Adopting system engineering methodology to Virtual Power Systems design flow

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Abstract—**The concept of Virtual Power System (VPS) emerges as a promising response for increased concerns on secure, sustainable and at the same time 'clean' energy supply requests. This novel concept aims at boosting operational efficiency of Distributed Energy Resources (DER) but also at establishing them as an autonomous commercial actor on the open energy market. Nevertheless, VPSs are fairly complex HW/SW systems that require holistic multidisciplinary approach and also novel specification, modeling and analysis instruments to facilitate mutual understanding among stakeholders from different fields.**

We introduce UML/SysML based modeling methodology to describe such power system related issues aiming at providing an unified modeling instrument applicable for VPSs design flow. In the proposed system engineering methodology, system representation starts from a very general context description and gets refined through different levels of abstraction down to concrete embedded systems employed to perform defined tasks.

I. Introduction

Awareness to global climate changes caused by different kinds of pollution on the one side and increasing concern about sustainable energy supply on the other side have created a global sensitivity to energy efficiency as well as an interest in finding pollution-free and sustainable solutions. Pushed by such scenario, 'green' technologies are getting considered in an increasing number of fields ranging from transportation and power systems to building efficiency management. Enabling technology and main driver for realization of such envisaged concepts are information and communication structures and in particular embedded systems.

A novel concept of Virtual Power System (VPS) has been introduced by the AlpEnergy research project [1] and it aims at efficient integration of DERs - Distributed Energy Resources (including energy storages and consumers) in a single entity in technical and commercial sense. A cluster created in this manner would be able to autonomously participate as an actor in energy market and trade energy still providing reliable supply and optimal energy prices for customers and producers inside it. VPS covers wide range of commercial, power system and ICT (information and communication technology) related issues. Nevertheless, due to the fact that many heterogeneous and uncontrollable generators must be coupled together with indeterministic open market conditions, such systems require complex and robust ICT solutions to support needed technical and commercial advances. This in turn could create an opportunity for development of a new generation of embedded systems in form of customized platforms that could be deployed in VPS to provide its optimal operation.

In that sense VPS represent a cross-disciplinary topic in which many fields as automation, control, finance, legislation and many more, meet. Tackling the challenge posed by system complexity and interdisciplinary cooperation, requires a holistic and standardized approach which systems engineering provides.

In this work we introduce a specification, modeling and analysis methodology for VPS design flow developed in scope of AlpEnergy project. The methodology is based on UML/SysML system engineering approach [2]. We aim at providing an instrument to cope with the complexity of the VPS providing a communication platform for stakeholders coming from different fields and at the same time facilitates analysis, simulation and design of the system.

The final result of the project would be an instrument that formally describes the system context, efficiently gathers user requirements, transfers them into system requirements and ultimately into concrete functional requirements for system components.

The paper is organized as follows: Section II, provides a review on existing solutions for DER integration and system engineering concepts. In Section III, a conceptual, general structure of VPS is presented and explained. In Section IV the system engineering, model-based design methodology is exposed, while in Section V we provide as a case study simplified UML/SysML modeling methodology which shows the design flow from context description to concrete smart-metering solutions. Finally, Section VI presents conclusions and future work.

II. State of the art

Global energy demand growth urges for evolution of modern power systems in both commercial and technical terms. The Smart Grid [3], [4] concept has emerged as a promising response to these needs. Nevertheless, such complex system will require tremendous amount of data to be collected, transmitted and processed (in real time) which will pose another challenge to underlying ICT structures. Such scenario calls for partitioning and clustering of SmartGrid in certain autonomous modules.

On the other hade, efficient integration of heterogeneous distributed energy resources represents another challenge to be tackled by power systems engineers (several international research projects are dealing with this issue). Considering these facts, Virtual Power Plants (VPP) [5], [6] have been introduced as a means to aggregate DERs and represent them as a single, autonomous entity/module inside SmartGrids. The VPP concept aims at leveraging security of energy supply coming from renewable resources with their optimal commercial exploitation. In that sense it aims at presenting DERs in form of reliable, independent actors at energy markets able to trade its produced energy in an optimal way. It interacts with electricity Distribution System Operators (DSO) and energy market according to set of defined legislative rules. Integration of various micro-plants and renewable generators into VPP which is an aggregation of DER takes into account the actual location of individual DERs in the network. VPPs will have flexibility and controllability to provide different services to energy and ancillary services markets [5]. Such concept requires novel communication, control and automation solutions at lower DER level requiring new generation of embedded systems to be developed. At the higher VPP level, novel Energy Management Systems (EMS) have to be developed.

The Virtual Power System (VPS) can be seen as an extension of VPP. It actually additionally considers integration of consumers and prosumers (producer-consumer) entities in the system with renewable generation.

Nevertheless, such complex and inter-disciplinary concepts require appropriate instruments to manage user requirements collection and design complexity. In order to efficiently manage design of complex systems many system engineering and modeling concepts and languages have been introduced. In other environments, system-level specification languages have been introduced and are by now fairly widely used. AADL [7] has been introduced mostly for the purposes of modeling complex systems in avionics and space domain with an aim of expanding to other field. SysML [8] has been introduced as an extension of UML [9] for specification and modeling of complex systems including hardware components, personnel, facilities etc. Recently MARTE [10] has been proposed as a UML profile for modeling and analysis of real-time and embedded systems.

In the scope of our project we use UML/SysML language as it is currently the most widely accepted specification instrument and modeling standard in both industry and academia. UML has been already introduced as a modeling tool for finance issues and through the CIM [11] standard in power systems engineering.

III. Virtual Power Systems overview

The Virtual Power System (VPS) concept has been developed in scope of AlpEnergy project [1] with the aim of providing an instrument for efficient aggregation of renewable resources into an entity, seen from outside as one computational, communicational and trading module able to autonomously manage its commercial exploitation. The enabling technology for such concept is considered to be ICT in particular different types of embedded systems.

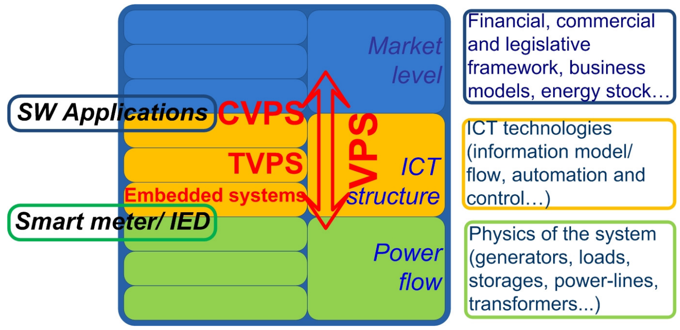

Fig. 1. VPS layered structure

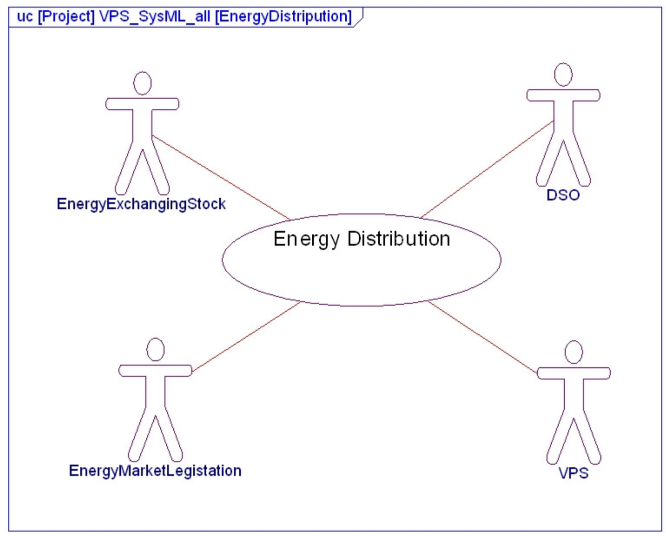

Fig. 2. VPS as an actor in energy distribution

The Virtual Power System (VPS) concept heavily relies on the VPP concept developed in [5]. The fundamental extension of VPP is the fact that VPS considers also involvement of storages, consumers and prosumers in the same system. Following its dual role to aggregate DER in a technical and commercial sense, the functionalities of VPP (and VPS accordingly) have been logically encapsulated in two entities [6]:

- Commercial VPP (CVPP/CVPS)
- Technical VPP (TVVP/TVPS)

CVPS considers DERs as commercial entities optimizing economical utilization of VPS portfolio in environment of an open electricity market [12]. In other words, the purpose of CVPS is to schedule an optimized DERs utilization and set bids to Energy Exchange Stock according to market conditions versus current and predicted demand/supply balance. The operational employment of particular DERs in technical terms is managed by the TVPS. It ensures that the power system is operated in an optimized and secure way, taking into account physical constraints and available resource. So that, in terms of service layers, TVPS is a lower layer providing services to the CVPS as a higher layer.

The place of VPS and its components is the power systems structure is represented in Figure 1. The relation of VPS with other 'external' actors can be represented in UML fashion as in Figure 2.

IV. System engineering methodology

The remarkable complexity and interdisciplinary nature of VPS calls for standardized and unified approach to its design. Many system engineering methodologies have been developed to tackle similar problems in safety critical systems such as avionics. Considering the nature of VPS we have chosen UML/SyML based approach as this language has been widely accepted. Moreover, it is already introduced in many fields that are correlated in VPS (like finance and power systems).

The methodology starts with project context description in which basic ideas and goals of the system are defined as well as system environment situation. The next step consist of stakeholders identification which is followed by requirements determination. The efficient translation of user requirements into system ones, requires a platform for mutual communication and understanding among variety of stakeholders from different fields. Precise and clear system requirements definition and structuring is a key step towards good system design. This is the place where SysML *requirements diagrams* are showing their importance.

Once well defined and organized, system requirements (functional and non-functional) are, by means of UML/SysML instruments (i.e. *use cases*, *activity diagrams*, *block definition diagrams*, *sequence diagrams* and finally *internal block diagrams*) mapped into functional requirements of concrete system components (i.e. embedded systems to be deployed in the field).

V. Case study - system engineering approach for VPS design flow

The VPS represents a strongly interdisciplinary oriented topic. Many issues from control, automation, communication, power and electronic engineering as well as commercial, financial and legislative field are interacting in this concept. For this reason an unified and simple yet efficient approach to the topic must be adopted.

Considering the analysis of system engineering approach in previous section, we have concluded that UML/SysML based methodology can be applicable for the required needs. In the sequel we apply and show step by step the proposed approach. It is important to mention that the analysis concern only a part of VPS concept but the topics discussed are chosen as an representative subset so that simplification of the model is done without loss of generality.

A. VPS project context

In the initial phase of project design many fundamental decisions have to be taken. The subsequent design heavily depends on this step and that's why it implicitly requires deep understanding among stakeholders. Basic ideas and goals have to be defined in a clear way and their impact on all sides concerned must be fully transparent.

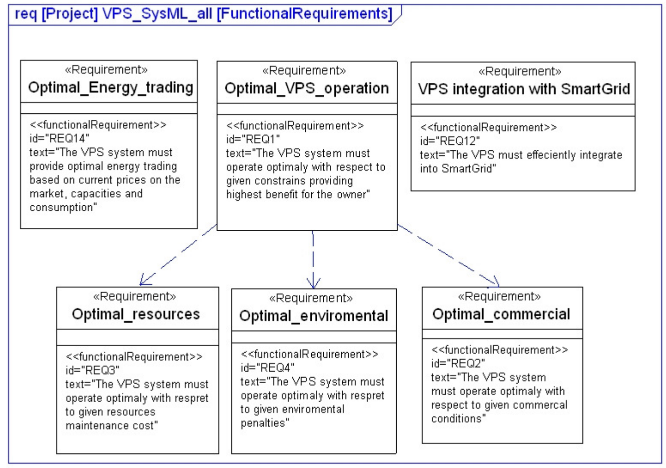

Fig. 3. Functional user requirements structure

At this point the project description is given in a textual form using common natural language as it is usual starting point for expressing thoughts and ideas. More formal description has to be derived through set of steps exposed later in the work.

The discussions yield project description in terms of VPS role and interaction with its environment, as follows. The basic goal of VPS is to aggregate heterogeneous, uncontrollable renewable resources (windmills, photovoltaics etc.) into single reliable entity in commercial and technical terms. In order to achieve such an aim additional energy storages and controllable generators (e.g. gas turbines) have to be introduced in the system. VPS has to interact with the rest of power systems and it is decided that it would operate at distribution level (middle and low voltages). It means that VPS would interact with Distribution System Operators (DSOs) to provide technically correct operation. On the other side, it would interact with Energy Exchange Stock in order to enable optimal economical performance of VPS.

B. Stakeholders identification and requirements determination

Based on the analysis given above, we have identified *stakeholders* involved in VPS operation. It is important to mention here that all the steps in the proposed methodology are subject to an iteration process in which some new actors or services related to VPS can be revealed and additionally inserted in the system description/model.

The selected stakeholders are listed here:

- Dispatcher
- VPS shareholders
- Distribution System Operator (DSO)
- Energy Exchange Stock
- Energy market legislation
- Local authorities
- VPS trading agent
- VPS operation manager

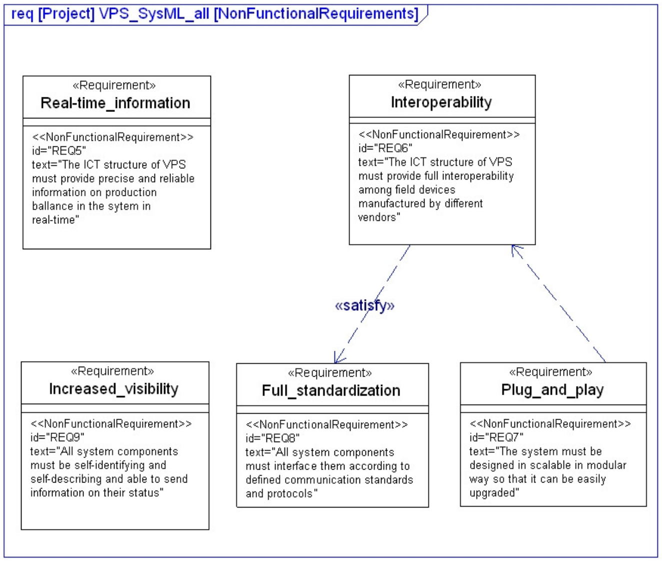

Fig. 4. Non-functional user requirements structure

Following stakeholder identification, their functional and non-functional requirements are determinated. Those requirement are at first 'coarse grain', technically imprecise and uncorrelated. In order to resolve possible collisions and to get more precise 'finer grain' requirements, further decomposition is needed. It is important to mention here that we distinguish, from the begging, between functional and non-functional requirements. As an example, we consider the selected set of VPS requirements gathered form stakeholders given in SysML form in Figures 3 and 4. Such a set of requirements represents only a simplified example that is used to show further decomposition steps. The requirements are organized and presented in a structured and hierarchical manner. This step marks the beginning of the transition process of user requirements into system ones. In a particular case, we choose to refine a requirement for 'optimal resources utilization' (given as *optimal resources* in Figure 3) by decomposing functional requirement according to [13]. Scenarios are represented as UML use case diagrams showing VPS interaction with relevant actors as given in Figure 1.

Sequence of actions that are necessary to fulfill user requirement of *optimize resources* is given in Figure 5. Based on those actions further decomposition of *optimize resources* requirement is done in order to obtain system requirements as shown in Figure 6.

C. System services description

Once we are aware of actors and system requirements we focus our attention to services that system must provide to satisfy stakeholders' demands. This actually means that we have to develop behavioral model of the system. For the sake of modeling system services and functionalities we use *use cases*. For each set of functional requirements a proper use case that refines them is defined as shown in Figures 7 and 8. this way, we have related system services (i.e. use cases) with

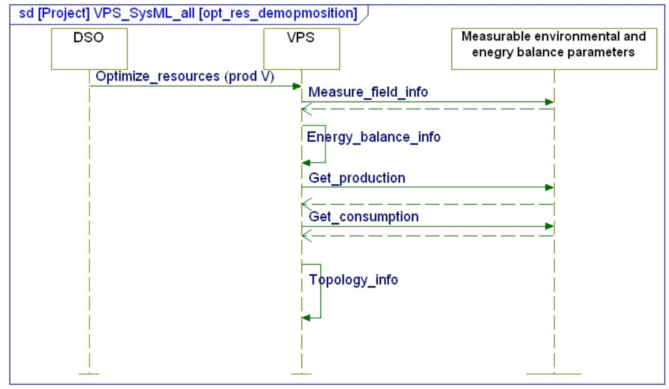

Fig. 5. Sequential diagram of 'VPS optimize resources' scenario

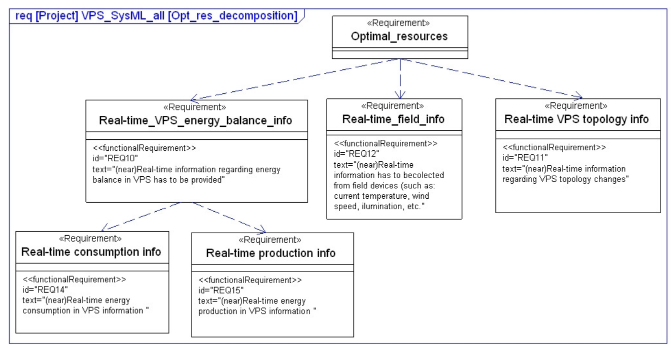

Fig. 6. System requirements obtained by decomposition of 'optimal resources' functional requirement

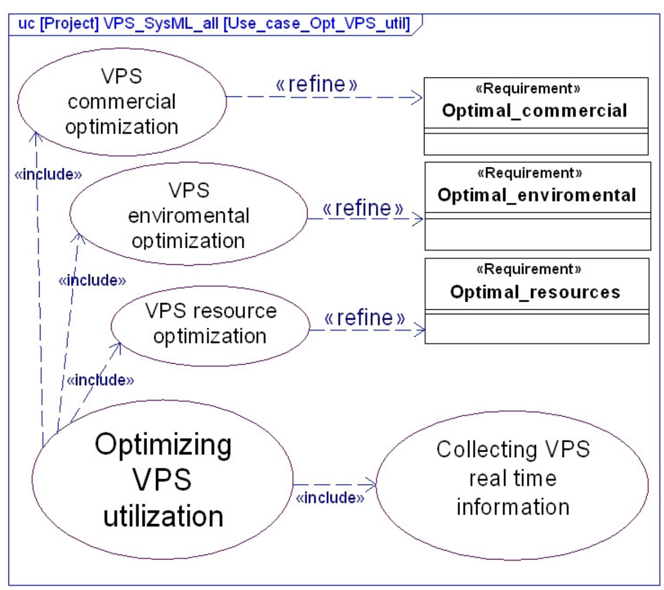

Fig. 7. Refining use cases, requirements relation

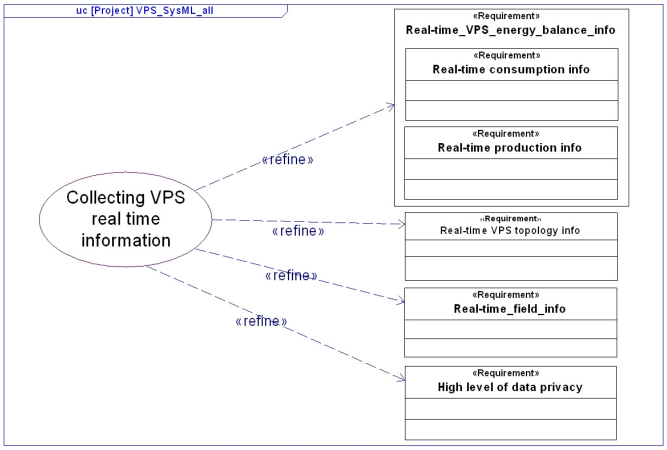

Fig. 8. Refining use cases, requirements relation

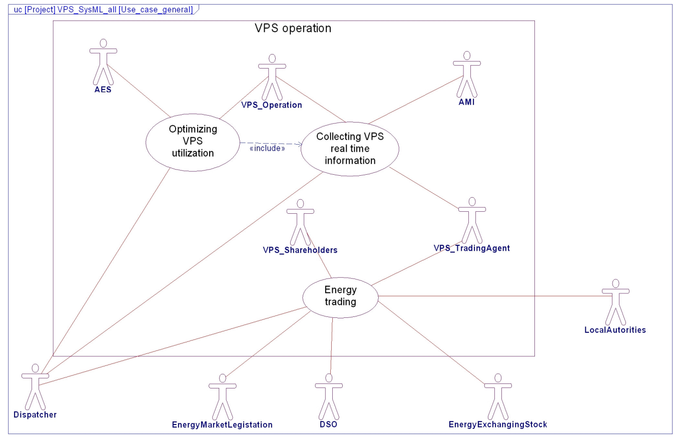

Fig. 9. VPS operation use cases

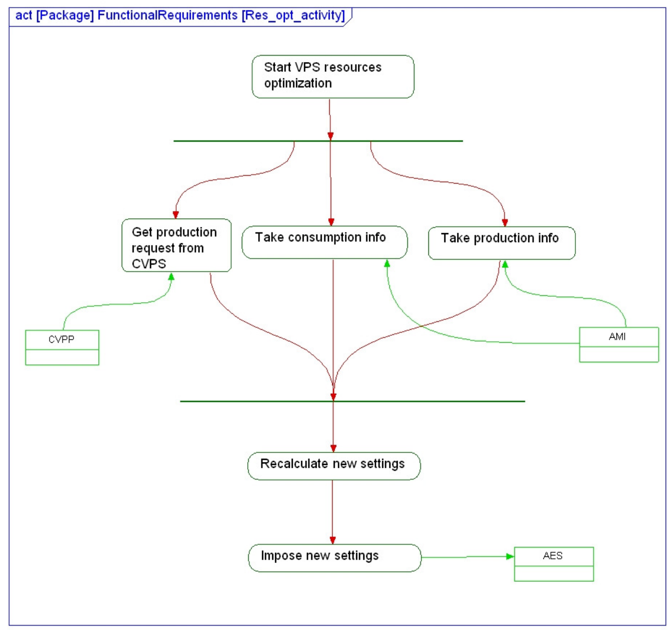

Fig. 10. VPS resources optimization activity diagram

appropriate system requirements. In Figure 9 we represent in a very general manner fundamental services (actualy use cases) that VPS must provide with related actors (stakeholders) involved in each of them.

Next step involves realization of use cases through activity diagrams. As an example we chose a use case of 'optimizing VPS resources' that is included in use case of 'optimizing VPS utilizations' (Figure 7).

Optimizing VPS resources represents system settings update done in regular time periods aimed at boosting efficiency of VPS resources utilization. These periods depend on the speed of environmental changes (i.e. pricing fluctuations, weather changes and so forth). Inside this period TVPS must recalculate new system settings based on production request from CVPS and current status of energy production/consumption (energy balance). The real-time (or 'near' real-time) information on energy balance in the system is obtained from use case 'Collecting VPS real-time information' through the Advanced Metering Infrastructure (AMI) [14] that represents a network of sensing, metering and measuring embedded system devices (i.e. sensors, smart-meters etc.). In the activity diagram in Figure 10 the resource optimization is represented through use cases flow. Activities of production/consumption information collecting (from AMI, that is represented as a component) and new request obtaining (from CPVS), are executed concurrently. The control and data flow are indicated in the diagram (represent as red and green lines respectively).

Upon reception of needed data and recalculation of new settings, TVPP imposes them into the system through the network of deployed actuating embedded systems (AES; i.e. Intelligent Electronic Devices (IEDs) and Programmable Logic Controllers (PLCs)).

D. System components

At this point we can start identify components (i.e. structure) of the system. For the sake of a methodology demonstration we will focus on AMI component. Below we describe its relations with the rest of the system (relating it with appropriate use cases it is involved in), using standard UML/SysML instruments.

Hence, we speak of static (structural) *block diagrams* and dynamic (behavioral) *sequence diagram* representations of interactions in the system. It is important to note that at this stage we do not distinguish between software and hardware components, they are both simply represented as blocks.

E. Optimizing VPS utilization - Block diagram

The appropriate components to realize use case given in Figure 9 have to be determinated and then represented in form of *block definition diagram*. Such a model shows relations among components and actors that are involved in realization of the use case of optimizing VPS utilization providing an insight in concrete structure of the system. The block diagram that represents these relations is given in Figure 12.

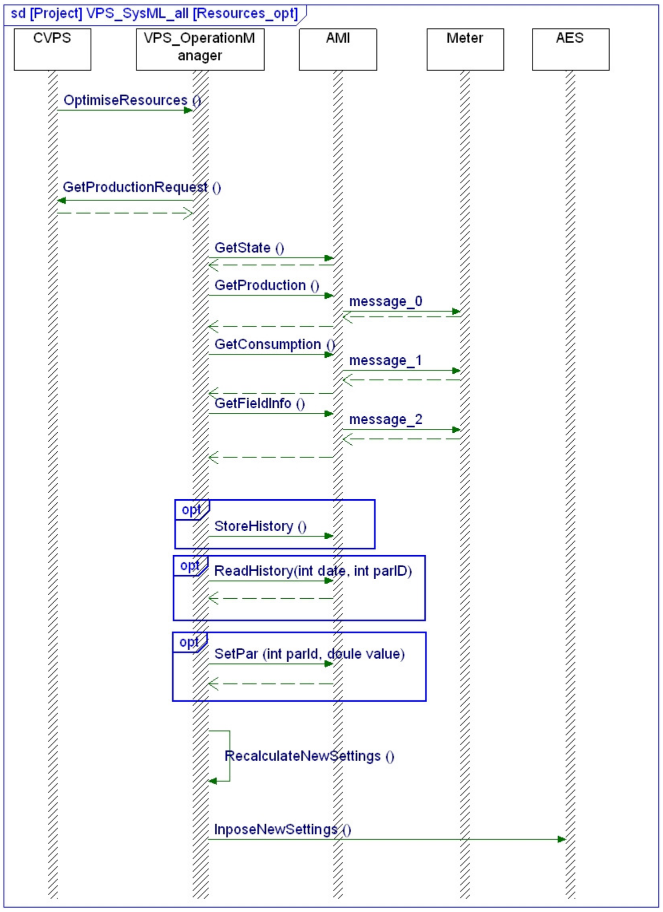

Fig. 11. VPS resources optimization sequence diagram

F. Optimizing VPS resources - Sequence diagram

Realization of use case of optimize VPS resources is performed through a given sequence diagram (in Figure 11) considering previously given block definition diagram. This figure shows dynamic interaction among components and actors that are involved in realization of the use case of optimize VPS resources. It provides a basic idea on system behavior.

G. AMI internal block diagram

Having determined all the components (of the considered use case), their relations and functionalities, we are able to propose a concrete realization for each of them. In our case we focus on a possible implementation of AMI internal structure. As an example of one possible solution for AMI we give simplified *internal block diagram* represented in Figure 13. Communication among components iis represented by *flow ports* with given flow specifications.

Internal block diagram gives a suggestion for concrete realization. These components represent concrete embedded systems (i.e. their functionalities and interconnections).

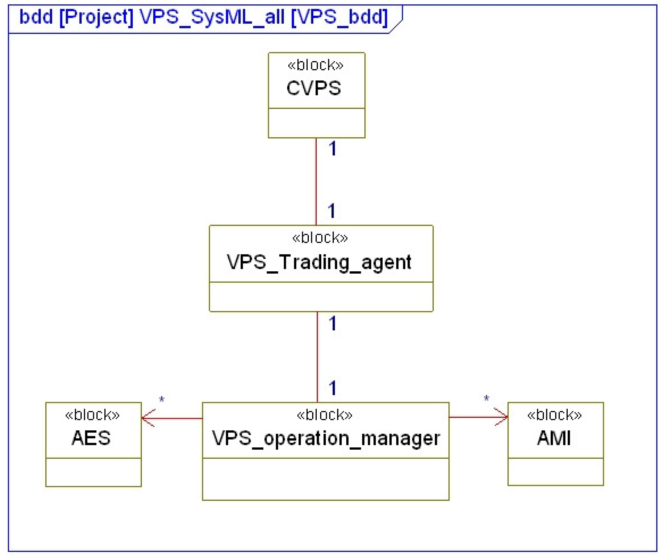

Fig. 12. VPS resources optimization block diagram

VI. Conclusion and ongoing work

VPS has been introduced as a response to growing concerns for sustainable energy supply. It is the concept developed in scope of AlpEnergy project which aims at providing an instrument for efficient aggregation of heterogeneous renewable resources into reliable commercial and technical entity able to independently acts at open energy market and interacts with other actors.

A relevant point that emerges from this and other studies is the fact that in many cases renewable resources are individually of too little relevance to be considered on the wide energy market, that they are highly heterogeneous and often not reliable from the ”continued availability” point of view. As a consequence, VPP and VPS emerge as solutions to aggregating such resources and leveraging their cumulative capacities; on the other hand, this requires a strong presence of ICT supports beyond the traditional energy management ones, namely distributed and ad-hoc hardware/software solutions consisting of suitable embedded systems. If the VPP-VPS concept is adopted, the diffusion of the above recalled embedded systems reaches a critical market mass granting future investments in their design and implementation. The goal of our study is creating the background analysis and assessment for such venture. Given the complexity of of the envisioned overall systems we introduce a system engineering methodology based on UML/SysML as a specification, modeling and analysis instrument supporting mutual communication and understanding platform among variety of stakeholders from different fields. The ultimate goal of this methodology is to reach a comprehensive description, eventually leading to the functional requirements, of embedded systems to be deployed as one of enabling technologies of VPS.

Our ongoing work concerns further expansion of the methodology with the aim of providing finer grain models,

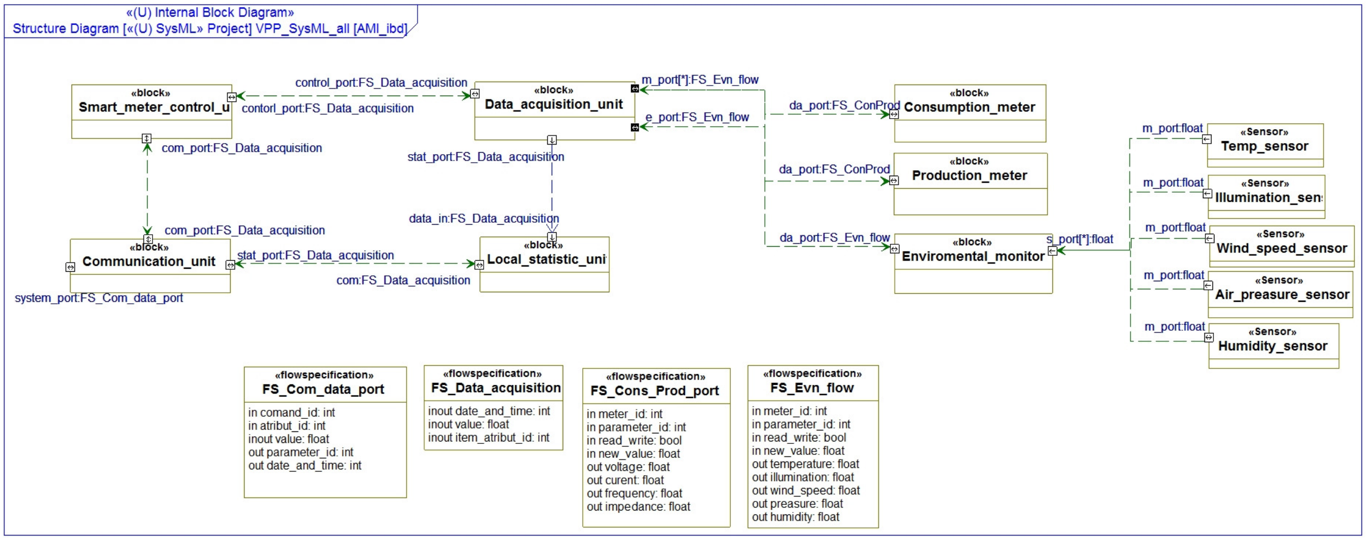

Fig. 13. AMI internal block diagram

internal block diagrams for concrete embedded systems and developing meaningful simulation strategies for developed models.

Acknowledgment

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