ADVANCED MODELING APPROACHES AND SIMULATION TOOLS FOR POWER ENGINEERING RESEARCH AND DEVELOPMENT

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ABSTRACT

The paper discusses two issues that are considered important part of the advanced research and development activities, namely the modeling approaches and simulation tools. It is pointed out that modeling of the dynamic interaction between the power system and various controllers is particularly important and requires the use of real-time approaches. The role of the simulation environment and digital simulators in evaluating various control scenarios and testing physical controllers is elaborated on. Examples of protective relaying studies that illustrate the use of the new modeling approaches and simulation tools are given at the end.
Keywords: modeling, simulation, power systems, protective relaying, real-time systems, testing, digital simulators

1. INTRODUCTION

The use of modeling and simulation in the field of power engineering has been a standard practice for many years. Being a large-scale nonlinear system, the power network requires the use of advanced modeling approaches and simulation tools when solving complex research and development problems. In the past the standard approach was to use elaborate software packages to simulate such phenomena as faults, switching transients, transient stability and long term oscillations. In the case that the user had access to significant financial resources, physical models such as Transient Network Analyzers and Network Simulators were used [1,2]. The latest developments in the modeling and simulation techniques as well as implementation technologies opened new possibilities for advanced research and development activities. This paper gives a state of the art review of the approaches taken and tools developed in the last ten years.

The paper addresses two issues: implementation of integrated modeling and simulation environments and development of advanced real-time digital simulators. First topic of interest is the integrated simulation environment. The paper analyses the new simulation environments where both the power network and controllers are modeled including the capability to simulate dynamic interactions between the two [3]. Several approaches to integrating the modeling techniques and presenting the simulation results are outlined. Next, the paper discusses a variety of implementation approaches for real time simulators and discusses future trends in this area [4-7]. The issues of hardware, software, user interfaces, multi-terminal configurations and simulation automation are presented. The final part of the paper gives several examples of how the advanced tools can be utilized in solving complex research and development problems.

2. REQUIREMENTS FOR R&D STUDIES IN POWER ENGINEERING

With an increased competitiveness in the power industry introduced by deregulation, the R&D activities have again intensified. The expectations are that new solutions are needed to gain a competitive edge.

In most cases, the research and development related to the new solutions assumes availability of advanced approaches to the engineering design. The examples of the requirements are:

- Defining context dependent solutions for the systems consisting of a variety of interconnected subsystems
- Mixing together different mathematical representations used for representing various parts of the system
- Evaluating the entire solution without having built a physical system
- Testing physical devices by simulating the interaction with other parts of the system

Defining context dependent solutions: A context dependent solution may be defined as the one that reflects various control actions aimed at changing the system topology as well as affecting the variables. This makes the whole problem difficult to handle and even more difficult to visualize by the user. To facilitate solving of the problem and better understanding the underlining techniques, it appears that modeling and simulation became an indispensable tool for achieving the goal. It is well known that modeling of complex physical systems and related control algorithms is not an easy task, but is required if a detailed solution is to be found. The outcome is rather obvious: most of the studies had to be simplified and carried out by investigating the behavior of various subsystems separately never having an opportunity of getting an accurate assessment of the overall system performance. The limitations experienced in the past emphasized the need of having better approaches to modeling and simulation that will allow for the overall system assessment to be performed rather accurately and efficiently.

Mixing together different mathematical representations: Another common property of complex system representations is the use of multiple mathematical techniques to obtain the final solutions. In the case of the power system, the differential equations may be mixed with artificial neural networks and various signal processing techniques when obtaining the solutions. The process of finding the solutions may start with calculating the voltages and currents, analyzing them for the purpose of determining particular state changes, and then processing them in order to obtain the type of the control required to maintain power system stability. Providing an easy way of mathematical representation of all the steps working together is not trivial. As a rule, the process involves defining the problem using rather lengthy and tedious mathematical derivations as well as partitioning the problem into smaller and easier to handle subsystems. Modeling the complex system through some mathematical means that have rather simple symbolic representation of different mathematical models working together makes the mixing much easier to understand and explain. The new modeling and simulation tools have to have this capability to be attractive and desirable.

Evaluating the entire solution through modeling and simulation: Sometimes the study of complex systems and solutions requires that the entire problem is represented in the modeling and simulation environment. Hence it is desirable that software tools for implementing such environments are readily available. In the case of the power system R&D, this means that the power system and related controllers can be represented in the same modeling and simulation environment. In addition, the transducers connecting the controllers to the system need to be represented in the same way. Once all the components of a complex solution are available as software modules, the next requirement is that the use of the modules is facilitated through some easy-to-use graphical means. The existence of a library of different components as well as multiple representations of the same component is a desirable provision.

Testing physical devices: The analysis of complex system can sometimes be greatly enhanced if the interaction between a system that is being controlled and the controller can be evaluated in detail. This translates into a requirement that a physical controller be directly connecting to the simulation system. Having such a provision in the power system studies may again mean that rather expensive facilities are available where the controllers can be connected to the physical system. This approach allows a flexibility of connecting the controllers at a point of interest, and evaluating the interaction in great detail. The overall performance of the controller and the system being controlled can be assessed today providing an affordable set-up. The entire system is represented via a computer and a few controllers attached to it.

3. MODELING AND SIMULATION ENVIRONMENT

The simulation environment is defined as a suite of software modules that enables modeling of power system components, assembling them into a model of a power system, adding the models of the controllers, connecting the models of the controllers to the power system model using the models of instrument transformers, and running the interactive studies. A functional block diagram of a typical simulation environment is shown in Figure 1.

Implementation Issues

When trying to satisfy the requirements for advanced studies, the designers of the simulation environment are faced with several important implementation issues:

- Ability to represent the entire simulation environment in one programming environment
- Flexibility of dealing with all the interactions between the environment and the operator through one graphical user interface
- Availability of variety of options in simulating different study scenarios
- Possibility of integrating different types of device/component models in one simulation environment

Use of one programming environment: The power system studies can be performed using specialized programs developed for particular type of studies. The examples are: load flow programs for planning and operation studies of the system loading [8]; short circuit programs for planning study of short circuit currents and co-ordination of relay settings [9]; electromagnetic transient programs for study of fast fault transients [10]; stability programs for planning study of transient stability and low frequency oscillations [11]. All of these programs are typically implemented as stand alone programs that are run separately. This means that the power system data needs to be entered for each study separately, and the program results can not be passed from one program to another. The problem found in the advanced studies is the need to run a simulation that has a "continuous" representation of power system dynamic states. This assumes starting from the load flow reflecting the normal network conditions, unfolding into fast transients at occurrence of a fault, showing the phasor short circuit values when the fault transients die out after some period of time, and then going into the transient stability state and evolving into slow stability oscillations. The existing programs are not capable of supporting the mentioned needs since, as already mentioned, each of the power system states is simulated with a separate program without any easy ways of supporting the co-ordination of program execution.

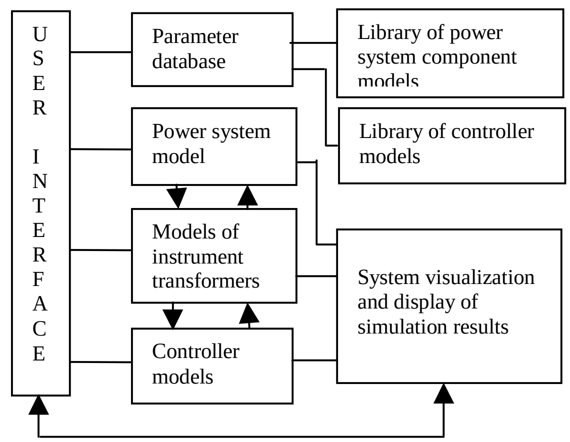


Figure 1. Typical simulation environment

Use of one graphical user interface: As an extension of the need for one programming environment, the need for one graphical user interface is also critical. The users should be able to select the models to be used, enter the model parameters, and set the simulation scenarios through a common interface. This not only saves the time required to run simulations, but it also enables storing and viewing of the simulation results as well as utilizing and exchanging the model and parameter data among programs. The user interface needs to be easy to use and flexible enough to show simultaneously the outcomes of the simulation performed by various modules.

Some attempts along those lines have been made recently where a whole suite of software modules is made accessible through a common user interface [12,13]. This is very convenient when entering simulation data. However, in most of the solutions implemented today, the other interactions mentioned above are not available. The software modules are still separated during execution and can only be run as sequence of batch programs and not as part of a simultaneous simulation.

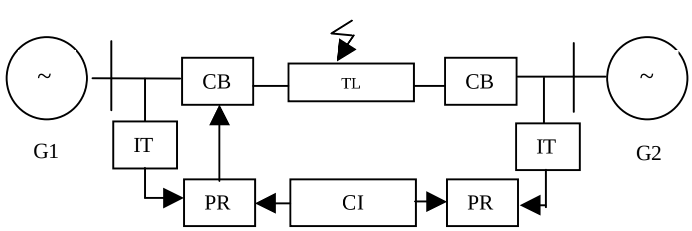
Options in running different simulation scenarios: One extremely important requirement is the ability of running the mentioned studies in an interactive mode where the outputs of one simulation can be provided as inputs to the other, but automatically. An example is the case when a controller receives inputs from the network simulation program, and after making a decision, reacts by issuing a command back to the network. The command may cause changes in the network parameters, which in turn affects the simulation that may already be running with the previous set of parameters. This interactive feature is essential when trying to simulate dynamic behavior of complex systems including the object of the control as well as the controller itself. The existing application programs used for simulation of power system dynamics are not typically equipped with the ability to model the controllers and provide an interactive connection with the simulation program. In same rare instances, a separate programming language may be used to implement such features [14,15]. However, the problem still remains unresolved when different modules have to be utilized interactively since one type of interfacing for a given controller module will typically not work for another type of the power system module.

Integration of different types of device/components models: One problem commonly encountered in advanced power system studies is the varied level of complexity and the type of mathematical representation used for different device/component modeling. For example, modeling of network transients may require solution of time-domain representation of linear differential equations while modeling of the controller may require solution of a non-linear neural net algorithm. To cope with such a requirement, a decomposition modeling approach has been proposed in the literature [16]. It has been shown that a careful approach to decomposition with proper consideration of the boundary conditions for each of the modeling subsystems can yield the model integration required for some of the complex studies. An important feature of this approach is the ability to run simulations using separate models at different time steps and with different levels of detail that would be perfectly acceptable when individual models are considered. This contributes to an efficient simulation while maintaining acceptable accuracy levels. Unfortunately, this decomposition approach is not readily used in the existing software packages and hence the advantage of the integration is not readily available.

Application Issues

Based on the above implementation issues, further consideration of the advanced simulation environment can be illustrated by discussing the applications issues. Typical application issues are as follows:

- Localized studies
- System-wide studies
- Studies related to cascading events



CB - Circuit Breaker TL - Transmission line
IT - Instrument Transformer CI - Communication Interface
PR – Protective Relay G1,G2 - System Equivalent Sources

Figure 2. Connection between the power system model and the model of the protective relay controller

Localized studies: Typical localized study is the case of a protective relay acting as a controller on a given transmission line in the power system. The block diagram of the model is shown in Figure 2.

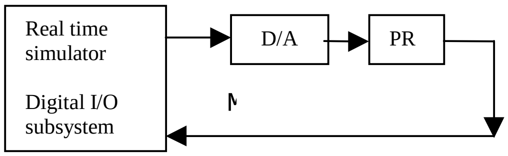
The connection indicates that the entire power system can be represented by a simple transmission line with equivalent sources representing the behavior of the rest of the system. The modeling of the fault events on the line can be quite detailed and the relay model can be evaluated for a variety of operating conditions. This simulation set-up is not difficult to implement and it enables rather detail study of the localized behavior of one controller.

System-wide studies: This type of study assumes that a number of the controllers shown in Figure 2 are connected to the network. It is quite feasible that a number of such controllers may exceed 1000. Obviously, studying the co-ordination of all the controllers may require enormous computational capability. To simplify the problem, one can select a much smaller number of controllers since the interaction of the particular controller is tied through some application rules where one controller may have only a few controllers acting as a back-up. In that case it may be sufficient to simulate the power system size that encompasses the locations of the main and back-up controllers, while the rest of the network and controllers are not included. If carefully selected, this configuration may be sufficient to model the system-wide impact of a given controller and the back-up controllers. One of the main principles of the back-up relaying is that the other relays acting as the back-up will typically operate with a time delay. This application feature enables one to use a detailed model of the localized controller and the transmission line directly served by this controller, while the back-up controllers and related transmission lines may be represented using simplified models.

Cascading events: The most difficult and at the same time the most realistic application case is to have several controllers acting in a sequence producing a cause-effect type cascading event. This situation may not be as frequent in the every day operation of the power system, but once occurring, it can have devastating affects. This type of the event has happened in the Western U.S. power network recently where several protective relays operated in a sequence causing the network to be partitioned and eventually being forced to be shut down. Such events called "black outs" may have tremendous negative impact since they may leave a large number of customers (millions) out of service. To prevent such events from reoccurring, it is essential to be able to model and simulate this situation to better understand the behavior of the network and controllers that brought the system to a shutdown. Even though some software packages and simulation methods may be used to explain some of the events, it is still not feasible to have a detailed representation of this scenario. Of course, the requirement would be to have a dynamic allocation of the models that will allow one to repeat localized and system-wide studies for each of the cascading events while also being able to "move" the representation dynamically as the fault events unfold around the network.

4. DIGITAL REAL-TIME SIMULATORS

Digital simulator is defined as a set of hardware and software tools allowing one to carry out the test and evaluation studies using a mixture of software representations of the power system and hardware representations of physical controllers interacting during the study. This obviously requires that appropriate interfaces between the computer running the software and controllers acting on the system are made available. A functional diagram of a typical real-time digital simulator configuration is shown in Figure 3.



D/A – Digital to Analog Interface PR – Protective Relay
I/O – Input/Output Interface

Figure 3. Typical real-time digital simulator configuration

Implementation Issues

When trying to satisfy the requirements for advanced studies, the designers of the simulators are faced with several important implementation issues:

- Ability to represent large scale systems
- Possibility of finding an optimal simulation time-step
- Availability of variety of implementation configurations
- Flexibility in allowing operators to interact with the object of simulation

Large scale system representation: In real-time simulations related to power systems, large matrices representing system states need to be changed based on the input from the controllers. Since the input to the controllers is based on the measurements from the system, and controllers are used in its physical representation, an interface between the controllers and the computer running the simulation is a critical implementation issue. The time it takes to calculate the signals in the computer using system simulations, output the signals to the controllers through the interface, make a control decision by the controller, and return the control action through the interface to the computer running the system simulation may have to be as short as one time step of the simulation. Hence, modeling large scale systems having complex topology requiring large matrices to represent system states, and representing a large number of physical controllers being simultaneously connected to the simulation computer requires quite often multiprocessor architectures with real-time operating systems. It appears that in the past this was only possible by developing a custom-designed real-time digital simulator [4], while more recently the general computer architectures have been used [6].

Finding optimal simulation time-step: Selection of the simulation time-step for real-time simulations is a critical issue for the digital power system simulator implementation [17]. The reason is the multiple effects that the time step selection has on the simulation outcome. The first consideration is associated with the real-time interaction between the controller and the simulator that may have to be completed in the time step. Obviously, the physical interface between the controller and the computer has its inherent delays, and designing the interface to match rather small simulation time-steps may be indeed challenging. The next consideration in the power systems is the physical property of the power system where the signal travel time along the transmission lines has to be matched with the selection of the time-step to allow for numerical de-coupling of the equations representing the topology. The travel times requiring the time-step of 50 micro seconds are rather common [4]. The next consideration is the numerical stability of the approximation techniques used to solve the differential equations and some other model representations. It is well known that selection of an inappropriate time step may produce numerical oscillations and instability of simulations as well as model errors and misinterpretations.

Variety of implementation configurations: The power system studies may be performed at various levels of details. The simulators need to be available in a variety of configurations to accommodate different levels of complexity. The main reason is the cost of the simulators today. A rather powerful real-time simulator may easily cost today over $1M, while a somewhat relaxed version can be as low as $10K. Having the price difference of two orders of magnitude between the two options is not a trivial fact since the utility business is very sensitive to the R&D investments today. One interesting observation should be made regarding the cost of the interfaces and appropriate signal amplifiers that may be needed when connecting certain types of physical controllers. In some very common studies using real-time simulators and protective relays as controllers, the cost of power amplifiers used to amplify analog signals coming out of the simulations and going into the relays can be indeed excessive. It can even offset the cost of the computer hardware and software needed to implement the simulator.

Operator's interaction with the object of simulation: As with the simulation environment, the operator interface is extremely important when using real-time digital simulators as well. The problem of interfacing operators in this case is somewhat different due to the real-time nature of the simulation. The interaction between the system and controllers may be taking place in the millisecond range, and hence the human interaction can not be considered in such fast events. However, the operator interaction is still rather important when setting up the simulations. The complexity of selecting the model types and system size, finding an optimal simulation time-step, determining an appropriate connection points for the physical controllers, and finding the best options for presenting the simulation results are the issues that do require careful design approach and corresponding implementation features.

Application Issues

For comparison reasons, the same issues are discussed here for the simulators as they were discussed earlier for the simulation environments:

- Localized studies
- System-wide studies
- Studies related to cascading events

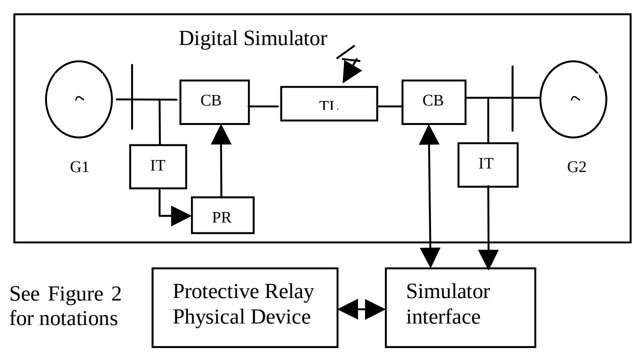


Figure 4. Connection of physical relays to the simulator

Localized studies: Again, the study of the protective relaying interaction with the power system switching elements is taken as an example. The connections using real-time digital simulators are shown in Figure 4. It can be noted that the relaying studies can be divided into two types of studies: one that investigate fast reaction of physical controllers, and one that investigates time-delayed actions of other controllers represented through models. The interactive part is sufficient to demonstrate the outcome of the reaction of the physical controllers. This identifies the time delay allowing one to study the rest of the controller reactions using models.

System-wide studies: When the studies require large scale representation including complex power system topology and numerous controllers, several iterative simulation runs can be made to reflect this situation rather accurately. This may be called an "embedded" approach. The approach can be best described as employing two levels of simulations. One level is reflecting the fast events where the real time interaction with a few physical controllers is carried out in the system location where the controllers are going to act first due to an event initiated locally (such as faults). This simulation study can be used to obtain the timing needed to better understand the behavior of actual controllers. The second step is related to the use of the results from the previous step to improve simplified models of the controllers. This allows for substituting the physical controllers with the improved models to run a system-wide study using the simulation environment only. This can be easily done since there is no restriction on dealing with "outside" controllers in real time. The term "embedded" is used to reflect the fact that the physical tests with small time steps are used to come up with system simulations that may have somewhat relaxed time-step requirement once the final outcome of the interaction is known "ahead" of time.

Cascading events: Simulating cascading events represents an ultimate complexity in the power system modeling and simulation today. The above approach proposed for system-wide studies can be extended to accommodate the cascading events. The localized studies using physical controllers can be performed in parallel with the simulations affecting the stability constraints. In other words, as the random event of a fault is introduced, the controllers are connected to the simulator to reflect the behavior of the first controller action accurately. At the same time, the stability study is initialized based on the switching outcome. Knowing which set of controllers may be acting next, the simulator connection can be automatically switched to run detailed study for the next set of controllers. Again the switching actions may be used to re-initialize the stability study. In this way, the dynamic behavior of the unfolding controller actions can always be represented accurately both at the localized and at the system level.

5. EXAMPLES OF COMPLEX R&D STUDIES

To illustrate some of the advanced modeling approaches and simulation tools required when performing R&D studies related to protective relaying, the following examples are discussed:

- State-of-the- art testing and evaluation of local protective relaying operation
- Future needs for a system-wide study of cascading protective relaying operation

State-of-the-art local analysis

Such an approach would require the use of both the simulation environment and digital simulators. The simulation environment based on general purpose signal processing package MATLAB is recently developed by Texas A&M University as a part of the MERIT 2000 software for protective relaying studies [18]. An elaborate set of models representing protective relaying modules and devics is implemented as a customized library allowing users to construct almost any relay or relaying scheme they wish to study. In the same programming environment, an electromagnetic transient program called Power System Block-Set is implemented by a third party and offered as a toolbox by the original vendor of MATLAB. The high level interface of MATLAB called SIMULINK is utilized to provide the required user interface. Through this interface the user can set-up the parameters and select models for power system simulation, construct the relaying controllers and select their connections to the power system, and run the simulation studies. A number of signal measurement, waveform display and data storage tools are available under the same user interface to facilitate the visualization of the study results. Besides the mentioned simulation environment, another software package called Relay Assistant and corresponding hardware interfaces are developed by Test Laboratories International, Inc. for the studies using digital simulators [19]. This set-up allows users to utilize either recorded or simulated waveforms when testing and evaluating physical relays. The relays are connected to the simulator using specialized interfaces that enable the use of various types of power amplifiers for amplifying the test signals before reaching the relays. Customized high precision I/O interface is developed for providing interfacing between the computer and amplifiers for outputting the waveforms as well as between the relay and the computer for collecting relay control actions.

The two sets of tools can be used together today providing a unique capability to test physical relays and collect the information to set up more elaborate studies in the simulation environment. The joint use of the tolls is shown in Figure 5.

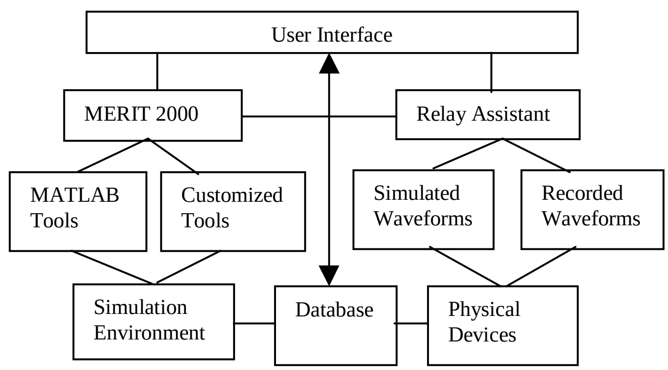


Figure 5. State-of-the-art tools for study of the local protective relaying operation

Future system-wide analysis

As mentioned earlier, the "embedded" simulation environment will have to be implemented to meet the needs for advanced studies related to system-wide analysis of protective relays. A conceptual software configuration is given in Figure 6. The hardware set-up needed to interface the physical devices to the simulation environment is not shown in Figure 6 for simplification reasons. The study types that are represented by the functional blocks on the left hand side of Figure 6 are not meant to be separate packages but one modeling and simulation environment capable of producing different types of outputs for different power system operating states that are being simulated. For example, during the normal state, the power flow type of outputs will be available in the form of phasors that can be "unfolded" into sinusoidal waveforms for testing physical devices or relay models. As the fault events occur, the electromagnetic transient type of simulation will be carried out producing corresponding outputs. After certain period of time as the fault transients die out, the short circuit type of computation will be performed and unsymmetrical phasors of steady state fault waveforms will be produced. Finally, simulation of the follow–up events will be carried out reflecting the slowly evolving stability disturbances. In terms of dynamic interactions between the power system and controllers, the parameters and appropriate models of both the controllers and power system components will be dynamically selected and allocated to fit the right time-window associated with particular power system state. In particular, the local events will be evaluated using physical controller interfaces while the remaining controller actions will be represented through interactions in the simulation environment. The allocation of the physical controllers to the certain transmission lines will dynamically be allocated depending on the evolving situation in the network. In doing so, the cascading events will be "fatefully" represented using dynamic modeling and simulation tools shown in Figure 6. Last, but not least, the simulation set-up will need to support the interaction with operators that should be able to control the simulation scenarios and initial selection of the simulation parameters.

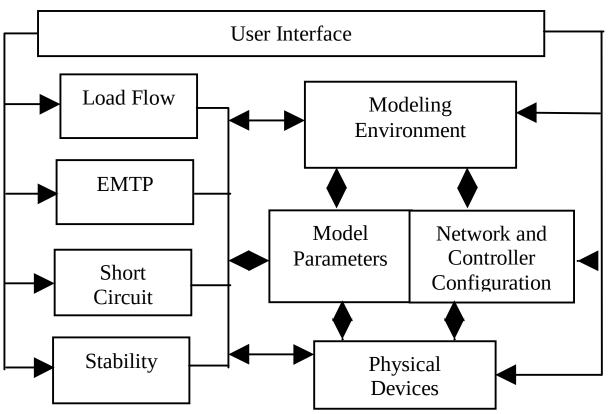


Figure 6. Future set-up for the use of dynamic tools for modeling and simulation of cascading protective relay operations

6. CONLUSIONS

Based on the discussion given in the paper, the following conclusions related to the advanced modeling and simulation tools for power engineering research and development can be stated:

- The state-of-the-art tools allow for very elaborate study of the local actions of controllers and related interaction with the power system
- The tools provide for the use of both the simulation environment and real-time digital simulators in carrying out the studies
- The joint use of simulation environments and digital simulators seem to be a promising approach when studying complex behavior of cascading events
- Future use of dynamic simulation tools that can accurately represent different power system states is yet at a conceptual level and further developments are needed to make this option a reality

7. ACKNOWLEDGEMENTS

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