. Exact-π representations for steady-state, and frequency scan studies.
2. Explicit modelling of a the cross-bonded cable under consideration using six-conductor FDQ models for each minor section to examine sheath overvoltages for sheath protection studies.
3. Three-conductor FD models where sheaths are assumed to be continuously transposed and grounded for simulations where core voltages and currents are important. A six-conductor FD model, on the other hand, is not generally suitable for the simulation of sheath overvoltages.

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