Equivalent Circuit Model for the AC Cable in a Given Frequency Ranges Using Artificial neural network

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Abstract: *In this paper, a detailed harmonic analysis of an AC submarine cable connecting an offshore wind farm with an electrical network is performed. It is well known that due to the capacitive nature of submarine cables AC, it is very common to find resonance problems and temperature variation have direct impact on the transmitted power. For this reason, this paper analyzes firstly the circuit which is appropriate "gamma" equivalent circuit model for the cable AC in a given frequency ranges using the ANN. Then, a detailed model and a spectral analysis of the entire transmission system is developed to validate the model of uniform cells in cascade.*

Key words: *Harmonic, Segmented Model, Artificial neural network, lumped parameter, submarine Cable.*

I. INTRODUCTION

*P*ower transmission cables are the critical network component of the electric power system. For large scale power system studies, cable is traditionally modeled via either an uniformly distributed parameter or a lumped parameter configuration. These line models have been historically developed for investigation at the fundamental frequency and under nominal operating conditions. Several assumptions are often made when modeling transmission lines.

However, especially in recent years the high demand in electric power and renewable energy resources, with corresponding enabling technologies (e.g. power electronic devices), has an impact on the electric power system. For example, with the augmented use of power electronic devices, an increase in non-fundamental frequency components in the power system can be expected. Under the increasing presence of harmonic frequency components, transmission line models are investigated in this work.

There is a compromise that lines and cables can be modeled with a multiphase coupled equivalent pi-circuit. For balanced harmonic analysis, the model can be further simplified into a single-phase pi-circuit determined from the positive sequence impedance data of the component. It is important to include shunt element and its associated long become quite significant at higher frequencies. This effect can be easily represented using the exact or equivalent pi-circuit model [1].

The exact number of gamma or pi forms cells that are used to model the power lines is rarely addressed and it is either determined arbitrarily or by trial. Indeed, none of the published works has demonstrated the accuracy of such a modeling technique. In [2] it has been reported that the model is completely inaccurate above the cut-off frequency which is the natural frequency of a cell. Even at frequencies below the cut-off frequency, the frequency performance of the line may be inaccurate.

Several purely numerical methods have been developed to simulate the finitely cells as in [3] has proposed the tool for electric power line modeling to determine the adequate structure of the power line model. The approach consists of a step by step computation to achieve the corresponding finitely segmented. However, this tool takes longer computational time because it uses an iterative process.

The main purpose of this paper is to develop a *ANN*-based technique that allows the user to determine the appropriate number cells of the line model for studies under harmonic frequencies. This technique will give the appropriate line modeling without any iterative computation and in shorter time [4]. At the end of this technique is validated by application to the modeling of a submarine cable in the presence an alternative to connect a wind farm to the network.

I.1. MODELING APPROCH

The proposed approach tends to determine the frequency characteristics of the distributed line model to compare them through a set of parameters for a required loading condition.
To assess the accuracy of the line model, the study is based on the features and performance of wave propagation in particular the attenuation and phase shift of the voltage, then the model is compared to the first reference. Hence sensitive parameters are selected to compare appropriate models representing the line at the desired frequency, and then the required characteristics are expressed as follows [5]:

1. Validity of the model after the terminal behavior i.e. at the sending and receiving ends;
2. Insensitivity to load changes in fact, this characteristic is crucial for nodal analysis in power system studies.

The selection of parameters and insensitivity to load variations of the finitely segmented model is well justified by [6]. The model performance is characterized by reproduction of wave propagation including wave attenuation and phase shift. For this purpose, quantification of the accuracy of the model is based on the analysis of loading voltage in term of difference in the magnitude and phase shift between distributed and finitely segmented models:

a) $\Delta V = \left| \left| V_{Load}^{Distributed} \right| - \left| V_{Load}^{Segmented} \right| \right|$ *-Difference in loading voltage magnitude*

b) $\Delta\theta = \left| \theta_{Load}^{Distributed} - \theta_{Load}^{Segmented} \right|$ *- Difference in loading voltage phase*

The desired level of accuracy of the model is expressed in terms of threshold values for the attenuation of the loading voltage and the phase shift. These thresholds are expressed by:

$\Delta V_{Threshold}$: *Threshold value on difference in loading voltage magnitude*
$\Delta\theta_{Threshold}$: *Threshold value on difference in loading voltage phase*

These threshold values representing the desired accuracy depend on the application of the resulting model.

The *K*-segments models (Fig 1) were obtained by dividing evenly the basic Γ-model in a number *K (K* = 1, 2, 3 ...*n*). When *n* = ∞, we obtain the distributed parameter model. Figure1 shows the basic model of a lossless finitely segmented line with *K* segments.

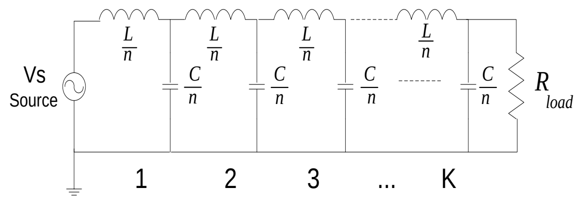

Fig.1. *K*-Segments Γ Line Model of a Lossless Line

I.2 MODELING WITH NEURAL NETWORKS

They provide an alternative to mathematical modeling where system models are non parametric statistics and non-linear [7]. Their main advantage lies their capacity of generalization. *ANN* has attracted interest due to their computational speed and robustness.

Learning and architecture design of the *ANN* are based on a comparative approach of the line governed by the distributed model as a reference and the finitely segmented models under various predefined frequencies and accuracy.

A. Database Set

The selection of the finitely segmented model in Γconfiguration and the test application are stated in [3]. The Cable characteristics at the fundamental frequency (50 Hz) are illustrated in Table I:

Table 1: Characteristics of the cable

R_ℓ	*0.0311Ω/km*	line resistance per unit length
L_ℓ	*0.0311mH/km*	line inductivity per unit length
C_ℓ	*0.233µF/km*	Capacitance per unit length

The models are simulated using cadence Pspice software in a desired frequency range. $|V_{load}|$ and θ_{load} are recorded to quantify the wave attenuation and phase shift with the desired accuracy.

B. Implementation of ANN

The proposed neural network is a multilayer perceptron (*MLP*) type with a supervised learning from a given data base formed by simulation with for different cable lengths and different levels of precision. For the *ANN* outputs are the finitely segmented model is defined as the number of segments appropriate for a given line, whereas the inputs of the *ANN* include Cable type i.e. parameters per length unit, the frequencies of interest with the desired accuracy of the model expressed in terms of threshold values selected for the voltage attenuation: $\Delta V_{Threshold}$ and phase $\Delta\theta_{Threshold}$. Another input parameter is reserved to the user in order to select among the voltage attenuation or the phase shift according to the requirement.

The first layer of the neural network contains four neurons and one neuron (the eighth) is selected depending on the model objective either $\Delta V_{Threshold}$ or $\Delta\theta_{Threshold}$.

The application of network strategy for modeling the line for harmonic frequencies is given by the *ANN* model with whose structure is shown in Table2.

The obtained *ANN* is trained by a database matrix of dimension (640, 10) with normalized values. Once the learning phase achieved the *ANN* is tested with a new set of input/output that forms the basis of generalization. This step verifies the behavior of *ANN* on cases not learned. The optimization results after 1200 iterations with an error performance are presented in Table 3.

Table 2.Structure of optimized ANN

Type network	Input Layer	1st hidden Layer		2nd hidden Layer		Output Layer		Training Algorithm
	Nb. of neurons	Nb. of neurons	Activation Function	Nb. of Neurons	Activation Function	Nb. of neurons	Activation Function	
MLP	5	16	TANSIG	21	TANSIG	1	PURLING	TRINLM

Table3. Error of the ANN model.

ANN	AARE (%)	AARE (%) Generalization	**MAE (%) Test case**
Output	0.12	0.09	0.087

The desired outputs and those predicted by *ANN* which lead to a very satisfactory correlation that demonstrates the effectiveness of the developed neural model and that is characterized by an optimal capacity of prediction for segment number and the parameters forming the finitely segmented model which cover the harmonic and inter-harmonic frequencies of the power cable. Test results are carried out from a new base including data are not used in the learning phase. The validation test is yielded from fig. 2 representing the segment number changes (*ΔV=1db*) against the Upper Bounds frequencies show good agreement between simulated and predicted values by *ANN*.

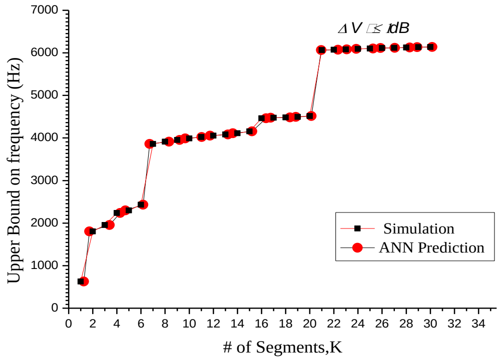

Fig.2. Upper Bounds on Frequency vs.≠ Segments for selected Accuracies (ΔV≤1deg)

From the simulation results, it can be viewed that accuracy level against the voltage magnitude, where $\Delta V \leq 1$ dB, a discrete step behavior is observed.

This a practical method of neural network modeling for power line to predict the appropriate finitely segmented model to steady-state analysis of non-fundamental frequencies with a predefined accuracy level. The optimized architecture *ANN- MLP* enables to predict the number of cells with high performance error. The simulation was tested on a real line confirming the robustness and the predictive ability of our model that is only based on the characteristics data of the line.

II. VALIDATION METHODE:
Application to Submarine Cable Connecting a Wind Turbine to an Electrical Network

In this application, a detailed spectral analysis of an offshore wind farm, based on AC submarine cables is carried out. It is well known that due to the capacitive character of the AC submarine cables, it is very common to find resonance problems in the transmitted power, associated to this issue.

For that reason, this application is presented for the proper "Γ" or "π" electric equivalent circuit to model the AC submarine cable in a given frequency range. Then, a detailed model and a spectral analysis of the entire transmission system is developed, deriving how factors such as submarine cable parameters, transformer parameters , etc… affect to the amplitude and location of the resonances of the system.

Harmonic amplification and harmonic interaction between offshore installations and onshore grid can be unacceptable for grid requirements and energy integration, thus, it becomes essential to know the frequency response of the transmission system [8]. It is well known that the risk of harmonic resonance is bigger for AC transmission configurations than DC transmission configurations [9].

II.2 FREQUENCY RESPONSE OF THE TRANSMISSION SYSTEM VIA PSCAD SIMULATION.

The selected reference model to carry out the evaluation of the frequency response of the offshore wind farm is the PSCAD's frequency dependent phase model based on the idempotent model is analyzed in [10],[11]. The reason to select the most complex and accurate model is because the cable model has to represent a wide frequency range.

The transmission system is the part of the offshore wind farm which makes possible the energy transmission from the collector point (offshore) to the point of common coupling (onshore). The transmission system is made up by the step-up transformer, the submarine cable, reactive power compensation elements (if required), and the support devices to integrate the energy in the main grid (if required).

The knowledge of the frequency response of the transmission system and the influence of each component upon this frequency response can help to avoid undesired resonances and harmonics [12]. For that purpose, firstly, in this section the simplest layout for the transmission system (transformer, cable and grid, Fig. 3 is considered.

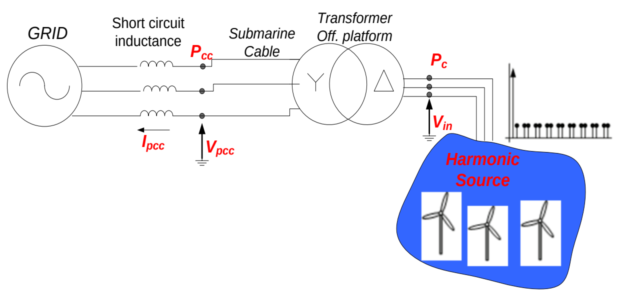

Fig .3 Simulation scenario of the simplest layout of the transmission System: the transformer, the submarine cables and the distribution grid

To calculate the impedance of the transmission system in function of the frequency, a harmonic voltage source is used. The harmonic train of input voltage (V_{in}) is composed by sinusoidal in the range of frequencies: 50-5000Hz. The amplitude of these harmonic voltages is 10% of the fundamental (50Hz-150kV). Starting from the 50Hz, the harmonic train has voltage components separated 10Hz one from other, as illustrated in Fig.4.b.

These input harmonics in a simplified way can represent the effect of the harmonics generated by the wind turbines, when they are generating energy from the wind. Measuring the current at the *PCC* (I_{pcc}) and performing the *FFT* of the signal, it is possible to obtain the impedance of the transmission system for each one of the excited frequencies, i.e. it is possible to obtain the evolution of the impedance in function of the frequency. To model the grid in a simple way, a voltage source and short circuit impedance is used.

Its characteristics are summarized in Table 4. The transformer's connection is Δ-gY, while its characteristics are shown in Table 4. Finally, the cable characteristics and cable model are the same of the section 1. The frequency response of the described transmission system layout is depicted in Fig.5.

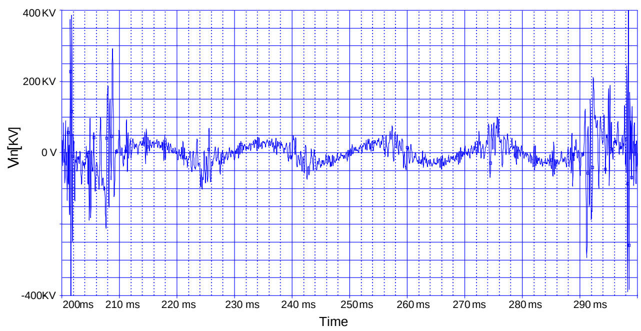

Fig. 4.a. voltage (*Vin*) applied to the submarine cable model

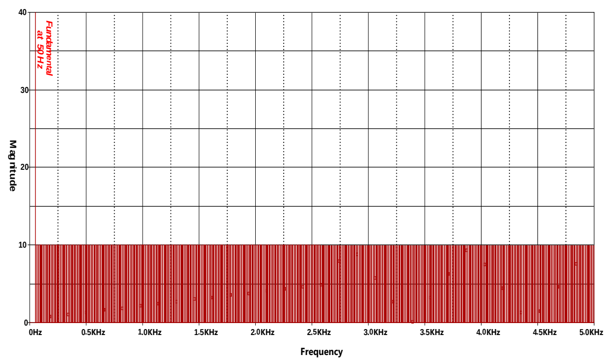

Fig. 4.b. Harmonic voltage train applied to the submarine cable model (resolution 10 Hz)

To model the grid in a simple manner, a voltage source and short circuit impedance is used. And its characteristics are summarized in Table 4. The transformer connection is Δ-gY, while its characteristics are shown in Table 5. Finally, the cable characteristics and cable model are the same of the section 1. The frequency response of the described transmission system layout is depicted in Fig.5.

Table 4. Characteristics of the main grid

Parameter	Value
Nominal power (Pn)	*150MW*
Nominal voltage (Vn)	*150kV*
Short circuit inductance	*5%*

Table 5. Characteristics of the step-up transformer

Parameter	Value
Rated power	*150MVA*
Primary voltage	*33kV*
Secondary voltage	*150kV*
Connection	*Δ- gY*
Transformer leakage resistance	*1%*
Transformer leakage inductance	*6%*
No load losses	*1,78%*

Looking at Fig. 5, it is possible to observe that all the multiples of the third order harmonics generated in the wind turbines, cannot trespass to the *PCC*. This is due to between these points a transformer with star (grounded)-delta connection. The transmission system is composed with several inductive components such as the transformer or the short circuit impedance of the main grid. This inductive impedances leads to a significant attenuation of the high frequencies, as can be seen in Fig. 5, thus, the high frequency harmonic voltages do not affect the current of the *PCC*. In fact, in the present analysis, the harmonics higher than 700Hz almost do not affect the current at *PCC*.
However, the interaction of the inductive component of the transmission system with the capacitive component of the submarine cable drives a resonance at 400Hz, becoming these frequencies which are around the 400Hz potentially problematic.

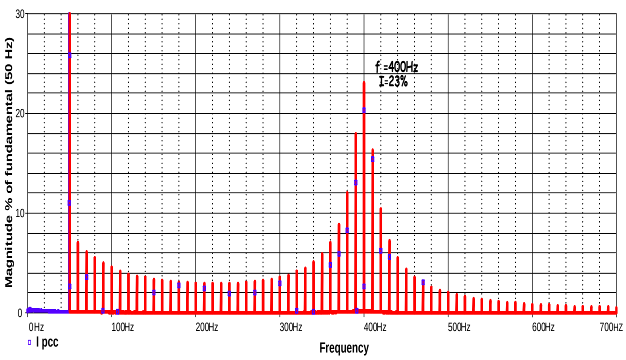

Fig.5. Frequency response of the transmission system with only: grid impedance, step-up transformer and submarine cable (50 Km). FFT of the current at PCC in the neighborhood of the main resonance

α. Frequency response of the transmission system via equivalent circuit

The purpose of this section is to estimate the main resonance frequency in a simple and accurate way, alternatively to the method described in the previous section. To characterize easy way the main resonance frequency, with a potential risk of harmonic amplification, in [13] is presented a simple method. This approximation takes into account all components of the cable and the impedance of a short circuit of the main grid, with the advantage that is simply used as the first method. Finally, to validate this method, the results obtained via simulation in cadence Pspice the equivalent circuit calculation are compared with the results obtained in simulation with PSCAD because this Software is very precise over a larger frequency domain (DC to roughly 50 kHz).All of the frequency dependent parameters of the cable [14].

β. Transmission system with the submarine cable modeled as a unique "Γ"circuit

At first, in order to explain with an example this method, the simplest case is analyzed. The step-up transformer is considered as an equivalent inductance and the main grid as an ideal voltage source with short circuit impedance. In the first step the circuit is established as illustrated in Fig. 6.

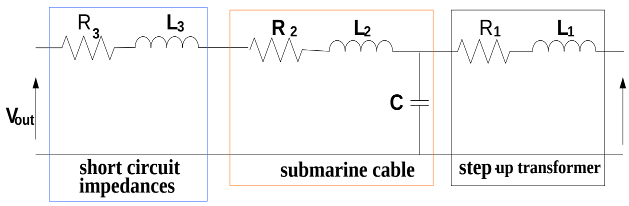

Fig.6. Mono-phase representation of the transmission system with the submarine cable modeled as a unique "Γ" circuit

The frequency response of the transmission system with the submarine cable is modeled by the localized model parameters (1-Seg. Γ), the step-up transformer and primary network is simulated in Cadence Pspice with their parameters given by Tables 1, 4 and 5. is shown in figure7.

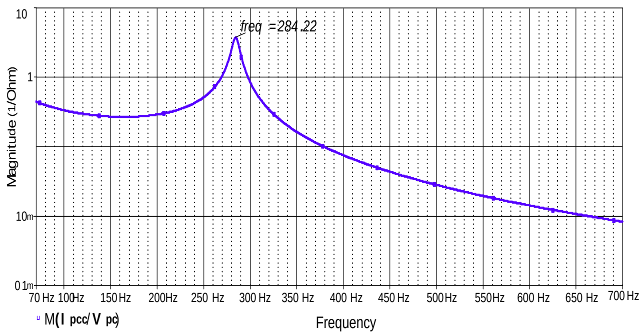

Fig.7. Frequency response of the transmission system with the cable modeled as 1- segment "Γ" circuits in series.

As we have presented in the previous section the model parameters localized conventional (single segment) is not able to represent the cable to a resonance frequency caused by the interaction of the inductive component of the transmission system and component the capacitive submarine cable to 400Hz likely to produce harmonics. The approach to *ANN* modeling proposed in detail by [15] that allow us to obtain the exact number of cells to model the cable at this frequency.

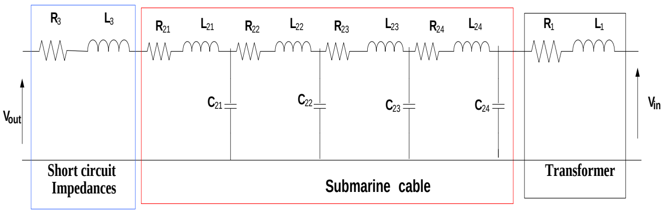

Fig.8. Mono-phase representation of the transmission system with the submarine cable modeled to 4-segments "Γ" circuit

The choice is based on the steps in the first part of this work, the model of 4_segments is appropriate to represent the submarine cable properly in presence to harmonics with a compromise between precision and number of segments. A precision $\Delta\theta_{Threshold} \leq 1$ deg and $\Delta V_{Threshold} \leq 1$ dB (shown in fig.4 and 5), the model corresponding to 4-Segments cascaded to represent the submarine cable at a frequency of 400Hz.

Finally, applying the modeling approach with *ANN* proposed, to the considered transmission system, the frequency response depicted in Fig. 9 is obtained.

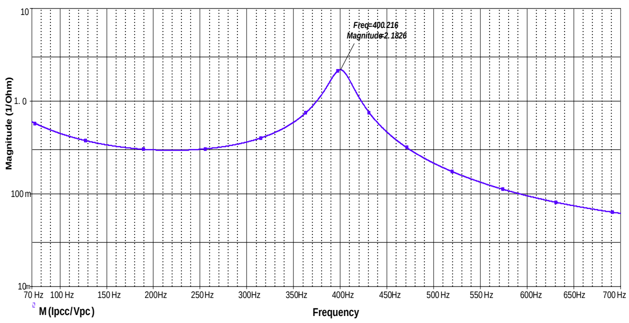

Fig.9. Frequency response of the transmission system with the cable modeled as 4- segments "Γ"circuits in series.

From Figure 13, we can view that the first resonance of the system is located at 400.215 Hz, very close to 400 Hz estimated by simulation of the transmission system in PSCAD. As for the amplitude of the resonance in this case is an approximation.

VI. CONCLUSION

The first part to this paper presents a neural network modeling for power line to predict the appropriate finitely segmented model to steady-state analysis of harmonic frequencies with a predefined accuracy level. The simulation was tested on a real line emphasizing the robustness and the predictive ability of our model that is only based on the characteristics data of the line. In the second part in a real application, the modeling approach is applied to a submarine cable connecting the wind by a grid in presence to harmonics to demonstrate the accuracy and efficiency of our proposed method.

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