Handbook of System Safety and Security

The Algebra of Systems and System Interactions with an application to Smart Grid

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Abstract

Systems are integrations of devices or component elements and even other systems. The notion of a system comprehends engineered and biological or mechanical or physical systems. Examples include information and dynamical systems as well as integrations of the two, sometimes called cyber-physical systems (CPS). Cyber-physical systems have computational and physical elements. Systems integration allows us to build more complex or compound systems from given ones. In such systems, computers and measurement devices are combined to deliver functions that may impact or influence the physical elements. Feedback loops are used where physical elements influence in turn computational elements and vice versa. Applications of CPSs have an economic and societal potential that goes beyond what has been realized. CPS revolutionize several domains including energy by transforming a traditional electric power grid into *smart grid*.

The existing electric power grid has components for generation, for transmission and finally for distribution of electric power to large and small users. Power flows from generation components over transmission components to distribution components, servicing large commercial and public facilities as well as our homes. Growth in demand is responded to by augmenting the grid with additional generation, transmission and distribution capacity. This enhanced capacity is costly and takes years to provision. Failure to accurately predict growth in demand or inaccurate estimates of grid performance can lead to excessive and unnecessary cost or inadequate capacity. Finally, awareness of the impact of less than optimal operation of the power grid and of the impact of continued use of fossil fuels for generation has increased.

As a result, leadership and the public are increasingly interested in alternative approaches to meeting demand for electric power. In response to this interest we see more and more a willingness to reshape our electric power 'grid' as a 'Smart Grid'. The proposed changes challenge traditional approaches to grid infrastructure and organization. The 'smartness' of the Smart Grid consists in two distinct innovations. The first involves our integrating new technologies into the power grid and the second involves our radically changing the ways that grid elements relate to one another. A Smart Grid manages distributed generation and bidirectional power flow. In the Smart Grid, each new component could potentially affect the performance of many other elements of the grid and so we must have a means of expressing and evaluating proposed grid innovation.

In this chapter we will focus on CPS, rather than general systems, for the sake of clarity and we propose a language for expressing the elements of a CPS and an operation of 'composing' CPS elements that we will show is a simple algebra that is capable of helping planners and engineers design and test the CPSs of the future. That will enable planners and engineers to design, and ultimately simulate, the composition and the integration of CPSs such as grid system. This 'CPS algebra' is based on a formal language that offers the expressive power needed to capture the observable behaviour of CPS components, allows the composition of existing CPSs, and supports a methodology for the study of critical properties of the CPS such as safety and security, properties that are especially important for critical infrastructure such as the electric power grid. We will give examples of the resulting *smart grid algebra*, using a model of smart grid simplified for our purposes here.

1. Design Behind Success of a Smart Grid

The current state of the grid may be described as extremely sophisticated; it is already carefully designed as a critical facility to modern society. However, this grid remains very sensitive to integration with the new concepts involved an open power market. Additionally, an important percentage of the power generation is encouraged to be based on renewable energy sources (RESs). Hence, utilities need to carefully weigh the effects of the integration of such systems when designing the composite smart grid. In particular, they should take into account the factors that go beyond their own grids and that influence their operating stability. Indeed, the communication with grid partners is an important factor in the new grid design in order to allow actions beyond the local grid boundaries. The grid has to know whether there consumers are "plugging into" another electric provider or installing new solar panels in order to act like a producer. Following this logic, utilities are facing a real need to rethink, and redesign existing parts of the grid to accommodate these end-user changes and bidirectional power flows. Our proposed algebra helps the utilities' engineers to think about such challenges, design them, and verify the important design properties for their utilities.

2. Trends in renewable energy integration

The power grids are real time energy delivery systems. Real time means that electricity is produced, transported, and delivered when we turn on the light switch. Power systems are not storage systems such as water and gas systems. Indeed, in a conventional power system, the generators produce the energy that the demand requires [1]. The system begins with the production, by which the electrical energy is produced in the power station and then transformed in the transformer station into high-voltage electrical energy that is more suitable for efficient long distance transport. The electrical plants transform other energy sources, in the process of generation, into electrical energy. For example, heat, mechanical energy, hydraulic, chemical, solar, wind, geothermal, nuclear, and others are used in the production of electrical energy. The power lines, in the transport segment of the electric power system, are intended to efficiently transport electrical energy over long distances to the points of consumption. Finally, the transformer stations 'step down' the high voltage electrical energy into low voltage, which is, transmitted via the electrical distribution lines that are more appropriate for the distribution of electric power to its destination, where it is again stepped down to a voltage level appropriate for residential consumption, commercial and industrial.

Unlike the tree structure of unidirectional descending power flow from generation toward consumption, the next-generation of power systems integrate distributed RES generators and the *structure* becomes one of bidirectional power flow where each node in the system can either be producer and/or consumer. Fig. 1 shows the basic blocks of a next-generation electric power network.

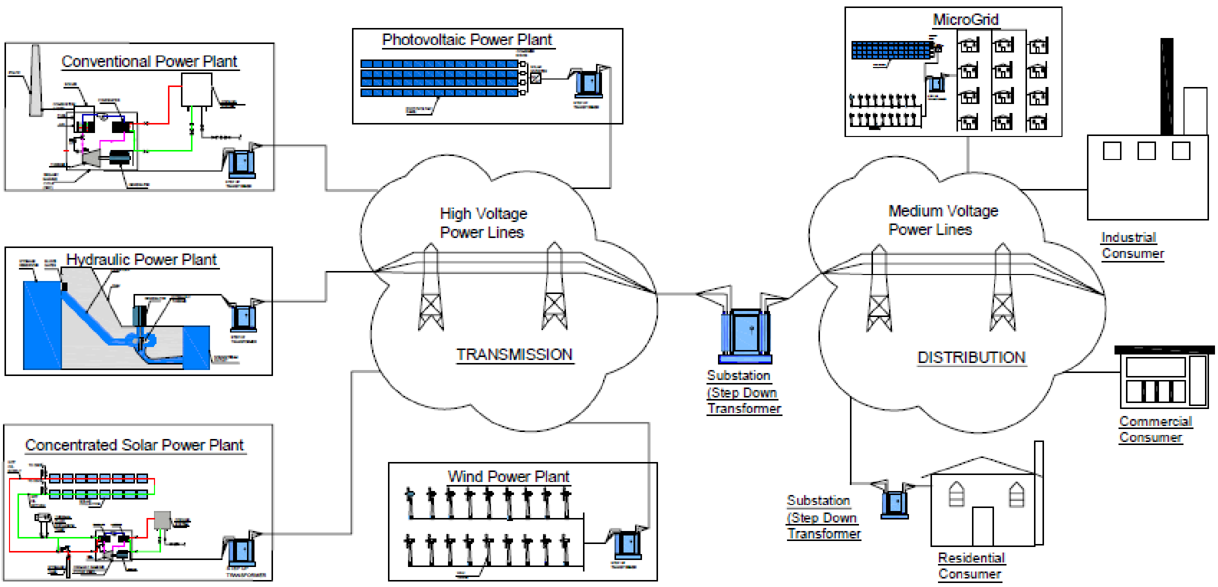


Fig. 1 Smart Grid Components

In recent decades, many studies have been done on designing hybrid renewable energy systems and proposing operation modes for its components. These systems can be classed according to the scale of designed network.

On one hand, the RES Integration can be into a Micro-Grid or a *sub-grid*. This class consists of small networks powered by a hybrid electric production system as Micro-grids. Several studies have been conducted in order to optimize the design of a hybrid system. In [2], the authors present a comparative study of different structures of hybrid renewable energy systems. Combinations of photovoltaic, wind, diesel generators and batteries are regarded as presenting the system designer every possibility that he/she might need to make the right decision when *sizing* the system for its intended use. For each of the scenarios, the study takes into account the annualized cost and reliability of the system as a multi-objective system. In fact, the proportion of renewable energy, the probability of load loss and the operating time of backup diesel generation represent the system reliability. The decision variables included in the optimization process are the power to install photovoltaic generator, wind power, number of batteries, and the diesel generator power. This approach has employed a multi-objective *genetic algorithm* [2] for solving the described optimization problem. Moreover, the study developed in [4] presents an overview on the design and implementation of hybrid RESs.

On the other hand, several studies have been conducted on the RESs integration into national networks on a large scale. For instance, the study presented in [5] addresses the penetration requirements of different RES technologies, which are assessed by considering, at the same time, other attenuation strategies aiming to reduce the global emissions of electricity networks and achieving the required objectives. Then, the study of the impacts of the climate change attenuation strategies on the demand and the mix production has been envisaged to facilitate the RES penetration. As an application of this approach, marginal emissions associated with individual production technologies in the state of New South Wales (NSW) were modeled and the total emissions associated with the electricity grid of NSW was evaluated. Furthermore, in [6], the authors present long-term strategies for transmission network infrastructure in order to integrate increasing amounts of renewable energy for the periods from 2030 to 2050. Another study developed in [7] points out the research problems whose solutions would allow us to prepare and to better manage the impact of RES integration into the German power system. This study was investigated in the framework of the German energy transition goals, called "Energiewende". Many solutions have been proposed as a network expansion and revision, more flexible production in conventional power plants and demand control in the context of this new concept of smart grids and smart markets. In the same context, the United States has launched several studies, including a comparison of two studies (“Sunshot Vision” and “Renewable Energy Future”) as presented in [8]. The study developed in the framework of “Sunshot Vision” evaluates the potential impact of solar technologies implementation with very low cost, while the “RE Future” study analyzes the benefits and impacts of providing up to 90% of the country's electricity from RES technologies. Both studies show that solar technologies could play a very important role in the US power system over the next 20-40 years. They also state that there are many challenges along the way to achieving such future results. Other countries have initiated research projects on the RES integration in order to increase penetration into their national grids such as Canada, Brazil, South Africa, to name a few.

3. Power systems laws

Power systems are constrained by many laws that must be considered, in order to meet the widely varying electricity demands while ensuring the correct and safe operation of the whole system. However, the most important power system constraint is “Power Balancing”, which requires that the power produced be exactly the sum of the power consumed and the grid losses, as expressed in (1).

$$P_g = P_d + P_{loss} \tag{1}$$

where P_g is the produced power, P_d is the electricity demand and P_{loss} is the power lost in the grid links. Since electricity cannot yet be economically stored in large quantities, the logistics of power production is done dynamically in order to maintain this power balance at any given moment. With the conventional production, generation adjustment was possible (primary, secondary and tertiary) to maintain this balance of production power and demand power. However, with the distributed and intermittent generation sources associated with the smart grid concept, it will be necessary to develop system designs that will guarantee the power balance. We will need tools to produce, assess and assure these system designs.

4. A Cyber-Physical System algebra

The aim of this section is to present a formal framework that provides the underlying semantics for a high-level *CPS design language*. This framework is defined as an algebra, i.e., a mathematical structure with a set of elements and a set of operations on those elements. The operations of an algebra frequently satisfy properties such as commutativity, associativity, idempotency, and distributivity. Our proposed framework provides some built-in smart grid related properties that use smart/micro grids as processes. They are used as values for a *parallel composition* of a new CPS design. Parallel composition is defined to be a commutative and associative operation on CPS.

4.1. The π-calculus as root

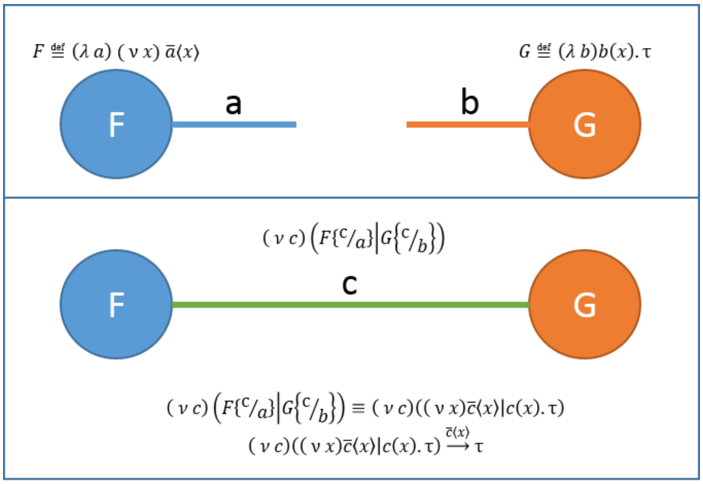
In our approach, a CPS is regarded as a composition of concurrent parts. The overall behavior of the CPS is structured by the combination of the behaviors of its sub-systems. We can assimilate each subsystem to a process or an agent within the overall CPS. The π-calculus [9] is a model of computation for concurrent systems. It is also a process calculus that lets a designer represent processes, parallel composition of processes, synchronous communication between processes through channels, fresh channel creation, processes replication, and nondeterminism. The extension of such an algebra, as proposed here, gives rise to a CPS Domain Specific Language (CPS-DSL). In this DSL, a CPS component is defined as a process. Indeed, in this framework, a CPS component inherits properties from the π-calculus such as those of composition and communication. Those properties alone are not sufficient to address the specific case of CPS. The CPS-DSL introduces a *specialization model* for which the CPS under study being specified is modeled using the proposed modeling language. In order to enrich the semantics of the CPS-DSL, we define a framework where CPS process is defined within the *specialization model* based on the general π-calculus processes. We use the higher-order capabilities of the π-calculus to exchange agents that capture the specific behavior associated with smart grids.

The monadic π-calculus operations, between and on processes, are explained below. If P and Q denote two processes then:

- $P \mid Q$ denotes a process composed of P and Q running in parallel.
- $a(x).P$ denotes a process that waits to read a value x from the channel a and then, having received it, behaves like P.
- $\bar{a}\langle x\rangle.P$ denotes a process that first waits to send the value x along the channel a and then, after x has been accepted by some input process, behaves like P.
- $(\nu\, a)\, P$ ensures that a is a fresh new channel in P.
- $!\,P$ denotes an infinite number of copies of P, all running in parallel.
- $P + Q$ denotes a process that behaves like either P or Q.
- $\emptyset$ denotes the inert process that does nothing.

The polyadic [10] form of the π-calculus introduces *vectors*, as parameters exchanged over the channels, of the form $a(\vec{x}) \stackrel{\text{def}}{=} a(x_0, x_1, x_2, \ldots, x_n)$ where a is a channel, n is the arity if the vector x noted $n = \|x\|$. In addition to this notion, two other notions are introduced and they will be at the heart of our CPS-DSL:

- Abstraction on names for processes from a given process: $(\lambda\,\vec{x})P$.
  - This is the essence of the parametric definition. It may be used to define the parameters of a process inside its definition instead of writing the parameter on the process's name
    - We can write $K(\vec{x}) \stackrel{\text{def}}{=} P$ as an abstraction of $\vec{x}$ over P $\;K \stackrel{\text{def}}{=} (\lambda\,\vec{x})P$



  - This is the basis of the chaining combination between processes. Consider an example, as illustrated in Fig. 2 where $F \stackrel{\text{def}}{=} (\lambda\,a)\,(\nu\,x)\,\bar{a}\langle x\rangle$ and $G \stackrel{\text{def}}{=} (\lambda\,b)b(x).\tau$. In order to enable the chaining of those two processes, we can create a new channel c and use the renaming to obtain a chaining combination as
    - $(\nu\,c)(F|G) \equiv (\nu\,c)\left\{F\{^{c}/_{a}\}\middle|G\left\{^{c}/_{b}\right\}\right\}$

- Concretion of names from a process: $[\vec{x}]P$. This is a way to treat output dually to input. The concretion is used in order to communicate datum already bound. Consider a process K that defined as $K(\vec{x}) \stackrel{\text{def}}{=} P$ and we have to send the output $\vec{x}$ over the channel a as $\bar{a}\langle\vec{x}\rangle.K\,(\vec{x}) \stackrel{\text{def}}{=} P$. We can consider the output prefix $\bar{a}\langle\vec{x}\rangle$ by bypassing the need of the parametric definition as $\bar{a}.K$ if $K \stackrel{\text{def}}{=} [\vec{x}]P$
  - $K \stackrel{\text{def}}{=} \bar{a}\langle\vec{x}\rangle.P(\vec{x})$ can be represented using the concretion based notation as $\bar{a}.K \stackrel{\text{def}}{=} [\vec{x}]P$

4.2. Cyber-Physical System Specific Language

Figure 2 Abstraction used for chaining combination

The CPS design framework, that we are proposing, offers the primitive structures built into the language to deal with CPS components and their composition operator. Two distinct categories of elements are modelled in this approach:

- Components: are atomic building blocks of the system. Those elements are characterized by their inputs, outputs, and behavior. They are considered by the system as a black box offering a function on the system. The components are used to model both the cyber objects and the physical objects.
- Composites: are building blocks composed from components or other composites. They aim to be composed to provide a "Glue" that enable connecting the components to each other and offer a new feature. Composites may be considered complex components as they aim is to provide a function, even if they are using component to provide that function. Composites are characterized by their inputs, outputs and the components that they incorporate.

We introduce here *syntactic sugar* as a syntax within CPS-DSL to make the composition easier to read or to express. Indeed, the name $CPS(\vec{b})$ is used to refer to both the composite grid and the elements of the CPS. Therefore, we define the term CPS in (2) as a parallel deterministic choice between a $Composite$ in (6) and a $Component$ in (5). The term CPS has a parameter vector $\vec{b}$ that stands for 'behavior'. This parameter is used to pass an agent as a higher-order parameter. The agent will drive the behavior of the grid according to his specificities.

$$CPS(\vec{b}) \stackrel{\text{def}}{=} [\|b\| = \underline{1}]Component(b_0) + [\|b\| \neq \underline{1}]Composite((b_i \otimes)^{\|b\|}) \quad (2)$$

The definition of the term CPS calls $Component$ if the arity of the vector $\vec{b}$ is equal to one. It calls the term $Composite$ if the arity is greater than one. Before calling $Composite$, we apply the composition operator, defined in (10) below, to the elements of the vector $\vec{b}$ in order to *chain* them.

4.3. Application to the Smart Grid

The aim of our design framework is to provide a domain specific language for CPS. The language needs to embrace the application domain of the CPS to provide relevant syntactic elements. In the smart grid domain of application, we distinguish the composition operator that is used to build a structural composition between two elements that may be a macro-grid [11], micro-grid [12], or a grid component [13].

The term $Component$ is a generic term that represents the elements of the Smart Grid [14]. This term is a generic one for grid elements like:

- Asset Management Systems: elements used to help in the optimization if the OpEx and CapEx.
- Building Automation and Control System (BACS): elements including the control and management technology for building, plant, facilities, etc.
- Decision Support Systems: elements used to protect the equipment from fatal faults and avoid instabilities and blackouts in the power systems.
- Distribution Automation: elements that promote automatic self-configuration and self-healing features.
- Distribution Management System (DMS): elements used as the control center for the distribution grid.
- Energy Management System (EMS): elements used as the control center for the Transmission grid.
- Power Monitoring Systems: elements that supervise all activities and assets/electrical equipment.

- Smart Consumption: elements that lie at the interface between distribution management and building automation.
- Smart Generation: elements used for fluctuating generation from renewable energy.
- Smart Homes: elements representing houses that are equipped with a home automation system and may generate green energy.
- Smart Meter: remotely controllable electronic meters, also called Advanced Metering Infrastructure (AMI).

As this components list is not exhaustive and terminology is standardization is still ongoing, the proposed composition language will evolve to meet the standardization effort under the leadership of NIST (United States National Institute of Standards and Technology) that is yielding good results as illustrated by the NIST Framework and Roadmap for Smart Grid Interoperability Standards (NIST-SP-1108, Release 3.0). Moreover, the behavior of each element varies depending on his physical and/or cyber properties, the proposed algebra allows the framework to decouple the behavior from the composition mechanism. In other words, the composition of the grid components needs to be agnostic to the execution context. In order to be more concrete, let us consider the case of three agents, as shown in Fig. 3. In this example, three communication channels are connecting these agents. A consumption channel c, a production channel p and a metering channel m. The definition of the tree agents' behavior that we using for our use case are given in (3), (4), and (5).

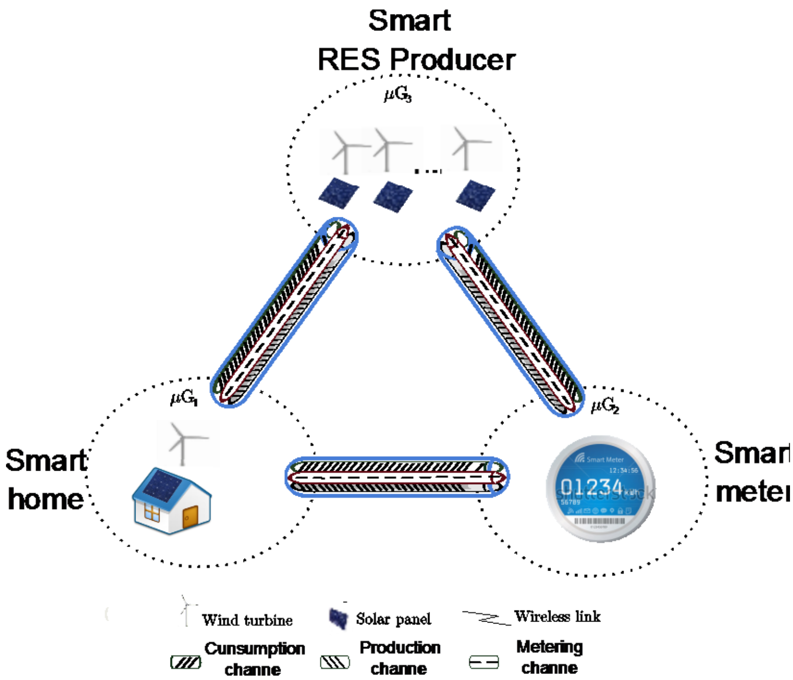


Figure 3: Algebra of three components

The agent $SmartHome$, as defined in (3) below, represents the behavior of a smart home that consumes energy reserved on the channel c, send a message to the smart meter on the channel m and, if the home is not producing energy, it sends a null value $\bar{p}\langle\emptyset\rangle$ on the channel p.

$$SmartHome() \stackrel{\text{def}}{=} in(c,m,p).\,(c(unit).\,\overline{m}\langle unit\rangle.\,\bar{p}\langle\emptyset\rangle).\,(\nu\, p')\overline{out}\langle p,m,p'\rangle \qquad (3)$$

The agent defined in (4) receive messages on the canal m about the usage and then executes a *non-observable action*. That means that in this example, the metrics are not observable at this abstraction level, only the exchange of the information influences this system.

$$SmartMeter() \overset{\text{def}}{=} in(c,m,p).(m(unit).\tau).(\nu\, p')\overline{out}\langle p,m,p'\rangle \tag{4}$$

In (5), we present a $SmartGeneration$ agent that represents a power generation behavior, this component produces power, sends it on the channel p and updates a smart meter using the channel m.

$$SmartGeneration() \overset{\text{def}}{=} in(c,m,p).\big((\nu\, unit)\bar{p}\langle unit\rangle.\bar{m}\langle unit\rangle\big).(\nu\, p')\overline{out}\langle p,m,p'\rangle \tag{5}$$

At this point, we define the term $Component$ that is used as *wrapper* for a behavior agent. This term is used to manage the input channel in and the output channel out that are used by the behavior agent to communicate.

$$Component(A()) \overset{\text{def}}{=} (\lambda\, in\ out).A().(\nu\, out')[out\ out'] \tag{6}$$

4.4. The composition operation

Now we define the *composition pseudo-application* ⊗ from an abstraction to a concretion with an equal arity. Let A_1 and A_2 be two behavior agents. We define two corresponding $Component$'s in (7.a) and (7.b) below.

$$Component(A_1()) \equiv (\lambda\, in_1\ out_1).A_1().(\nu\, out'_1)[out_1\ out'_1] \tag{7.a}$$

$$Component(A_2()) \equiv (\lambda\, in_2\ out_2).A_2().(\nu\, out'_2)[out_2\ out'_2] \tag{7.b}$$

The composition of the two components is defined in (8) as the substitution, in the sense of the lambda-calculus [15], of the input streams of the second $Component$ with the output of the first $Component$. In this way that the channels of production, management, and consumption will be shared by the two components.

$$Component(A_1())\otimes Component(A_2()) \overset{\text{def}}{=} (\nu\, out'_1)\left(\left\{{}^{out_1\ out'_1}/_{in_2\ out_2}\right\}A_2().(\nu\, out'_2)[out_2\ out'_2]\,\middle|\,(\lambda\, in_1\ out_1).A_1()\right) \tag{8}$$

The last part of our definition is there to enable the loop between the first and the last term on our composition chain. For that, we use the term $Composite$ to allow the input output substitution to end with a communication loop as defined in (9). This definition creates a fresh output channel out'' that is used as to communicate the outgoing information from the first component. In addition, this term uses the output of the last component out' transmitted by the concretion as an input for the first component.

$$Composite(Components()) \overset{\text{def}}{=} (\nu\, out'')\left\{{}^{out'\ out''}/_{in\ out}\right\}Components()[in'out'] \tag{9}$$

In order to have a more *user-friendly* definition of the smart grid design, we propose the definition of the composition operator ⊗ to include natively the input and the output channels without an explicit use of the term $Component$. This syntactic sugar did not affect the behavior of the composition operator as illustrated in (10).

$$A_1()\otimes A_2() \overset{\text{def}}{=} (\nu\, out'_1)\left(\left\{{}^{out_1\ out'_1}/_{in_2\ out_2}\right\}A_2().(\nu\, out'_2)[out_2\ out'_2]\,\middle|\,(\lambda\, in_1\ out_1).A_1()\right) \tag{10}$$

5. Illustration

To illustrate our approach, let consider a composition based on the terms defined in (3), (4), and (5). We can define a grid as in (11). Please note that here that we are using the syntactic sugar defined in (10).

$$Grid3E() \stackrel{\text{def}}{=} Composite(SmartHome() \otimes SmartMeter() \otimes SmartGeneration()) \quad (11)$$

The reduction of this system ends as a structural congruence with a composition of null processes. That means that this system is stable as illustrated in (12). With $GridE3'$ we denote the system $Grid3E,$ obtained after sending and receiving using all the channels.

$$Grid3E() \xrightarrow{\bar{p}\langle unit\rangle, \bar{m}\langle unit\rangle, \ldots} GridE3'() \quad (12)$$

$$GridE3'() \equiv GridComposite(\emptyset \otimes \emptyset)$$

The case illustrated in (12.a) and (12.b) is a simple case where the system ends. Another interesting case is where the system is acting as a loop. In this case, the reduction of the system leads to a structural congruence with the original definition as illustrated in (13.a) and (13.b).

$$Grid3E() \xrightarrow{\bar{p}\langle unit\rangle, \bar{m}\langle unit\rangle, \ldots} GridE3'() \quad (13)$$

$$GridE3'() \equiv Grid3E()$$

So how we can identify a design issue in the system? To answer this question, we redefine the consumption term $SmartHome$ for an infinite consumption as in (13). The reduction will highlight the fact that the system $Grid3E$ has load balancing to support the demand in terms of energy by the $rtHome$.

$$SmartHome() \stackrel{\text{def}}{=} in(c, m, p).!(c(unit).\bar{m}\langle unit\rangle.\bar{p}\langle 0\rangle).(\nu\, p')\overline{out}\langle p, m, p'\rangle \quad (14)$$

In (15) we illustrate the result of the reduction of the newly defined $Grid3E$. The two terms $SmartMeter$ and $SmartGeneration$ have been reduced, but the $SmartHome$ is still in the definition due to its new replicate definition. This is one of the most interesting contributions of this framework so far: we are able to identify, using the framework, the cause of the issue. As a result the designer can rethink his/her design and determine solutions.

$$Grid3E() \xrightarrow{\bar{p}\langle unit\rangle, \bar{m}\langle unit\rangle, \ldots} GridE3'() \quad (15)$$

$$GridE3'() \equiv Composite(\emptyset \otimes \emptyset) \mid SmartHome()$$

6. Conclusion

Defining appropriate concepts, methods and tools both for the design and test of CPS, in the case of the example here for smart grids, is a huge challenge and research in this area is of critical importance. Since *smart grid* began as an idea of an overlay, on top of existing infrastructure, the languages and tools to help us design such systems are not mature enough to help us meet the significant economic, technical and strategic challenges brought by the smart grid concept. The challenges of doing the same for CPS is the more general case.

Our efforts here are intended to help the designer and tester think about their activities and to study the critical metrics for CPS success in a conceptual and disciplined way. To this end we offer an algebraic domain specific language called CPS-DSL and abstract notion of composition.

Our future work will focus on the extension of this language to support a more precise definition of system elements, including the definition of the behavior agents and extension to address other CPS application domains. Moreover, we are designing a tool to help the designer to *reduce* the CPS-DSL definition in order to be able to identify design issues. This tool will provide, for example, automatic design suggestions based on issues or concerns identified for a system design or for an actual system.

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