21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

Model Based Systems Engineering Concepts and Methodologies for Modeling of Renewable Power Plants

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Abstract. Model-Based Systems Engineering (MBSE) is the formal application of a model-centered methodology for the design activities of engineered systems, being especially useful to support design requirements verification and validation of complex systems. The complexity of a system can be measured according to the number and relationships of the system elements. The design of renewable power plants has grown in complexity in last few decades, due to the integration of new technologies and the application of grid-code requirements. In this paper, a review of MBSE main concepts and leading methodologies (processes, methods, and tools) will be made with the objective of analyzing its application on the renewable power plants modelling and design.

Key words. Model-based systems engineering, renewable power plant, complex system, model, methodology.

1. Introduction

The design of renewable power plants brings up challenges to engineering teams due to its complexity and the need of integration of different engineering disciplines. Normally, engineering practices are based on a document-centric approach and require engineers to manually generate design artifacts like: specification documents, sheets, diagrams, etc. Nowadays, the use of engineering software as a tool to support the design and analysis of renewable power plants is more common. Engineers can rely on software for the realization of complex calculations, and for the verification and validation of the power plant behavior during operation. This is especially important when the power plant is going to be connected to the grid. In this case, legislation and grid code requirements have to be met in order for the plant to be approved for connection. Thus, proper modelling and simulation of the plants structure and behavior becomes crucial for the realization of the project.

There is extensive research already done on the modelling of renewable power plants from the point of view of their electric and technical behavior. RMS and EMT models of different levels of complexity are being used to verify and validate the power plants compliance with the electrical and technical requirements established on grid codes. Software tools like Power Factory, MATLAB/Simulink, and PSSE are being extensively utilized for this purpose. Other powerful tools are used for weather conditions simulation, control design, mechanical and civil structures design. In this distributed design context, the analysis of the overall system is done in an iteratively process to integrate the simulation data provided by every discipline design team. As a result, the design process becomes complex and prone to errors, which leads to rework and time and money losses.

Some research has been done to model energy systems from a systems perspective. An off-grid hybrid photovoltaic-wind power system model based on MBSE is presented in [1]. A Goal-Oriented Requirements Engineering (GORE) method, based on MBSE for System of Systems, is applied to the requirements analysis of a photovoltaic-diesel microgrid in [2]. In [3] the author illustrates how MBSE can be applied to a Smart Grid structural and techno-economic analysis. But none of these researches have applied MBSE to the design analysis of an on-grid power plant that involves the verification of grid code requirements.

The purpose of this work is to review the existing systems engineering concepts framework and the MBSE modeling methodologies, to contribute to the analysis of its application for the modeling of grid-connected renewable power plants. With aims of developing a standardized method for grid code requirements verification and plant behavior validation from a model-based perspective.

2. Model Based Systems Engineering Concepts

A. *Systems Engineering*

In general, engineering can be considered as "the practice of creating and sustaining services, systems, devices, machines, structures, processes and products to improve the quality of life of the users." [4] There exist many definitions of systems engineering, but it can be thought to be the engineering field that handles the design, integration and managing of systems from a systems' perspective.

Although, the origins and first definitions of modern systems engineering can be traced back to the 1930s, it was not until 2002 with the publication of the ISO/IEC/IEEE 15288 international standard that systems engineering was formally recognized [5]. The 15288 international standard defines system engineering as an "interdisciplinary approach governing the total technical and managerial effort required to transform a set of stakeholder needs, expectations, and constraints into a solution and to support that solution throughout its life." [6]

The International Council on Systems Engineering (INCOSE) defines systems engineering as "a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods." [7]

Holt and Perry on their book 'SysML for Systems Engineering' make an extensive review of systems engineering concepts and define it as "a multi-disciplinary, common-sense approach that enables the realization of successful systems." [5] Where a successful system is "one that satisfies the needs of its customers, users and stakeholders."

B. The Concept of System

The ISO/IEC/IEEE 15288 international standard establishes that a system is "a combination of interacting elements organized to achieve one or more stated purposes." [6] INCOSE gives a more expanded definition of system as "an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements." [4]

While these definitions cover the systems created by systems engineers (the engineered system), it is also necessary to consider the need, which serves as starting point of the system life cycle, and it is part of the system context. The system context includes the natural or social problem situation (the need or requirement), the social system or systems that develop, sustain and use the engineered system, and also the commercial or public enterprises in which all of these sits as a system [8].

The MBSE ontology developed by Holt and Perry in [5] resumes the concept of system as follows:

> "A system is a set of interacting elements organized to satisfy one or more system context. Where the system is a system of systems, its elements will be one or more constituent systems, and where the system is a constituent system, its elements are one or more system elements", being a system element "one basic part of a constituent system."

It also defines requirement as "a property or capability of a system that is either needed or wanted" by the customers, users or other stakeholders.

C. Model Based Systems Engineering

A model can be defined as a simplified representation of a real system from a particular view or system context, with the intention to assist the understanding of the real system [9]. As representations of a system, models can be used to capture, analyze, and/or communicate information about the system [10]. Engineers have used models and simulations for some time with two main purposes [4]: i) Validation of calculations/analysis and verification of the behavior of the system; ii) To communicate the concepts and architecture of the system to others. A model will present a clear and coherent design to those who will develop, test, deploy and evolve the system.

The main purpose of modeling and simulation is to obtain as much information as possible about the system, before significant resources are committed to its design, development or construction. A proper and well-defined model allow the analyses team to gather important data of the system in an affordable and timely manner to support the decision-making processes. Models also help development, deployment, and operational staffs to comprehend the design requirements and constraints of the technology, management and operation of the system.

MBSE emerges from the need to stablish standardized tools and methods for modeling and verification of systems. MBSE can be defined as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." [8]

The MBSE approach is known as "the model-centric approach" and is expected to replace the long time used "document-based approach." [5] The main difference between the two approaches is the nature or type of artifacts produced during the engineering activities. With the document-based approach engineers manually generate sets of text documents, spreadsheets, diagrams, and representations of the system. The problem with this approach is that it is time consuming and inconsistency and error prone. With the model-based approach, the model becomes the primary artifact of the engineering process [11]. All diagrams and text documents can be generated from the model and become merely views of the system model. In this way, if the model changes, the diagrams and documents also change for the entire engineering team, avoiding inconsistencies and errors. Furthermore, the value of modeling increases as the complexity of the system or system of systems also increases. According to [5] most system disasters during construction or operation are caused by systems complexity, lack of understanding and communication issues. The MBSE approach provides the "ability to detect limitations and incompatibilities early in a project and helps avoid higher project cost and schedule overruns later in a project, especially during system operation." [4]

3. Renewable Power Plants as Complex Systems

Complexity can be defined as “a measure of how difficult is to understand how a system will behave or to predict the consequences of changing it.” [12] According to ISO/IEC/IEEE 24765:2017, it can also be defined as the “degree to which a system’s design is difficult to understand because of (its) numerous components or relationships among components.” [13] In this way, complexity can occur when the relationship of the system elements cannot be described as simple, or when an element of problem solving is included in the system in order to achieve the system’s goals [8].

An interdisciplinary complex system can be defined as a system characterized by a numerous number of elements and/or constituent systems in interaction that require the integration of various engineering disciplines know-how [14]. The design of such a system becomes a collaborative task, that requires high-quality efficient systems engineering activities and communication across different multidisciplinary teams using a variety of tools and methods [15].

The principles of complex systems according to [12] are applied and analyzed for a converter-based grid-connected renewable power plant and the results are presented in Table I. A comparison is made to a Smart Grid based on [16], [17]. It can be said from Table I that a renewable power plant cannot be strictly classified as a complex system, because its operation can be controlled by or depends on a central authority. Despite this, a renewable power plant is highly complex since it meets all the other complexity principle that were included in this analysis.

Table I. Principles of complex systems analysis.

	Renewable Power Plant Grid-connected Converter		**Smart Grid**	
1. Autonomous interacting parts (heterogeneous elements)	From an operations point of view, wind generators or PV arrays cannot be considered autonomous elements since they alone cannot take decisions on when or how much energy to generate. Converters are also non-autonomous elements given that they need a control to govern their actions.	N	Autonomous elements of a grid can be: conventional power plants, converter grid-connected power plants, micro grids, storage elements, transmission system, distribution systems, load centers, etc.	Y
2. Self-organization	Elements of a power plants self-organize to keep their operation point within the stability limits or requirements of the grid.	Y	A smart grid acts as a self-organizing system maintaining balance between generation resources and load demand.	Y
2.1 Energy in and out (examples)	Primary energy source (wind, sun light), and active and reactive power delivered to the grid.	Y	Active and reactive power energy from generators and active and reactive power demanded by users and system losses.	Y
3. Display emergent macro-level behavior	The dynamic behavior of a grid-connected power plant shows an emergent behavior that differs from that of its elements. The behavior of the plant can only be predicted, managed, or controlled by understanding the relationships of the plant elements.	Y	It is been proven by [18] that an electrical grid shows an emergent behavior which responds to a "power law" different from that of the grid elements. The behavior of the grid can only be predicted, managed, or controlled by understanding the relationships of the grid elements.	Y
3.1 Nonlinearity	Power electronic converters and their control dynamics are highly non-linear at different frequency scales. Primary energy sources have a non-linear and non-predictable behavior.	Y	Grid dynamics show high nonlinear behavior, sometimes chaos, and non-longrun equilibrium as load demand is constantly changing. Nonlinearity of grid dynamics depend on the frequency of electrical phenomenon.	Y
3.2 Non-hierarchy and central authority	From the operation point of view, the plant follows the grid as a central authority for determining its operation point, and it also largely depends on the availability of primary energy sources to operate.	N	There is control hierarchy between grid elements, such as generators. There can be one Transmission System Operators (TSO), or more and can be seen as a central authority during operation.	N
3.3 Various scales of structure	Frequency/time scales for the plant dynamics: switching pulses, primary DC control, secondary DC control, etc.	Y	Frequency/time scales for dynamic phenomena: transient overvoltages, short-term stability, long-term stability, etc.	Y
4. Adapt to surroundings (environment)	Repowering of wind farms by more powerful and efficient turbine models, inclusion of new technologies for compensators and storage, more sophisticated controls for better compliance of grid code requirements, etc.	Y	Grid grows according to demand grow. Technology is evolving to reach the grid total decarbonization. Grid structure and operation are changing with distributed generation, new substations and lines, new types of loads, integration of prosumers, etc.	Y
4.1 Become more complex with time; increasingly specialized	Decarbonization of energy resources and generation is pushing plants' technology to become more complex and specialized: more powerful, efficient and controllable.	Y	Grid transition to decarbonized generation, integration of distributed generation and new types por loads, new types of energy markets for storage energy (BESS) or synchronous compensators, are making the grid operation more and more complex.	Y
4.2 Elements change in response to pressures from neighboring elements	Investment on renewable power plants in response to new policies and plans for decarbonization of energy. Integration of power electronics converters, static compensators, synchronous compensators, storage, power controllers, on plants for compliance with grid codes and contribution to grid stability.	Y	Grid operation and markets adjust to new prices and policies, new generators adjust to grid codes and integrate new technologies and compensators, consumers become prosumers, small consumers enter the variable energy market and adjust their demand for better prices, etc.	Y

4. Renewable Power Plants as Cyber-Physical Systems

Another way of analyzing a renewable power plant as a system is to consider its cyber or computer-based parts in interaction with its physical parts. Cyber-Physical Systems (CPS) refer to the "integration of computation with physical processes whose behavior is defined by both cyber and physical parts of the system. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa." [19] See figure 1.

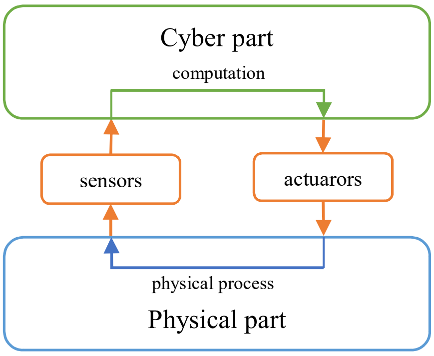

Fig. 1 Interaction between the cyber and physical parts of a cyber-physical system (CPS), based on [20].

The majority of current renewable power plants are built from physical and cyber parts. A typical topology of the cyber and physical parts of a photovoltaic (PV) plant can be seen in figure 2. Physical parts are responsible for the exchange and transformation of energy, and the cyber parts deal with data monitor and processing, communications, and energy and resources control [21]. As the process of decarbonization of energy advances, the cyber parts of plants are increasing on usage and sophistication, with the objective that energy systems will exhibit more flexibility, efficiency, sustainability, reliability and security [20], [22].

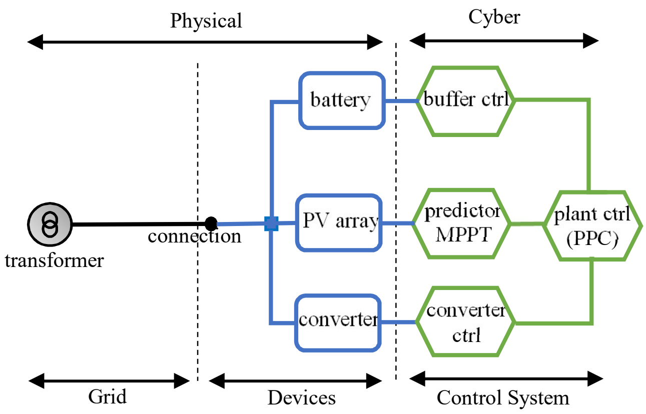

Fig. 2 Cyber-physical topology of a typical PV power plant, based on [20].

According to [22], some examples of cyber-physical developing technologies applications in renewable power plants, among others, can be: i) Advanced power plant controllers for energy control; ii) Advanced energy management systems; iii) Big data for energy management and control; iv) Machine learning for renewable resources and demand forecast; v) Advanced metering infrastructure; vi) Digital-twin models for operation and maintenance.

New models that include the impact of cyber parts on plant's behavior and the grid are necessary. On [21] a survey of research activity on energy systems from a CPS approach is presented. These areas of research include: i) modeling of energy systems; ii) energy efficiency; iii) energy resource management; and vi) energy control. There is lot of experience on the application of MBSE to the design and modeling of CPS systems and embedded computers in industries like automotive, aerospace and defense. MBSE offers advantages for CPS modeling such as [23]: i) enabling of a platform form bringing together different related models of the system, ii) broad in scope for multiple stages of system development and disciplines, iii) allows for the development of prototypes; iv) facilitates communication among disciplines; v) provides tools for management of system complexity.

5. MBSE Methodologies

In general, a methodology can be defined as "the collection of related processes, methods, and tools used to support a specific discipline." [24]

"A MBSE methodology can be characterized as the collection of related processes, methods, and tools used to support the discipline of systems engineering in a "model-based" or "model-driven" context." [25] Some leading MBSE methodologies being applied by various industries to support systems engineering practices for systems design and development are being reviewed hereafter. This review aims to find suitability of methodologies for renewable power plants design or modeling. It is not intended to be a throughout review. For the interested reader, more information on MBSE methodologies can be found on [25]-[29].

Most MBSE methodologies review in this work, utilize or are based on a lifecycle development model. There are three lifecycle development models mostly utilized by industry and academia, a brief description of the three is offered here based on [8], more information can be found on a large volume of literature: i) The waterfall model: traditional and sequential, each phase of the development process wraps up completely before the next phase begins; ii) Spiral model: iterative and incremental, it goes through each phase of the development process as many times as necessary; iii) Vee model: it includes a decomposition and definition line, that goes from concept to implementation phases (first line of the "vee"), and a system test and verification line for every phase (second line of the "vee"). Many modified versions of the Vee model have been extensively applied in areas of system engineering and systems development.

A. INCOSE Object Oriented System Engineering Method (OOSEM)

It is a traditional top-down process, scenario driven, model-based, system engineering approach to support the specification, analysis, design, and verification of systems [25]. Its main objectives are: i) Capture as much information as necessary, throughout the life cycle of the system, to specify, analyze, design, verify and validate the system; ii) Integrate MBSE methods with object-oriented software and/or hardware; iii) Support system-level models and design reuse.

The OOSEM process is consistent with a typical "Vee" lifecycle development model. It utilizes object-oriented concepts such as blocks (classes), value properties, generalizations, specializations and objects, and unique techniques [4]. The system development activities include: i) Analyze stakeholder needs; ii) Define system requirements; iii) Define logical architecture; iv) Synthesize candidate allocated architectures; v) Optimize and evaluate alternatives; vi) Validate and verify system.

OOSEM is supported by the Systems Modeling Language (SysML) and tool support for OOSEM can be provided by SysML-based tools and associated requirements management tools.

B. IBM Rational Telelogic Harmony-SE

It is service request-driven, model-based, "Vee" process approach to support requirements analysis, system functional analysis and architectural design of systems [25]. It assumes that model and requirement's artifacts are maintained in a centralized repository. Test cases and test data for system verification and validation, are also kept in a different centralized repository. Its main objectives are: i) Identify or derive required system functionality; ii) Identify associated system states and modes; iii) Allocate system functionality and modes to a physical architecture.

The service request-driven modeling process is supported by SysML structure diagrams, using blocks as basic structure elements. Communication between blocks is based on messages or signals that are interpreted as service requests between the system's elements or parts [5]. The work flow on the Harmony-SE follows three top-level activities: i) Requirements analysis; ii) System functional analysis; iii) Architectural design.

The Harmony-SE processes was developed to be tool and vendor-neutral, however it is supported by IBM Rhapsody software along with DOORS for requirement management. One important highlight is that Rhapsody allows the integration of models and simulations with Simulink, making it possible to convert SysML models into Simulink models and vice versa [15].

C. Vitech MBSE Methodology (STRATA)

The Vitech methodology organizes the development process into four main activities or domains [26]: i) Source requirements analysis; ii) Functional behavior analysis; iii) Architecture synthesis; iv) Design validation and verification.

These four primary concurrent activities are linked and maintained through a common system design repository, and are considered elements of a particular context domain. It uses an incremental process known as "Onion Model", that allows complete solutions at increasing levels of detail. This process supports top-down, reverse engineering and middle-out system approaches, defining sub-activities for each system approach. It distinguishes three system concepts: the system context, the system under design, and the system used to design the system [25], [28]. It needs an agreed-upon System Definition Language (SDL) to manage model artifacts. The software tools that supports the Vitech MBSE are CORE and GENESYS. GENESYS has a built-in behavior simulation and can connect to MATLAB, Simulink and DOORS. It also offers add-ins to be installed in MS Excel and Power Point to connect them to the design repository.

D. ARCADIA

It is an integrated modeling methodology for interdisciplinary domain activities of complex systems. Besides adopting many SysML concepts, it introduces a metamodeling concept. The structural behavior is defined through diagrams with interlinked relationships that represent activities occurring between interdisciplinary elements. These diagrams and their relationships conform the metamodel [28]. ARCADIA is focused on structure and functional analysis, thus provides robust ways of dealing with strong constraints related to cost, performance, safety, security, reuse, consumption, and weight. It introduces four levels of engineering or engineering perspectives: i) Operational analysis; ii) System analysis; iii) Logical analysis; vi) Physical analysis. The first two perspective cover the expression of the need, and the las two cover the expression of the solution [30].

ARCADIA provides its own modeling language and it is supported by Capella, an open-source software tool.

6. Conclusion

MBSE has proven to be a powerful design technique for complex and cyber physical systems that require the integration of interdisciplinary analysis and tools. For the application of MBSE to the design of renewable power plants, a comprehensive review of MBSE concepts theory and leading methodologies has been made. Methodologies have been assessed considering their methods (system' perspective and analysis, and main objectives) and available tools. Renewable power plants are highly complex systems and can be designed and modeled focusing on structure and operational analysis, for the compliance of strong constraints, such as cost, performance (grid code requirements), safety and security. For this purpose, the ARCADIA/Capella methodology has been found to be more suitable. Also, renewable power plants can be analyzed as cyber physical systems where control plays an important role on their overall performance. For the design and modeling of renewable power plants from their control's perspective, the OOSEM and the Harmony-SE/Rhapsody methodologies have been found more suitable.

Acknowledgement

The authors gratefully acknowledge the support from the Basque Government (GISEL research group IT1522-22) and from Sener Energy and the Hazitek Project "Towards Model Based Enterprise (TMBE)". Special thanks to Arkaitz Ruiz Barbero for his always positive advice.

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