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Modelling and simulating new power grid control architectures

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Abstract—With the growing number of distributed energy resources, electricity grids have a stronger need for resilience that can be met by automation. Various architectures for such automated mechanisms are possible and they need to be systematically evaluated. The NACRE platform presented here allows to model and simulate various control architectures and to evaluate their behaviors against different types of communication hazards. The first version of the platform is evaluated on a use case.

Index Terms—Electric transmission networks, distributed control, model-based engineering, co-simulations

I. INTRODUCTION

A. Problem description

Electric utilities face steep rises of renewable energy production and growing uncertainties about energy mix evolution. Using automated systems to control the constraints on the grid, acting on all or part of the electricity area concerned, is no longer just an opportunity but a necessity.

The functions of these systems are organized in three layers [1] with distinct characteristics: Protection, Adaptive Control and Optimization. The Protection layer ensures the protection of people and property through simple and very fast automatic actions (tens of milliseconds) based on local information from substations. The Adaptive Control layer implements sophisticated zonal automated functions that leverage information from a zone, a cohesive network of substations and power lines from a grid perspective. This layer, which operates at a slower pace (from 1 second to 1 minute), serves to alleviate the human operator of tasks too fast-paced or too numerous for them to handle. On top, the Optimization layer provides the Adaptive Control layer and the operators with simulation and forecasting resources that enable them to develop a tactical vision of the network and of possible and desirable trajectories, on the scale of the entire electricity network, over an extended time horizon (past and forecast situations).

One of the most urgent issues is to limit the current flowing into transmission lines below a maximal value in a given zone. To do so, RTE can act on all types of flexibility (generation curtailment, batteries, demand response...) as well as on the grid topology (circuit breakers). This function is provided by a control infrastructure called NAZA: New Adaptive Zonal Automaton [2]. RTE estimates that more than 150 NAZA

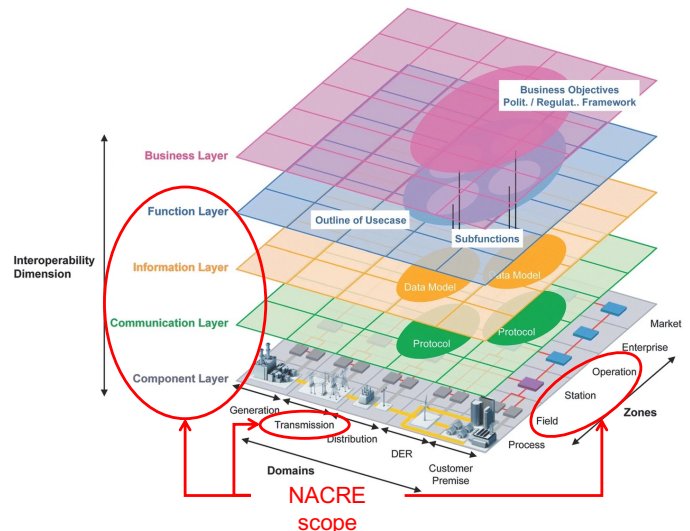


Fig. 1. Scope of NACRE within the Smart Grid Architectural Model

zones will be needed in the next 10 years, so the choice of IT architecture is crucial to ensure the resilience of the overall grid control system in the face of events such as the loss of data centres or telecom links.

A systematic and structured approach is required (i) to compare different possible IT deployments of NAZA and (ii) to compare the functional NAZA architecture to alternative functional control architectures, (i) and (ii) being evaluated according to various criteria of interest.

B. Adopted approach

Within the NACRE project, we aim to assess the behaviour of a set of communicating controllers with regards to a chosen communication architecture in the presence of communication or IT infrastructure failures. To this end, a platform which allows for the modelling and the simulation of a large range of functional and material control architectures is needed. The targeted scope of such a platform is shown in Figure 1.

The modelling aspect of the NACRE platform relies on the concepts and methods of model-based systems engineering (MBSE), which has been widely adopted for years for the development of complex systems and in particular cyber-

physical systems (CPS) [3]. Among the benefits of the MBSE approach, we highlight:

- description of a system architecture in a non-monolithic way, as a coordinated set of views and viewpoints, each focusing on a specific aspect of the system as explained in the ISO/IEC/IEEE 42010 standard [4]
- possibility to develop a system architecture through successive refinement steps [3]
- use of domain specific modeling language (DSML) [5]

Indeed, at least two architectural views can be usefully identified : the Control view to design the control architecture of the power system and the Communication view to design the communication between the controllers. Similarly, four architectural layers can be usefully identified : the Function layer, the Information (data) layer, the Communication (protocol) layer and the Component (resources) layer, according to the concepts of Figure 1.

In order to provide a DSML able to model the above views and layers, we choose to rely on the OMG standard System Modeling Language (SysML) [6]. SysML has been widely used in MBSE of complex systems including smart Grid [7]–[9]. However, as a generic modeling language, SysML should be customized to manipulate concrete, domain-specific concepts. For the NACRE DSML, we also rely on MARTE [10], another OMG standard modeling language devised for real time and embedded system, which is appropriate to design the communication and the component layers of Figure 1.

II. RELATED WORK

The co-simulation of an electrical network, the communication network for its management, and associated controllers, has multiple purposes in the field of smart grids [11]. A large part of use cases concerns the simulation of real electrical components or control systems, also called Hardware in the loop, which requires real time capabilities and interfaces with the real systems under test [12]. On the other hand, several test benches are more focused on the control or SCADA systems [13]. In addition, the vast majority of telecom network simulators, such as NS3, OPNET or OMNETT++ work at the IP network layer or even lower layers with a fine-grain level of description [14]. Finally, there are a few simulations that combine a large number of controllers that operate at the same time, from a system-of-systems perspective.

Existing platforms are insufficient to meet our needs, especially with regards to the cooperation and synchronization of several controllers, the description of complex telecommunications and IT infrastructures and the creation of high-level models of communication contingencies.

III. PLATFORM

A. Objective and architectural decisions

The NACRE platform has been developed to meet the following needs :

- Ability to model and simulate complex control systems, including multi-zones and multi-controls architectures at the layers shown in Figure 1.

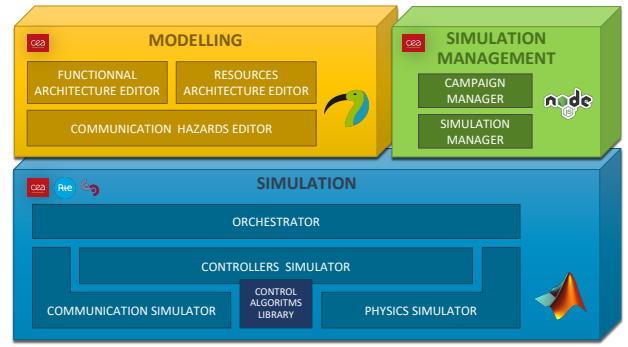


Fig. 2. Platform general architecture

- Ability to model and simulate communication hazards
- Ability to support various control algorithms

The main design decisions for the realization of this platform are the following :

- Appropriate subsets of SysML 1.6 (i.e Block and Allocation sections in [6]) and MARTE (i.e GRM, SRM and Allocation sections in [10]) as modeling ground
- Abstract communication between controllers
- Physics within the steady state AC modelling
- Maximal separation of concerns to have a modular and evolutive platform

As a result of the above design decisions, the platform is structured into two layers (upper and lower), each layer further divided into modules as described above (cf. Figure 2)

B. Upper layer description

The upper layer is responsible for building the data structures needed for the operations of the lower layer, and displaying the results. It is composed of a Modelling function, through which the user follows a MBSE approach to model various control situations, and a Simulation Management function, through which the user can define and pilot the corresponding simulations. The upper layer is implemented as a dedicated customisation of the Papyrus platform (for the Modelling function) together with a specific user interface in NodeJS (for the Simulation Management function).

Control Functional Architecture (CFA) Editor. This module uses the NACRE functional metamodel (cf. Figure 3) to define controllers and power devices, associate them to substations and buses, attribute specific behavior (i.e control algorithm) to each controller and define abstract communication links between them. It allows to model different control principles, such as central or hierarchical control.

Control Resources Architecture (CRA) Editor. This module uses a MARTE metamodel subset (cf. Figure 4) to define various computing resources and communication media, and to allocate control and communication functions from the CFA onto them. It allows to model different deployment principles, such as centralized or distributed deployments.

Communication Hazard Editor. This module uses the NACRE communication hazard metamodel (cf. Figure 5) to schedule various communication malfunctions, such as partial

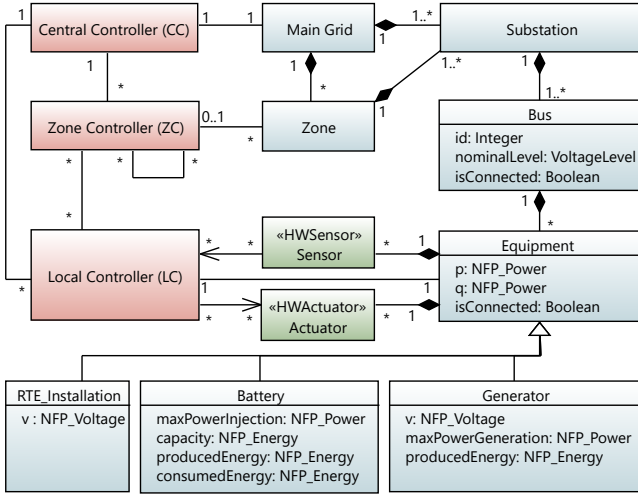


Fig. 3. An extract from the NACRE functional metamodel

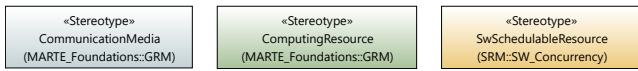


Fig. 4. An extract from the NACRE resources metamodel

or total loss of messages, delayed or corrupted messages, and assign them to CFA functions and CRA resources. An example of a communication hazard assignment is shown in Figure 8.

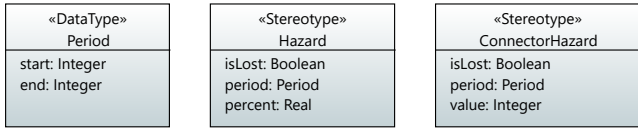


Fig. 5. An extract from the communication hazards metamodel

Simulation Manager. This module allows to configure a simulation, to control its execution and to display its results.

Campaign Manager. Built upon the Simulation Manager, this module allows to configure, execute and analyse several associated simulations as a simulation campaign.

C. Lower layer description

The lower layer is responsible for simulating the communication, power control and physical aspects of the situation defined in the upper layer. It is entirely implemented in Matlab® and partially based on code produced by CentraleSupélec [15] which predates the NACRE project.

Controllers Simulator. This simulator is responsible for configuring and executing controllers behaviours. It includes execution of specific control algorithms as well as generic controller actions such as inter-controller messaging (commands and telemetry) and power-system interactions (sensor measurements and actuator operations).

Communication Simulator. This simulator is responsible for simulating communication exchanges among controllers and the associated hazards that have been scheduled for them. It intercepts all messages transmitted by controllers, applies the hazards, and directs the messages to their intended recipient

based on the communication structures that have been modeled in both the CRA and CFA.

Physics Simulator. This simulator is responsible for computing the physical quantities needed to build the physical state of the power grid. It relies on the Matpower library [16] and simulates the electrotechnical equipments (generators, battery, etc.) behaviors, whose state depends on the commands sent to their actuators and on the environmental conditions of production. It is also responsible for responding to telemetry requests sent by the controllers to sensors.

Simulation Orchestrator. This module drives the three previous simulators and beats the time for them. It is responsible for maintaining the causal relationships between events and provides a global date to the different simulators.

Upper and lower layers communicates through files in order to easily provides simulation snapshot and replay capabilities. Data exchange between the orchestrator and the three simulators are performed through regular Matlab® function calls, each simulator having a defined RPC API. This design choice keeps open the possibility of using external simulators in the future.

D. Simulation of communications

Communication simulation ensures the proper propagation of simulated messages and the realistic application of communication hazards. The simulation does not take into account the lower layers of an OSI model but focuses only on three high-level aspects of communications:

- network message delays
- message transmission hazards
- coarse-grain encapsulation: endpoints, sending date, data

Routing aspects are only considered abstractly, based on the network topology defined in the CRA. The calculation of the non-functional properties of the transmissions (delays, hazards) is carried out only according to the network crossed and their associated timing and failure model parameters. For each transmission the simulator checks if the message crosses a network subject to failures according to the hazard model. Then it can change the value of a message, delay a message, eliminate the message or keep the message unchanged by placing it in a reception queue of the recipient, or not.

E. Simulation of control strategies

In our present usage, control strategies are governed by algorithms that are computed by zone controllers. These algorithms uses high-level instructions that are dispatched by central controllers as input. Zone controllers collect telemetry measures from the local controllers and produce curtailment orders for energy producers. The primary objective of these strategies is to enforce high-level directives while safeguarding the integrity of the zone's equipment. The NACRE platform currently gathers multiple control strategy algorithms, whose the Model Predictive Controller [15] is an example.

F. Simulation of electricity physics

As the other two simulators, the physics simulator performs periodic state updates based on calls from the orchestrator.

The NACRE platform has the capacity to simulate all forms of electrical production equipment. However, the simulator focuses primarily on fast-changing intermittent power generation, which typically convey the available power from wind farms.

Voltages and power flows of the power grid are calculated using the Matpower 7.1 Matlab® package [16]. The controllers and the sensor data acquisition considered in the simulations have a very large time constant compared to 50Hz (several seconds), so we use a steady state AC model. Transient behaviours of the grid elements or the generators are therefore assumed to be damped.

IV. FIRST CASE STUDY AND RESULTS

The platform is currently in prototype stage and has been tested on the following use case.

Motivation. We study partial message losses on a communication network and the possible impacts on the capacity of the zonal controller to prevent conductor overload.

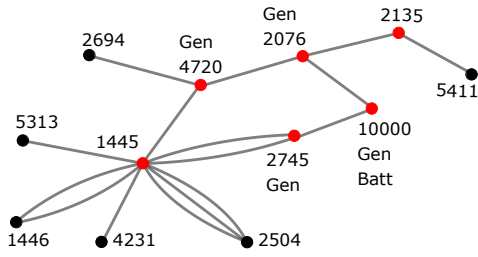


Fig. 6. Topology of the zone *VGSmall*

Situation being simulated. The situation modelled is a zone named *VGSmall* containing 6 substations (red nodes in Figure 6). Each substation contains a bus defined by its unique id. The red nodes and their connections define the zone. Black nodes are border nodes (outside the zone) to connect the zone to the entire power grid. According to the NACRE metamodel (Figure 3), equipments (such as generators and batteries) can be installed in busses. In the *VGSmall* zone, 4 generators are located in the 4720, 2076, 2745 and 10000 busses. A battery is also installed at the 10000 bus level.

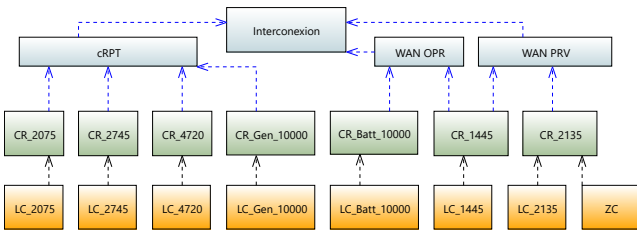


Fig. 7. An extract from the CRA model of *VGSmall*

Each zone's equipment (generator or battery) is locally controlled by a *LocalController* designed in the CRA (Control Resources Architecture) model using the MARTE stereotype

"*SwSchedulableResource*" (see Figure 4). Each *LocalController* software resource is executed on a computing resource designed in the CRA model using the MARTE stereotype "*ComputingResource*" that is connected to the network designed using the "*CommunicationMedia*" MARTE stereotype.

Figure 7 shows an example of a CRA model for the *VGS-small* zone. Controller software resources (in orange, LC_{id}) are allocated to computing resources (green components, CR_{id}) that are connected to networks (blue components). In this specific CRA, the zonal controller ZC is allocated to one of the several computing resources available in the substation of the bus 2135. this substation is connected to the private wan *WAN PRV* Communication Media. All Generators' local controllers are allocated to substations connected to the cRPT client network. Other CRAs can be designed and evaluated by simulation in order to choose the most convenient CRA according to different criteria such as dependability, robustness, efficiency, etc.

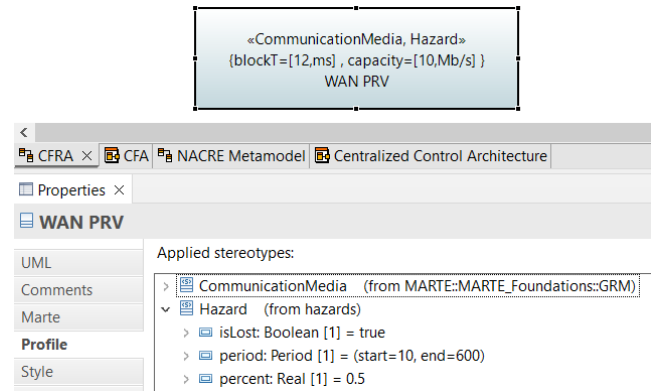


Fig. 8. Defining communication hazards

One interesting criteria to evaluate a specific CRA, is its robustness against communication networks' hazards. Figure 8 shows an example of a communication hazard added to the *WAN PRV* network. This hazards indicates that half of the network messages are lost from 10 seconds to 100 seconds during the simulation.

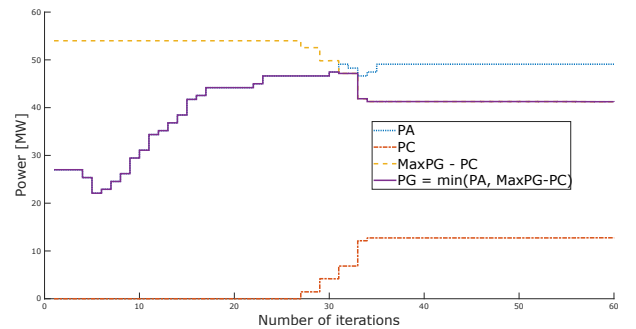


Fig. 9. Generation curtailment

Results and discussion. During the simulation of zone *VGS-small*, the power flow of the line between bus 2745 and 1445 threatens to go over the limit. In order to prevent this from happening, the MPC algorithm initiates curtailment measures

especially lowering the power generation at bus 2745, as depicted in Figure 9.

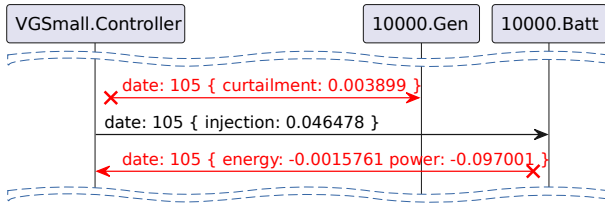


Fig. 10. Communication sequence diagram extract

Figure 10 shows a sequence of communication between the zone controller of *VGSmall* and battery and generator of bus *10000*. By using data from the communication hazards metamodel, our simulator proactively restricts the delivery of certain messages to their intended destinations. The responsibility of handling message presence or absence falls to the controller, which in our current design choices, interprets the absence of orders as a lack of directives, while the absence of measurements signifies that the latest measurement holds.

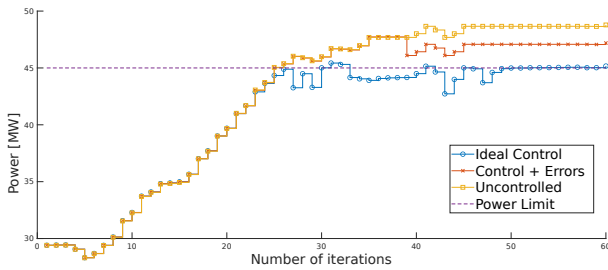


Fig. 11. Comparison of transmission line power flows under different control conditions.

In Figure 11, we investigate the impact of controller communication errors on transmission line power flow in the studied zone. The power flow for a zone controlled by the approximate linear algorithm, in ideal conditions, is represented by the blue circle-dots line. The red cross-dots line depicts the power flow in a zone controlled by the same algorithm, but subject to intense errors (95% curtailment control loss). Finally, the yellow square-dots line illustrates the power flow in an uncontrolled zone. While our current simulator is unable to account for line measurement errors that could have a significant impact on control performance, these results provide first insight into the crucial role of robust communications in ensuring effective control mechanisms.

V. CONCLUSION AND FURTHER WORK

The first version of the platform presented in this paper is a proof of concept that demonstrates the usefulness of the approach. The platform allows to model in a precise way the communication architecture of controllers in the electricity grid, and to simulate their behaviour.

Other use cases with more zones must be implemented to test the scalability of the simulation. Furthermore, the HMI ergonomics need to be better for industrial use, and

the platform must be rendered user error proof. New control algorithms could also be integrated so as to expand the comparison capabilities of the platform. Three types of metrics of interest have been defined : performance, reliability and energy footprint, but not all of them are implemented yet. Further work is to implement them.

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