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An Incremental System-of-Systems Integration Modelling of Cyber-Physical Electric Power Systems

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SUMMARY

Simulation of Cyber-Physical Systems (CPS) can be quite complex due to heterogeneity of their components and their interactions, which include physical phenomena, levels of abstraction used in modelling the physical and computational structures and processes, and engineering approaches to CPS design and analysis. The concept of system-of-systems (SoS) to designate complex integrated CPS infrastructure engineered as the interacting network of physical and computational processes in electrical networks is proposed. Due to the heterogeneity, the SoS simulations are architected as distributed co-simulation of multiple models. One of the standardized distributed co-simulation platforms is the High Level Architecture (HLA) that runs as a Federation of interacting simulators where the term Federate (FED) is used for designating each system that is a component of an SoS. The lack of a methodology for model characterization and integration into an accurate co-simulation framework of such a complex SoS limits the capability to analyse and design critical CPS infrastructures in electric power systems.

To address the challenges of how to design, evaluate and verify models of such complex SoS infrastructures, we propose an incremental SoS Integration modelling framework that will allow representation of complex SoS dynamic behaviour by incrementally characterizing dynamic properties of the components, and then building the SoS models by integrating the component models and their interdependencies. This framework entails extensive use of large-scale Hardware in the Loop (HIL) and System in the Loop (SIL) testbeds and its functionality is demonstrated in synchrophasor-based wide area monitoring, protection, and control of electric power systems.

KEYWORDS

Synchrophasors; Cyber-Physical Systems (CPS); Design and Implementation; Hardware in the Loop (HIL); Heterogeneity; Integrated Modelling; System in the Loop (SIL); System of Systems (SoS).

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A typical example discussed in this paper is a suite of controller applications for real-time operation of power systems that require careful coordination between monitoring, control and protection solutions to accommodate various physical system states such as normal, alert, emergency and restorative. The cyber FEDs designate systems for monitoring, control and protection, and the physical system FEDs designate different power system models representing the aforementioned operating states. A rigorous methodology for characterizing and combining such FEDs into a distributed co-simulation platform to reflect real-time computing, communication, object dynamics and control interactions of SoS components is missing. Moreover, many of the essential SoS component interactions emerge from their implementations details: timing properties of monitoring and control applications, digital communication channels, input/output channels, fault management processes and security controls. Communication links, middleware, schedulers, and computing times insert time-varying delays in control loops, and many faults and cyber-vulnerabilities are created by physical components and computing/communication platforms used in the cyber side.

The rest of the paper is structured as follows. Section 2 introduces the heterogeneous CPS elements of the smart electricity grids. Section 3 presents the characterization of the complex system components. Section 4 discusses model decomposition and incremental integration of the models through HIL and SIL experiments. Application of the proposed framework in power system protection and control is described in Section 5 followed by the conclusions in Section 6.

1. WAMPAC CYBER-PHYSICAL SYSTEMS (CPS) IN SMART GRIDS

The electricity grid is composed of a wide range of components. Heterogeneity is pervasive throughout physical components (e.g. transmission lines, power generation equipment), computational components, human elements, etc. Heterogeneity of the required models even increases considering simulations spanning a wide range of design domains, from network planning and formulating operating strategies, to operations planning and operations management of the transmission system, dispatching the generators, designing control strategies, etc. The components of such cyber physical systems (CPS) interact through communication networks and represent different simulation domains that are modelled by means of domain-specific modelling languages with unique semantics and simulation tools.

One of the complex and yet critical applications in smart electricity grids is Wide-Area Monitoring, Control and Protection (WAMPAC) [1]. It entails multiple FEDs representing local and system-wide control components used to detect the electricity grid operating states and perform control actions needed to mitigate various grid disturbances. It can use synchrophasor technology to offer robust performance of the grid but being still prone to many well-known application issues originating from poor data quality, hard-to-characterize application performance, and depending on tightly controlled timing issues. Hence, design of the co-simulation tools that is applicable to any time-sensitive control system and can be used to characterize SoS models in WAMPAC applications is of urgent necessity.

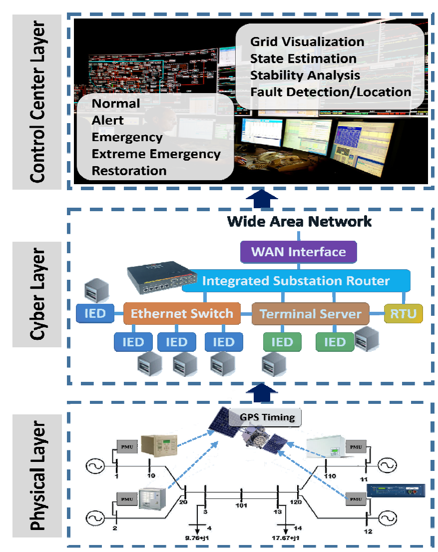


Figure 1. Layered SoS for Grid Monitoring, Control, and Protection

The current state of the art in designing and upgrading critical infrastructures is severely restrictive since it does not allow designers to fully represent and understand the interdependencies between the control systems and physical systems: a) The electricity grids are still prone to major failures (blackouts), and b) The control concepts are still hard to verify since they are designed to track only given states of the grid at a time, and there is no integrated model capable of tracking and controlling the grid dynamic behaviour [2].

The layers of the SoS components of the smart electricity grid comprising the physical (power), cyber (information technology), and control (algorithms) layers, is shown in Fig. 1. To comprehensively represent the SoS behaviour, each layer in Fig. 1 needs to be integrated in a common co-simulation platform, and models need to represent the dynamics of all the operating states in one

SoS framework. The proposed co-simulation architecture in this paper aims at overcoming this challenge by using fundamental understanding of the physical and cyber systems as well as the dynamics and control to define boundaries of the relevant SoS components so that the critical modelling properties can be fully characterized.

2. CPS CHARACTERIZATION IN SMART GRID

Complex SoS consisting of physical and cyber systems are difficult to characterize since they integrate properties of their various parts that are multi-rate, multi-scale, multi-data, multi-user, and multi-model from different domains. Architecture of a novel decomposition approach that will identify boundaries of various SoS components and then pursue characterization of the component properties through a HIL and SIL experimentation is suggested in this paper. From a simulation point of view, the major barrier is finding a flexible solution for HIL and SIL simulation integration. While the HLA-based simulation integration platform [3] enables the interfacing of HIL and SIL simulations, synchronization of the logical-time based simulators with real-time processes is hard and demanding. Reviewing the former studies in this domain results the following conclusions and insights:

- HIL testing of various distance protective relays revealed that the response time in Zone I (direct control) for various commercial products is in the range 15-70 milliseconds, which affects the control performance profoundly when represented correctly.
- To gain insights into dynamic interactions between the grid and protective relay, power system representation of this complex CPS had to be modeled using a time domain co-simulation, which required model calibration to use field recording during faults to assure the verification.

3. INCREMENTAL SoS INTEGRATION OF SYSTEM MODELS (ISoSIM)

Once the properties of system components are identified, modeled and validated through HIL and SIL experiments, and the FEDs are created, they are utilized through an incremental model integration approach by using various modeling tools of a versatile model-based simulation integration platform, CPSWT [4]. CPSWT is a novel, distributed, heterogeneous open source simulation integration platform that is constructed over the High Level Architecture (HLA). HLA is an IEEE standard for distributed simulation in which individual simulations (called FED) join together to form a cooperative federation [5]. All FEDs in a federation interact using a runtime infrastructure (RTI) which provides a set of services such as publish-subscribe messaging, time management and simulation control. Data exchanges between the FEDs must adhere to a distributed federation object model (FOM). From time management point of view, the FEDs can be time regulating or time constrained (or both of neither). Time regulating FEDs influence the progression of logical time in the federation, while time constrained FEDs only adhere to the federation time.

HLA is a general purpose architecture for constructing distributed simulation systems that is independent from the underlying distributed computing platform. CPSWT is a model-based integration layer over HLA. CPSWT tools provide for rapidly composing integrated simulations using a variety of simulators that span many CPS domains. The key features of the model-based integration technology are [4]: (1) the introduction of a Model Integration Language (MIL) that captures system-level data models and interaction models connecting heterogeneous domain-specific component models (i.e, FEDs) into the integrated model of a SoS, and (2) the auto-generation of the required glue code for the integrated distributed simulation. CPSWT uses a Simulation as a Service (SaaS) model, including a web-based front-end for all user interactions and a MIL for specifying SoS integration models and experiment scenarios.

Independently from the advanced model and simulation integration architecture, creating SoS simulations that include processes with large dynamic range remains a significant challenge. Power system monitoring and control with synchrophasor systems for WAMPAC are good examples for CPS whose design can be significantly impaired by poor design decisions about timing interactions. There are two fundamentally different approaches in dealing with very broad time-scales in simulations, temporal decomposition and HIL simulation.

Co-simulation of the dynamics in this wide time range is expected in CPS, but it is usually represented, in modelling schemes for example, as a single flat physical phenomenon. Such an abstraction fails to facilitate the exploration of deep dynamic properties of the system and forces different temporal notions on to the same basic description. Just as the functional properties of a system can be modelled at different levels of abstraction or detail, its temporal properties should be also representable in different, but provably consistent time-scales. *Temporal decomposition* of SoS into FEDs with different time resolution is proposed in [6]. Super dense time in modeling interactions among FEDs is also proposed in [4], [7]. Using temporal decomposition, the first step in constructing a virtual prototype for a SoS is model composition using component model libraries. The next step is decomposition–but not along physical component boundaries, but dynamics. This decomposition separates slow and fast dynamics and defines their interactions. The new opportunity enabled by distributed co-simulation is the re-composition (or aggregation) of the new components with different timing characteristics as interacting but independently running simulations on the HLA platforms.

The cyber layer in WAMPC (Figure 1) includes networking, whose high fidelity simulation is a notoriously hard, computation intensive task. To mitigate this problem, the replacement of network simulators with emulators offers an effective solution. In order to exploit the higher fidelity of communication network emulators, or using real-time control platforms integrated with plant simulators, solutions for combining real-time *HIL platforms* into distributed simulations are proposed. The goal of the HIL support is to enable some or all parts of a federation to be deployed onto embedded devices which may interact with a real system, e.g., a plant and controller. By developing support for these devices, the fidelity of simulation can be increased, the relevant Application Business Logic (ABL) which governs the sensor/actuator control and communication between the HIL devices can be tested prior to final deployment, and controllers (simulated or on HIL) can be tested with correct sensor input streams and actuator outputs in place of model or previously recorded data.

4. ISoSIM APPLICATION IN POWER SYSTEM MONITORING AND CONTROL

In order to capture the complexity of the electricity grid CPS for monitoring, control, and protection, an SoS representation, as well as decomposition and aggregation approach are pursued. One way of representing integration of CPS using multiple models of decomposed physical and cyber components is offered, as illustrated in Fig. 2, to create an aggregation framework by observing certain time-interaction rules and model interaction boundaries [8]. This results in integration of protective relay models and power system models in one co-simulation environment to represent physical (power system) and cyber (relay) components, respectively.

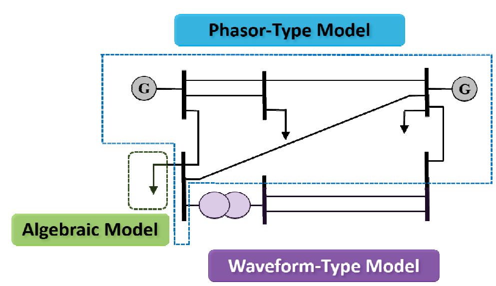


Figure 2. A new decomposition approach using three different modelling domains

To illustrate the proposed approach, the WAMS cyber system is implemented via synchrophasor technology shown in Fig. 3. It consists of: a) substations representing the physical (power) system; b) phasor measurement units (PMUs), phasor data concentrators (PDCs), GPS receivers, and communication system representing the cyber system; and c) the Apps representing control algorithms. As noted in Fig. 3, there are quite a few industry standards specifying the performance of various parts, but not sufficient to characterize the synchrophasor system performance under various operating conditions of the physical system where different control actions associated with various operating states are taken. The presented approach reveals how the HIL and SIL testbeds, combined with a fundamental understanding of the dynamics of the SoS components, can lead to a novel co-simulation and model integration platform that preserves tight timing of such control systems.

5.1. WAMPAC SoS Decomposition

In performing the decomposition, three control time-scales are taken into account: a) fast, such as protective relaying with a control loop time response of several milliseconds, b) medium, such as islanding control with a control loop time response of several seconds, and c) slow, such as market transactions with a control loop time response of several minutes and longer.

5.2. Power Grid Decomposition

Several physical (power) system decomposition issues associated with system behavior at each of the above time-scale control paradigms are focused as follows: (1) Electromagnetic transients with time scales of microsecond; (2) Electromechancial oscillations with time scales of couple of seconds. Such phenomena are resulting in various power system operating states ranging from normal operation, to voltage instability, transient instability, small signal instability, and faults. All such operating states can be correlated to the control stages: normal, alert, emergency, in extremis, and restorative. The key to understanding the SoS dynamic interactions is to first characterize the WAMPAC performance during such operating states. HIL and SIL tests help reveal and characterize such behavior.

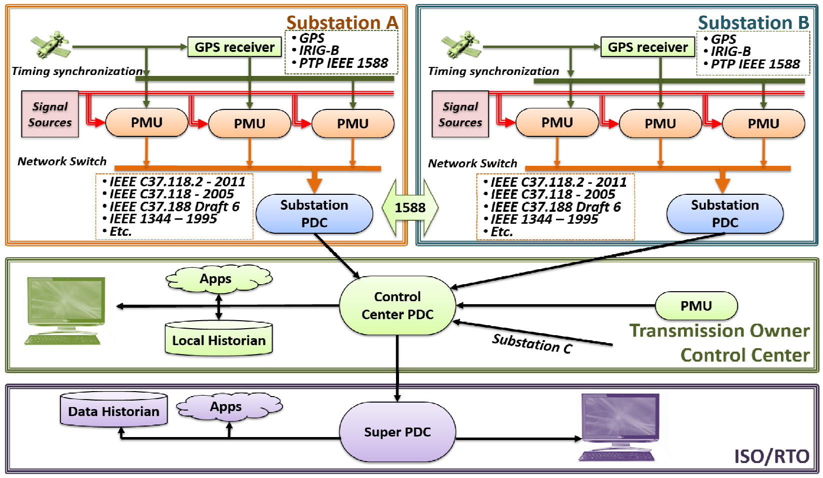


Figure 3. Overall synchrophasor architecture in the propsoed WAMS SoS

5.3. The Timing Interactions

The decomposition process focuses on three interrelated domains: physical (power system), cyber (synchrophasor system) and control (applications). The key issue is dynamics of timing requirements to reflect model interactions: inaccuracies in GPS clock synchronization, time stamping of synchrophasor measurements, communication delays, etc. For control actions in various time-scales, SoS models that accurately represent the time-scales in the co-simulation platform are developed.

5.4. Use of HIL and SIL Testing for Model Characterization

Power system simulators are capable of producing analog waveforms that resemble analog signals from power system nodes. In turn, the controller can be tested under such conditions and its control signals can be taken by the power system model and appropriate control actions can be executed on the model. For the WAMPAC system, the notion of the HIL testing and evaluation is shown in Fig. 4. As can be observed from the figure, each element of the WAMPAC system can be tested in the HIL environment using one of the three options: waveforms recorded in the actual power system, waveforms created through signal generators, and waveforms created by a powerful real-time simulator. The SIL simulator allows testing of integrated portions of the WAMPAC system, or the entire end-to-end WAMPAC system, indicated with nested testing configurations in Fig. 4.

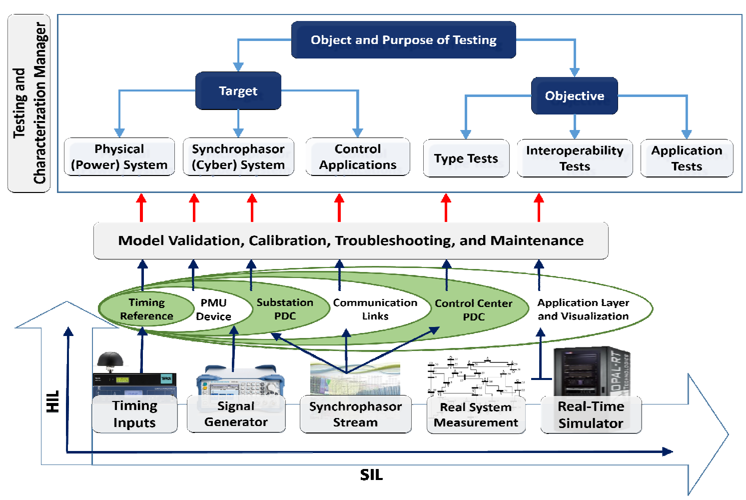


Figure 4. Testing and model characterization using synchrophasor HIL and SIL co-simulation platforms

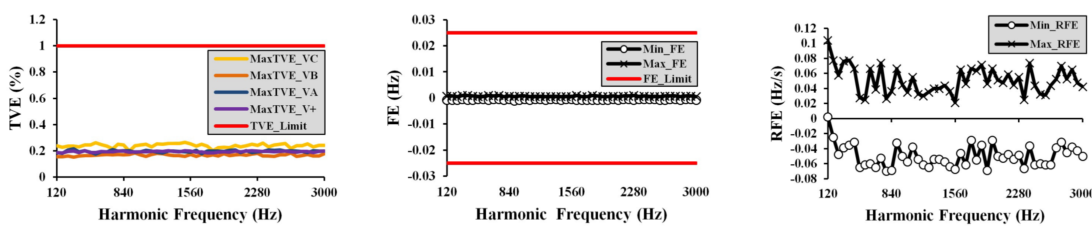
To characterize various parts of the WAMPAC system, different types of tests are conducted. The procedural test tree that will be used in this project is shown in Fig. 4. The object and purpose of the tests need to be defined for each of the SoS components that comprise CPS for WAMPAC control of the power system:

- **Test Target:** The targets may be the physical system, in which case a field recording of the power system responses to natural operating phenomena may be observed. Some can be detected and characterized by monitoring systems such as Supervisory Control and Data Acquisition (SCADA) of the Energy Management System (EMS). Faults and related switching actions can be captured by the disturbance monitoring systems such as digital relays, digital fault recorders or sequence of events recorders. Other parts of the WAMPAC SoS, such as the cyber components and control algorithms, can also be the test targets.
- **Test Objective:** The objectives need to be classified into type, application and interoperability tests. The type tests aim at verifying the performance of the hardware/software cyber solution according to the existing standards or expected performance. The application tests are aimed at characterizing the device/software behaviors under exposure to actual waveforms created during a physical system event which may not be specified by any standards and most likely is not known based on the device/software specs and manuals [10]. Example results of the type-tests conducted on the phasor measurement units (PMU) to characterize their performance under several static and dynamic scenarios are shown in Fig. 5 [9], [10]. The interoperability test assures that models created based on type and application tests are interoperable.

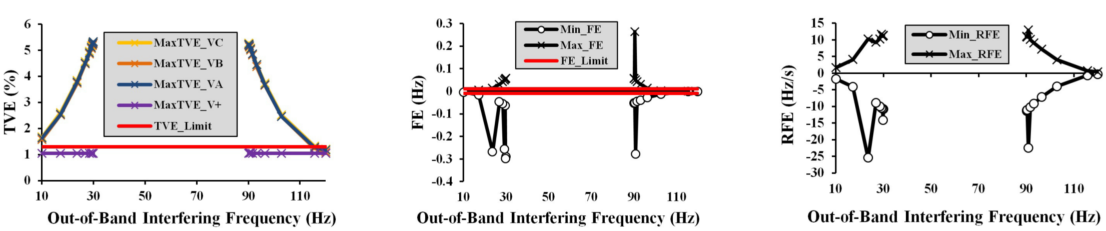
The model-based generation of HIL/SIL gateways consistent with the system model representing testing and model characterization architectures formally specified in the MIL of the CPSWT is automated. The primary role of the gateway is to provide synchronization between the logical time events sent and received by FEDs and the "wall clock time" controlling the evolution of devices and systems living in real time. Besides, the gateway needs to marshal data between the federation and the HIL/SIL modules.

5.5. Incremental Model Aggregation

The ***first stage*** of this process is integration of power system models during a simulation scenario where the control action is taken as a result of an emergency (e.g., fault) in a given grid operating state. During normal operation, power system is described with a phasor-based (frequency) domain model representing steady state phasors. During fault, the system experiences transients, which are best represented with a time domain electromagnetic transient model. Due to relay operation during a fault, the grid operation transitions into the restorative state, again is described with a phasor-based model. In order to correctly represent the dynamic interaction between the grid and the controller (protective relay in this case), one has to implement a co-simulation platform that allows correct interfacing and sequencing of multiple models to correspond to different control actions. In the ***second stage***, the WAMPAC models are integrated to represent a particular implementation case under a given system operating scenario. An example is the case of the use of synchrophasors in a wide area monitoring configuration, which quickly changes into a Special Protection Scheme (SPS) scenario once the detection mechanism determines what type of a disturbance is inflicted. Selecting appropriate models,



(a) harmonic distortion test



(b) out-of-band distortion test

Figure 5. Sample results of PMU static and dynamic type-test performance.

integrating them at the run time, and creating accurate simulations of the overall WAMPAC behavior has many applications in both operations of power systems, as well as contingency analysis and predictive control at the operations planning stage. The ***last stage*** is integrating models of the control algorithm with models of the physical (power system) and the cyber (WAMPAC) system states. The control algorithms are formulated as the model integration tools and are formalized in a state space domain representing the sequence of control actions and assisted model representations as the state machine sequence.

5. CONCLUSIONS

Cyber-Physical Systems (CPS) can become quite complex due to heterogeneity of their components and their interactions, which include physical phenomena, computational structures and processes, and engineering approaches to CPS design and analysis. In this paper, a new approach to power system cyber-physical model development using experimental characterization of cyber-physical systems through automated HIL and SIL co-simulation platforms is proposed. Formal specification of how the cyber-physical system components are defined and System-of-Systems (SoS) models are composed, and then decomposed into modules with different timing characteristics and finally aggregated into an integrated SoS co-simulation is presented. A set of improved co-simulation tools for SoS complex model development using an incremental integration and verification is introduced which would further improve the capability to analyze and design the critical cyber-physical infrastructure.

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