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AN APPROACH FOR DEVS BASED MODELING OF ELECTRICAL POWER SYSTEMS

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ABSTRACT

The size and complexity of modern power systems, as well as emergent technologies and the uncertainty in energy planning, make the design and engineering of these systems challenging. One of the main challenges is the development of models that adequately capture the complex relationships between the components of these systems. We present a DEVS (Discrete Event System Specification) based framework for modeling a power system for energy planning. DEVS preserves the hierarchical and modular construction properties of a system (Chow and Zeigler 1994). That is, it enables each of the components of the system to be modeled separately, as well as the representation of the multilayer architecture of that system. As a proof of concept, we present a power system model, simulating the deployment of energy sources, on the PyPDEVS platform (Van Tendeloo and Vangheluwe 2015), considering dispatcher, unit commitment, load, generation, storage and transmission lines components.

1 INTRODUCTION

An electrical power system is an interconnected network of components involved in the supply, delivery, and consumption of electricity (IPCC 2007). This system consists of *generation stations* which produce electrical power, *transmission lines* which transport electricity from distant sources to demand centers, and *distribution centers* that provide power to users (Kaplan, 2009). According to the Department of Energy, a power system needs to be secure, economically competitive and environmentally responsible (DOE 2015). These objectives, which are not always converging, constitute what Bale et al. (2015) called the “energy trilemma”, illustrating the complexity of the power system. For example, renewable sources may be environmentally friendly, but are intermittent, and may require a back-up plant or a storage unit, which comes at an additional cost. This trilemma consists in finding a way to (1) continuously achieve security of the energy supply, (2) consistently provide affordable energy services, and (3) considerably reduce greenhouse gases, all at the same time. The diversity of supply and mitigation technology options available, the increasing demand (Castells 2000) as well as the dynamic variation of system’s conditions, including environmental and social changes (Heinrich et al. 2007) make the electricity system even more complex.

Over the years, such complexity has been tackled by planners and policymakers via the use of models, which remain the main supporting tool, to assess energy policy and evaluate the implications of actions taken (Jebaraj and Iniyan 2006, Bhattacharyya and Timilsina 2010).

Several types of models have been presented, namely power flow models (Milano 2010, Preece 2013), capacity expansion models e.g. RPM (Mai et al. 2013), ReEDS (Short et al. 2011) and SWITCH (Fripp 2012), and production costs models, e.g. PLEXOS (CAISO 2010), GridView (Feng et al. 2002), and GE

MAPS (GE Energy 2010). Power flow models help simulate transmission network, looking to find optimal conditions of functioning of physical components (resistor, conductor, capacitor, etc.). These models are mainly used to address power flow issues, namely frequency and stability, and voltage control. Capacity expansion models help simulate generation and transmission capacity investment, considering scenarios about future power demand, fuel prices, technology cost and performance (Blair et al. 2015). These models help answer questions related to the transmission or mix of generators capacity to build in order to match future loads. Typical outputs include generation and transmission capacity expansions or retirements, annual generation, etc. Production costs models help simulate operations of power systems, namely security-constrained unit-commitment and security-constrained economic dispatch, considering economic, environmental and operational constraints (Stoll et al. 2016). The models analyze conditions which would allow least costly dispatch of energy sources. Typical output include hourly generating unit usage, locational marginal prices, emissions, etc.

The model we present combines the attributes of both production costs and capacity expansion models. It captures the costs of operating generators and simulates security constrained unit commitment and economic dispatch simulation. The main goal is to perform energy planning, by analyzing expansion plans for electricity-generating, transmission and electrical storage technologies, on a long term while ensuring reliability of the system, on the short term. Though capacity expansion and production cost models could be used in tandem for planning purposes, this procedure may require several iterations to arrive to optimal solutions (Mai et al. 2013). In addition, these models use optimization methods, with no heuristics (Examplar 2017). This makes the analysis of large scale power systems, sometimes impossible, given calculation time limitations and the large data requirements (Ryan, Johnson and Keoleian 2016). In this case, computational burdens become large and more assumptions are made, which negatively affect the integrity of the model (Klosterman 2012). Our model proposes a priority list-based heuristics, based on costs and operational constraints, which addresses this issue, and eliminates the need for additional assumptions.

We elect to use a DEVS formalism to build the model, as it allows the description of the system in a formal, mathematically grounded or structured way. That way, we reduce subjectivity in the model building.

DEVS formalism represents systems over a continuous time base. This formalism is appropriate for event-driven models, that is, systems whose states change anytime an event takes place (Zeigler 1976). DEVS describes the inputs, outputs, and states of the modeled entities, as well as the functions that enable state transitions. Models represented in this manner are referred to as *atomic*. They can be used as building elements to construct larger, *coupled* models (Solcány 2008). A coupled model describes interconnections either between atomic models or between atomic and coupled models. In DEVS, modularity is enforced through the fact that all model's interactions with the outside world occur via its input and output ports. The integrity of models is thus preserved, with no direct access to internal state. Another important property of DEVS is the *closure under coupling*, which ensures that both atomic and coupled models use the same interface protocol (Zeigler 1984). That way, the atomic or coupled model can be used as a component in another larger model, enabling hierarchy in the overall model design. DEVS presents a design of communication mechanism between the components, where when information is shared, components alter their behavior and decide on their own actions, accordingly.

Several studies have presented DEVS-based models of power systems. Beltrame and Cellier (2006) present a new Dymola library, ModelicaDEVS, which supports the basic components needed to run DEVS simulations, combines simulation types of ModelicaDEVS and Dymola (discrete-event and discrete time simulation) and creates hybrid models with both ModelicaDEVS and standard Dymola components. The authors model a power system as a proof of concept, in order to estimate the possibility of performing not only accurate mixed simulations, but also hybrid simulations. Capocchi et al. (2007) model an electrical power system built around resistances, inductances, capacitors, voltage sources and current sources. The authors use equations relating currents and voltages in order to describe the behavior of these components.

Nutaro et al. (2007) model the integrated operation of a power system and its communication network. The authors consider a system for automatic load control, consisting of a bus system, with loads and generators interconnected. Their focus is to investigate situations of frequency disturbance, as this would lead to imbalance between the load and generation. In their work, Maatoug, Belalem and Mostefaoui (2014) model a new energy management system of a building, in the event of uncontrollable and controllable consumption. The proposed model divides the system into eight subsystems, namely costs, optimizer, solver, regulator, equipment, sensor, HCI and occupants. The objectives are to assess the behavior of the system and to determine circumstances enabling cost minimization and consumption reduction.

These studies look at power system in terms of network of electrical components (capacitor, resistor, inductance, etc.) or appliances (refrigerator, dish washer, washing machines, etc.), describing their physical behavior. Their main objective is to specify optimal operating limits of the electrical components. Contrary to that approach, we situate ourselves at a higher level of abstraction. By power system, we mean network of entities interacting with one another to enable supply, transport, distribution and use of electricity. In that sense, the model we are proposing would represent elements or components able to perform these activities. Unlike the models cited above, ours would rank at the activity level, with the focus on activity development to implement strategies. In our case, these strategies are plans or actions in an attempt to ensure security, sustainability and cost effectiveness in the system.

Jarrah (2016) models renewable energy sources in smart grid using DEVS formalism. In his model, the author represents the four main components in smart grid, namely photovoltaic arrays, wind turbines, storage, load demand and collector (entity coordinating and implementing an optimization algorithm which ensure equilibrium between supply and demand). The results would assist in decision making regarding capacities needed for photovoltaic arrays, wind turbines, and storage, given changes in demand.

Although this model captures some essential elements in power systems, it only considers distribution within a single location, and disregard costs. Our model (1) captures import/export of power between several locations or zones via transmission lines, (2) performs hourly chronological security constrained unit commitment and economic dispatch, (3) support all main generation, storage and transmission technologies, and (4) supports stochastics due to changes in load, wind, irradiance, and disruptions). Our model presents thus a more complete representation of a power system, addressing ongoing issue in the domain of energy planning.

We offer an implementation of the proposed approach, using the PyPDEVS platform. Section 2 gives an overview of the conceptual model, introducing the proposed model entities and their specifications. Section 3 provides an application, with the simulation of a power grid to give some insight on the functioning of the model. Finally, the conclusion summarizes and discusses future works.

2 CONCEPTUALIZATION OF A POWER SYSTEM

Functionally, a power system is divided into generation, transmission, and power flow regulation. *Generation* refers to power plants, using both renewable (solar, wind, hydro…) and non-renewable (coal, petroleum, gas…) energy sources to produce electricity. *Transmission* refers to the transmission system, meaning the configuration and physical constraints of transmission lines. *Power flow regulation* refers to the Unit Commitment (UC) and the power dispatch. UC problem consists of determining the schedule of generating units within a power system, and taking into account operating constraints (Tahanan et al. 2015). Power dispatch consists of identifying the optimal use of a number of electricity generation facilities, in the least costly and environmentally damaging manner. These functional delineations naturally present a case for model units that can be independently built and useful for analysis of individual components, while additionally offering the capacity to be seamlessly composed for a holistic analysis of the overall system. Based on this characterization, we propose a conceptualization of a power system as a composite of interconnected autonomous and dynamically evolving subsystems, with the purpose of maintaining the balance between supply and demand of electricity, under constraints imposed by the "energy trilemma".

Figure 1 shows a simplified UML class diagram conceptual model of a power system. The power system (interzone) is decomposed into geographic zones. Transmission lines enable the transmission of power between zones. Each zone has a dispatcher which manages the supply of power from the generators to the loads. The dispatcher also manages the exchange of power and information between zones, to meet all demands and to determine market-clearing prices, while considering all constraints. Generators are committed daily or weekly by a unit commitment component, which schedules them when available, technically feasible, and cost effective, to supply power to the loads. Dispatchers manage the local power distribution using hourly information of load demand, generation capacity and operating costs. Each zone is composed of one dispatcher, and any number and type of loads, generators and storage units. Transmission lines and unit commitment are not assigned zones. Storage and generating units can be of different technologies. The key attributes and behaviors of the model components are provided in Table 1.

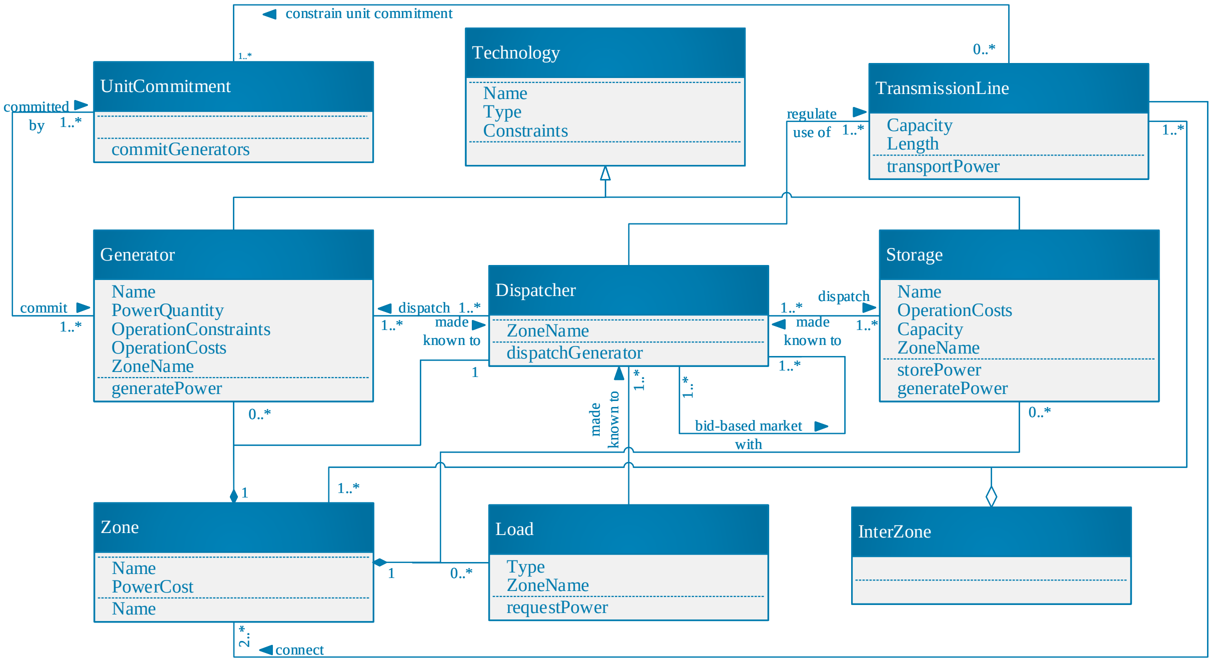

Figure 1: Conceptual model of a power system.

2.1 Process Overview and Scheduling

The process flow of the model is presented in Figure 2. The default simulation time increment is one hour. This time unit captures the hourly fluctuations in daily electricity demand, as well as weather changes. The *Unit Commitment* gathers data regarding generator & storage units' technologies, economic parameters and climate & weather variation, and estimate the net load. Then, it can schedule non-renewable generators over a commitment period. This scheduling uses a priority list based heuristics (Senjyu et al. 2003), considering operating costs and operational constraints, which ensures that enough power is committed, that the least costly generation use is implemented and that transmission line capacity permits the sharing of power between zones. Committed *Generators* exchange information with the *Dispatcher* regarding their availability, specifying the available power capacity as well as the operating costs. At the same time, *Loads* also inform the *Dispatcher* of their need for power. The *Dispatcher* compares supply and demand quantities, and assesses the need for power. It then engages in electricity market trading through bids to buy and/or offers to sell electricity if imports prove cheaper than use of local generators and storage units. The model also accepts or rejects bids from other D*ispatcher* models. Once all offers are settled and no further trade is made, the system has reached equilibrium.

Table 1: Power System Components.

Agent: Load Model Attributes: • Type of demand: Residential, Commercial, Industrial • Zone: Name of the zone it belongs to Objectives: Request power, consume power, adjust power usage to demand side policies Behaviors: • Create aggregate load from customer demand • Compute the amount of demand met
Agent: Generator Model Attributes: • Technology: committable, not committable • Zone: Name of the zone it belongs to • Operational constraints: ramp rate, minimum uptime and downtime, planned and forced outage, minimum operating capacity • Fuel type: oil, gas, geothermal, nuclear, biomass, biogas (No fuel when technology is renewable) Objectives: Supply power Behaviors: • Create supply quantity from power plants demand and specify on what prices to charge the capacity to submit • Update the capacity after hourly use • Compute hourly operating costs and total usage costs
Agent: Dispatcher Model Attributes: • Name Objectives: Perform economic dispatch. Balance power supply and demand Behaviors: • Dispatch generators hourly, based on availability • Engage in electricity market trading through bids to buy or offers to sell electricity • Accept or reject bids based on economic gain.
Agent: Transmission lines Model Attributes: • Origin • Destination • Capacity • Loss coefficient: Loss during transmission Objectives: Supply power over transmission grid to meet dispatchers' requests. Behaviors: Transmit electric power from zones to zones
Agent: Storage Model Attributes: • Name • Technology: Type of storage • Zone: Name of the zone it belongs to • Operational constraints: Planned and forced outage, maximum capacity Objectives: Store power, Supply power when economical Behaviors: • Create supply quantity from storage units and specify on what prices to charge the capacity to submit • Update the capacity after hourly use • Compute hourly operating costs and total usage costs
Agent: Unit commitment Model Attributes: • Name Objectives: Commit power generators Behaviors: • Estimate net load based on variable generation availability • Schedule generating units ahead, by deciding when to turn them on/off • Decide how much power to commit per generator, based on costs, transmission lines and generators constraints (SCUC)

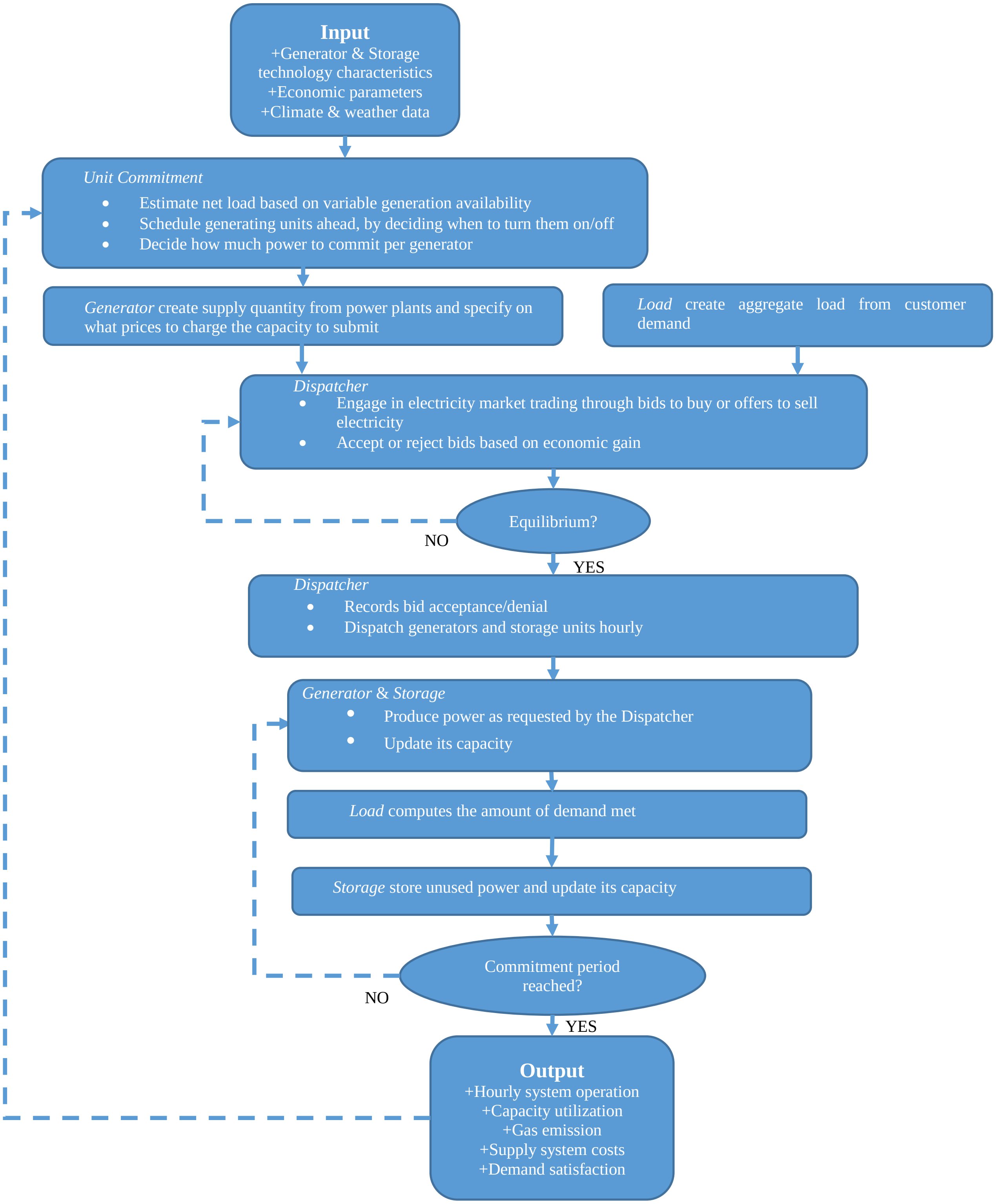

Figure 2: Simulation process overview.

The *Dispatcher* then eventually dispatches local generators and storage units, and calculates the amount of demand met. Unused *Generator* capacity is sent to *Storage* components, which subsequently update their stored capacity. The default commitment look-ahead period is set to 24 hours.

2.2 The multi-components system

Each component of the power system is modeled as an *atomic DEVS* model, considered as agents, with autonomous behaviors, which can change not only due to internal mechanism but also to external inputs. Table 1 displays all components in the model, as well as their characteristics. It also lists the behaviors of each of them.

2.2.1 Modeling *Unit Commitment* component

This model represents the entity responsible for the scheduling of on/off decisions and output levels for power plants over a given time horizon (Dentcheva et al. 1997). Here, we refer to this time horizon as *commitment period*. It commits generating units, by deciding which of them are available for operation, how much electricity can be generated and for how long, based on how costly and technically feasible such arrangement would be. This scheduling is done in such a way that costs are minimized, but also that both generators (ramp rate, minimum uptime and downtime, planned and forced outage, minimum operating capacity) and transmission lines (capacity) constraints are respected. The model computes the net load, that is, the remaining system load not served by renewables, rather by conventional sources, before scheduling generators. This computation requires stochastic planning method, in order to capture the variability of renewable energy sources. In their study, Tigas et al. (2015) present the approach of the "Residual Load Duration Curves", which consists in computing the remaining load to be covered by conventional units after the contribution of variable renewable energy is subtracted, using a stochastic analysis. This analysis helps approximate the changing renewable energy generation over time. The generators scheduled here are non-renewable sources only, since renewable sources are intermittent. In the present study, stochastic planning is performed to calculate a "Residual Chronological Load Curve". This scheduling requires (1) a time horizon along which the decisions, which are sampled at a finite number of time units, are made, (2) a list of generators available in the zone, with the corresponding operating costs, gas emission outputs as well as technical constraints, (3) a list of all transmission lines in between zones, their technical constraints and costs, and (4) a forecast of the demands to meet.

2.2.2 Modeling *Generators* component

This model represents electricity generating plants. They present various characteristics, namely a minimum uptime (minimum time the plant has to remain ON), minimum downtime (minimum time the plant has to remain OFF), ramp rate (the speed at which the plant can gradually increase it capacity), minimal capacity (the minimum stable capacity at which the generator can operate) and nominal capacity. The model provides the dispatcher with the amount of power available and the cost it will charge for usage, hourly. It then updates its remaining capacity when informed by the dispatcher, about the actual power quantity needed at this hour.

2.2.3 Modeling *Loads* component

Loads model represents demand expressed by consumers. They request electricity. In our case, this model includes all types of electricity demands, namely residential, commercial and industrial. Their characteristics are name and size. Size represent the quantity of electricity requested. Similarly to the generator model, *Loads* provides the dispatcher with the aggregated demand of power, hourly. It then computes the quantity of demand met when informed by the dispatcher, about how much demand was covered.

2.2.4 Modeling *Dispatchers* component

Dispatcher model represents entities responsible for ensuring a balance between power supply and demand every hour. The goal is to satisfy the overall demand, in the least expensive way possible. The *Dispatcher* thus decides between dispatching local generators, or importing power from other zones. Will it be more economically advantageous to import power? To sell power to this specific dispatcher? To use power from a specific storage unit? The *Dispatcher* engages in market trading with other dispatchers, comparing bids received for sales and making bids for buys. Once a decision is made, it assigns priority to all power sources, including storage units, local generators and imports, and dispatches them. Then it provides the *Load* model with information regarding the amount of demand covered, on an hourly basis.

2.2.5 Modeling *Transmission Lines* component

Transmission Lines are entities responsible for carrying high voltage power from one point to another. In our model, they are related to the dispatchers of each zone. Their characteristics are length, power loss factor and capacity limits. This limit represents the maximum quantity of electricity that can be carried over.

2.2.6 Modeling *Storage* component

Storage behave as electricity generating plants. They produce electricity that was stored at an earlier time. Each of them have various characteristics, namely storage efficiency (percentage of power which can be retrieved, out of what was stored), discharge rate (rate at which the electricity is retrieved for usage) and nominal capacity. The model updates its remaining capacity following requests from the dispatcher model.

2.3 The multi-layer system

Several levels of modeling are used in a power system architecture (Figure 3). They correspond to the layers capturing the relationships between the different components of the system. Between these layers, a flow of information is exchanged. We consider three layers, namely the local, zone and inter-zone layers.

Each of these layers is represented by a coupled model. Unlike the atomic models which require functions to specify their behavior, coupled models don't. Rather, they group atomic models or coupled and atomic models as components into a composite model (Solcány 2008). They specify couplings between these components. There exist three types of coupling: External Input Coupling (set of links connecting input ports to components), External Output Coupling (set of links connecting components to output ports) and Internal Coupling (set of links connecting components to components) (Goldstein, Breslav, and Khan 2013). These connections all follow the same protocol, that is, before sending a message to the target component, the output specification of the source is mapped to the input specification of the target, protecting the integrity of the message.

2.3.1 Modeling the local layer

The local layer is a coupled model, composite of *generators, storage, loads* and *dispatcher* atomic models. These components are connected via an internal coupling. This layer captures the information exchange between those elements, highlighting the activities at the operational level.

2.3.2 Modeling the zone layer

The zone layer is a coupled model, which specifies the connections between components of the local layer and its ports. These connections are made via both external input coupling, with links between the model external inputs and component inputs, and external output coupling, with links between component outputs and the model external outputs. This model captures the exchange of information between dispatchers in different zones. This communication is critical, as zones may be in excess and exporting power or in deficit and importing power. As indicated earlier, this communication takes place between dispatcher in each zone.

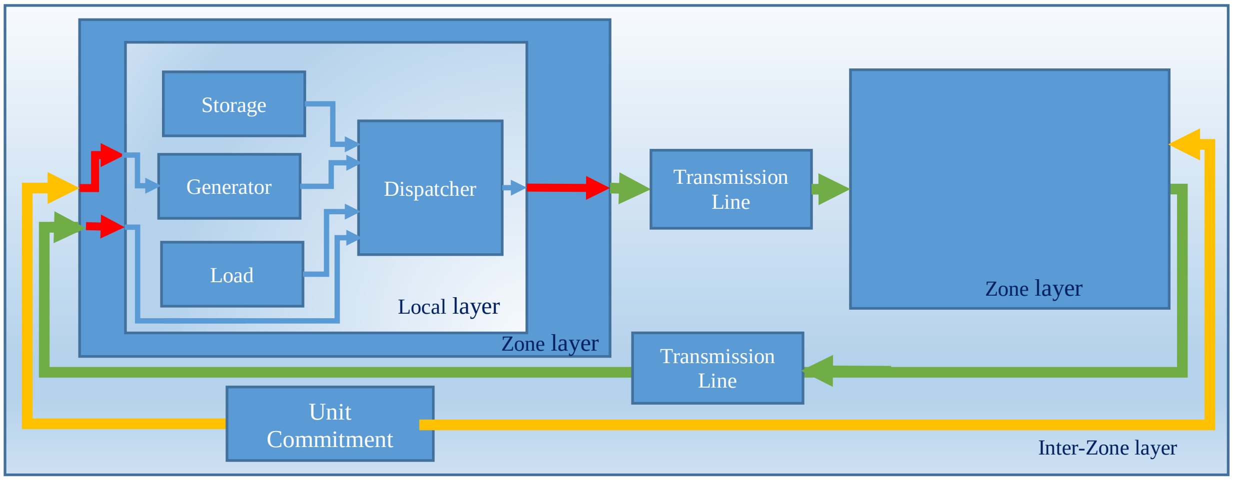

Figure 3: DEVS hierarchical representation of the electricity system.

2.3.3 Modeling the inter-zone layer

The inter-zone layer is also a coupled model, composed of zones coupled models, *Transmission Lines* atomic model and *unit Commitment* atomic model. These models are connected via internal coupling, with each of these components linked to one another. This model highlights the transfer of information between zones.

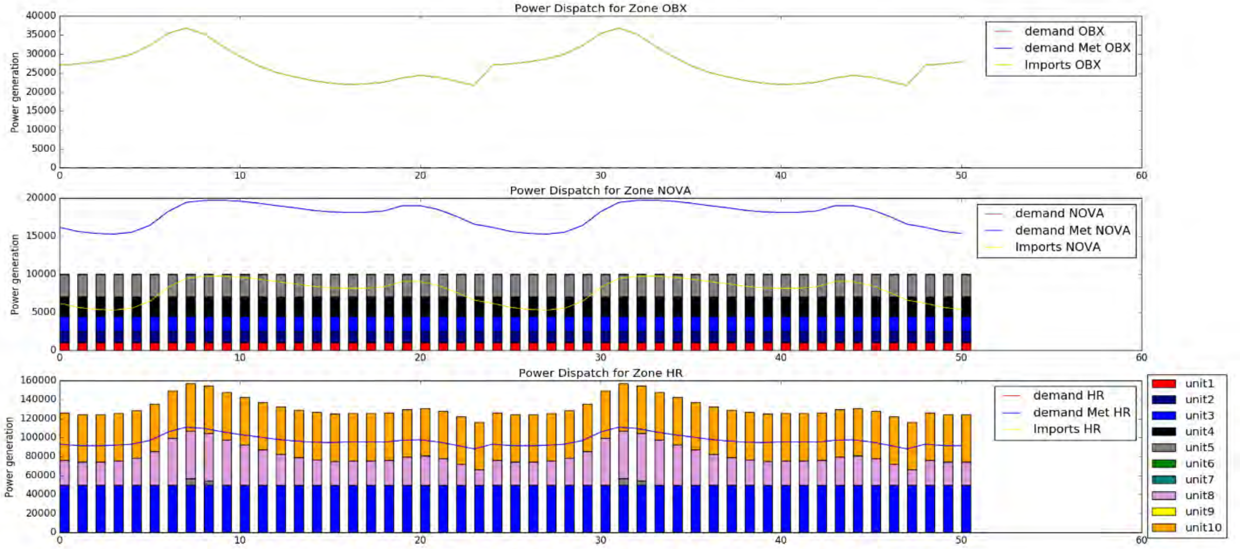

Figure 4: Generators dispatch.

3 MODEL SIMULATION AND RESULTS

An example case that we present is to illustrate the ability of our model to perform energy planning. Three zones are considered here, with ten power plants per zone. The model is simulated for 50 hours (two days). Two zones are assumed in deficit while one in excess. In all zones, the respective dispatchers assess the needs for electricity and, if necessary, send requests to neighboring zones. NOVA and OBX being in deficit, are unable to respond favorably to any requests. Only HR can, if in the position to answer both requests, supply some electricity. This is contingent on both the surplus quantity and the transmission lines capacity.

Figure 4 displays the results of our simulation. All demands are met in HR, which can therefore export its surplus to other zones. NOVA can only meet part of its demands with some of its local generators which are dispatched. The rest is not, for economic reasons. As explained earlier, generators are committed from the least to the most costly. In this case, it is more economically advantageous to import electricity than to use some local generators. In zone OBX, while all of the demands are also met, no local generators are dispatched. The reason is also that local generators operations cost more than power imports. Eventually, this situation could change and generators in OBX could be dispatched if the demands grow, or if fuel costs change over time

4 CONCLUSION

An approach is presented using DEVS formalism to model the power flow and generators dispatch in an electrical power system. The proposed conceptual model includes key components of that system and captures both the hierarchical and modular structure of that system (Schweppe and Mitter 1972). The rationale is to make the model building formal enough to facilitate reuse of verifiable model components, with positive implications for simplicity.

Future work includes the application of this modeling framework to large-scale power grids, connecting areas within a great distance. This will enable the identification of additional parameters and performance indicators to include in the model.

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