An Embedded Communication Network Simulator for Power Systems Simulations in PSCAD

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***Abstract*—The emergence of distributed communication based control schemes in power systems emphasizes the need for a realistic power systems simulation tool that allows inclusion of communication components. Communication performance parameters like delay and loss in transfer of measurements and commands can affect the result of control and should be taken into account while studying a control mechanism over power system dynamics. In this paper we present the method and tools that we have developed to allow simulation of communication networks inside off-the-shelf product for power system transient simulation, PSCAD. In particular we present the structural designs and interfaces of modules that are needed for implementing an embedded communication network simulator in PSCAD, and provide a brief guide on how power system engineers could use these modules in their designs. In addition, we present an example of a control scheme using communication for stabilizing a power system that incorporates integration of a renewable energy source and energy storage. We use the IEEE 13-node test feeder as our case study. A wind generator and battery are connected to the system to add more dynamic behavior; a control for the system has been designed which works with communication interface and modules implemented in PSCAD. The test system is used to validate and verify the embedded communication simulator and its implementation.**

I. INTRODUCTION

Application of two-way communication technologies in power systems has recently increased. Power systems are evolving in terms of active distributed control enabled by smart grid technologies. Shifts in fuel prices, policy, and technologies are changing the character of the electric power system to include more distributed generation, more generation from variable renewables and natural gas, more energy storage, and greater participation of consumer assets in operation of the grid. This has brought up many research challenges to the design, control, and protection of new power systems; consequently Smart Grid, Smart Energy Management Systems (SEMS) and Multi-Agent Systems (MAS) have emerged. These new fields need a new architecture for the control of the power system dynamics, rather than old hierarchical control structure.

Smart generation and consumption between energy suppliers and consumers, as well as distributed control schemes; bring up the necessity of communication between elements in the system. Therefore, communication technologies and their impact on power systems (e.g. in a smart grid) need to be studied closely [1] whenever smart grid ideas are being considered for electric power system reform [2]. Smart energy management systems also need smart communication networks to achieve their goals [3]. In all MAS architectures, a communication interface is necessary to implement the control strategy which can be utilized in power system for emergency control of power system [4], protection of the system [5], voltage regulation [6] and restoration of power [7]. All these modern power systems rely on control algorithms operating over communication networks. The network effects, such as delay and loss of data will be added to the probable failure of control systems itself. Therefore, a great deal of effort has been dedicated to coupling the design of power system and communication networks to allow for the study of the whole system as one integrated entity [9][10][11][12].

There are already many different tools for simulation of both power systems and communication networks, like EMTDC/PSCAD, MATLAB, SIMULINK, OPNET, and NS2. However most of the power system dynamics is modeled as a continuous time simulation while network simulations mostly use discrete-event systems based on their nature. Several recent efforts in coupling the models of power systems and communication networks have been reported in literature [9][10][11][12]. In [9] authors present a method to imitate the impact of network by simulating the desired network in OPNET (which is a network simulator) and then feeding the OPNET simulation trace (delay profile for example) into the controls used in their power system model. In another work [10] authors try to model vulnerabilities and couple the power grid with control and communication systems failures simply by formulating an optimization problem for the control with new constraints, to capture those vulnerabilities. This is done without dealing with integrating simulations. Hybrid simulation of the power system and communication is the other approach found in the literature.

For example in [11] the method is to introduce Discrete Event System Specification (DEVS), which integrates existing simulating tools into a joined simulation structure. In [12] a power/network co-simulation framework has been proposed which integrates power system dynamics simulator and network simulator using an accurate synchronization mechanism. They discussed methods like EPOCHS which use federation and ADEVS [11] that requires its own modeling of the dynamics of power system by converting it to discrete events by different state event detection mechanisms.

The work presented in this paper complements the existing methods and takes a different approach by providing an embedded simulation environment inside the widespread commercially available tool PSCAD. PSCAD is a framework currently used in study of dynamic behavior of power system components and transient phenomena. It can be used widely in assessment of renewable energies integration as well as evaluation of control strategies in power system. In this work we introduce an easy to use method for putting the power system and communication network dynamics together using power system simulator EMTDC/PSCAD. The objective is to provide communication simulation capabilities right where transient analysis for power systems are done, i.e., in tools such as PSCAD. PSCAD simulates the power system as a continuous system for transient analysis, while it is operating on time step basis. Therefore, the contribution of this work is to use the configurable time step in PSCAD and embed the communication network simulation inside the PSCAD. Therefore, for studying communication vulnerabilities on power systems there is no need to go outside the PSCAD, a sample use of these modules can be observed in Figure 1. The effects of communication will be applied on the system by using components and modules introduced in this paper to set up a network topology inside PSCAD and make communication between different modules possible. A set of easy to use components and modules have been developed which are easy to configure and have desirable network properties within the power system and more importantly inside PSCAD with no considerable overhead for federation of other discussed methods introduced so far.

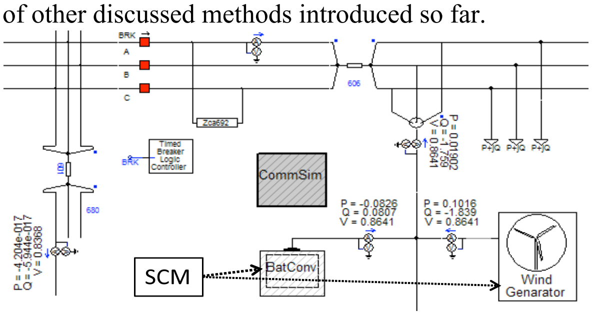

Figure 1 CommSim module and SCMs within PSCAD IEEE 13node test feeder

I. Design of an Embedded Communication Network Simulator in PSCAD

Every network simulators has a set of different stochastic and deterministic building blocks to be able to simulate the behavior of the network as close to reality as possible. This event based simulations results in a queue of events and their timestamp. The list of events should be executed in accordance with continuous time domain simulation of the power system simulator. This coupling is challenging and many methods have been proposed in literature [8][10][11][12]. Some of them suggest using federation like in [8] which will have a considerable overhead as well as being error prone because of synchronization time lags explained in [12]. The co-simulation framework proposed in [12] is stated to remove those errors by doing the simulation globally in a discrete event-driven manner. By using this method the simulations will be implicitly synchronized without need of defining explicit synchronization points. In this study we are using the existing time steps in PSCAD transient power simulator, which is a popular power system simulator, and couple the discrete event-based simulation of communication network at these time steps. So the high level idea of this work is to couple the communication simulator with power system simulation by implementing the network simulator within PSCAD and trying to imitate discrete event-based behaviors by using available capabilities inside PSCAD rather than going outside.

What is important in studying communication in accordance with power systems simulations is the impact of communication on the whole system from control and stability standpoint. These effects are mostly caused by network effects such as delay and loss. It is important to note that all the complexity involved in complete network simulators will end up in list of events obtained from the simulator with their timestamp. These events are at high level packets sent, the time taken for each packet to be received (delay) and whether it is received at receiver or not (loss). Therefore, one main focus of this study is on simulating these network effects (seen in the form of delay and loss pattern profiles) within the PSCAD. In addition to these two elements, delay and loss, which are defined at lower levels of communication, each communication network at application layer features a communication protocol (how to establish communication) and communication strategy (when and where to communicate) defined for the entities to be able to communicate. The communication is established through protocols, and nodes act according to the accepted strategy to communicate. All these elements have been considered in the architecture introduced for this study; allowing almost any protocol and strategy to be implemented on top of the framework provided here. The other important problem is designing a point of integration between power system simulation and communication simulation. This is considered as communication interface within PSCAD which will be introduced and explained in the next section.

II. Power System Communication Interface Design

The communication interface in PSCAD can be separated into Application layer communication interface and lower level communication. The application layer interface is implemented in Sensor Control Modules (SCMs) while the lower level communication simulation has been implemented in Comm-Sim Component. These modules schematic can be viewed in Figure 2.

SCMs are the points of communication which will need communication to mainly control the stability of the system. These SCMs will be chosen based on power system design. SCMs are basically regular modules within PSCAD which have Comm-Modules inside them as communication points.

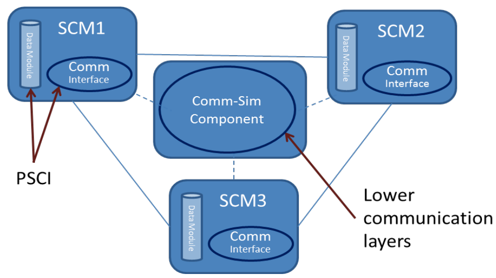

Figure 2 Communication interface design within PSCAD. The whole system schematic

SCMs are the communicating nodes within the PSCAD which need to send and receive different control parameters or other information to/from other SCMs. The nature of communication is discrete and event based, but in PSCAD we are dealing with a continuous time simulation process and consequently continuous signals. Therefore, the SCMs need to bring that continuous domain into discrete domain by use of sampling and then asynchronous packetization. In complex networks of this type, where a physical phenomenon has to be controlled, sampling is the method to make the continuous signal discrete. This signal could be trajectory of a car moving on the road or frequency in a power system. This sampling mechanism is one of the most important features of the Comm-Modules within SCMs.

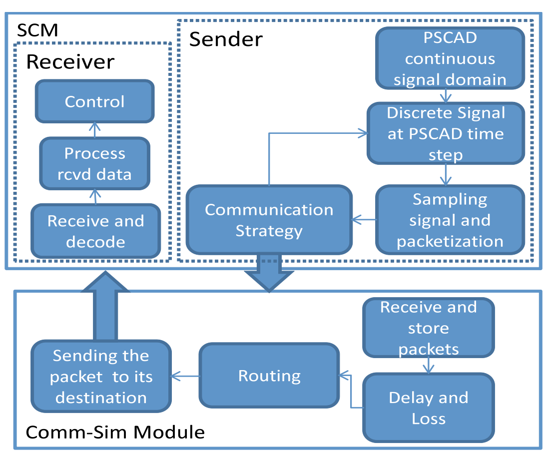

Figure 3 Communication network architecture coupled with PSCAD continuous time domain

In real communication networks connected nodes send out their packets based on a communication strategy; they look at the values at a single point in time (sampled value) and perform some processing (for control purposes) and send out the packet if it is necessary. The same design has been considered in this work. The packet containing the sampled and processed data will be sent through Comm-Sim module to its destination. In Comm-Sim module, packets are stored and will be sent to the indicated receiver based on configurable delay and loss. The packet is received at its destination in a discrete fashion and will be decoded based on DNP-3 protocol data formats; the control parameters will be taken out of the packet, processed according to the control being applied and then control actions will be performed in the destination SCM. The overall design of the communication interface can be seen in Figure 3. Each of the modules therein will be explained in more details in later sections.

A. Sensor Control Modules (SCM)

As described previously, these modules will be placed within the whole system and wherever communication is needed. The SCMs are the simulation of the application layer communication of the whole communication interface. Application layer interface consist of communication protocol and strategy. The communication protocol implemented in this study is DNP-3.The other element is communication strategy which can be applied by user and based on type of control. The SCMs are combination of a module within PSCAD, which has been chosen for communication, and a Comm-Module which is the point of communication for that SCM, this module can be interpreted as communication device installed on any element in the power system, such as storage or wind generator. SCMs are needed to be placed at both sender and receiver; the main functionality of these modules can be named as discretization, packetization, processing and making the decision to send out the packet or not based on communication strategy. At receiver side, they receive the packet decode it and wrap all the control variables based on DNP3 protocol and put them in a Fortran structure and do the control at receiver using these received data.

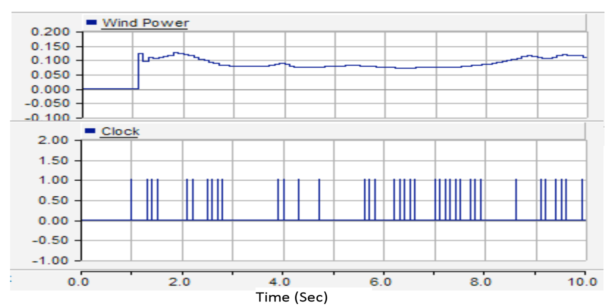

Figure 4 **An example of sampled signal along with its clock signal.**

The sender can configure a sampling rate for the Comm-Module to sample the control variables, process and possibly reduce them to fewer numbers of control values and then put them into the packet for being sent over the communication network. These packets will then be sent based on communication strategy. In PSCAD we are working with continuous time signals as communication links. These signals are being sent using radio link components in PSCAD which have only the capability of sending continuous signals rather than discrete ones. Therefore, to determine the event of sending a packet we are using a clock which will be sent along with packets to the Comm-Sim module and the receiver consequently. This clock has an important role in packetizing process and will help simulate discrete events of communication coupled with this continuous time domain simulator. This can be observed for a sample case in Figure 4.

B. Communication Simulator Module

The Lower level of communication network has been designed as a separate module within PSCAD named Comm-Sim Module Figure 5. This module is designed to simulate lower layers of communication network while allowing the use of typical topologies in a communication network.

There are two components within this module named Comm-Router and Comm-Link. Comm-Link component acts like a simple communication link and simulate a Point to Point (P2P) connection between 2 different SCMs.

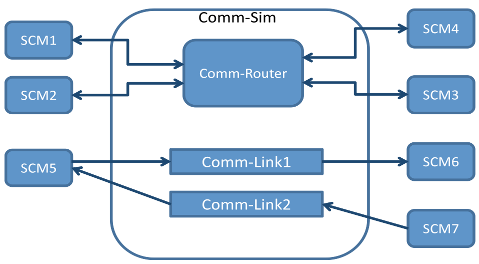

Figure 5 Comm-Sim module components and how they can be used to have different network topologies

This component simulates the network by applying delay and loss on the packets sent through this component. The delay value can be configured to be a fixed value, or it can be set to be a random value in a specified range, or it can be read from a delay profile; this profile can be simply a text file containing delay values obtained from a network simulator like NS3 or OPNET. The loss is applied by sending out a single packet to its destination or not. Loss is considered as one of the vulnerabilities of the communication network which should be considered in its simulation within PSCAD. The loss can be configured as random or it can be based on a profile, driven from a network simulator as well.

Comm-Router component is used for having more complex topologies than a simple P2P connection. Using this component user can set up links between different SCMs and allow sending from any of them to any other SCM while this component allows broadcasting too, so any of the SCMs can send a packet to all other SCMs connected to the Comm-Router.

III. CASE STUDY: IEEE 13 NODE TEST FEEDER

The IEEE 13 node feeder is used as a test platform to study the effects of communication in power systems [13]. The test feeder is simulated in PSCAD. The test system also consists of a 0.66MW MOD 2 type wind turbine connected to an induction generator at feeder 675. A storage component with a bidirectional converter is also connected to feeder 675 [14][15]. The storage component capacity is designed to completely absorb the power generated by the wind generator.

The storage component stores the real power generated by the wind turbine and provides power when real power produced by the wind decreases. The converter is designed in such way as to control the direction of power flow either into the storage component or out of it. The converter control compares the wind power and the power from the storage and generates a reference current signal which determines the direction of power flow across the converter.

Initially the wind speed is kept constant at 6m/s and then stepped up to 20m/s. After 2 sec the wind speed is stepped down to 10 m/s. These values are chosen only to see the effect of communication in two different cases, when there is a step up in wind speed from low value to a high value and the step down in wind speed from high value to an average value. The turbine torque and the real power generated by the wind generator vary according to the wind speed. The wind power goes from -4 pu to 0.65 pu and then to -0.5 pu. In the case of ideal communication, a radio link is used to communicate the real power generated by the wind generator module to the storage converter module. Initially the wind component acts as a load due to the low wind speed. The storage component provides the necessary power to keep the system stable at a frequency of 60 Hz. When the wind steps up, the wind power increases to 0.65 pu and this power is stored in the storage component. During this time the frequency at the point of grid integration deviates from 60 Hz and comes back in about 0.5 seconds as shown in Figure 6. Similar results can be seen when the wind speed changes from 20m/s to 10m/s.

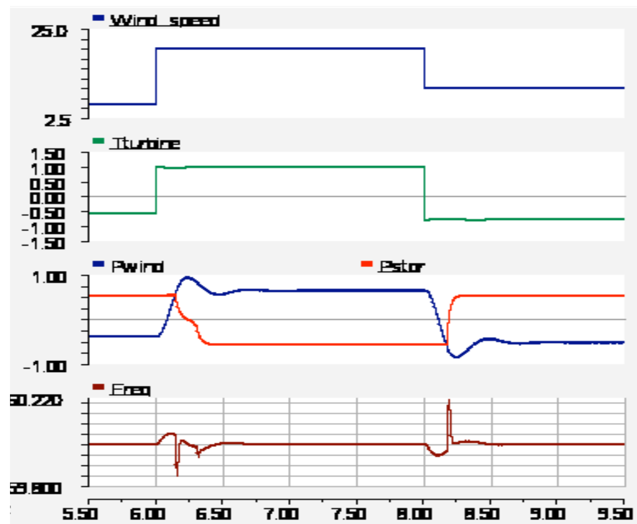

Figure 6 Wind Speed, Turbine Torque, Wind Power, Storage Power and Frequency for ideal communication

The ideal communication link is replaced with a Comm-Sim module which communicates the real power generated by the wind generator to the converter control circuit in the storage component at different delays and packet loss. The sampling rate of the Comm-Module is given as 10 samples per second and the loss is considered as random loss. Here wind generator and storage modules are the two SCMs.

At delay equal to 0.1and 0.5, the control signal at the storage SCM is delayed due to the delay in communication and hence the instant at which the power flow direction changes is delayed. The effect of this delay can be seen in the storage power signal represented as Pstor in Figure 5, Figure 6 and Figure 7. The frequency also deviates from the steady state value for about 0.6 seconds for 0.1 delay and approximately 0.9 seconds for delay equal to 0.5 as shown in

Figure 6 and Figure 7. The real power values of the wind generator communicated to the storage converter control through the Comm-Sim communication link is shown in Figure 8.

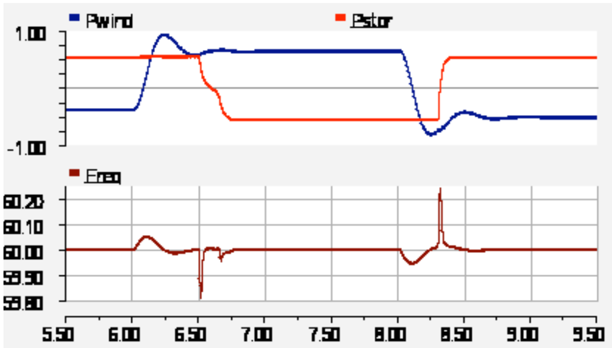

Figure 7 Wind and Storage Power, Frequency for 0.1 delay

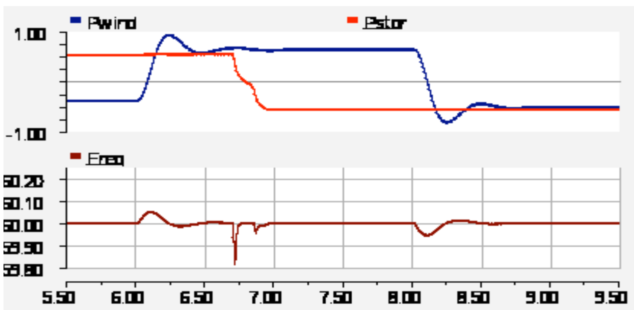

Figure 8 Wind and Storage Power, Frequency for 0.5 delay

Here we are showing one instance of change and control action. For a dynamic situation where a controller should follow the change in wind generation, the larger delay will mean more prolonged frequency instability. We report a study of these cases in our upcoming publication Figure 9.

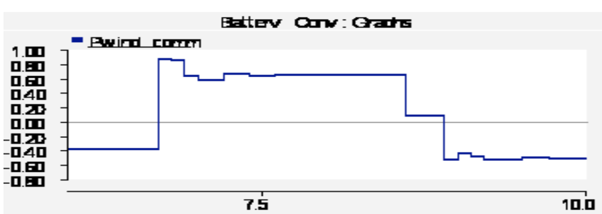

Figure 9 Wind Power Communicated to Storage component

IV. CONCLUSION

In this paper, we have presented the design and implementation of a communication network simulator embedded in PSCAD for power system simulations. The presented simulation environment allows for simulation of emerging distributed control and monitoring schemes in advanced smart power systems. The main contribution of this work is in coupling the dynamics of power systems and communication networks, given that they are considerably different (continuous vs. discrete event-based dynamics). The coupling was made possible using a synchronization mechanism embedded in PSCAD (as opposed to other methods that use synchronization with outside tools). We have implemented a communication interface to enable power system designers to integrate their system with communication links and routers to have a more thorough perspective over the entire system as one coupled system. This work makes the communication network simulation possible in PSCAD by presenting its concepts and components in terms familiar to PSCAD users, in order to keep simulations as easy as possible for them. The design and development of PSCAD-based automated control and protection system that incorporates power flow and communications is planned. The developed embedded communication network simulator in PSCAD can be used to show the effect of communication and therefore the evaluation of an automated control and protection system in specific configurations and operational conditions.

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