

Equivalent for Electromagnetic Transient Calculation in Power System with Multiple Transmission Line

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ABSTRACT

The results of searching of equivalent for electromagnetic transient calculation in power system with the big number of transmission lines are shown. Brief information on the proper transmission line model is given. Comparison of results of simulation in real and reduced system is presented taking into consideration three methods of identification. Some example are examined for different number of transmission lines in reduced system and consequently the recommendation are given for searching of equivalents of systems with many lines.

Keywords: Electromagnetic Transients; Equivalents; Transmission Line Representation

1. Introduction

For a large complex system the full representation for transient electromagnetic analysis is not necessary or practicable. The main interest during the study of dynamic phenomena in power system is directed to the waveform occurring only in certain parts of the system. Very often, this is defined as the internal system, and the remaining part is referred to as an external keyboard. Internal networks are modeled with an accurate representation of all the properties that are important in the analysis of the phenomenon. The external system can be mapped on the basis of reduced structure or can be replaced by equivalent defined on the basis of one of the available methods in the time or frequency domain.

The network models are replacement parts, corresponding to the reduced power of the system. Very often there are mistakes, involving the creation of a model too careful or too radical for its simplification.

There is no generalized criterion by which it can be determined in advance the structure of the reduced equivalent circuit for systems in which the study of electromagnetic transients will be made. Despite many years of research, as yet, the universal equivalent was not found that would faithfully reproduce the behavior of the power system during these events.

Of course, the most reliable analytical results can be obtained from measurements in a real power system. Unfortunately, in the case of the study of electromagnetic transient phenomena, which usually are the result of faults, conducting measurements is due to economic, technical and organizational reasons very rare.

These measurements are carried out in two ways:

- Carried out at various points in the system, eg at protection location, during short-circuit in the line
- Measuring devices are connected to the selected node and recording waveform during faults (for which "waiting").

In the first case, the choice of specific situation (the type and location of fault) is possible, but safety considerations require the introduction of a number of restrictions in order to avoid the possible consequences of the development of the faults. Limitations cause disconnection of the system, some of the load off, carrying out tests on specified dates, etc.

In the second case, the recording of the actual events in the original system without restrictions is possible. However there are "accidental faults", which recorded even within a few years, are not sufficient for a comprehensive analysis.

Computer simulations have the advantage that it is possible their multi variability forcing different types of disturbances in the power system anywhere, without any risk to its future work.

Recently, most studies were performed in systems to replace a large part of a complex system using simple impedance calculated on the basis of short-circuit power of these systems. This approach is acceptable only for very simplified analysis of transients. The biggest problem in such cases is to determine - based usually on the experiment, how is the part of the system which must be modeled in detail and which is the remaining part must be replaced by equivalent.

Since many years, there are a lot of approaches trying to find a universal solution for this issue. According to [1] is recommended taking into account the elements in the branches of the two neighboring nodes in relation to the node to which is attached the object studied. However such solution, in the case of a very complex network comprising a many transmission line give not guarantee receiving exactly the same results as in the real system. This is due to the specific requirements that are placed on the line models in the calculation of electromagnetic waveforms.

This paper presents the results of the analysis of structures and patterns of substitution parameters for systems containing a large number of transmission lines.

2. Transmission Line Representation

Transmission line is the only element of power system with spatially distributed evenly parameters. Transmission line representation with concentrated parameters (multiphase Π , T, Γ circuits) used during steady state and dynamic electromechanical investigation, is a mistake, especially when in many computer programs there are distributed-parameter line models at disposal which for transient solutions, are usually better. In addition frequency dependent line model must be taken into account. As demonstrated [2], the resistance, in particular for zero sequence strongly increases with increasing frequency. This includes the motivation was to create a so-called. Marti transmission line model [3], in which the accurate modeling of transmission lines over the entire frequency range using the Foster I network realization is developed.

The biggest limitation (and disadvantage) of Marti model is the need for a transformation matrix which is also depended on frequency. The importance of this factor increases with the degree of asymmetry of the line configuration.

Transformation matrix, shown symbolically in block form in **Figure 2**, between the phase and the modal components is independent on frequency.

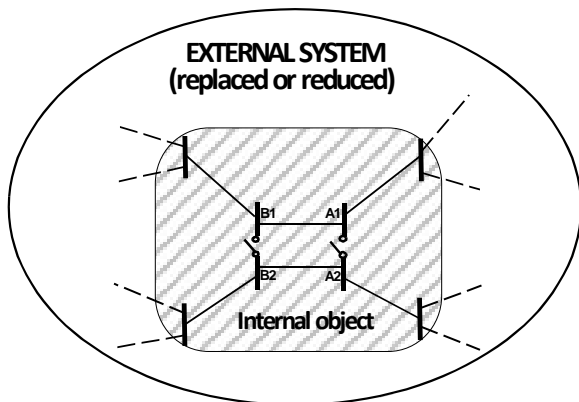


Figure 1. Test object as internal system.

This matrix should include elements of fixed and real, and the approximation will be with errors that for some frequency range may be negligible, but for others too much. Representation of multiphase lines in modal components is therefore a great simplification that can be used for most analyzes of electromagnetic transients, however, the results of calculations to be verified by measurement or different modeling of transmission line.

The new representation: Z-line (shown schematically in **Figure 3**), consisting of two main elements: the ideal line represents only the external flux and adjustment represents the external inductance and resistance is in [4] proposed.

3. The Choice of Equivalent Circuit Structure

In most cases the calculations in equivalent system are necessary. The results of analysis are depend on a number of factors and must be appropriately validated by comparing the results obtained in the real system (preferably measuring). The use of equivalents makes sense because of difficulty in the access to measurement data and taking into account the possibility of a safe and rapid computing verified result.

The determination of structure and parameter of equivalent circuit diagram, using traditional methods is very difficult, and in reality non possible taking into account the complexity of the system, non-linear properties of individual objects, the spatial distribution of the parameters in the model line, as well as its frequency dependence.

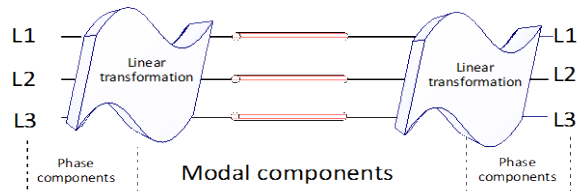


Figure 2. Line model in modal components.

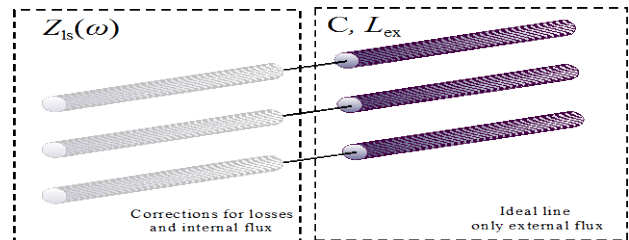


Figure 3. Z-Line model.

In many studies of electromagnetic phenomena assumes a “double standard” during computer simulations. The test object (e.g. transmission line) representation takes into account all possible requirements, but the remaining system is reduced to a simple structure consisting of few elements.

A classic example is the diagram shown in **Figure 4**. Transmission line model as the test object is supplied from both sides systems, which are represented by lumped parameters R, L . The irrationality of such approach is the fact that to the same node, which is connected to the test line, may be attached other transmission lines, of which the parameters have the same importance as the test object. The question is: why the “object” line is modeled with distributed, frequency depended parameters, but the other lines are modeled with the help of lumped parameters R and L .

Elements of equivalents in Figure 4 are determined on the basis of short-circuit power system (calculation of reactance) and the estimated time constant (determination of resistance).

Among supporter of such simplification is the simple idea that systems characterized by high power short circuit do not substantially affect the electromagnetic waveforms - especially the higher frequency components, which quickly disappear and therefore do not play a major role.

Very interesting is the proposal to CIGRE [5], a simple equivalent circuit (**Figure 5**), which may reflect the impact of adjacent lines connected to the common node of the test object. Additional parallel system provides impedance Z_s , the value of which is determined by the ratio of wave impedance Z_f and the number of transmission lines n operating in the system that is being replaced.

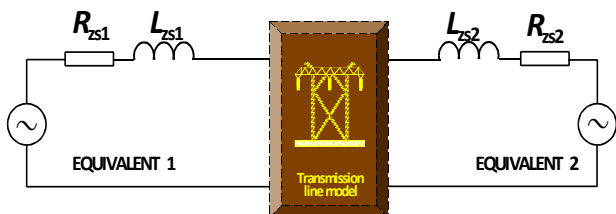


Figure 4. Simply representation of system during simulation.

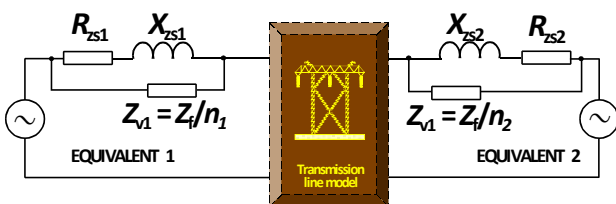


Figure 5. Equivalent of systems with multiple transmission lines.

The search for optimal equivalent circuit for electromagnetic waveform is the most difficult task, due to the fact that there are components of high (but also low) frequency and the periodic component. For this reason, a replacement system must take into consideration frequency-dependent parameters. The search for alternative structures is possible patterns in the time and frequency domain. Mostly the method in the frequency domain is preferred. In such case, the external system is replaced by an equivalent, consisting of elements of R, L, C , whose frequency response is the same as the original system. The methods developed in the time domain these elements play not important role in the equivalent.

In some publications the combination of modeling in the time and frequency domain has been. Such a solution - the hybrid system proposed in [8], where a replacement of external system is defined in the frequency domain, and the analysis of the test object in the time domain.

4. Search for Structures

For the analysis of searching for structures of equivalent the real system was selected and the network topology was chosen similar to 400 kV Polish transmission system.

The investigation were started in simple system as shown in **Figure 4** and the single phase to ground fault was simulated at the end of lines with a length of 100 km but the current was measured at the beginning of the line.

In **Figures 6** and **7** shows the comparison of the calculated transient current at the beginning of the line to the L1 phase, the short-circuit phase (L1 + e) at the end of the line.

As can be seen the introduction of a parallel branch in equivalent circuit reduces the error calculated from the difference in waveforms of the real system and simplified. The calculations were performed using MicroTran

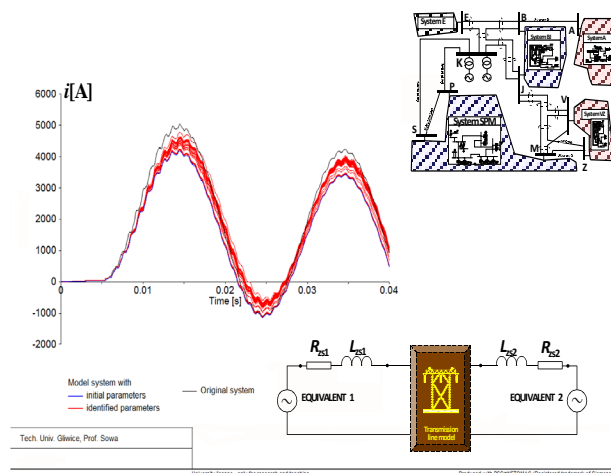


Figure 6. Current waveforms in the system without taking into account the number of lines in external system.

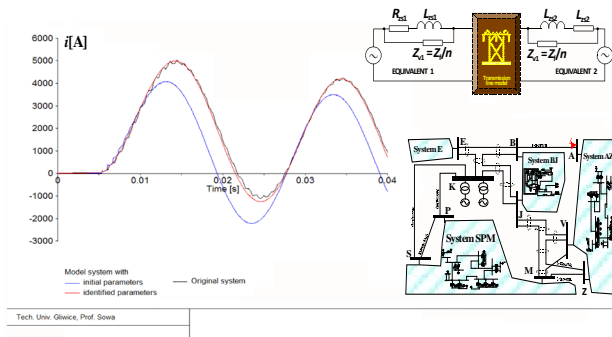


Figure 7. Current waveforms in the system taking into account the line of $n = 10$ in external system.

[6], and for the equivalent circuit a different number of transmission lines simplified was assumed. The best results are obtained for $n = 10$, which corresponds to a real system connected to the line taking into account the 5 adjacent nodes.

5. Parameter Identification of Equivalent Circuit

Regardless of how is determined equivalent circuit structure (in the time or frequency domain, by reduction of the original), it is always necessary to identify the parameters of components which are part of the structure.

The choice of identification method - based on literature reviews is very difficult because the examples have been shown for the well-defined problems associated with adapted for this purpose simulation programs.

In practice, the universal methods of identification, which would be accurate enough for all solved the problem has not been developed so far. All of the existing methods have advantages and disadvantages, many different criteria are used, such as: possible convergence of numerical solutions, the number of iterations required

computation time as well as the number of induced objective function. In Netomac-program [7] there are three optimization methods: least squares, quasi-Newton and Powell.

The search for the minimum of the objective function using the least squares method is generally numerically stable, but it requires a long calculation time. In addition, in case of large number of identified parameters, may arise similar linear relationship, which can cause non-convergence of the solution. Therefore the similar gradient method was implemented: instrumental variable and maximum likelihood, which are applied particularly in the regulation technology.

For this reason, the so-called “quasi-Newton” group of methods were introduced, where during simulation the numerical calculation of second derivative of objective function was avoided. Instead, they are looking for the approximation of the second derivative matrix inversion (metric matrix).

Quasi-Newton method cannot be directly applied to solving problems in the power system without appropriate modifications and additions. There are many technical problems that cannot be ignored and which impose limitations of this method, and in some cases prevent its use. In Netomac-program the additional methods are taken to eliminate all the disadvantages of “Newton-like”-methods (see Table 1).

Among proposed in the literature so-called coupled optimization methods that do not require the calculation of derivatives, there is a group called: “gradientless” methods, based on the criterion of Powell [8], but very often the combination of the original and the modified method of Powell is used. Many additional modifications have been forced, as the quasi-Newton method; the restrictions resulting from the imposed legal ranges identified parameters.

Table 1. Remedies for errors of "Newton-like" methods used in Netomac program.

REMEDIES	GENERAL	NETOMAC
CRITERION DOES NOT PROVIDE:		
search function with a minimum of restrictions	Stop changing parameters on their limits	in each iteration use of the procedure for determining of the new search direction until the convergence of solutions
values of parameters with different range	Scaling parameters at the beginning of the calculation	adaptive scaling
impact of the time-step on convergence solution	1) determining any change in the objective function, 2) determination based on the value of the objective function	Search procedure using interpolation
rounding error during determination of the positive definiteness of metric matrix	constant examination of positive definiteness of the matrix	The introduction of vector correction
problems during calculation of search direction of partial derivatives	procedures to avoid the impact of rounding and truncation errors	

For the previous studied example, the identification were made using three methods which are available in Netomac-program. The subject of optimization was the equivalent circuit where four parameters (two on each side): resistance R_{zs1} , R_{zs2} , and reactance X_{zs1} , X_{zs2} were identified. The initial values for these parameters are assumed, which are subject to change during the identification. In addition, the impedance Z_s is varied by changing the number of lines.

The best results were obtained for the least squares method identification as shown by comparing the resulting voltage waveform at the beginning of the line during two-phase to ground short-circuit (L1 + L2 + e) simulated at the end of this line.

In **Figure 8** the voltage waveforms received in a real and equivalent system are compared before and after the parameter identification. The waveforms were calculated for determined number of transmission lines connected to both sides of the test line. The results are received using least-squares method of parameter identification.

Throughout the identification process was observed the domination of individual parameters of both systems. This allows accelerating in a rational manner by blocking the iteration parameter changes, which do not have or have very little effect on the change in the objective function.

There is no doubt that, much easier and faster was to identify the current signals without components of free higher frequencies, which is clearly visible after comparison of waveforms in **Figures 7 and 8**.

In **Figures 9 and 10** show the effect of changes in the parameters identified by the replacement of one chosen system on the current and voltage waveform respectively, for the cases of identification from **Figure 7 and 8**.

The results obtained using Powell (gradientless) method is disappointing. As shown in **Figure 11** the identification of parameters takes effect opposite than expected.

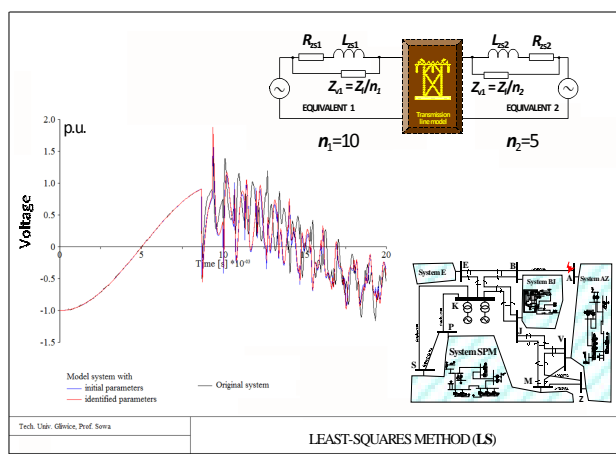


Figure 8. Voltage waveforms compared before and after identification (LS).

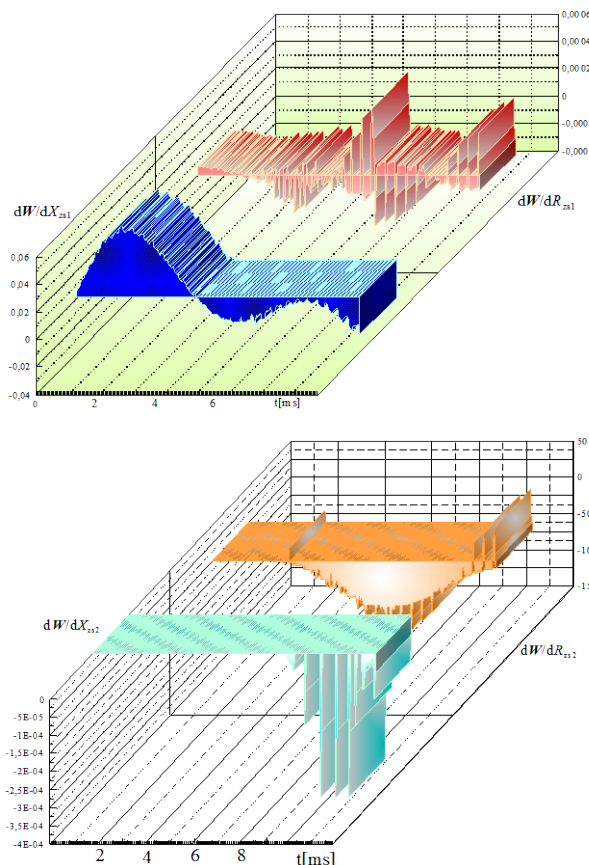


Figure 9. Influence of the identified parameters of equivalent system on the change of the current waveform for chosen working point.

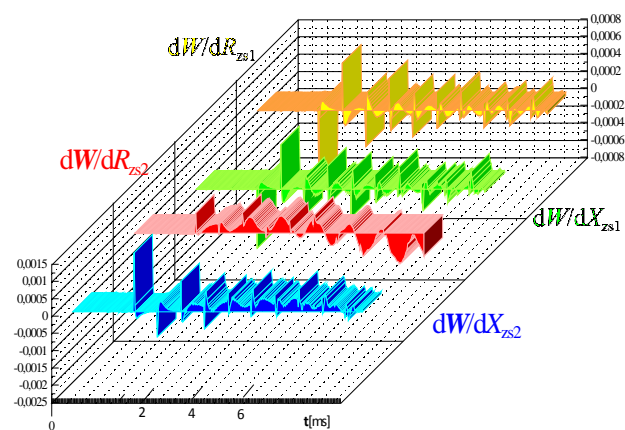


Figure 10. Influence of the identified parameters of equivalent system on the change of the voltage waveform for chosen working point.

On the basis of these results cannot be generalized, however, derive recommendations. Very difficult to clear even the qualitative opinion that the methods discussed above allows for a greater approximation of passes in the original and reduced systems. Comparison of the rate of change in the parameters of identification may give false

impression about the suitability of a particular method in comparison to the others.

Pessimistic statement is that, despite many years of research so far has not found a universal equivalent system that would faithfully reproduce the behavior of the electromagnetic power system transients. It seems that is necessary to distinguish between the structure and the search process parameter identification.

6. Final Remarks

To obtain reliable results in reduced system containing a large number of transmission lines will be subject to fulfillment of conditions:

- Transmission line, for which transient current and/or voltage should be determined, must be modeled taking into account the depending on the frequency parameters and without any simplifications.

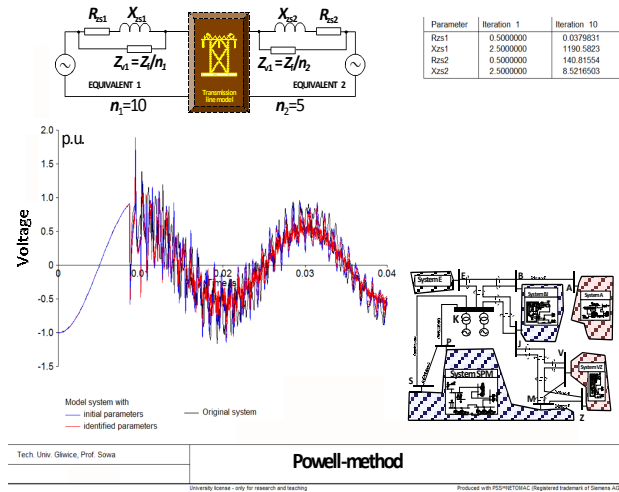


Figure 11. Voltage waveforms compared before and after identification (Powell).

Table 2. Recommendations for equivalents during study of electromagnetic transient.

Action	Knowledge of the structure of the original system	Finding structure in domain	Parameter identification	Reduction	Starting structure
YES	Simply supply or non-connected system	<i>lm</i>	frequency	static	redundant
		<i>all</i>	time	inadvisable	
	connected	<i>lm</i>	frequency	obligate	dynamic
		<i>all</i>	time	obligate	inadvisable
NO	Results from measurements				exact π system or ANN
	Only short circuit capacity (determined number of lines)	redundant		redundant	consistent with Figure 5 or ANN

- Remaining part of the system which have to be reduced must be represented by equivalent whose parameters are identified by an appropriate optimization method.

Table 2 summarizes the recommended procedures in the search for equivalents for the analysis of electromagnetic transient phenomena.

REFERENCES

- [1] GIGRE WG 13-05 III, "Transmission Line Representation for Energization and Reenergization Studies with Complex Feeding Networks," *Electra*, Vol. 62, 1979, pp. 45-78.
- [2] P. Sowa, "Over voltage and Overcorrect During Non-Simultaneous Faults in Transmission Lines," *IPST 95 International Conference on Power Systems Transients*, Lisbon, 1995, pp. 161-166
- [3] J. R. Marti, "Accurate Modeling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-101, No. 1, 1982, pp. 147-152. doi:10.1109/TPAS.1982.317332
- [4] F. Castellanos and J. R. Marti, "Full Frequency-Dependent Phase-Domain Transmission Line Model," *IEEE Transactions on Power Systems*, Vol. 12, No. 3, 1997, pp. 1331-1339
- [5] CIGRE Working Group 02 (SC 33), "Guidelines for Representation of Network Elements when Calculating Transients," CIGRE Brochure 39, 1990.
- [6] M. Tran, "Transients Analysis Program for Personal Computers," MicroTran Power System Analysis Corporation, Published, 1991, Vancouver, B.C., Canada
- [7] B. Kulicke, "Simulationsprogram Netomac: Differenzen-Leitwertverfahren bei kontinuierlichen und diskontinuierlichen Systemen," Siemens Forsch. und Entwickl. Ber Bd., Vol. 10, No. 5, 1981 pp. 299-302.
- [8] P. Sowa, "Dynamic Equivalent by Investigation of Electromagnetic Transients (in Polish)," Wydawnictwo Politechniki Śląskiej, Gliwice 2011, p. 218.
- [9] P. Sowa, "Replacement Diagrams of Systems with A Large Number of Transmission Lines (in Polish)," *Electrical Review*, No. 9, 2011, pp. 197-201.
- [10] P. Sowa, A. M. Azmy and I. Erlich, "Dynamic Equivalents for Calculation of Power System Restoration," *Energetyka*, 2004, pp. 104-108.
- [11] P. Sowa, "Representation of Power System for Electro-

- magnetic Transient Calculation,” *Proceedings of World Academy of Science, Engineering & Technology*, Vol. 30, 2008, pp. 223-226.
- [12] M. Kielbon and P. Sowa, “Electromagnetic Transient Components Induced by Faults in the Different Coupled Transmission Line,” *Proceedings of the International Conference on Power Systems Transients*, 1999, pp. 169-72.
- [13] A. Semlyen and M. R. Iravani, “Frequency Domain Modeling of External Systems in an Electro-Magnetic Transients Program,” *IEEE Transactions on Power Systems*, Vol. 8, No. 2, 1993, pp. 527-533. [doi:10.1109/59.260831](https://doi.org/10.1109/59.260831)