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A Simulation Approach to Solve Power System Transmission Problems

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Abstract

The cost of electricity is an indicator of a country's level of development. This industry involves billions of dollars. Hence, the operation of Electric Power Systems constitutes a real problem that consists of a set of stages related to distinct components. In this paper, we propose a novel simulation model to study the state of transmission line systems due to scheduled and unscheduled maintenances. The simulation model is founded in an extension of the Discrete Event System Specification formalism called Routed DEVS. The transmission line system is modeled with a set of discrete-event simulation models that provide a complete state description of components. Such a simulation model can be adapted to describe any transmission line system through a network topology. A case study is presented with aims to show who the simulation works. Our proposal is the starting point to study real-life operations of Electric Power Systems from generation to transmission stages.

Keywords- Discrete-event simulation, Electric power system, Routed discrete event system specification, Transmission lines.

1. Introduction

The operation of electrical systems is a complex problem given its size and constraints. The study of the Electric Power System (EPS) was first focused only on the behavior of generator units (Hara et al., 1966). Over time, it became evident that the study of transmission lines was also important with aims to obtain efficient scheduling of the EPSs. In this context, inefficient programming of EPSs could suffer consequences that represent great economic or social impact (Hara et al., 1966). Simulation tools allow recreating the dynamic behavior of EPS on a short and large scale. In consequence, such simulation tools promote the evaluation for dispatching electricity from different far regions, with both large- and small-scale generators, such as hydropower plants, thermal power plants, photovoltaic parks, and wind parks. There are several simulation tools for studying the dynamic behavior of EPSs. For example, many authors affirm that the dispatcher simulator EPRI-OTS (Bhatt et al., 2015) is the current standard for simulators of EPSs. Other simulation techniques pre-scheduling the power system by including time series analysis (Nogales et al., 2002) along with simulation approaches. In these works, a detailed model of the system is presented, and the solution is obtained by considering several constraints. Other works were developed to reduce the computational effort, simplified models of generators, and a static model of the power. The integration step is variable and is based on the calculus time of the previous step. Each step considers the parameters of all islands that compose the EPS. An island is a group of elements of an EPS that works with the same frequency. Another simulation tool is

Python for Power System Analysis (PyPSA). This tool is a free software tool for EPS simulation and optimization that considers multiple periods (Brown et al., 2018).

On the other hand, existing simulation tools also include the possibility of modeling several stages like planning, operating, and design of EPSs. When the stage of operation of EPS is considered, analysis of network conditions provides the demand data and the information required for the behaviors of devices. In this context, most simulation approaches employ specific simulation tools for building the simulation models required for each case. In Debs et al. (2002), the authors develop the Electricity Market Operation Simulator (EMOS) tool. This tool is implemented for competing market biddings, independent system operators (ISOs), and independent market operators (IMOs). The tool helps with operating decisions relating to getting bidding strategies by energy trading participants. In the simulator, participants implement the Unit Commitment to get bidding strategies by scheduling generating operations. Frameworks are implemented for users to apply their applications to represent competence generically.

Several works have been developed to attend the operation and planning of transmission lines considering uncertainty in their availability. The random disturbances of transmission lines are considered. However, the resolution of this problem is faced by using a stochastic approach. Regarding the simulation of EPS, in Brown et al. (2018), its functionality is analyzed, including linear power transmission equations and the optimization model for operating the systems (i.e. a mixed simulation and optimization approach). The test system of the paper is based on two datasets of the transmission system in Germany and Europe. In Chen et al. (2013), a hybrid simulation of the HVDC (high voltage direct current) power transmission system at 500 kV voltage is performed. The simulation considers dynamic response outputs due to three fault conditions. The validation of the simulation waveforms is performed by using an Advanced Digital Power System Simulator (ADPSS).

Even when all these approaches are useful, new types of problems emerge when scheduled and unscheduled maintenances are studied as part of transmission line systems. The Discrete Event System Specification (DEVS) formalism (Zeigler et al., 2018) has been successfully used for the Modeling and Simulation (M&S) of EPS. In Byon et al. (2011), the author uses DEVS to present a simulation model for wind EPS operations and maintenance. Authors account for results based on historical data for different maintenance strategies, scheduled maintenance, and the called condition-based maintenance. Also, the authors Pérez et al. (2013) developed a DEVS framework that represents the operations of a wind farm. Each generator is represented as a separate module for enhancing the scale up to more than one hundred units. The simulator can handle random events and, consequently, unscheduled maintenance. In Beccaria et al. (2018), a model based on DEVS is presented to simulate the production and storage of biogas. Additionally, the model addresses the operation of EPS with the produced biogas. It validates different scenarios of production and demand for a better decision-making process regarding the production of biogas. However, in that work, it is assumed that units do not suffer any failure during the programming horizon. The authors Alvarez and Blas (2020) developed a simulation model for studying the scheduled maintenance of high-voltage transmission lines to prevent outages, or even worst, blackouts. Additionally, a full recompilation of the methods to organize the scheduled maintenance can be found in Shafiee and Sørensen (2019). This last paper reviews several methodologies, including mathematical programming and DEVS approaches.

Based on the above, in the present paper, we propose a novel simulation model to study the state of transmission line systems due to scheduled and unscheduled maintenances. Our model provides a full definition of the Transmission Line (TL) states considering as *active*, *inactive*, *under maintenance*, and *outage*. The basic simulation model of the Transmission Line System (TLS) is designed using RDEVS formalism (Blas et al., 2017). To show how the simulation model is defined, we introduce a case study obtained from the literature.

The main contributions of this paper are:

- The definition of a simulation model that provides a behavioral description of transmission lines (individually) but, that can also be integrated as part of a system without requiring any changes. That is, our approach does not depend on the size of the EPS under study.

- The study of transmission lines that considers real-life scenarios with detailed information to enhance the operation of EPS. Specifically, our approach studies the impact of scheduled and unscheduled maintenances on the availability of transmission lines.

- The development of a simulation model for a generic transmission line system that can be integrated with other approaches/models related to other stages of EPS.

The remainder of the paper is organized as follows. Section 2 explains the methodology and test cases. Section 3 presents results and discussions. Finally, conclusions and future works are detailed in Section 4.

2. Methodology

We use the RDEVS formalism as the M&S approach to support the design of the TLS simulation model. Such a formalism was proposed in Blas et al. (2017). Recently, it has been improved to support the definition of routing processes from a conceptual modeling perspective (Blas et al., 2021). From the general approach, we introduce a discrete-event simulation model that is used to support the dynamic of TLs. Such a model deals with scheduled and unscheduled maintenances. Then, we show how the TLS defined in a one-line diagram can be translated to RDEVS models required when such a system is modeled as a routing problem.

2.1 The M&S Approach to Study the Dynamic of a Transmission Line System

A TL is a structure that circulates the power flow between two buses. It is composed of several elements, such as steel and guard wires and buildings. The TLs involve equations of the electromagnetic area to find their optimum operation. Their behaviors are in concordance with the boundary conditions imposed by the circuit theory and topography characteristics. Parameters included in the analysis of line flows are inductance, resistance, capacitance, and conductance. When the circuit is large (500 kV lines), the theory of TLs must be considered. Hence, the study of the limits of electrical energy transfer is crucial to enhance the operation of EPS. Here, constraints are required. These constraints involve thermal limits, bus voltage limits, and dependencies between lines.

When a TL stops working and has not yet finished its life cycle, the line has failed. A line failure involves a total loss of voltage. These failures can be caused by issues in the electrical network, such as animals attacking phases, trees, weather conditions, and failures in the generation equipment. Their occurrence can cause generator out of service, impossibilities to supply users, or even worse, blackouts. A line failure analysis is useful to determine the cause of a failure and reduce the chances of it happening again. To address this kind of analysis, this paper proposes an underlying abstraction model based on the basic configuration of EPSs. The abstraction model focuses its attention on the way in which lines are connected and the relationships between them with aims to define a network topology. Hence, a simple and configurable abstraction model is defined based on the connection among lines with aims to study a TLS.

The RDEVS formalism is based on three types of simulation models: *essential model*, *routing model*, and *network model*. Each type of model helps to define components used for the M&S of network topology as follows: *essential models* are used to define the behavior of routing entities, *routing models* are used to define the structure of routing entities, and *network models* are used to define the structure of routing processes. When a TLS is modeled with network topology, interdependences between lines are represented explicitly. A TL is influenced by its predecessors, and simultaneously, it may act as a predecessor of other TLs. If a line L1 does not carry electricity for any reason (i.e., due to scheduled or unscheduled maintenance), the successors of L will not carry electricity either. Hence, the set of components of a TLS modeled as network abstraction can be mapped into RDEVS models. Table 1 presents these mappings using a top-down description. Since RDEVS defines the formal structure for routing and network models (i.e., TL structure and TLS, respectively), only the essential model (i.e., the TL behavior) should be formally defined (Section 2.2).

Table 1. RDEVS models used for the M&S of TLS.

Component	**RDEVS Model**	**Description**
TLS	Network model	The TLS is modeled in a RDEVS network model following the case study under evaluation.
Transmission line structure	Routing model	Each TL is modeled in a RDEVS routing model that unifies its behavior with the routing policy obtained from the TLs placed upstream and downstream.
Transmission line behavior	Essential model	All TLs modeled in routing models shares the same behavior. Then, the TL behavior is modeled in a RDEVS essential model.

The specification of a generic and unique simulation model for any TLS is the main benefit of employing RDEVS formalism as the M&S foundation (i.e., modeling only the behavior of the domain elements as components without worry about the implementation of the routing process (Blas et al., 2017)). Then, once the essential model for the TL is defined, our approach allows using such a M&S model for structuring a TLS based on any number of TL.

2.2 The Model of the Transmission Line (RDEVS Essential Model)

The behavior of a TL is defined in an essential model. The model state is structured as a set of variables named *phase*, *sigma*, *upstreamTL*, *inactiveUpstreamTL*, *time*. In the initial state, the model is in phase *active* for an undefined period (*infinity*). Moreover, the model is configured with the number of upstream TLs (parameter named *U*) and zero inactive lines detected at upstream. The simulation time is zero. Hence, the initial state is *(active, infinity, U, 0, 0.0)*. This means that the TL is *active* (waiting for incoming events). Also, it means that all the TL that compose the overall simulation are considered *active* (because *inactiveUpstreamTL* is zero). A TL can receive five types of input events: *active*, *inactive*, *maintenance*, *outage*, *restoration*. Each input event has its structure. When an *active* event arrives, the model decreases *inactiveUpstreamTL*. If the model was in phase *active*, the model stays in this phase. However, if the model was *inactive*, the model changes to phase *active*. Instead, when an *inactive* event arrives, the model increases *inactiveUpstreamTL*. If the value of *inactiveUpstreamTL* is equal to *upstreamTL*, the model goes to phase *inactive*. In this case, the model sends an *inactive* event to all its downstream lines. If some upstream lines are still active (this is, the value of *inactiveUpstreamTL* is less than *upstreamTL*), the TL stays in phase *active*.

When a *maintenance* event is received in phase *active*, the TL is about to start its maintenance (scheduled). Then, the model sends an *inactive* event to its downstream lines with aims to inform this situation. Then, it goes directly to phase *maintenance*. Once the scheduled maintenance is over, the model goes to phase *inactive* or *active* according to the value of *inactiveUpstreamTL*. If *inactiveUpstreamTL* is lower than *upstreamTL*, the model changes to phase *active*. In another case, the model goes to phase *inactive*. When an *outage* event is received (in any phase), the model goes immediately to phase *outage*. Also, the model sends an *inactive* event to its downstream lines to inform the outage state. An *outage* event is also sent to the controller (independent system operator) to inform the situation. Once the model is in phase *outage*, only a *restoration* input event can be used to activate the model again. When a *restoration* event arrives, the model changes to phase *active* or *inactive* with the same criteria that the one used in phase *maintenance*. In any case, if the model goes to phase *active*, the model sends an *active* event to its downstream lines. Then, all the downstream lines will know that the TL is now *active*.

2.3 Transmission Line System as a Routing Situation through a Case Study

2.3.1 Transmission Line System (Real System)

The case study is formed of 6 buses, 3 generating units, and 11 lines. The one-line diagram of this system is presented in Figure 1. The figure represents the whole EPS, even showing several elements that are not considered in this paper. The next section is focused on the TLS structure. Such a system is defined by the 11 lines (labeled as L1-L11) and their dependencies. Data about this system can be found in (Grey & Sekar, 2008).

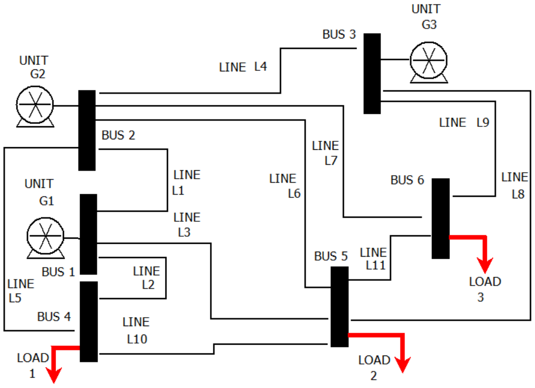

Figure 1. The 6 buses system one-line diagram.

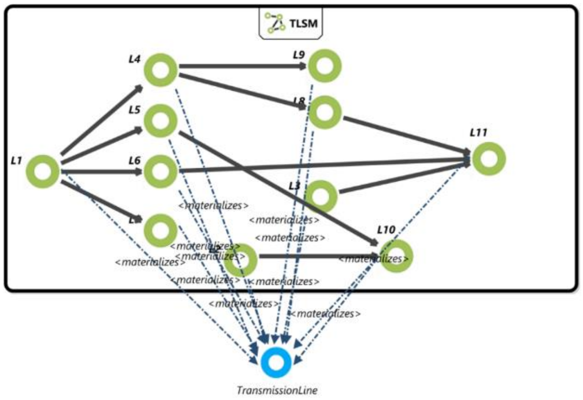

Figure 2. Routing situation of Figure 1 modeled with the RDEVS tool (Blas & Gonnet, 2021).

2.3.2 RDEVS Models (Implementation and Simulation)

To get a Java implementation of the RDEVS models required to simulate a TLS, we use a graphical modeling tool that is explicitly designed for getting RDEVS models from routing situations. Such a tool is presented in Blas and Gonnet (2021). The tool uses a graphical definition of the routing situation and performs a set of translations between the situation description and the RDEVS formalism to get a pre-defined set of simulation models. Hence, it automatically generates the executable Java code required to execute the model.

Figure 1 depicts the routing situation attached to Figure 2 Green circles are routing entities (i.e., the TLs) while the blue circle is the behavior shared by entities (here, the TL behavior). Then, each TL materializes the behavior of TL. Over such a routing situation, the M&S tool provides a set of Java classes that implement the structural models required for the simulation of the TLS. To complete these models, the model described in Section 2.2 was codified in a Java class named *TransmissionLine.java* to provide the behavior shared by classes that implement TLs entities.

The Java code that defines RDEVS simulation models was executed with the DEVSJAVA simulator (Arizona Center of Integrative Modeling and Simulation, 2005). Figure 3 presents a screenshot of the simulator viewer when the TLS simulation model (named TLSM) is executed. As the figure shows, the final simulation model is composed of two models: *Experimental Frame* and *TLSM*. The *Experimental Frame* is a DEVS coupled model defined to test the *TLSM* model. Such a simulation model is in charge of (i) ensuring the scheduled maintenance of the lines (i.e., module named *Maintenance Team*), (ii) creating outage events to produce unscheduled maintenances in the lines (i.e., module named *OutageGenerator*), and (iii) restoring the normal activity of TLs ones the maintenances are over (i.e., module named *RestorationGenerator*). During the simulation execution, both models evolve according to the set of events exchanged by the internal models. As a result, the *TLSM* model generates a CSV output file named *TL-name.csv* that is used to store the TL state information.

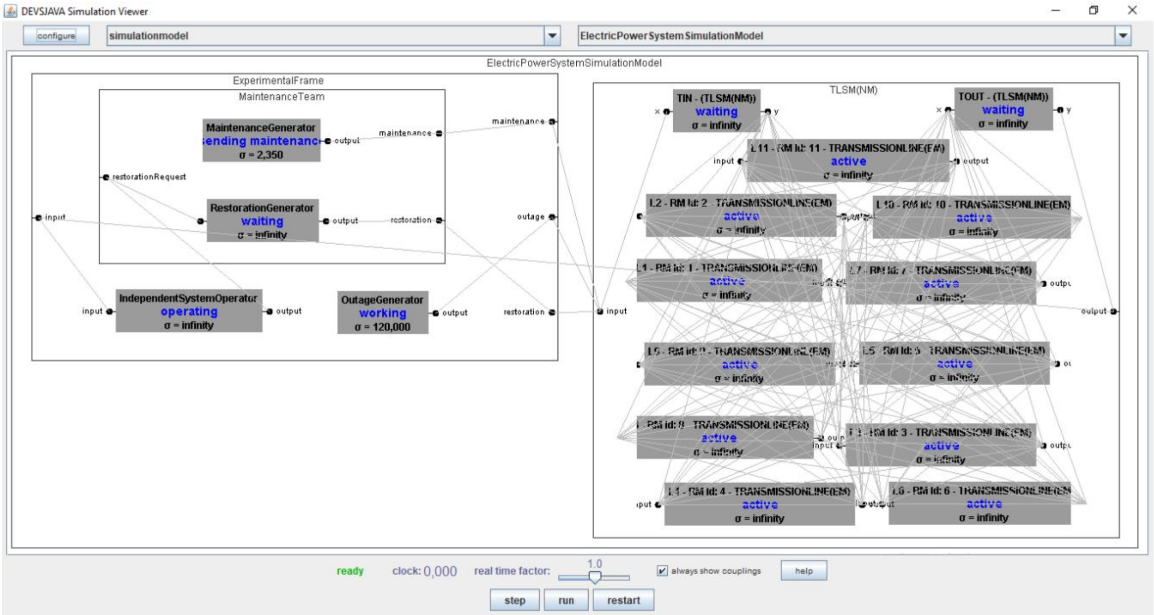

Figure 3. Screenshot of the simulation viewer when simulating the scenario depicted in Figure 2.

3. Results and Discussion

The results of the different iterations of the model prove an adequate response to different configurations that the system can take. In the case study presented above, experiments have been performed considering different time periods and different situations. In the first case, the operation during 1 day with scheduled and unscheduled maintenance is considered. In the second case, it is considered 1 year and the reaction that the transmission line system experiment when only unscheduled maintenances are produced. For the first case, line L4 is out of service at minute 315 and the maintenance lasts 150 minutes. Consequently, the organization of the transmission of electricity must be modified. This outage is caused by scheduled maintenance. As a result of the cascade connection, lines L8 and L9 will also be out of service between minutes 315 and 465. This action is remarkable because it constitutes one of the main contributions of the work, which is the elimination of redundant calculations. When the model detects that a line is out of service (and its consequences due to the cascade configuration), the model reschedules accordingly to the individual status changes. Thus, if the economic dispatch calculation is added to the model, the transmission over the aforementioned lines is not considered during that period. This differentiates the present proposal from many of the models available in the literature, which perform the calculation of power flow through these lines, even when a previously connected one is out of service. More cases have been calculated in order to study the effectiveness of the proposed approach. The first case is illustrated in Figure 4. Values of active lines keep equidistance to better show the operating of the system.

The simulation model defined in this paper provides suitable support for the individual description of the dynamic behavior of transmission lines. Here, we use all lines with the same behavioral description. However, an improvement of such a description can be defined in DEVS with the aim to enhance the transmission line representation. This feature allows using our models as a basis for other discrete-event simulation models (i.e., models attached to other EPS stages such as, for example, distribution) to introduce the behavior of transmission lines. Moreover, the modularity provided by RDEVS formalism provides the possibility of adding new EPS components to the routing situation. The integration of scheduled and unscheduled (outages) events is one of the main benefits obtained.

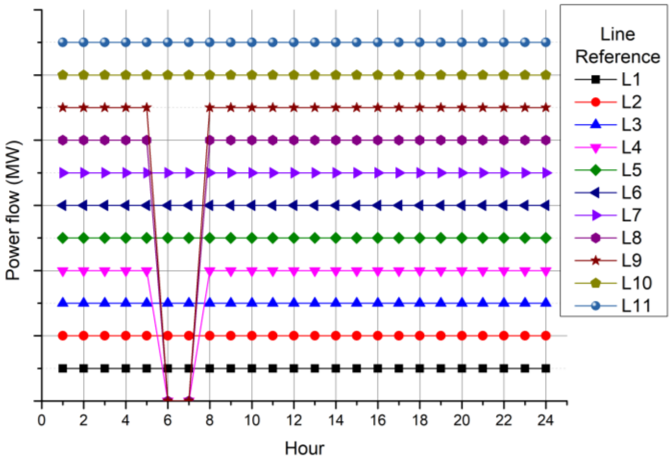

Figure 4. Simulation of the first test case. 6-bus electric power system.

Given the above, this paper provides the basis for the coupling of the optimization and simulation models, as part of future work. The first part of the mentioned integration is performed by the RDEVS approach. This model is structured using the topography of the system and it considers all lines as active at the beginning of the simulation time. After processing the data, as was explained before, an output file is obtained (a *csv* file). In the next step, the optimization model will incorporate the content of the *csv* file as a parameter to determine the best solution to solve the economic dispatch problem for loads through the transmission system. The formulation of transmission constraints will be implemented following the approach detailed in Alvarez and Blas (2020). In this case, these constraints are based on the DC power flow model.

4. Conclusions

This paper presents a novel simulation model for representing the dynamic of transmission lines in Electric Power Systems. We propose a new domain centered in discrete-event models to study the dynamic of transmission lines when distinct types of events take place as part of the overall system. The proposed simulation models are configurable. This means that they can be applied to any kind of electric system that require the study of transmission lines. This provides a suitable solution for studying the dynamic of transmission line systems in different EPS.

The final simulation model is founded in Routed Discrete Event System Specification formalism. The most common features of the real-life scenarios in the field of operations of Electric Power Systems are considered such as scheduled and unscheduled maintenances. As a result, our model considers outages of transmission lines due to scheduled maintenance. It also considers situations as unexpected outages due to climatological conditions. In this last case, we use Weibull distribution as support. Such a distribution has been proposed in Vásquez et al. (2009). The cascade relationships among lines are explicitly defined. This means that the model considers the dependency between connected lines and modifies the topography of the Electric Power Systems scheme to avoid redundant calculations (as considering the use of a line while it has an outage).

Tests indicate that the computational effort required for solving EPS problems can be reduced when our model is used. For instance, the availability to disable downstream lines in case of inactive upstream lines eliminates redundant calculations. Consequently, results suggest that our model is suitable to be coupled to larger optimization models with economic objectives as enhancing the dispatch of loads in the transmission system.

Hence, as part of future works, the simulation model will be integrated into optimization models to allow obtaining data attached to other EPS elements such as, for example, generators, transformers, and other power systems. A model as the one presented in Alvarez and Blas (2020) could be combined with the simulation model proposed here to obtain an integrated study between generation and transmission stages. Coordination among stages of EPS is the main goal.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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