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Estimation of the Required Modeling Depth for the Simulation of Cable Switching in a Cable-based Network

F. Faria da Silva, Claus L. Bak and Per B. Holst

***Abstract*—The simulation of an electromagnetic transient is only as good as the model's data and the level of detail put into the modeling.**

One parameter with influence in the results is the size of the modeling of the area around the switched-on line. If the area is too small, the results are inaccurate. If the area is too large, the simulation requires a long period of time and it is more likely the existence of numerical problems.

This paper proposes a method that can be used to estimate the depth of the modeling area using the grid layout, which can be obtained directly from a PSS/E file, or equivalent.

The simulation of electromagnetic transients in cable based-networks requires a larger computational effort than in an equivalent OHL-based network. Therefore, the method is demonstrated for the former, being the cases of OHL-based networks and hybrid cable-OHL networks addressed in a future paper.

One of the main reasons behind the long simulation times of a cable-based network is the simulation of all the cross-bonded sections. The introduced method can also be used to minimize the modeling of the cross-bonded sections.

***Index Terms*—IEC standards, Power cables, Power system modeling, Power system transients**

I. Introduction

INSULATION co-ordination studies are typically done when planning the installation of a new line. Guidelines for these studies are given in an IEC standard [1].

However, the standard was written with the more common Overhead-Line (OHL) based systems in mind and it does not reflect some specifies of cable-based systems.

One aspect requiring more attention is the modeling depth, i.e., how far from the busbar must one represent the network. The standard recommends representing the network up to two busbars from the operated line, which is not always sufficient [2].

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This paper presents a method that can be used to estimate the minimum required modeling depth for a cable-based system. The method can also be adapted for an OHL-based system and a hybrid OHL-cable system, as will be explained in a future paper.

The modeling of the cable cross-bonded sections is also addressed. The method can be used to estimate the lines that need an accurate modeling of the cross-bonded sections and those that can have a simplified model.

The method is exemplified using a model of West Denmark Transmission Grid and accurate system data. A possible inaccuracy in the method is pointed-out and at the same time it is explained how to avoid it.

II. Test System

The explanation of the method requires the use of a complex and large network. For that effect, it is used the West Denmark transmission network as planned for the year 2030. The network is characterized by the use of undergrounded HVAC cables at 150kV and OHL at 400kV [3].

The network has a total of 129 busbars, 27 OHL (400kV), 80 HVAC cables (165kV) and 36 transformers.

The cables are modeled by means of frequency-dependent phase models [4], which is the most accurate model available at the present for the simulation of electromagnetic transients [5]. The accuracy of the model and the cables were assessed by means of measurements and both are considered as valid for electromagnetic studies [6],[7].

The proposed method is demonstrated for switch-on operations in two different lines: The NVV-BDK line, which is surrounded by mix of short and long lines, and the STSV-LEM line, which is mostly surrounded by long lines. Fig. 16 shows the network single-line diagram.

III. Problem Description

The modeling of the area surrounding the switched-on cable influences both the waveform and the peak voltage magnitude.

Fig. 1 shows the voltage in one phase during the re-energisation of the NVV-BDK cable, for different modeling depths. By re-energisation is understood that the circuit breaker (CB) is forced to restrike half-cycle after the switch-off when the voltage difference at the CB terminals is maximum and equal to 2 pu. For all four cases, it is used an N-1 equivalent network representing the grid around the respective modeled area.

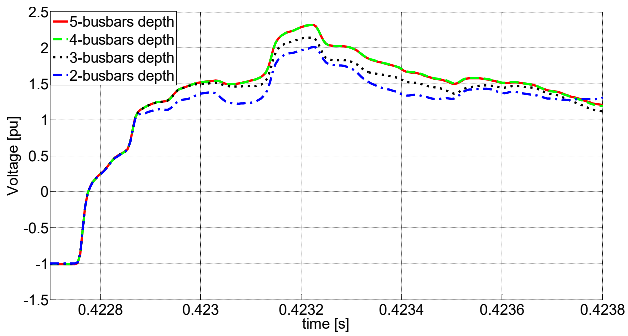

Fig. 1. Voltage transient in one of the phases after the re-strike for the different modeling depths. 5-busbars depth: solid-line; 4-busbars depth: dashed-line; 3-busbars depth: pointed-line; 2-busbars depth: dashed-pointed line

The simulation objective is to estimate the maximum peak voltage value. Therefore, it is concluded that the proper simulation of the NVV-BDK line energisation/re-energisation would required the modeling of the network up to at least four busbars of distance, the double of the recommended in the standard.

Other examples can be found when it is not necessary to model more than one busbar distance of the node, as when one short cable is surrounded by cables of the same type that are four times longer.

IV. Estimation Method

A. Peak time

The peak voltage associated to a cable energisation/re-energisation is not attained at the energisation/re-energisation instant, but some hundreds of micro-seconds later. This instant corresponds normally to the moment in which the voltage wave generated at the CB switch-on reaches the cable receiving end for the second time.

Fig. 2 exemplifies the wave propagation during this period. A wave is generated at *I* and reaches the cable receiving end at *II*. The cable is open in the receiving and the wave is reflected back, flowing back into the cable sending end, which the wave attains at *III*. At this point part of the wave is reflected back with opposite polarity and reaches the cable receiving end at *IV*, reducing the voltage magnitude. The peak voltage occurs at this instant.

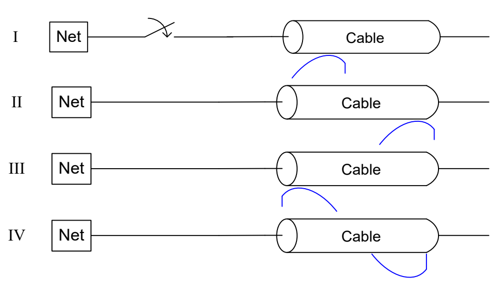

Fig. 2. Wave propagation between the energization instant and the peak overvoltage instant

This instant is used as time reference for the calculation of the required modeling depth. I.e., it is considered that the maximum voltage instant is independent of the area around the operated line. The cases where the overvoltage occurs later than this instant are analyzed later in the paper.

B. Theoretical Background

Two or more waves are generated when a cable is energized/re-energized. One of the waves propagates into the operated line, whereas the other wave(s) propagate into the line(s) connected to the cable energized end. The magnitude of each of these waves depends on the lines surge impedances [9].

Fig. 3 shows a simple example on how the waves act during the electromagnetic transient. The wave(s) injected into the neighbor line(s) (solid line in *I*) is reflected back at the line(s) end(s) (*II*) and is after refracted into the cable being energized (*III-IV*).

In order to the reflections of the neighbor busbars reach the receiving end of the energized cable (*V*) before the peak overvoltage, the busbars have to be at a distance inferior to half of the distance traveled by the wave between the switch-on and the peak voltage instant. If the wave(s) reaches the cable receiving end before the expected peak instant (*VI*), there are changes in both the waveform and the peak voltage.

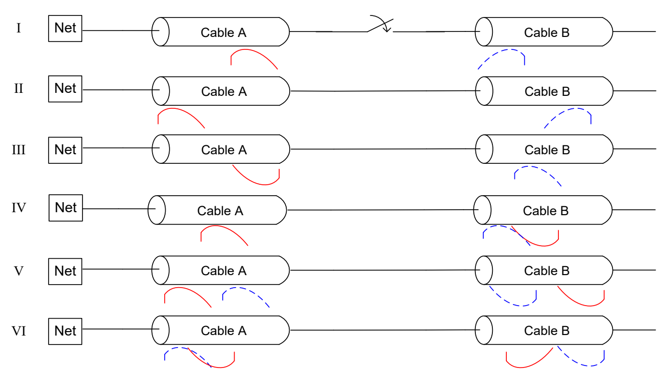

Fig. 3. Reflections and refractions of the waves generated at the switch-on instant. Solid Line: Wave propagating into the adjacent line; Dashed Line: Wave propagating into the cable being energized

C. Grid layout

Typically, a utility has a PSS/E file, or equivalent, containing the entire grid. The information contained in those files can be used to design a matrix where the rows and columns represent the network busbars and the matrix's entries are the distance between them, if directly connected.

Fig. 4 shows part of the network in the neighborhood of the NVV busbar, whose equivalent distance matrix is shown in Fig. 5.

In general, it is only necessary to model the elements whose voltage level is the same of the cable being switched [1]. Thus, the matrices contain only busbars with equal nominal voltage.

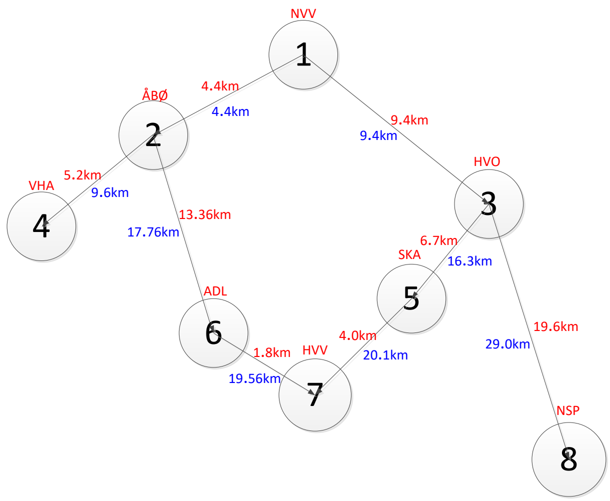

Fig. 4. Busbars in the neighborhood of the restriked node. Red: Distance between nodes; Blue: Distance between the nodes and the NVV node

$$\begin{bmatrix} 0 & 4.4 & 9.4 & 0 & 0 & 0 & 0 & 0 \\ 4.4 & 0 & 0 & 5.2 & 0 & 13.36 & 0 & 0 \\ 9.4 & 0 & 0 & 0 & 6.7 & 0 & 0 & 19.6 \\ 0 & 5.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 6.7 & 0 & 0 & 0 & 4 & 0 \\ 0 & 13.36 & 0 & 0 & 0 & 0 & 1.8 & 0 \\ 0 & 0 & 0 & 0 & 4 & 1.8 & 0 & 0 \\ 0 & 0 & 19.6 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Fig. 5. Distance matrix for Fig. 4 system

D. *Wave speed*

In order to estimate how far travel the waves generated at the switch-on instant, it is necessary to know their speed in each line of the grid. Therefore, a wave speed matrix equivalent to the matrix shown in Fig. 5, but containing the speed of the wave in the line instead of the cable length, has also to be design.

The distance between the busbars can be obtained from the PSS/E files, but the same cannot be done for the wave speeds, since a PSS/E file lacks information on the lines geometry, which would be necessary for the calculation of the wave speed [10].

Thus, one can use wave speed values a little larger than the typical ones, e.g. 180m/µs and 280m/µs for respectively a cable coaxial mode [10] and an OHL.

Another solution would be to create an extra file containing the precise wave speed for the different types of cables present in the system. However, such high level of accuracy is not necessary and typical values are normally good enough.

E. *Method*

The estimation of the modeling depth can be made in Matlab as following:

1) Insert the time for the first peak and the wave speeds
2) The code reads the grid information directly from the PSS/E files, designing two matrices equivalent to the network
3) The first matrix contains the distance between the busbars, in which the line and column identify the busbars. The matrix is symmetrical
4) The second matrix is equivalent to the first, but the distance is substituted by the wave speed in the cable (coaxial mode) or OHL
5) It is calculated the distance and the traveling time between the energized/re-energized node and all busbars up to 8 busbars of distance. At the same time are designed all possible paths up to 8 busbars of distance
6) Calculates which busbars are up to a distance inferior to 0.525 times the charging time of the cable being energized/re-energized. Ideally it would be 0.5, but it is given a security margin for the case of a reflection reaching the cable immediately after the expected peak time;
7) Indicates which busbars/lines need to be modeled, i.e., the modeling depth.

Note that the choice of 8 busbars as upper limit is normally more than enough for the simulation of a normal transmission network.

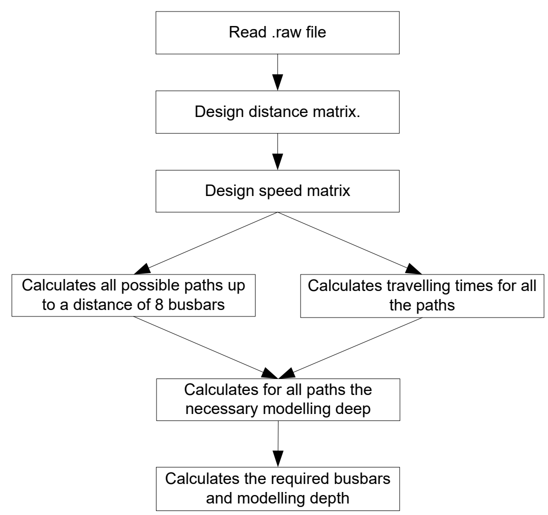

Fig. 6. Estimation method flowchart

The method is applied to the test system for an energisation of the NVV-BDK cable. According to it, the model should have a 4-busbars modeling depth, which, was demonstrated in Fig. 1 to be correct.

F. *Minimization of the number of nodes*

The estimation method provides not only the required modeling depth, but also the exact busbars that have to be included in the model. Using this information the model can be optimized, and instead of having a modeling depth of 4 busbars it can have only the necessary busbars.

According to the estimation method the simulation of the NVV-BDK cable switch-on from the NVV side, needs 14 busbars, whereas the use of a 4-busbars modeling depth corresponds to a total of 29 busbars. Thus, the optimization of the model to only 14 busbars would represent a substantial reduction of the simulation time.

Fig. 7 compares the voltage in the cable receiving end, similar to Fig. 1, for a model with a 4-busbars modeling depth (29 busbars) and another model with only the required 14 busbars. The voltage peak magnitude is the same for both models.

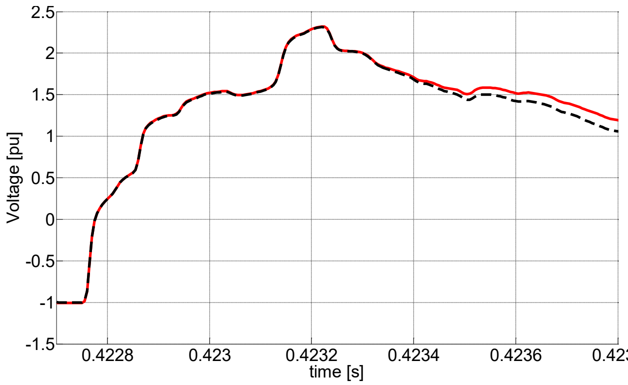

Fig. 7. Voltage transient in one of the phases after the re-strike for a 4 busbar modeling depth (solid line) and a model containing only the required busbars (dashed line)

V. Modeling of the Cross-Bonded Sections

A. Method Explanation

For several reasons, the modeling of all cross-bonded sections of the network cables represents a substantial increase of both the simulation total running time and the time necessary to design the system:

- To design *n* minor cross-bonded sections instead of three;
- The software needs more time to complete each time step;
- The time step has to be reduced in order to accommodate the shorter cable sections;
- Increases the probability of fitting and memory problems;

The IEC standard [1] suggests modeling all cross-bonded sections. An accurate modeling of all cross-bonded sections is indeed necessary for the simulation of some electromagnetic transient phenomena [2], as the wave during a transient can be reflected at the cross-bonded points [8].

Whereas the need of modeling all cross-bonding sections in the line being energized is clear, the same may not be true for the neighbor cables.

A method similar to the one proposed in section IV can be used to determine which cross-bonding sections to include in the simulation model. For the particular example of a restrike in the NVV-BDK cable it would be necessary to model all the cross-bonded sections of the system. Thus, the theory is demonstrated using another area of the network.

The method is exemplified to a restrike in the STSV end of the STSV-LEM cable.

The application of section IV method indicates that six busbars have to be included in the model. As one of the busbar is connected to two transformers, a seventh busbar is added, so that the transformers are included in the model. Fig. 8 shows the modeled single-line diagram.

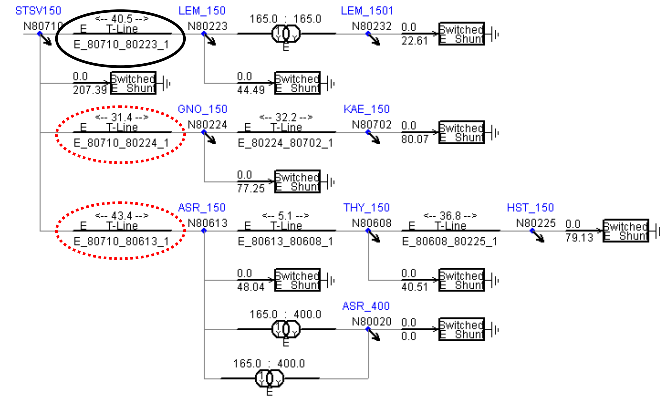

Fig. 8. Single-line diagram of the simulated system: Solid circle: Restriked cable. Pointed circles: Cables requiring accurate modeling of the cross-bonded sections

To estimate which cross-bonded sections need to be accurately modeled, it is used the same method that was used to calculate the modeling depth, but substituting the coaxial mode speed by the inter-sheath mode speed, which is approximately 80m/µs [10]. According to the method it is necessary to have accurate modeling of the cross-bonded sections in only two of the cables, more precisely the two cables adjacent to the restriked cable; the STSV-GNO and STSV-ASR lines (see Fig. 8).

B. Example

To simplify the analysis and comparison the system is kept as simple as possible and it is considered that all cables of the real system have only two major cross-bonded sections.

Three different models are prepared for comparison:

- Model 1: The switched-on cable model has two cross-bonded sections and all the remaining cables are modeled with one major cross-bonded section;
- Model 2: Equal to Model 1, but the two cables adjacent to the STSV node (STSV-GNO and STSV-ASR) are modeled with two major cross-bonded sections, whereas the remaining cables with one major cross-bonded section;
- Model 3: Equal to Model 2, but with two more cables (GNO-KAE and ASR-THY) modeled with two major cross-bonded sections;

According to the theory presented, Model 1 has an insufficient level of detail, Model 2 has the minimum level of detail required to an accurate simulation of the maximum voltage peak and Model 3 has an excessive level of detail.

Fig. 9 shows the voltage in the receiving end for the re-energisation of the STSV-LEM cable using Model 1 and Model 2. Fig. 10 shows the same results for Model 2 and Model 3.

The results confirm the accuracy of the method. The differences between Model 1 and Model 2 are visible before the peak, while the differences between Model 2 and Model 3 are only visible after the peak instant.

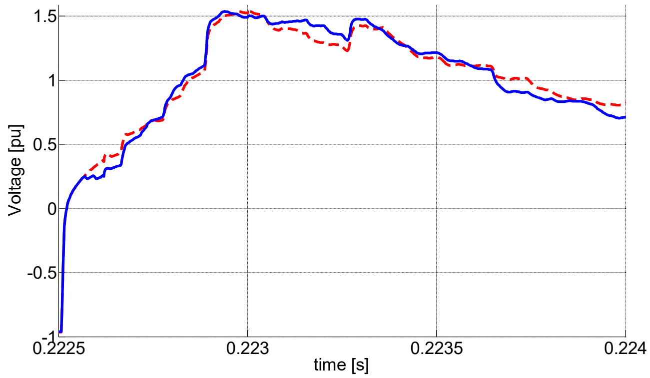

Fig. 9. Voltage in the cable receiving end during re-energisation. Dashed line: Model 1; Solid line: Model 2

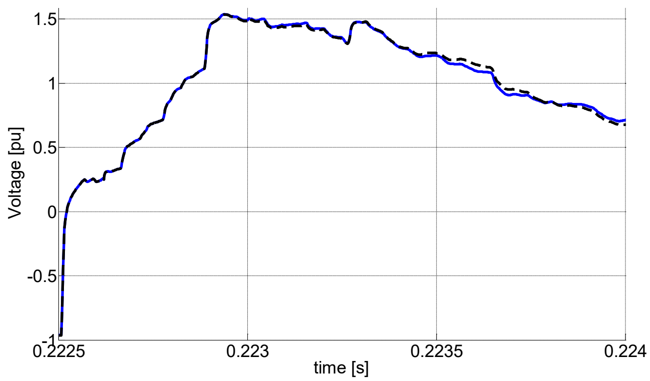

Fig. 10. Voltage in the cable receiving end during re-energisation. Solid line: Model 2; Dashed line: Model 3

VI. Possible Inaccuracy

The presented method assumes that the peak voltage occurs at a given instant that is independent of the network, which is not always true, because of a combination of low and large reflections coefficients in the same network, or a magnification effect resultant from different surge impedances. Possible examples are systems with:

- Very few lines;
- Low reflection coefficients in the joint points, meaning that the cables are connected in series and there is almost no load/generation in those points;
- An OHL is installed in the cable vicinity;

The last case is analyzed in a future paper. The first two are explained below. As example it is used the system shown in Fig. 11. The system consists in only two cables with the same characteristics, with Cable A connected to a voltage source.

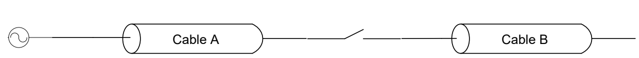

Fig. 11. Two cables system. Cable B>Cable A

Cable B is energised and one of the waves propagates into it, while another wave propagates into *Cable A*. The wave propagated into *Cable B* is reflected back at the cable receiving end and it eventually reaches the cable joint point.

Normally, part of the wave would now be reflected back into *Cable B* and the transient peak voltage would be at the moment that the wave would again reach the cable receiving end.

However, the cables have equal surge impedances and nothing else is connected at the joint point. Thus, the wave reflection in this point is almost inexistent; the small existent reflection is due to the grounding of the screen. As a result, the wave is almost entirely refracted into *Cable A*.

The wave reaches *Cable A* sending end, where it is reflected back and will reach *Cable B* receiving end. The peak voltage will occur at this instant, after the expected moment.

Fig. 12 shows the waveform during the transient for the system seen in Fig. 11, where it can be seen that the peak instant occurs later than expected.

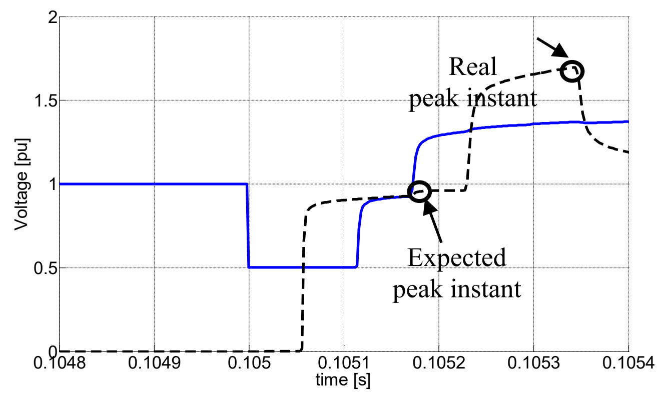

Fig. 12. Example of the voltage in the end of Cable B (dashed line) and the joint point (solid line) during the energisation of Cable B

If the peak overvoltage is after the expected instant it becomes necessary to estimate again the modelling depth for the new peak voltage instant. However, sometimes these overvoltages after the expected instant may not be real, but a result of simplifications in the model.

Fig. 13 shows a network reduction. To maintain the simplicity, the network is reduced from one busbar depth to one cable.

The *Eq. B* represents the lower/higher voltage levels connected to the node. The *Eq. A* represents the entire equivalent network seen from the sending end of Cable A.

The *Eq. C* is the parallel of *Eq. B,* with the series of *Eq. A* with *Cable A*. Thus, the impedance of *Eq. C* is always lower than the impedance of *Eq. A*.

The smaller the equivalent impedance, the larger is the wave reflection. Thus, a model with fewer nodes will have a larger reflection coefficient in the boundary nodes. In addition, the more complex the model the later is the reflection in a boundary node and the more damped is the wave before the reflection reaches the receiving end of the cable being energised/re-energised.

Thus, it is possible that the late overvoltage seen in the simplest model will not be seen in a more complex model. Fig. 14 shows an example of such case.

It is important to notice that in principle, if one does not see an overvoltage after the expected point in the model calculated according to the method previously explained, it should also not be present in a more complex model, i.e., with more busbars, as the reflections coefficients are smaller. Thus, the explained method provides accurate results as one can detect the cases where the overvoltage is after the expected instant.

There may be however some special configurations, more precisely areas with many short cables that may lead to a voltage build up, where the previous explanation may not be applied. Yet, such configurations should be unusual in a transmission network.

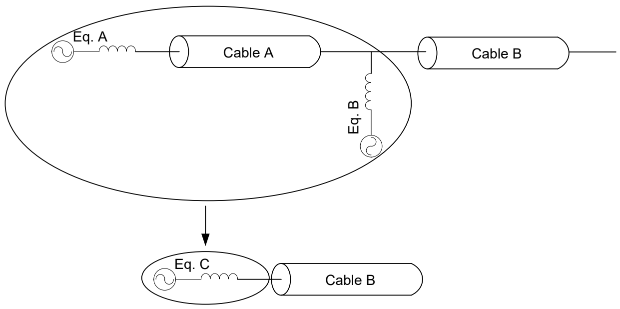

Fig. 13. Possible network reduction, where *Eq. C* is equal to the parallel of *Eq. B* with the series of *Cable A* and *Eq. A*

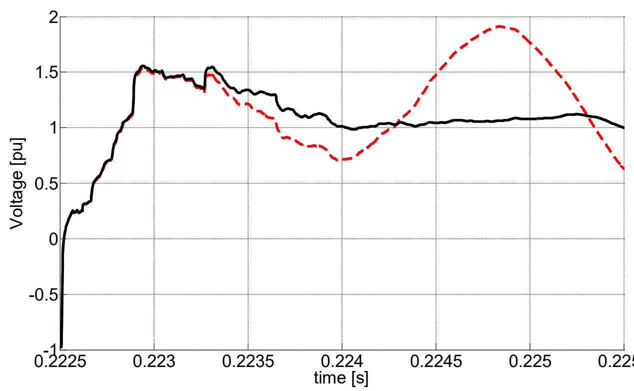

Fig. 14. Voltage in the cable receiving end during the de-energisation. Dashed line: Simple model; Solid line: Complex model

VII. Method Optimization

The inaccuracy explained in the previous section is a result of the reflections in the outmost nodes of the model. One can solve this problem by a combination of FD-models and lumped-parameters models. The addition of the lumped-parameter models increases both the system complexity and simulation running time, but much less than if FD-models were used all over. For a comparison of times consult [7].

A. Final Estimation Method

Like before, the cables adjacent to the energised/re-energised cable are modelled with maximum detail, i.e. FD-models and all the cross-bonded minor section modeled with the exact lengths, as the distance increases the cables are still modelled by means of FD-models, but with only one equivalent major cross-bonded section or ideal cross-bonding. According to the method previous explained, the model would now be complete.

To avoid the high reflections that could lead to inaccurate results after the expected peak and possible mislead the engineer doing the simulation, it is added a third level where the cables/lines are modelled by means of lumped-parameters models. This third level increases the simulation running time, but considerably less than if FD-models were used, and have a small influence in the total running time. Finally, an equivalent network is used to represent the remaining network.

Fig. 15 shows a diagram with the three levels, where the lines represent cables.

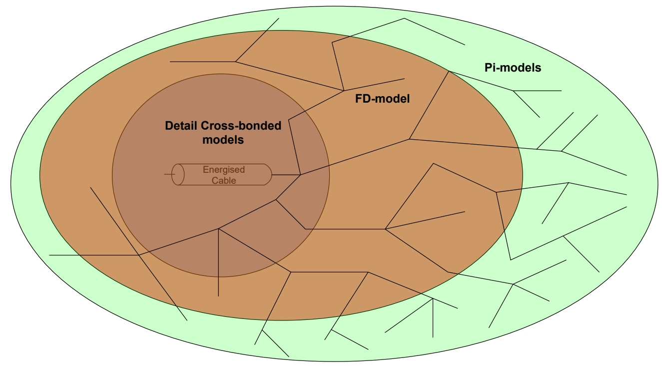

Fig. 15. Diagram of the final estimation method with the three levels of detail

B. Depth of the lumped-parameters modelling

One possible way would be to use a semi trial and error method. The simulation is run a first time with only the required busbars, and it is verified if the peak overvoltage is after the expected instant. If it is, it is added another level to model, but using lumped-parameters to model the lines. And the process is repeated.

A more efficient approach, would be to model from the beginning an extra level by means of lumped-parameters. This approach increases the trust of the user in the results at the expenses of only a small increase of the simulation running time. The process explained in the previous paragraph is then done.

If one wants to be completely safe, it can be modelled the remaining network by means of lumped parameters, but this high level of detail is normally unnecessary.

VIII. Conclusion

The method proposed on this paper can be used to estimate the minimum modeling required when simulating a switching transient in a cable-based network.

The method indicates which cables need to be included in the simulation model and which cables require an accurate modeling of the correspondent cross-bonded sections. For the application of the method it is necessary to know the grid layout and the time that goes between the CB switch-on and the cable maximum peak, which can be obtained by simulating the switch-on of the cable connected to an ideal voltage source.

A possible inaccuracy of the method, more likely to occur in a simple network, was also analyzed and proved not to be an issue as one can easily detect it. In these situations one should re-estimate the model depth using the obtained maximum as reference time. However, the use of the three-level approach strongly reduces the possibility of having this situation. Moreover, the phenomenon is associated to simple systems and in these cases one models the entire network for the sake of simplicity and accuracy.

The final proposed method divides the simulation model into three levels. A first level where full modeling detail is applied, i.e., FD-models are used and all cross-bonded sections are included into the model. A second level where FD-models are still used, but the cross-bonded sections modeling is simplified. A third level, where lumped-parameters models are used, which reduce the likelihood of erroneous high overvoltage at the expenses of a relatively small increase of the computational effort.

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Fig. 16. West Denmark Transmission Network. Note: Due to differences between the English and Danish names of some cities, the STSV-LEM link is named STS-LKR in the map