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Cable modelling in ATP – from NODA to TYPE94

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Abstract *- Cable modelling in ATP suffers from the lack of the most modern phase domain, vector fitting based approaches. This papers compares the available models with a frequency domain Fourier calculation. This revealed that the JMarti model is best for calculation of the dominant mode of propagation, while the PI-equivalent is best for finding induced voltages in a cable system when the fundamental frequency is known. The PI-equivalent actually gave the most reliable overall response. The paper then addresses two possible steps for overcoming the inherited weaknesses of the cable models: a) Replacement of the Noda model fitter (ARMAFIT) with a VectorFit MatLab routine, and b) Implementation of a state space model in a type 94 (Norton-Transmission) component. The ARMAFIT bypass failed while the type 94 implementation gave good results.*

Keywords*: Cable modeling, NODA, JMARTI, PI, Vector Fitting, Type 94.*

1. Introduction

Simulation of cable system transients in ATP [1, 2] can be based on the frequency dependent models Semlyen [3], JMarti [4] or Noda [5, 6]. The calculation of the propagation H and admittance Y_c matrices is performed by Cable Parameters or Cable Constants [7, 8]. The limitation in cable modelling in ATP is primarily not due to Cable Constants/Parameters although possible correction points are identified in [9]. The conversion from frequency domain cable data to a transmission line model requires some fundamental assumptions. PI-equivalent: only suitable for short cables and known frequency, Bergeron: only suitable for known frequency, Bergeron, JMarti and Semlyen: work in the modal domain and assume a constant transformation matrix. The most recent model, NODA, however, works directly in the phase domain. The NODA model approximates the propagation matrix elements with a polynomial z-domain transfer function using a pre-determined time step. The latest modelling techniques based on vector fitting and described in [10-12] are not implemented in ATP.

2. Test case

The test case is taken from [11] and consists of three 10 km long single core coaxial cables with core and sheath and the geometry and material data given in Fig. 1.

The test case in [11] is not necessarily based on the same calculations as Cable Parameters. In particular different approximations could have been used for the ground return impedances. Consequently, the results in [11] should only be compared qualitatively to the ATP results and for generality we will use Fourier Transform result as the true solution. The cable system in

Fig. 1 will have 4 dominant modes of propagation as reported in [11] with travelling times 56, 212, 261, and 663 μs.

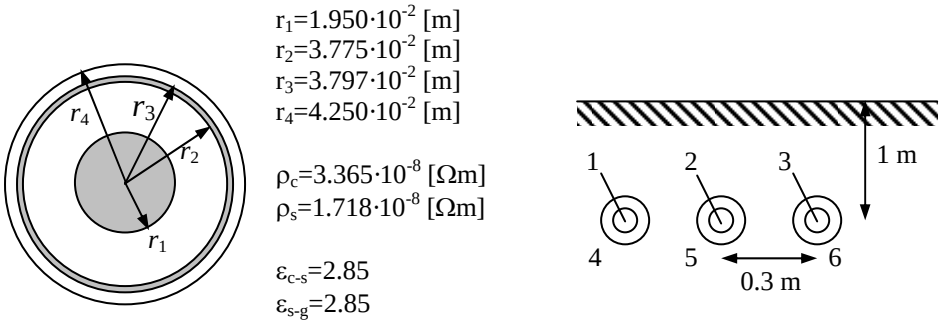

Figure 1. Geometry of test case.

3. Comparison with Fourier Transform

The cable system in Fig. 1 is excited by an open circuit step voltage as shown in Fig. 2.

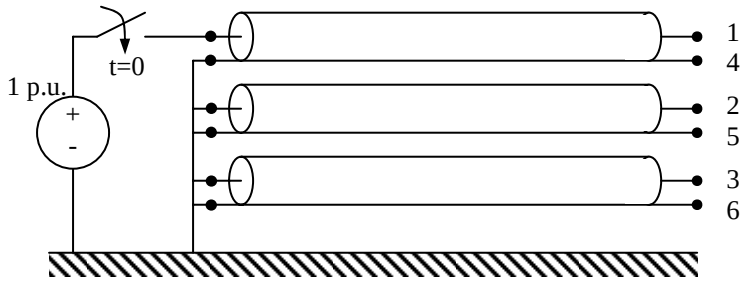

Figure 2. Open circuit step response of cable system

The open circuit step response (U_m) of the cable system according to Fig. 2 is given by (1):

$$(I + H \cdot H) \cdot Y_c \cdot U_m = 2 \cdot H \cdot Y_c \cdot U_k \qquad (1)$$

where $H = \exp(-\sqrt{y \cdot z} \cdot l)$ is the current propagation matrix (2)

$Y_c = z^{-1} \cdot \sqrt{z \cdot y}$ is the characteristic admittance matrix (3)

and $U_k = [1/s; 0; 0; 0; 0; 0]^T$ is the frequency domain excitation

The output from Noda Setup (TEMP.AFT) is used to establish the H and Y_c matrices as function of frequency. A frequency range of 1 Hz to 1 MHz with 20 samples per decade was chosen in the Noda Setup, with an additional high frequency point at 10 MHz (Freq. veloc. in ATPDraw). Noda Setup reports the Y_c matrix directly (called CZCHAR), while the H matrix is reported via its eigenvector matrices A and AI (inverse) and eigenvalues QN. The H matrix is then calculated as $H = \left(A \cdot diag(\exp(-QN \cdot l)) \cdot AI\right)^T$. The H matrix is transposed because Noda Setup reports the propagation matrix for the voltage waves. There are several eigenvalue switchovers in the Noda Setup output, but the calculated H matrix is smooth.

A discrete Fourier transform (DFT) routine is then used to calculate the time response as shown in Fig. 3. The number of sample points was increased to 80 pr decade in order to obtain a result equal to fig. 9 in [11]. With 20 points per decade the oscillations in the Core 2 voltage are somewhat smoothened. The induced voltages are used for comparing models because these are difficult to model accurately.

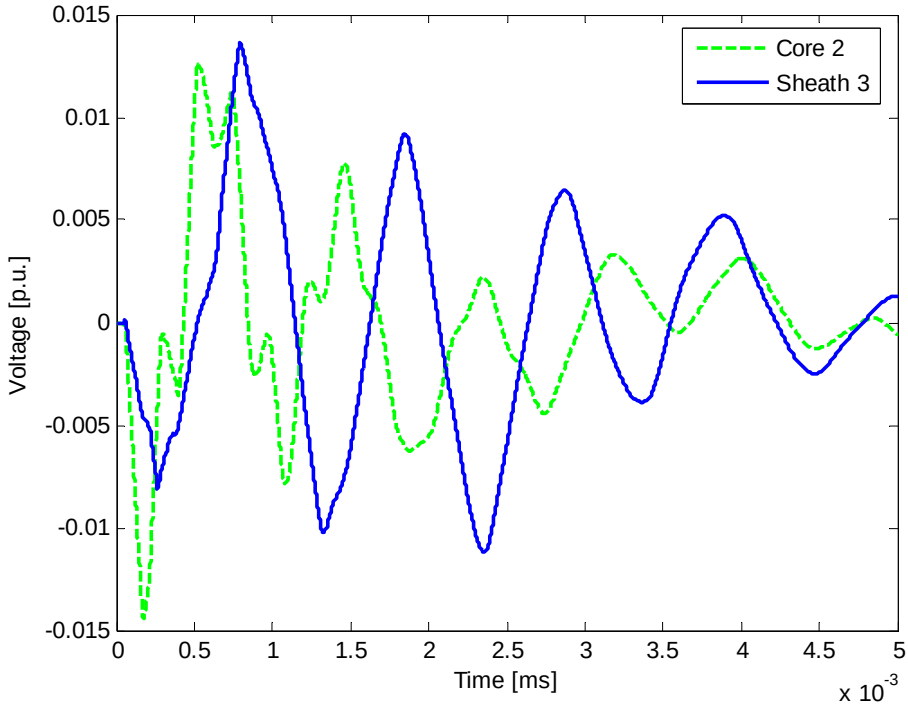

Figure 3. Open circuit induced voltage at remote end.

A) Noda cable model

In the Noda model there are two main challenges. The fitting (ARMAFIT) can fail and the time domain response can be unstable. First of all the time step has to be pre-determined. When a time step of 1 μs was used ARMAFIT was unable to fit element (5, 1) of the *H*-matrix, while for dt=10 μs fitting was achieved. The fitting and stability problems seemed less pronounced when the time step was closer to the minimum travel time (56 μs in this case). This is of course a great limitation for systems consisting of cables of various lengths.

Figure 4 shows the open circuit step response when the default fitting parameters are used (epsA=3, Hmax=16, Niter=3) and the time step is dt=10 μs. 'NO RESPONSE' is reported for all elements of the left part of the *H*-matrix except for the diagonal elements. The response in Fig. 4 is quite different from Fig. 3 with a double amplitude and higher frequency content. There is also a drift-off in the 'Core 2' voltage, but in this case the solution is stable, but apparently wrong. Increasing the accuracy of the model (epsA=1, Hmax=24) did change the result somewhat compared to Fig. 4 (drift-off in Core 2 voltage reduced, a bit lower amplitudes of the oscillations) but the result was qualitatively the same and still far from Fig. 3. If we increase the accuracy of the fitting (epsA=1, Hmax=24) we are able to fit the model also for 1 μs time step. The result is shown in Fig. 5 and the results are qualitatively closer to Fig. 3 concerning the amplitudes and frequency of the oscillations. However, the first negative peak is missing and there are superimposed high frequency oscillations that eventually caused the responses to become unstable.

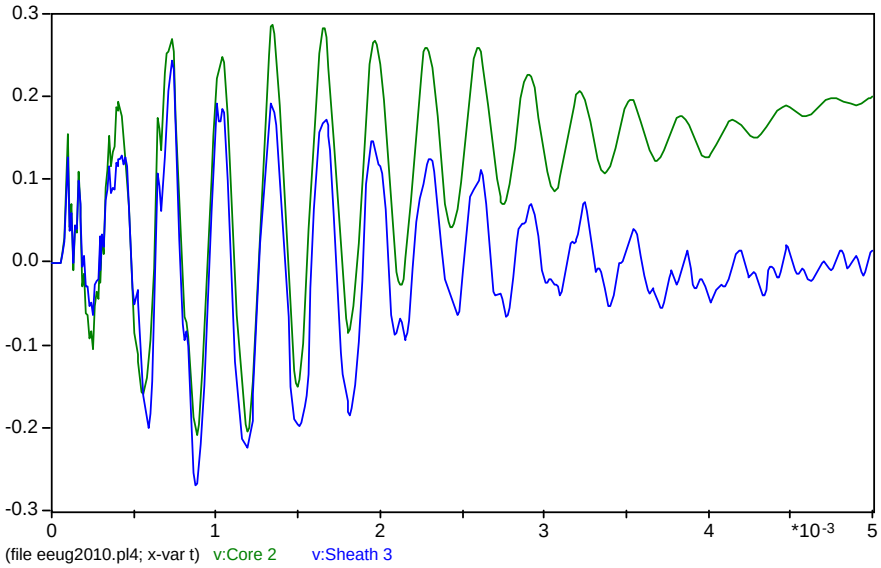

Figure 4. Open circuit step response as predicted by the NODA model (default fitting values), time step 10 μs.

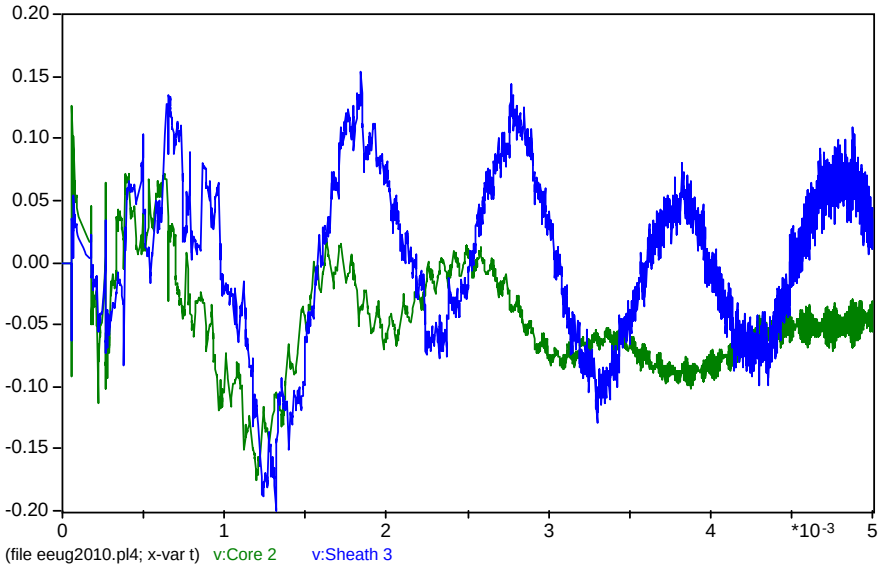

Figure 5. Open circuit step response as predicted by the NODA model (epsA=1, hmax=24), time step 1 μs.

B) JMarti cable model

The JMarti Setup was surprisingly unable to fit the model using the default fitting parameters. Expanding the frequency range from 0.01 Hz to 10 MHz resulted in an apparently successful fit, but the results for the induced voltage particularly in 'Core 2' is completely wrong as shown in Fig. 6. Using a frequency of 10 MHz for the transformation matrix calculation resulted in almost zero induced voltage.

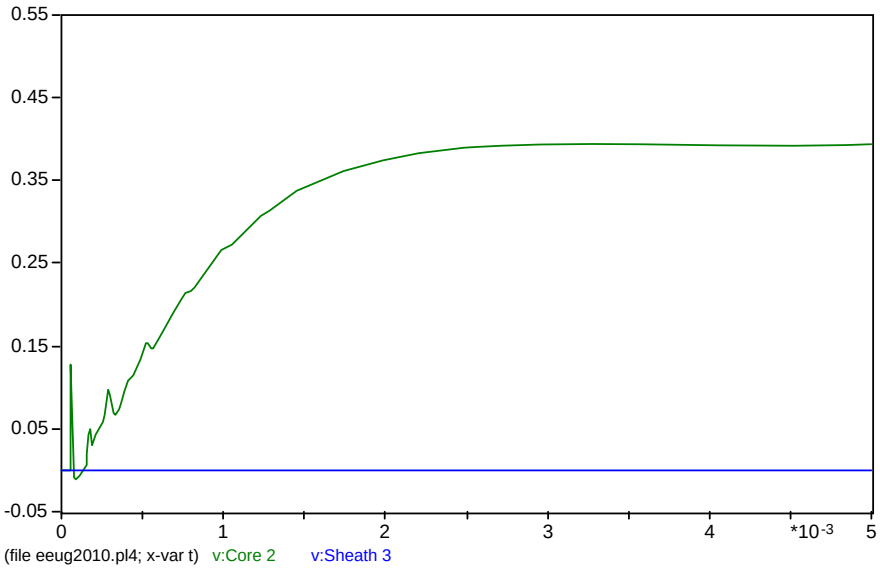

Figure 6. Open circuit step response as predicted by the JMarti model (default fitting), Fmatrix=5 kHz.

C) PI-equivalent

There are no problems in creating a PI-equivalent model of the cable system. The result of using 5 kHz for the calculation of the parameters is shown in Fig. 7. This is qualitatively equal to Fig. 3 but with lower amplitudes. The first negative peak is predicted correctly. Increasing the frequency to 100 kHz resulted in somewhat reduced amplitudes but the curves were qualitatively equal.

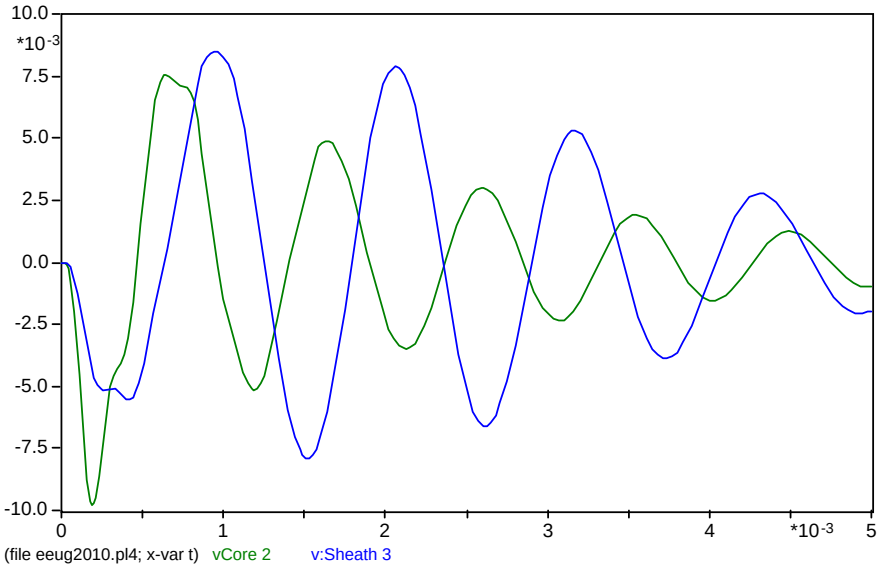

Figure 7. Open circuit step response as predicted by the PI-equivalent model, parameters calculated at 5 kHz.

D) Bergeron-model

Fig. 8 shows the result of the Bergeron model calculated at 5 kHz. The results are very different from Fig. 3.

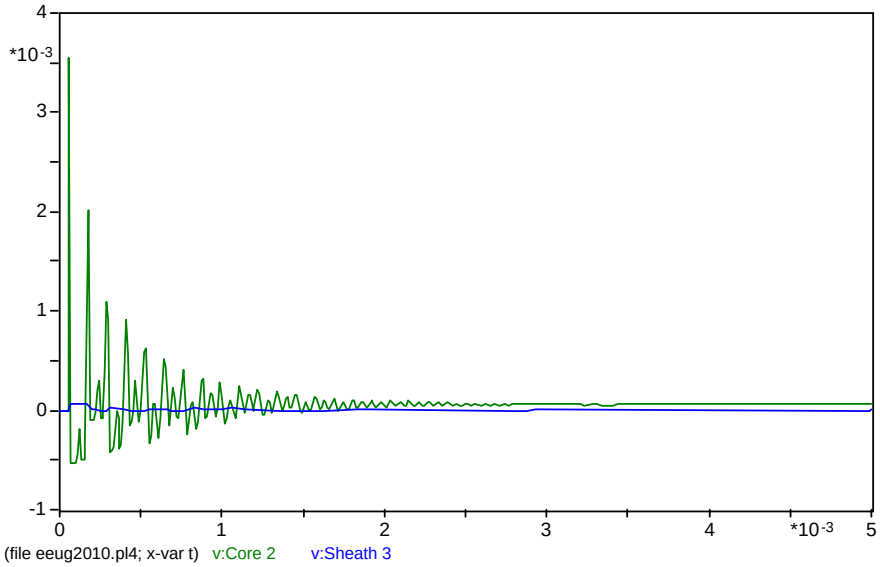

Figure8. Open circuit step response as predicted by the Bergeron model, parameters calculated at 5 kHz.

E) Comparison of Core 1 voltages

So far the PI-equivalent surprisingly gave the best results for the induced voltage at the far end. Fig. 9 now compares the direct voltage at remote end 'Core 1' for the NODA, JMARTI, PI, and FOURIER method. Now, the response is quite well represented by the JMARTI model. The PI-equivalent that gave the best agreement for the induced voltages is not an appropriate model, except for determining the first peak. The NODA model shows a larger peak and a remarkably longer travelling time in this case. The ARMAFIT routine adds the time step to the minimum travel time increasing it from 56 μs to 66 μs.

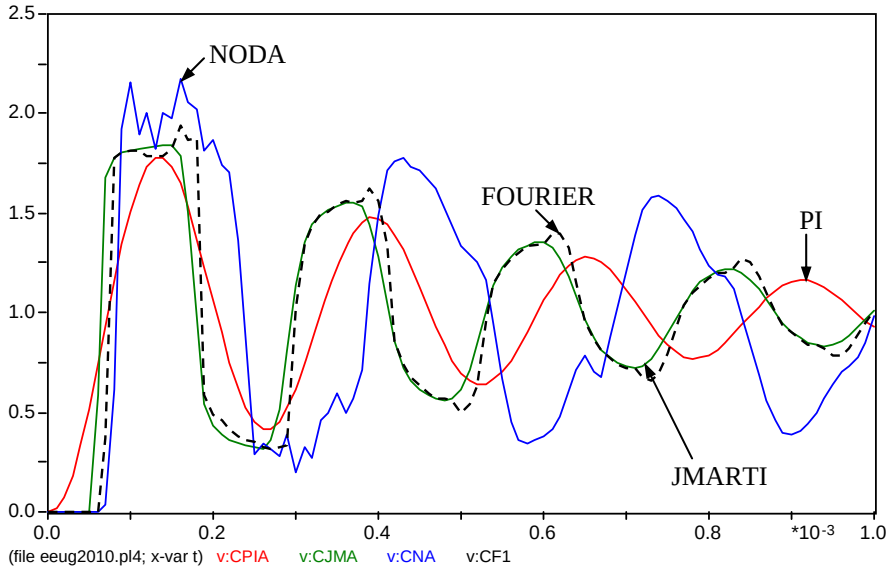

Figure 9. Open circuit step response as predicted by the NODA, JMARTI, PI, and FOURIER method. Parameters for PI model calculated at 5 kHz. Time step 10 μs.

From the above examples it seems obvious that cable modelling in ATP should be improved. Using a PI-model could to some extend match the Fourier reference calculations qualitatively, but this is only the case in situations when the dominant frequency component is know. The other models seem to have fundamental weaknesses.

4. Phase domain rational fitting

The vector fitting approach in the phase and frequency domain proposed in [11] seem to result in robust fitting with few stability problems. This section describes how to utilize the vector fitting approach based on the ideas found in [11]. The routine VectFit3 is used in this paper as documented in [12-14] (http://www.energy.sintef.no/produkt/VECTFIT/index.asp).

The fundamental rational fitting in the frequency domain becomes:

$$Y_c(i,j) \approx \sum_{k=1}^{n} \frac{c_{ij,k}}{s - a_{(ij),k}} + d_{ij} \tag{4}$$

$$H(i,j) \approx \sum_{g=1}^{m} \sum_{k=1}^{n} \frac{c_{ij,gk}}{s - a_{gk}} \cdot e^{-s \cdot \tau_g} \tag{5}$$

where the poles, a and residues, c can be real or come in complex conjugated pairs.

The Y_c matrix is fitted either element by element or by stacking the elements into a vector and fit this with a common set of poles ((ij)-notation). Each mode (g) of H is fitted taking the time delay into account. The poles of the modes are kept while new residues are calculated for each element in H. According to (5) the residue calculation is a linear problem solved by simple least-square fitting. This residue calculation requires extensions to the publicly available VectFit3.m MatLab routine.

The time delays of the modes are in this paper simply calculated from the eigenvalues of H at a high frequency point (Freq. veloc.=f_v) as shown in (6). A more optimal time delay calculation is presented in [17].

$$\tau_i = l \cdot \mathrm{Im}\left(QN_i(2\pi \cdot f_v)/(2\pi \cdot f_v)\right) \tag{6}$$

where QN_i is the eigenvalue of H and f_v is a high frequency in the range of 1-10 MHz. and l is the cable length

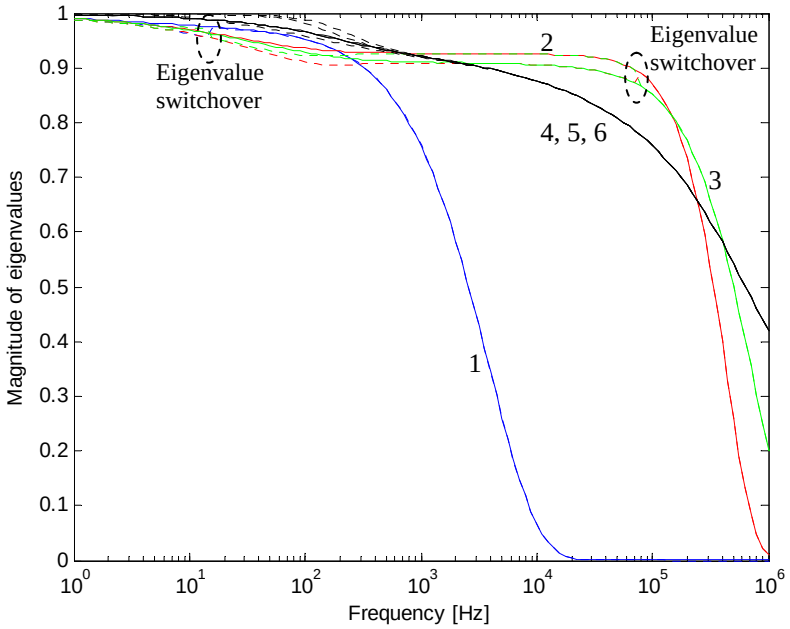

Figure 10. Eigenvalues of H matrix after removal of time delay. Dotted lines: true eigenvalues, solid lines: artificial eigenvalues calculated from (7).

There are problems with eigenvalue switchovers in the NODA output file and the constant transformation matrix assumption proposed in [11] is used here to avoid this problem as shown in (7). This will result in slightly wrong eigenvalues at low frequencies as seen from Fig. 10, but this is compensated by the residues.

$$H_{m0} = diag\left(AI(f_v)\cdot H\cdot A(f_v)\right)\cdot e^{s\cdot\tau} \tag{7}$$

Fig. 11 shows the magnitude of elements in Y_c and how they are fitted with rational functions (4) using Vector Fitting [10, 12, 13]. A common pole set is used for all elements in Y_c and an accuracy requirement of 0.01 % resulted in an order of 7.

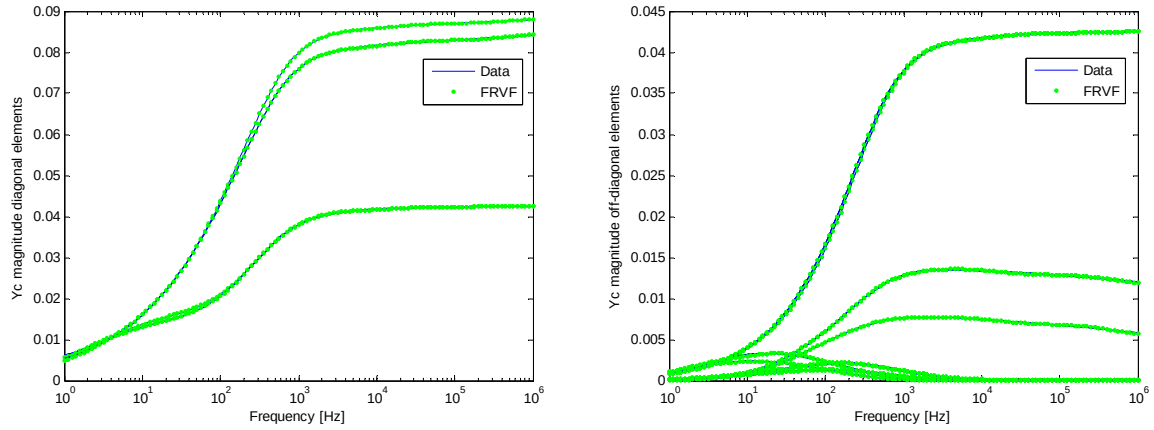

Figure 11. Diagonal (left) and off-diagonal (right) elements of Y_c and fitting[10, 12, 13].

Fig. 12 shows the magnitude of elements in H and how they are fitted with rational functions (5) using Vector Fitting [10, 12, 13] and external residue calculation in MatLab. An accuracy requirement of 1% for the modal fitting resulted in orders of [8, 6, 6, 5] for the four distinct modes shown in Fig. 10.

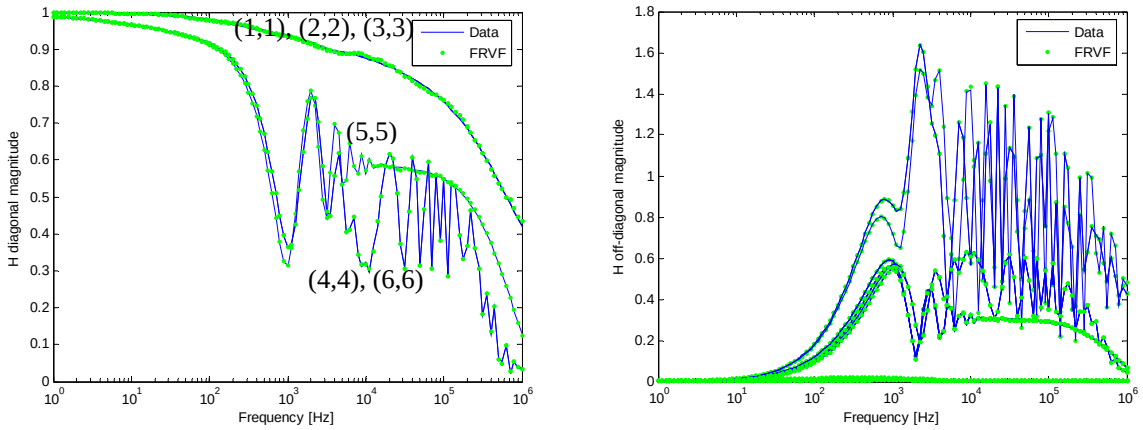

Figure 12. Diagonal (left) and off-diagonal (right) elements of H and fitting [10-13] with external residue calculation.

5. ATP implementations

The vector fitting routine produces poles, residues, and constant terms that easily are converted to a state space model. However, this does not fit with the present ATP interface.

Since the Noda model is a phase domain implementation it is first attempted convert the vector fitting data to the z-domain input required by the Noda model. Secondly it is attempted to implement an entirely new transmission line model in ATP using type 94.

A) ARMAFIT bypass with Vector Fitting

Since the NODA model is based on a polynomial z-domain approximation to the H^T and Y_c matrices, it is tempting to try to replace the ARMAFIT program with an alternative fitter based on rational s-domain fitting and conversion to z-domain. The fitting in the s-domain is done once for each cable while the z-domain conversion is done every time the time step changes. In principle this is rather straight forward using the linear conversion [15, 16]

$$s = \frac{2}{h} \cdot \frac{z-1}{z+1} \tag{8}$$

where h is the time step

Inserting the relation in (8) into (4) and (5) gives

$$Y_c(i,j) \approx (z+1) \cdot \sum_{k=1}^{n} \frac{cz_{ij,k}}{z - az_{(ij),k}} + d_{ij} \tag{9}$$

$$H(i,j) \approx (z+1) \cdot \sum_{g=1}^{m} \sum_{k=1}^{n} \frac{cz_{ij,gk}}{s - az_{gk}} \cdot z^{-\tau/h} \tag{10}$$

$$\text{where } az = \frac{2/h + a}{2/h - a} \text{ and } cz = \frac{c}{2/h - a} \tag{11}$$

with stable implementation for $|az| < 1$.

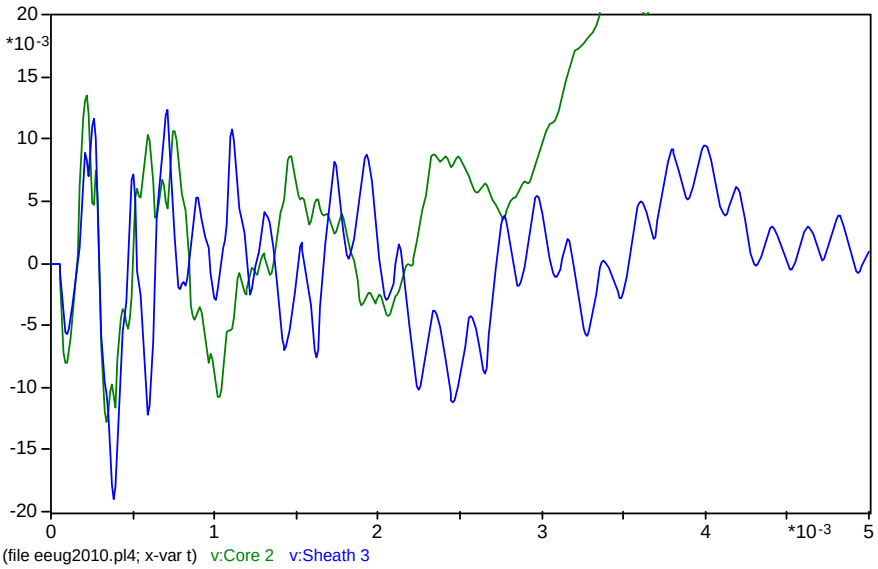

Figure 13. Open circuit step response as predicted by the NODA model when ARMAFIT is replace by Vector Fitting [10-13] with polynomials, 3 poles pr mode and time step 10 μs.

Now, the NODA transmission line model requires the approximations on polynomial form. In principle this conversion is straight forward using the 'poly' and 'conv' functions in MatLab. If *az* is a vector of poles then the MatLab function 'poly(*az*)' will produce the polynom

required by NODA. However, in reality this conversion is far from simple. The main problem is that the poles *az* in (11) for small time steps *h* become very close to unity (which is the stability boarder). With and increased number of poles and multiple poles closed to unity the roots of the polynom can be larger than unity resulting in an unstable solution. Typically it was observed in MatLab that 'roots(poly(*az*)))'≠*az*. The problem is particularly articulated for the *H* fitting as this also involves convolutions of several sets of poles. Fig. 13 shows the induced open end voltage when the number of poles per mode has been restricted to as low as three. An order of three will not produce a good fit for some of the small off-diagonal elements in *H* that are very important for the induced voltages shown in Fig. 13. Still, there is some instability in the result and the agreement compared to Fig. 3 is rather poor with more high frequency oscillations involved. In conclusion the ARMAFIT bypass option tested here does not seem to be a possible fix.

B) Type94 state space implementation

Instead of the polynomial representation used in the NODA model an implementation of (4) and (5) via a state space formulation is preferred as shown in (12) and (13).

$$\begin{aligned} s \cdot \underline{x_Y} &= A_Y \cdot \underline{x_Y} + u \\ y_Y &= c_Y^T \cdot \underline{x_Y} + d_Y \cdot u \end{aligned} \quad \text{state space model of } Y_c \cdot u \text{ convolution} \tag{12}$$

$$\begin{aligned} s \cdot \underline{x_{Hg}} &= A_H \cdot \underline{x_{Hg}} + i_{refl} \cdot e^{-s \cdot \tau_g} \\ y_{Hg} &= c_{Hg}^T \cdot \underline{x_{Hg}} \end{aligned} \quad \text{state space model of one mode of } H \cdot i_{refl} \text{ convolution} \tag{13}$$

where *A* is a diagonal matrix with the poles and *c* the vector of residues in (4) and (5). The trapezoidal rule of integration is then used to establish the equation on a discrete, recursive form in the time domain.

A Type 94 Norton-transmission state space model was developed where the output from vector fitting in MatLab (poles, residues, and constant terms) was included via a text file (declared as constants). The input to the MatLab code is still the output from NODA SETUP (TEMP.AFT file). MODELS does not handle complex numbers or matrices and this complicates the implementation considerably. For complex conjugated poles the real part is written to the text file with reversed sign as a flag. The interface process is illustrated in Fig.14 along with a terminal model as implemented in the type 94 component.

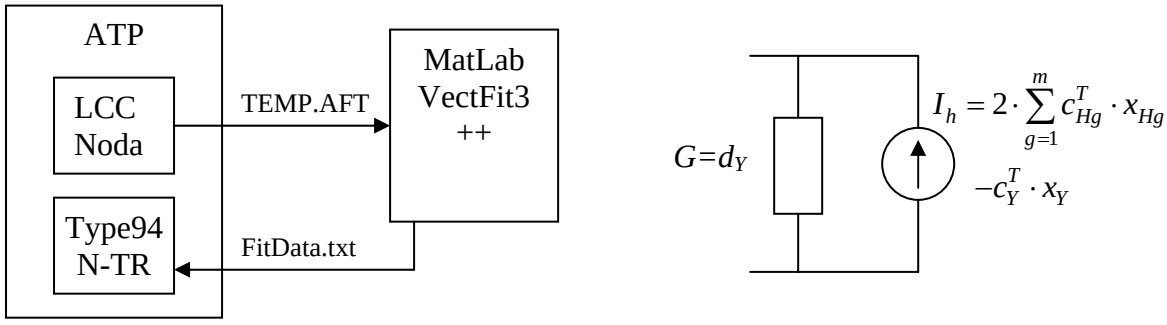

Figure 14. Interfacing ATP with the fitting routine in MatLab (left) and type94 implementation.

The Fig. 15 shows the induced core and sheath voltage comparable with Fig. 3, and Fig. 16 shows the open end core1 voltage compared to the JMarti line model which was seen to produce good results in Fig. 9.

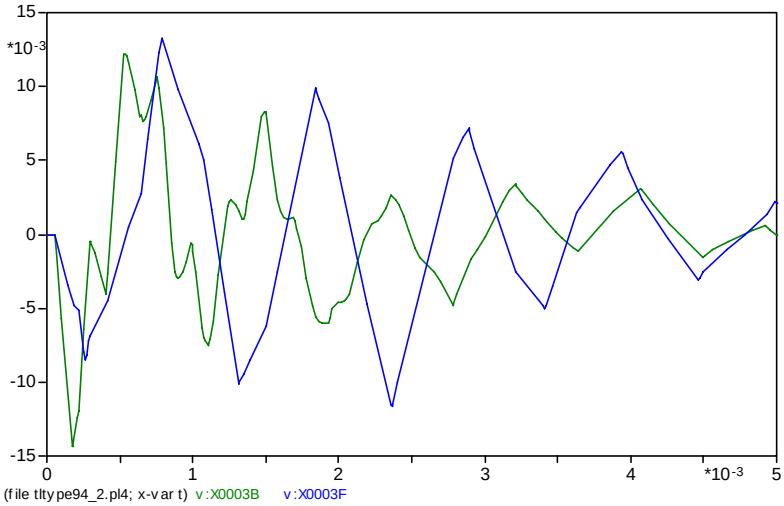

Figure 15. Open circuit step response as predicted by the TYPE94 model using Vector Fitting [10-13] with 6-8 poles per mode (4) of H and 7 poles for the whole Y_c. Time step 1 μs.

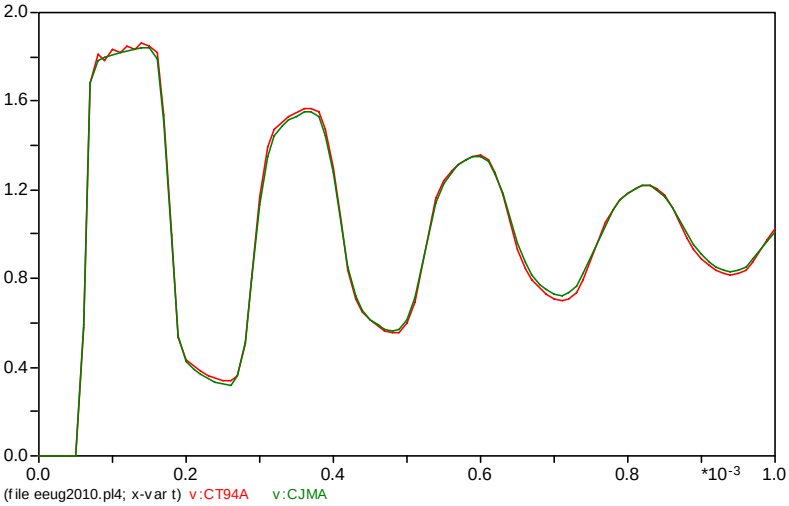

Figure 16. Comparison between the JMarti line model and the TYPE94 model for the direct open end voltage at Core1. Slightly more initial oscillations observed in the TYPE94 model. Time step 10 μs.

It was a concern that the amount of data would be too large for MODELS. The number of residues of the H-matrix is the square of the number of phases times the total number of poles of the modes. The 6-conductor cable with four distinct modes fitted with {8, 6, 6, 5} poles requires a residue array of 900 elements. It turned out that this was manageable in MODELS, but the calculation time is of course a concern. A case with 55 poles was also tested with success (36*55=1980 elements). The residues for the Y_c matrix are fewer; square of the number of phases times the number of poles (36*7=252 in this case).

6. Conclusion

There seems to be a need for better cable models in ATP. The JMarti model that traditionally is suitable for overhead line modelling show significant weaknesses both in the fitting process and in the calculation of induced voltages. The NODA model resulted in unstable responses and also required fine-tuning of the fitting parameters and large time steps. The PI-model actually gave the overall best and most reliable results; however such model is only suitable

for cases where the fundamental frequency is known. The attempt to replace the ARMAFIT *z*-domain fitting with vector fitting failed as the fundamental problem in the Noda model approach is a polynomial description that easily gives unstable poles for high order fractions and time steps below the smallest travel time of the cable. The implementation of a new transmission line model based directly on vector fitting and state space formulation was possible using a TYPE94 Norton-transmission component. The code is complicated and extensive due to lack of complex numbers and matrices in the MODELS language. This new model gave good and stable results in close agreement with the reference Fourier calculation and [11]. No challenges in specifying order/accuracy and time step were identified. The calculation is however slow and not very suitable for systems consisting of multiple cables. Initialization at time zero is a problem for the type94 implementation.

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