2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Dependability Analysis of Power System Protections using Stochastic Hybrid Simulation with Modelica

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Abstract - **This paper addresses the dependability analysis of protection schemes of transmission grids using a computer simulator. Following modern protection schemes, a stochastic hybrid model has been developed in Modelica/Dymola environment. The model supports the evaluation of required dependability on the basis of suitable probability indices. A different simulation strategy has been implemented and its main features are discussed in detail. A logging tool has been created to supervise discrete events and assist in the results analyses. Furthermore, a custom simulation control panel helps to manage and to launch the simulation outside the Modelica environment.**

I. INTRODUCTION

The recent organization of electrical market pushes towards a decentralized power production. Due to economic reasons, more and more the electrical resources are being exploited as fully as possible. As a consequence, safety guards of the power system have been reduced to minimal ranges. In addition, the information and communication technologies (ICT) rendered power systems more complex and interconnected. If on the one hand they bring new facilities and efficiency, on the other hand they might compromise the system security, since they increase the exposure of power infrastructure to accidental or malicious failures. Hence, innovate strategies of protection and control of electrical system are required to maintain overall dependability and energy quality.

However, "classic" criteria are still adopted to preserve the overall system safety. They are based on deterministic analyses and cover a limited range of contingences (the most severe and frequent). Of course, these procedures ignore completely the dynamic operation condition and result in an oversized system, reducing greatly the profits.

A more interesting approach seems to be evaluating the dependability through probabilistic and risk based assessments. Many studies [1-4] demonstrated their benefits. The dependability analyses of power system are particularly complex due to some special features of transmission grids. First of all, the electrical connection makes the propagation of disturbances very fast. Besides, the grid is formed by a large number of components interconnected to each other, which might lead to unpredictable behaviors [5] and cascading effects, involving even equipments located far away from the original instability area.

As immediate consequence, the interference caused by this strong interaction should be considered while analyzing a component operation. Then, both design as well assessment of protection systems become particularly critical.

Under these aspects, the dependability analysis shall take into account the dynamical conditions of power systems [6]. To accomplish this task, a stochastic hybrid model to evaluate quantitatively the system safety had been proposed in [7]. Here, the idea has been extended in order to capture the dynamical evolution of electrical quantities, and also to represent more complex control and protection schemes.

The paper first summarizes the relevant features of power systems hybrid model (Sect. 2) and then discusses its simulation strategy in Sect. 3. Sect. 4 deals with the evaluation of probabilistic indices and Sect. 5 presents some results of a case study.

II. STOCHASTIC HYBRID MODEL OF POWER SYSTEMS

The dependability of the power system, understood as union of security (the ability to refrain from unnecessary operations) and reliability (the ability to function correctly when required). It can be valuated quantitatively through a model capable to capture continuous dynamics, which regard the electrical phenomena, the event-driven evolutions, which represent the control and protection actions, besides the stochastic nature of failures. Hence, a modular stochastic hybrid model (continuous and event-driven) has been developed. Briefly, some of its desired features are expressed as follow (for more detailed information, refer to [8]).

1) *Modularity*

A modular approach is clearly worthwhile in a simulation environment, when a module corresponds to a physical component described with a-causal model. This permits a high versatility and reusability of sub-modules.

2) *Hybrid behavior*

The systems under investigation show not only continuous-time behavior for electrical phenomena (here modeled with DAEs), but also event-driven behavior for discontinuous phenomena like breaks and faults (here modeled with Petri Nets, PNs).

3) *Stochastic behavior*

To consider the stochastic nature of events like lightning and short-circuits, some transitions of PNs can be endowed with a time delay, stochastically distributed, as proposed in the Generalized Stochastic Petri Nets (GSPN) formalism [9].

Several simulators of hybrid Petri nets have been presented in the literature [12, 13]. Unfortunately, most of them are not appropriate to model bulk power system. Firstly, they can not represent stochastic transitions. The second and most important reason regards and scalability of models. Since power systems are composed by thousands of components, the solution of such systems involves inversion of large matrices, which requires ad-hoc numerical algorithms. These desired features are suitable treated in Modelica. In addition, Modelica possesses symbolic manipulation techniques, which allow to construct a-causal models. Finally, Modelica standard library contains several built-in components, such as generators, turbines, etc, that can be seamlessly coupled to create complex models.

In the next paragraphs, some details are provided on the modeling of the transmission line of the power system. The other components of the system follow the same concepts of line model and will not be present for simplicity.

A. Generalized Stochastic Petri Nets

Before introducing the hybrid models, we shall make a brief review of the custom stochastic PNs implemented in Modelica. Here, the purpose is to illustrate the usability of GSPNs for modeling and simulating discrete-event phenomena, rather than for defining a mathematical formalism of PNs.

Although numerous techniques can be used to model event-driven phenomena, stochastic PNs present some special features extremely convenient for representing power systems. First of all, PNs permit to easily introduce event constraints into the discrete models. For example, if the line in failure state, a short-circuit event has no meaning. This constraint is easily imposed on the model by not including a transition linking the corresponding states. Also, PNs admit different events rates and the possibility to execute concurrent events. Finally, they allow to follow the states and the sequence of events performed during a simulation; only through this information the diverse PNs can be synchronized to each other.

Essentially, the library of custom stochastic PNs contains three elements: places, deterministic and stochastic transitions. These elements have been developed by extending the standard Petri net library of Modelica [13]. The original PNs can be classified according to the execution semantic as normal[1], priority[2] PNs with maximum firing[3] [13]. In addition, the original places and transition have limited number of connection ports (up to two inputs and two outputs). Because of such characteristics, the standard PNs of Modelica allow to model a limited class of systems.

Still regarding the execution semantics, the custom PNs can be classified as Time Petri nets [14]. In this modeling approach, a lower and upper temporal bound are associated to the transitions, which means that a transition may fire as soon as time exceeds its lower bound and it has to fire before its upper bound is reached. Here, the lower and upper bound are both equal to the time delay imposed to the transition.

The time delay can be either deterministic or stochastic. In the first case, the desired time delay is imposed as a parameter in the deterministic transition. When all enabling conditions are verified, a timer starts up and the transition fires right after the specified time delay is exceeded, unless disabled before then. The last situation is solved by the so-called Preemptive Repeat Different (PRD) firing policy. This means the time delay of an interrupted transition will be re-sampled (reset) when enabling conditions are once again verified. The same firing policy is used for stochastic transitions, where the different regards only the estimation of time delay. In this case, a stochastic transition is associated with a value representing the mean time to fire, once enabled, generally represented with the symbol λ. The stochastic behavior of events might follow an exponential or normal probability distribution function (pdf).

Since GSPNs are autonomous and hold discrete places, the custom PNs should extend both places and transitions by introducing communication ports to interact with continuous models.

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[1] Places of capacity 1

[2] Priority transitions to eliminate non-determinism in Petri nets

[3] Enable transitions must fire immediately.

B. Continuous-Time Models

Continuous models represent the electrical characteristics of power components (e.g. line, transformer, etc) and perform the dynamic evolution of electrical quantities (e.g. current, voltage, frequency). They are mathematically implemented through differential algebraic equations and hold signal ports properly adjusted to communicate with discrete counterparts.

An entire library has been developed for modeling the continuous part of system elements. It is composed of generator, line, bar, transformer, circuit breaker and different types of load. In this section, only the line model is discussed.

The line is the most important element of transmission power systems. The continuous model takes into account the fact that a line can be interrupted (by a breaker or a fault), can be short-circuited (a fault, or an external cause, like a falling tree for example) or can be hit by lightning. The model of the lightning and delay propagation effects are currently under testing. The three-phase electric line model (Fig. 1) is composed by resistances (R1 and R2) representing losses, besides the traditional inductance (L1) and capacitance(C1). Their values are estimated based on some parameters as frequency, distance between conductors and line length, just to list a few of them.

As already mentioned, in order to communicate with discrete counterpart, the continuous model has been endowed with communication ports, as depicted in Fig. 1. Current and voltage measurements are sent to discrete model, whereas short-circuit (Int_{CC}) and line failure (Int_{FL}) commands are received from it. Through these signal exchanges, hybrid models can be formed to represent the desired behavior of components.

C. Discrete-Event Models

The discrete models describe logical behaviors of power system elements. These models are used to set off control decisions, protection actions and also failures. Phenomena like these introduce discontinuous trajectories which are not suitably represented by continuous models.

The approach based on [12] has been used to describe the components of power systems. In this approach, the internal behavior of components is modeled by its own Petri net. The Petri net places indicate the state of a component, whereas the transitions describe the possible events. Some events, known as temporized (delayed) events, hold a firing rate λ and can be classified as exogenous or endogenous. Exogenous events do not depend on internal characteristics of the system and they are used to represent phenomena like lightning and failures. Instead, endogenous events depend on internal state of the system and can be further divided into two categories. In the first one, the events are related to the continuous variables of the system. For example, the tripping of a overcurrent protection is modeled as an event whose enabling signal results from the comparison of a current threshold and the real current (continuous variable) flowing in the component under control. In the second category, the events depend on the logical states of the system. For instance, the event representing one of the failure conditions of the circuit breaker, characterized by stuck closed state, can only take place if the state of the breaker is closed. Currently, the transitions have been upgrading to introduce the firing rate dependency on operating conditions [7]. Such a development will permit to change the probability of occurrences according to the real state of the system, like modifying the probability of undesired trip under heavy load conditions. Fig. 1 sketches the transmission line logical model. The meaning of the places and transitions is explained in the following.

Places:

- L_{OK} = line is in normal condition.
- L_{CC} = line is short-circuited
- L_{CC_P} = line is permanently short-circuited
- L_{FULM} = line is lightened
- $L_{FAILURE}$ = line is faulty

Transitions:

- TL_{FULM} = the line is struck by a lightning
- TL_{F_OK} = the lightning is extinguished autonomously
- tL'_{F_E} = the lightning is extinguished by the intervention of protections,. This immediate transition is conditioned by $|I_{LINE}|<\varepsilon$
- TL_{CC} = from OK state to short-circuit with ground
- TL_{CC_OK} = the short-circuit is self extinguished
- tL'_{CC_E} = the short-circuit is extinguished by the intervention of protections. This transition is conditioned by $|V_{LINE}|<\varepsilon$
- TL_{CC_P} = from OK state to permanent short-circuit
- TL_{CC_REP} = permanent short-circuit repaired
- TL_{FAIL} = failure of a line
- TL_{REP} = line is restored to OK state
- TL_{F_FAIL} = failure caused by a lightning.
- TL_{F_CC} = the line goes to short-circuit because of a lightning. The energy of the lightning is considered discharged to the ground.
- TL_{CC_FAIL} = the line fails because of a short-circuit (normally caused by the breaking of an insulator)

The overall behavior of the Petri net model can now be deduced quite straightforwardly.

Up to now, just a few control and protection schemes have been implemented. Basically, the protection is capable to detect failures in the component under control and remove it from the circuit by opening the breaker around it. Since the dependability analysis of protection system is the major objective of this work, the protection model should be capable to represent both security and reliability aspects, independently of its actual operation principle. Then, a single protection module has been implemented, where security aspects are modeled as a stochastic transition meaning undesired trips, while reliability aspects are modeled by another stochastic transition representing hidden failures. Also, fast and slow reclosers and breaker failure device and overcurrent protection have been implemented.

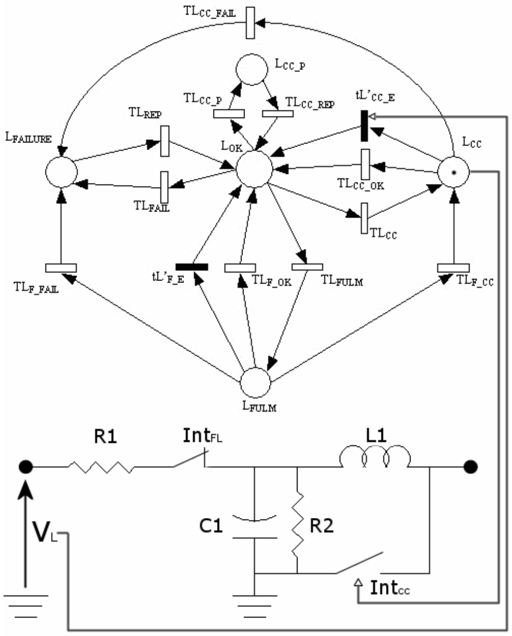

Fig. 1 – Transmission line hybrid model

D. *Hybrid Models*

The hybrid models can be easily formed by connecting the continuous and event-driven components. Fig.1 shows a simplified hybrid model of the transmission line. For sake of simplicity, not all the connections between the continuous time model and the discrete model are outlined. In particular, the scheme shows the interaction between the short circuit state of the discrete line model and the continuous line model. When the event TL_{CC} is raised, the token of the Petri Net flows from the L_{OK} state to the L_{CC} state. When the L_{CC} state is marked, an output signal orders the switch Int_{CC} in the continuous time model to close (the equation of the electrical node is modified). After the intervention of the protection, the circuit breakers are open and the line voltage value is approximately zero. A voltage sensor measures the voltage of the line and if the condition "$V_L < \varepsilon$" is true, then the event tL'_{CC_E} is raised. In this way, the token of the Petri net model flows from the L_{CC} state to the L_{OK} state that represents the clearance of the short circuit.

III. SIMULATION WITH MODELICA/DYMOLA

The simulation engine should be accurate enough to deal with continuous-time dynamics, event-based dynamics, and stochastic behaviors. Therefore, Modelica/Dymola has been chosen as simulation environment. Modelica is an open-source and object-oriented language suitable for modeling complex hybrid systems from different domains. The language permits a-causal and object-oriented models that greatly increases reusability through hierarchical modeling, encapsulation, and inheritance.

A. *Monte Carlo Method*

Considering the complexity of power systems, the Monte Carlo Method has been used to obtain quantitatively probabilistic indices [10]. Actually, finding an analytical solution is completely infeasible, because of large number of components and their possible states.

The Monte Carlo Method consists in the estimation of the solution of mathematical problems by means of random numbers, as a trial and error game. This method manages the generation of casual numbers, which regulate the evolution of the system, in order to simulate its stochastic behavior. Each simulation provides one of the possible trajectories, or scenarios, of the system. After several simulation cycles, the results tend to the mean solution.

B. *Event Arrays*

As we are interested in estimating the dependability/safety of power systems over long periods of time (e.g., over a year), it is just infeasible to simulate the model continuously inside Modelica because of time constraints. The power system is projected and managed so that, under normal operating condition and N-1 contingencies, it remains in safe state. Therefore, these time intervals do not bring new information to dependability accounts and it is worthless to simulate the system during these situations. So, the idea is to skip those intervals when the system remains in steady state conditions and to simulate only the transients due to a given event. By doing so, the load is supposed to be constant between two events, and the simulation resumes only when the next event takes place.

To do so, it is necessary to know in advance when an event occurs and how long its transient effects persist. The firing time instant of an event is calculated as a casual number obtained from exponential or normal distributions before its occurrence. This time extraction is carried out at the beginning of the simulation and after changing in the state of logical models. On the other hand, the necessary time to run out of transient effects has been estimated by observing the simulation results and can be set up by the user (usually 2 seconds).

Hence, a dynamic array has been implemented to trace chronologically the sequence of events and to make the control of "jumps" in time possible.

C. *Simulation Life-Cycle*

The simulation kernel is based on the DASSL solver (L. Petzold, 2000) for the DAE systems, while the *PN manager* and the *simulation manager* are written in ANSI C. The life cycle of the simulator is in the following:

1. The simulator kernel computes the initial state of PNs models, the time delay of stochastic transitions and the initial condition of continuous time systems. After that, the computed time delays are stored in an array called "next_event", where each item contains the name of the transition and the firing instant of the associated event (current simulation time plus the computed delay). A global variable called "offset", which allows for the time being advanced due to "simulation jumps", is initialized to zero.
2. The simulation kernel checks the transition states of discrete models. In particular, the firing condition is tested as follows: $t \geq (t_e - t_{offset})$, where t is the current simulation time, t_e is the computed firing instant of the event and t_{offset} is the global variable "offset".
3. The simulation kernel starts to integrate the DAE system. If the system reaches the steady state condition, the next event is read from the "next_event" array and the variable "offset" is updated as: $t_{offset} = t_e - t$. In this way the simulator can "jump" the time-consuming steady state and goes straight to the next transient.
4. When an event occurs, the simulator modifies the state of PNs models and computes new time delays for the new enabled transitions. At the same time, the array is updated by removing the raised event and storing the new ones.
5. The simulator computes the new consistent initial conditions for the state variable and returns to 4.

D. *Simulation Control*

A tool has been created to automatically control the simulation cycles. The software is implemented in Visual Studio .NET (C# language) environment. It is possible to set up the duration and decide when to stop/restart the simulation with respect to event occurrences. No longer needs the simulation to be launched inside Modelica, since the tool uses the model executable file to run it outside Dymola. At the end, a single data file is produced containing only the transient information occurred during the simulation time.

IV. PROBABILISTIC INDICES

The safety of the power systems can be seen as a distance of the current operating condition from an unstable condition. Although the clearness of such concept, it is somehow difficult to evaluate the safety. Usually, the dependability is appraised using several indices. Each index emphasizes a specific aspect of the system safety and should be chosen according to the objective of analysis. They are classified as deterministic, probabilistic or risk indices. Some relevant implemented probabilistic indices [10] are listed below.

A. *Expected Power Loss (EPL).*

It expresses the total load detached from the power system, in MW.

$EPL = \sum_i \frac{C_i}{N}$, where C_i is the load lost (MW) in the i-th simulation cycle and N is the number of cycles. EPL indicates the impact of hidden failures and cascading effects on system reliability.

In order to give a more significant indication, the index can be normalized with respect to the total system power. Also, it can be discriminated for each node of the system.

B. *Expected Unserved Energy (EUE).*

It expresses the total unserved energy to the utility, in MWh.

$EUE = \sum_i \frac{E_i}{N}$, where E_i is the unserved energy (MWh) in the i-th simulation cycle and N is the number of cycles.It gives more detailed information about the system damage than EPL, since it considers the unavailability of service.

C. *Bus Isolation Probability (BIL)*

It furnishes the probability that one or more bars of the system have been disconnected.

$BIL = \sum_i \frac{I_i}{N}$, where "i" indicates the simulation cycle and N is the number of cycles. I_i=1 if one or more bars are disconnected, 0 otherwise.

The BIL is a very important index, since bus isolation is one of the most damaging situations in the power systems. BIP shows the weakness of system in which a single component outage might result in bus isolation.

All indices listed above reflect someway the robustness of the system with respect to disturbance. Here, high indices represent unsafe systems.

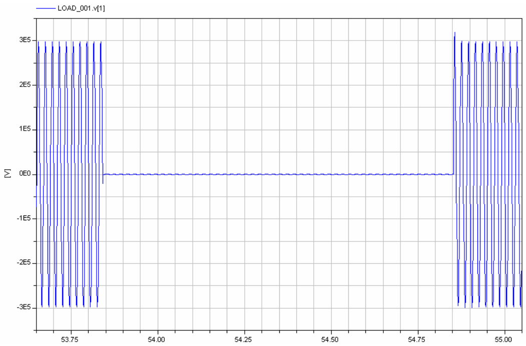

Fig. 3 –Partial blackout due to undesired trip

V. RESULTS

A reduced network (Fig. 2) has been used as a case study. It is composed by: 2 generators, 2 final users, 16 circuit breakers, 5 bars, 4 transmission lines, 2 transformers, 5 Breaker Failure Devices (BDF). Although the simplicity of the test system, it presents a ring structure and then a sort level of redundancy. It is possible to simulate partial and total blackout, and also to retrieve main behaviors of different components of power system.

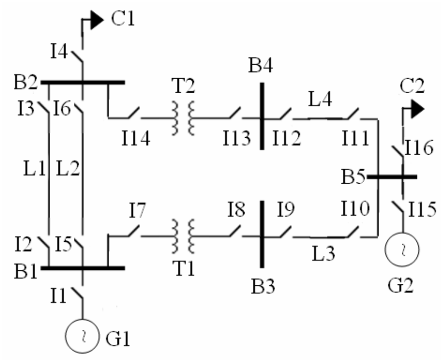

Fig. 2 – Reduced test system

To illustrate the simulator power, a partial blackout due to an undesired trip of circuit breaker 4 (Fig. 2 – I4) is exemplified. The Fig. 3 shows the voltage at the final user 1 (Fig. 2 – C1) as function of time.

After the opening of switch 4 (t≈53,84s), the user is completely detached from the grid, and its voltage goes to zero. Approximately one second later, the automatic fast recloser commands the circuit breaker to close and the voltage is re-established to the utility (t≈54,85s).

Forty one simulation cycles had been carried out with time duration of a year and the precision of results had been valuated through the variance of the sample series. After that, the dependability of the test system has been quantitatively estimated.

VI. CONCLUSION AND FUTURE WORK

A stochastic hybrid model has been proposed to take account of major characteristics of protection schemas of transmission system, considering both reliability and security aspects. Significant probabilistic indices are computed through a simulator developed in Modelica/ Dymola environment. Specific software has been created to manage the simulation procedures. The tool controls automatically file results and "simulation jumps" to reduce the time consumption.

New techniques for improving the simulation speed are being currently tested, since large models require significant computation efforts. Besides, the models are being continuously upgraded to include more precise information. The next improvements regard the time delay propagation in transmission lines, lightning model, automatic generation control and on-load tap changers.

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