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MICROGRID SYSTEM DESIGN BASED ON MODEL BASED SYSTEMS ENGINEERING AND GOAL-ORIENTED REQUIREMENTS ENGINEERING

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Abstract— Microgrids appear as a practical, clean and reliable solution to meet the demand of populations that, for various reasons, do not have access to electricity. The complexity of microgrid systems, requires considerable engineering effort in the design process. To design this type of complex systems, new approaches, methods, concepts and engineering tools are needed. Where, the requirements analysis has a preponderant role to better characterize, understand and specify the application domain and the problem that the microgrids must solve. This work proposes the introduction of a formal analysis of requirements in the life cycle of microgrid systems, using IEC 61850 as a reference architecture. The requirements would be represented in an Object Oriented Requirements Engineering (GORE) approach, using specifically visual diagrams based on the KAOS (Keep All Objectives Satisfied) method, where the operation and control of the network will be formally represented. The requirements analysis is presented using a combined representation that uses the GORE and Petri Nets methodology for dynamic modeling and formal verification. A case study for small communities in the Amazon rainforest is used as a case study for the proposed method.

Keywords— System Design, Formal Modeling, GORE methodology, Petri Nets, microgrid

Resumo— As microgrid surgem como uma solução prática, limpa e confiável para atender a demanda das populações que, por diversos motivos, não têm acesso à energia elétrica. A complexidade de sistemas microgrid, exigem um esforço considerável de engenharia no processo de design. Para realizar o Design deste tipo de sistemas complexos, são necessárias novas abordagens, métodos, conceitos e ferramentas de engenharia. Onde, a análise de requisitos tem um papel preponderante para melhor caracterizar, entender e especificar o domínio de aplicação e o problema que as microgrid devem resolver. Este trabalho propõe a introdução de uma análise formal de requisitos no ciclo de vida de sistemas microgrid, utilizando a IEC 61850 como arquitetura de referência. Os requisitos seriam representados em uma abordagem de Engenharia de Requisitos Orientada a Objetivos (GORE), usando especificamente diagramas visuais baseados no método KAOS (Keep All Objectives Satisfied), onde a operação e o controle da rede serão formalmente representados. A análise de requisitos é apresentada usando uma representação combinada que utiliza a metodologia GORE e Redes de Petri para a modelagem dinâmica e verificação formal. Um estudo de caso para pequenas comunidades na floresta Amazônia é usado como um estudo de caso para o método proposto.

Palavras-chave— Projeto de sistemas, modelagem formal, metodologia GORE, redes de Petri, microgrid

1 Introduction

The growth in the consumption of electric energy in Brazil and in the world has represented a challenge for the energy sector, one of the alternatives found by the referred sector to overcome this situation is the use of alternative sources of distributed generation.

Advances in research and development of energy alternatives based on renewable sources are changing this scenario. In this context, microgrid arises as a technically and economically viable opportunity to meet the demand of populations who, for various reasons, had never (or have limited form) access to electricity.

Microgrid systems has a viable alternative to diversifying and streamlining energy supply needs, where fossil fuels are being replaced by renewable sources (solar and wind generators, biomass and combined heat and power systems, etc. (Liserre et al., 2010). The integration of renewable sources and changes in the consumption side are causing new challenges and offering opportunities in the electricity sector.

In this context, microgrid is emerging as a new research area in Brazil that is essential for the care of isolated communities. However, there are still gaps in the technical, economic and management fields. Addressing these technical and operational issues represents a breakthrough in knowledge, which can be translated into benefits for the microgrid assisted consumer through improvements in the quality of energy supplied and an economical tariff, as well as for the utility, through the implementation more efficient and sustainable systems.

Microgrids have been used for many decades as part of rural electrification programs in remote and isolated locations, mainly in developing countries. However, the modern concept of microgrids, involves their integration with the electrical system, mainly to the distribution network and with the potential to operate in connected or island mode.

Besides, microgrid have inherent complexity because they are eminently heterogeneous, open and distributed systems, that could be adapted to different situations and application environments. Such characteristics imply the modeling of knowledge domains that combine general and local information during the design process.

In this context, the life-cycle of the this systems becomes more important at the early phase, which is characterized by incomplete knowledge. On the other hand, in the early requirements phase, it is strategically easier to deal with difficulties originated by the lack of information or incomplete requirements and introducing changes that prove to be necessary. That turns the requirements phase a key issue for the success of the whole design.

A structured requirements phase emerges from the formalization of microgrid requirements, and became a recent trend in electrical systems which challenge researchers and developers. Consequences for the absence of formal methods to model and analyze requirements are studied for some authors (Silva and Silva, 2015) to reinforce the need of a new approach.

Despite the great variety of works related to the design of energy systems, there is still a growing demand to introduce modern, more robust, consistent, and flexible requirement engineering methods (Mazzolini et al., 2011).

Some models and architectures have been proposed, such as IntelliGrid by the Electric Power Research Institute (EPRI, USA) (Commission et al., 2008) or the Smart Grid Architecture Model (Uslar et al., 2012). Both claim to give relevance to the requirements phase, which includes requirement elicitation, based on IEC / PAS 62559 and modeling - using Unified Modeling Language (UML) (Uslar et al., 2019). Thus, a repository of requirements for Smart Grid systems was built, including features to transmission, distribution, and integration.

Working with informal requirements seems to facilitate the work, but it can lead to undetectable failures during requirements specification (where error costs are lower) including the possibility to miss non-functional requirement using approaches object-oriented such as UML. Also, the complexity of dealing with a distributed arrangement of subsystems is another important factor that justifies the use of formal approaches

This paper proposes a recent alternative approach to microgrid systems design is based on use of reference model architectures, as the IEC 61850 (Deng et al., 2015). This model architecture facilitates the design of automated microgrid systems and is currently being used by many researchers and designers of this area.

The proposal also includes a systems approach, that includes a method to generate a formal analysis model of requirements elicited based in GORE and represented in KAOS, in addition to, a schematic representation on Petri nets.

The advantage of the proposed method is the systematic way to obtain Petri Nets as a formal model that can represent the dynamic of the automated distributed system. In fact the KAOS method also generate a formalism in LTL (Linear Time Logic) and that could be used to analysis (Van Lamsweerde, 2009).

However, as any formalism based on logic and automata, LTL could not represent a distributed system in a compact form. To do that a product of different representations should be used. The Petri Net representation model can also support property analysis to be used on the requirements model.

The paper is organized as follows: Section 2 brings a conceptual description of the proposed method. Section 3 presents a new approach combining KAOS and Petri Net representation. A case study is presented in Section 4. Finally, a conclusion section resumes the method and suggests prospective contributions in further work.

2 Conceptual description of the Method

A general schema for the proposed method is depicted in Figure 1, where the target microgrid requirements is mapped in the architecture IEC 61850, modeled in KAOS to insert details and the interaction with the user, and then transferred (automatically) to Petri Nets to be formally verified.

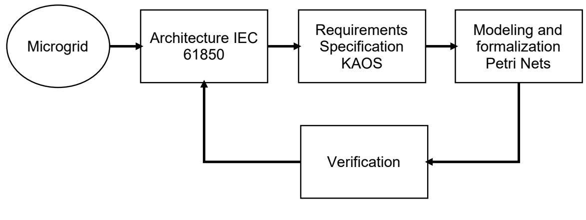

Figure 1: General schema of the proposed design method.

The microgrid initial scenario is defined by general information about the operational constraints, geographic characteristics, environmental and local restrictions. A reference architecture is selected to guide the process. For the proposed method we choose the IEC 61850.

A requirements model is then developed using Goal Oriented Requirement Engineering, and KAOS diagrams. Here, it is necessary to delimit the application domain and development scope, that is, define all inputs and outputs, interface and forms of communication.

The next step focus in the workflow model which is the base of the automation schema, which implies in transferring the KAOS model to Petri Nets. An algorithm called ReKPlan was developed by some of the authors to automate this process (Silva and Silva, 2019)(Silva and Silva, 2015). The main idea is to collect the reading of Intelligent Electronic Devices (IED) to feed the developed Petri net which could reproduce the dynamic of the microgrid operation using a system of systems approach.

Finally, requirements analysis and validation is performed evaluating behavioral properties and the performance target system, as well as the constraints and restrictions to the control automation algorithm.

In what follows we will describe in more details each one of the steps briefly mentioned in this overview of the method.

3 The Proposed Approach

The proposed method combines a new approach to requirements modeling, Goal-oriented Requirements Engineering (GORE,) with reference models frequently used in energy system design, normally applied to the operation of microgrids adding technical constraints and local peculiarities.

3.1 Microgrid System Scenario

Technically, a microgrid is a low voltage distribution network, located downstream of a distribution substation through a Point of Common Connection (PCC). The microgrid consists is a multisource system composed by conventional Renewable Energy Sources (RES), a storage systems and controllable loads, as shown in the Figure 2. The interface between the service network and the microgrid is used to interact with the microgrid; it provides voltage control, power balancing, and load sharing. A communications infrastructure, provide the transfer and exchange of data, in real time.

Therefore, microgrids play a key role in the integration of distributed generators and, in particularly in the integration of Renewable Energy Sources (RES)(Sechilariu and Locment, 2016). However, the intermittent and unpredictable nature of the power supply remains a problem to the integration with the service network, resulting in

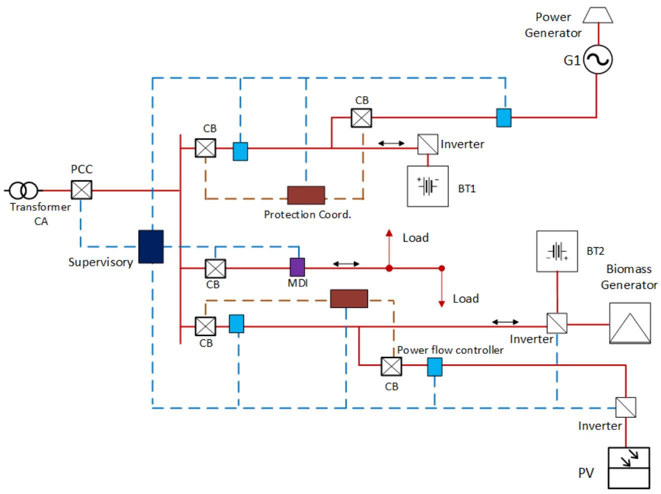

Figure 2: Proposed scenario for the microgrid

voltage and / or frequency fluctuations, harmonic pollution, and some difficulty in charge management.

On the other hand, there is great potential to develop and test new technologies for sustainable generation, specially in countries belonging to BRICS. The integration of these technologies has become a priority in microgrids in response to the pressure to implement a net of distributed energy resources, also including the integration of intelligent electronic devices. This arrangement should be surrounded by sensing and measurement systems, network nodes with computing capacities, actuation devices to allow supervision and the proper integration and coupling with user needs.

3.2 The Architecture IEC-61850

The IEC 61850 architecture was developed to define communication protocols to integrate power electric systems, focused in protection, control, monitoring and diagnostics functions in substations (Naumann et al., 2014). A multidisciplinary group was launched to create this standard in 1995.

More recently the standard was expanded to include the modeling of information tailored to the needs of the electric power industry (Berger and Iniewski, 2012), which includes the automation and distribution of electric systems.

Although the IEC 61850 originally addressed only substation automation recent versions also include additional information models based on the original standard to cover other domains such as renewable energy (Berger and Iniewski, 2012). In 2010, the US National Institute of Standards and Technology (NIST) recognized IEC 61850 as a major facilitator to design and implementation of microgrid systems.

One of the main goals of the current IEC 61850 architecture is solving interface problems and to provide a standard to communication avoiding the use of specific protocols defined by different manufacturers. Another goal is to provide a base to automation and control functions that allow electrical systems to evolve towards a microgrid mesh (Naumann et al., 2014).

Therefore, current versions of the standard include extensions and additional information models to micrograds domains. IEC 61850-7-420 provides information model and Logical Node (LNs) for distributed energy resources at the process level, including controllers, generators, power converters, DC converters, and auxiliary systems (such as smart meters and other devices). IEC 61850 7-1, 7-2, 7-3 and 7-4 provide the principle for modeling equipment information. Finally, the standard IEC 61850 also provides object-oriented models for inverters, power storage systems, and others, (Hongwei, 2014), approaching to new methods of engineering design and model based engineering.

3.3 GORE: Goal-Oriented Requirements Engineering

New approaches to requirements engineering evolved towards requirements management (elicitation, modeling and analysis) based on objectives - instead of functionality - decreasing the traditional dichotomy between functional and non-functional requirements. A requirement is viewed as a necessary condition to reach a goal in a specific application domain (Horkoff et al., 2017).

Functional requirements are more intuitive, generally associated with services provided to customers, in contrast with non-functional requirements, normally related to quality, performance or resources required for the service, and/or related to external demands such as safety, performance, scalability, operability, etc. Thus, in conventional the approach non-functional requirements are frequently neglected or fail to compose a complete and consistent set. Goal-oriented methods became an interesting alternative (Ghezzi and Tamburrelli, 2009).

3.4 KAOS modeling and the GORE method

KAOS (Knowledge Acquisition in Automated Specification) is a GORE method for modeling requirements as objectives (Horkoff et al., 2019). It is an efficient schema for adjusting descriptions, analyze problems, clarify responsibilities and manage different views between stakeholders. Improvements in traceability, completeness evaluation, reducing of ambiguity in requirement analysis are perceptible advantages of KAOS.

A comprehensive model of requirements is defined by four diagrams (only): Goal, Objects, Responsibility, and Operations, which can be resumed in a LTL (Linear Temporal Logic) formalism. Figure 3 show the main elements of a KAOS diagram.

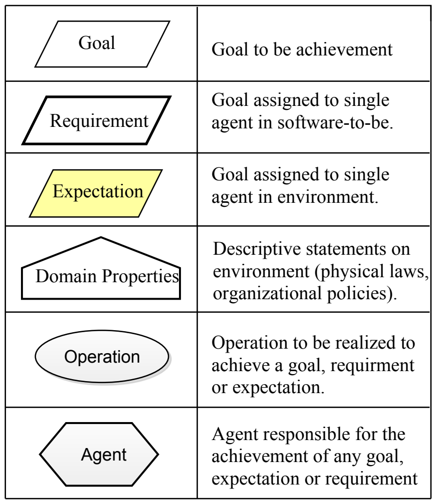

Figure 3: KAOS Elements

A goal diagram is a tree in which the root is represented by the main primary objective. This goal could be further refined into sub-objectives (requirements or expectations) which are the leaves of this top-bottom node.

Agents are responsible for satisfying one or more objectives (requirements or expectations). If the agent is part of the system to be developed then the objective is a requirement, whereas if the objective is linked to an agent belonging to the application domain the objective is an expectation.

In some specific situations, goals, requirements, or expectations need to be modeled as obstacles to a goal or requirement fulfillment - a fault detection, for instance.

Using obstacles is essential for safety-critical systems since that allows domain specialist to identify and address exceptional circumstances at the requirements stage, and converge towards robust requirements that could mitigate or avoid obstacles.

3.5 Converting KAOS diagrams into Petri Nets

A transfer algorithm called REKPlan (Requirement Engineering in KAOS for Planing) was proposed by some of the authors (Silva and Silva, 2015) to synthesize automatically a Petri Net from Goal diagrams. This Peri Net is used as reference model, integrating the application domain and the electric power plant.

Some advantages of Petri Nets as a reference formalism are: *i)* to be an efficient modeling schema to represent the dynamics associated with an automated grid system, *ii)* formally represent the flow of information associated with the behavior of microgrids. In addition, Petri Nets is a sound representation for analysis, and verification of requirements, as will be introduce in the following.

3.6 Verification of Requirements based on Petri Nets

Verification is a key issue to the proposed design process for power electronic mesh of sustainable resource, integrated in the conventional electric distribution system. The basic assumption is that requirements specifications should be formalized (modeled) analysed and verified before the effective design of the solution and its implementation.

As any automated systems, integrated electronic power plants has to guarantee the proper convergence of objectives towards the satisfaction of user nedds (as services) while also guarantee the avoidance of undesirable states and obstacles. That could be obtained from the modeling and verification of requirements, which would lead to the design of solutions that could also be verified using the same formalism, increasing tracebility in the whole design process.

Verification could be done by generating the state space and analysing workflows (of control and items), by property analysis of the Petri Nets, or both. Temporal and hierarchical extensions are also welcomed.

4 Application of the proposed method to Microgrids

The case study presented here was based on the R&D Project "Microgrids with intermittent sources applied in isolated areas", presented by the Energy Group of the Department of Automation and Electrical Engineering of Polytechnic School-USP in the year of 2012 (Martinez et al., 2016).

The main objective of this project was to supply energy to small isolated communities in the interior of the Amazon. Those communities have the ability to use micrograds, based on sustainable energy sources.

Microgrids should provide power for the isolated loads of interconnected systems.They are generally systems that rely on the use of some firm source of conventional energy (to ensure regularity and stability in the supply of electricity), and a range of renewable sources (to minimize the use of the conventional energy source).

Based on the context information and following the IEC 61850 standard, distributed energy resources (DER) are divided in two groups: Programmable DER (DER-P) and Not Programmable DER (DER-NP) (Postigo and Silva, 2018). The battery energy storage system (BESS) and the combined head and power (CHP) are part of the DER-P. On the other hand, natural sources like Photovoltaic system (PV) and Wind Power (WP) belong to DER-NP, due to the uncertainty of power generation and randomization in renewable energy production. A microgrid control will be responsible for the switching of the DERs.

The microgrid connected to an electrical network by the common connection point (PCC), whenever the PCC interconnect switch is closed (grid-connected mode). If the PCC is open, the microgrid is separated from the electrical network and goes into autonomous mode. Figure 4. shows the operating dynamics based on IEC61850

Different modes are defined as:

- Autonomous Mode: Whenever the microgrid supplies power to the loading with the only Distributed Generator(GD), every time an uncommon situation of the main network or manual operation occurs.

- Grid-connected Mode: Normal operation occurs when the microgrid is connected to the main network and distributed energies (DER).

- Fault Operation: Whenever a fault is detected, the PCC switch opens, and microgrid is separated from the service network and switches to Automatic Mode.

- Synchronization Operation: Whenever the network power is reestablished, transition mechanism are required to synchronize distributed generation (GD) with the main network.

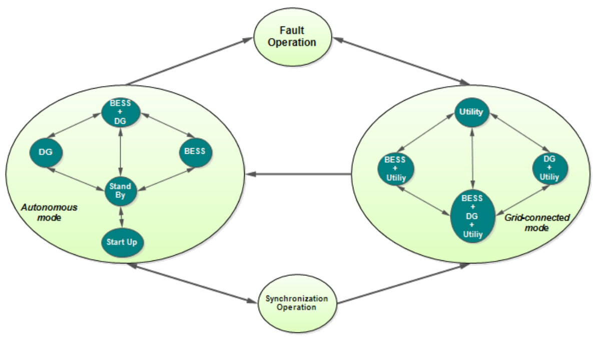

Figure 4: Operation Microgrid IEC-61850

After defining the basic requirements, the next step is concerned with the synthesis of goal-driven requirements based on the IEC 61850 reference architecture and considering the geographic, environmental, and technical restrictions. For KAOS modeling, we used the ObjectivER 3.0 tool developed by Respect-IT. The resulting KAOS model is shown in Figure 5.

In the objective model, a microgrid is modeled through a Top Down view. The main purpose of this system is to provide a "Control Operation of microgrid". This objective is refined

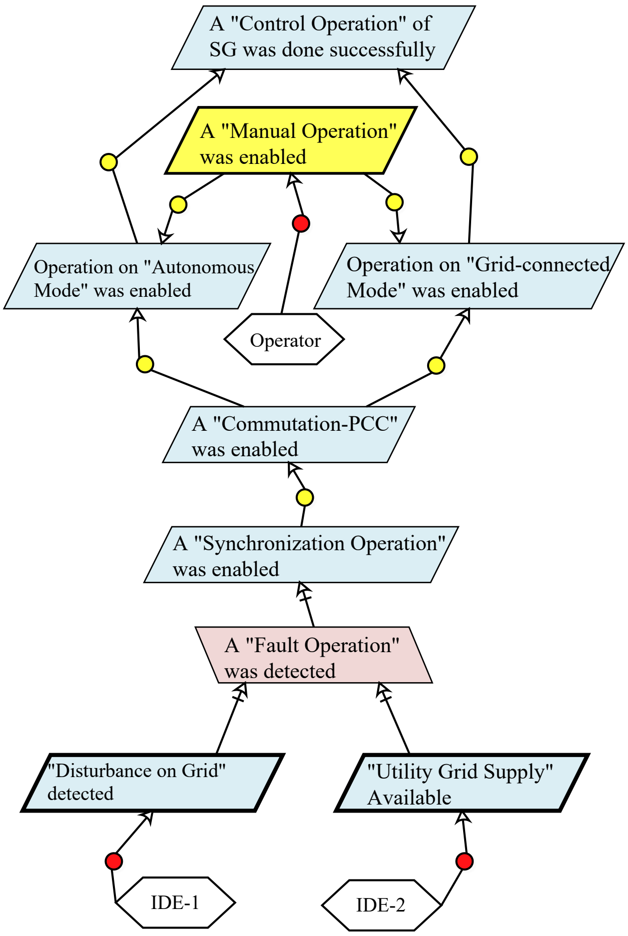

Figure 5: Objectives Diagram

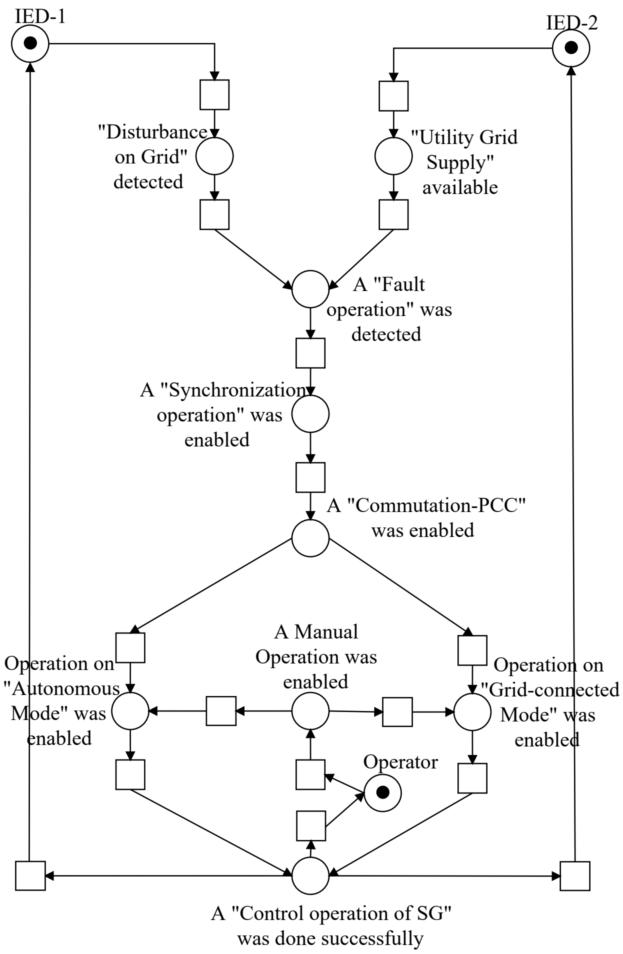

Figure 6: Petri Net of microgrid control

into two other sub objectives which are: operation on “Automatic Mode” and operation “Grid-connected mode” these sub objectives are refined into an expectation that evaluates ”Manual operation” and the sub objectives ”Synchronization operation” and ” Commutation PCC” which assesses whether any ”Fault operation” is related obstacle has been detected.

The final refinement passes by ”Disturbance on Grid” requirements and ”Utility grid supply”, each one linked to the IED-1 and IED-2 agents respectively.

In the fourth step, a Petri Net is derived from a KAOS model, modeling the automation of the microgrid system operation. In this step, when analyzing the readings of the IED’s, the Petri nets developed should switch the most appropriate mode of operation for the microgrid system.

Figure 6 shows the working dynamic of microgrid modeled in Petri Net. The control of the microgrid operation is in charge of receiving control signals through the IED’s, processing and transmitting signals to the system. Thus, once the controller receives a signal from the IED’s, it will enable the triggering of the transition ”grid-connected mode” or ”autonomous mode”.

From the control processing, also available Stand-By state and two switching possibilities, the available ”Utility Grid Supply”, and ”Disturbance Grid” control locations which may lead to a possible change or return of the operating state the Synchronization.

Each time the controller detects the PCC circuit breaker the microgrid accesses the grid and switches to Grid-Connected mode, the power supply initially operates on state called Utility, and, depending on the load demand, can switch to the Utility + DER-NP + DER-P, or Utility + DER-NP or Utility + DER-P.

When the PCC switch is open, the microgrid is disconnected from the Utility services network and switches to Autonomous-Mode, that is, a situation where the system is in isolated mode, in which the power supply is through the DERs, BESS and CHP, the switching will depend on the load.

The final step is the validation of the requirements model, which allows us to verify that the model is in accordance with the specification, that is, it meets the requirements, considering the particularities and restrictions of the Amazon region.

To validate the requirements model, the functional properties of the Petri Net are used. The objective is to support Design by solving problems related to incomplete states, ambiguities and inconsistencies.

The Petri net model shows the control solution for the microgrid. In which the modes of operation change according to the readings of the IEDs. The inboxes (places of entry) in the petri net, representing the IEDs.

Figure 7 shows the summary of analysis of the properties of the Petri Net, using the PIPE2 tool.

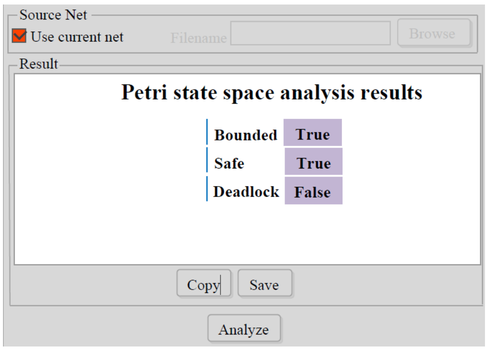

Figure 7: PetriNets Analysis

Based on the functional properties (dependent on marking) of Petri Net, it can be concluded that:

- The Petri Net obtained is live, because it's deadlock-free;
- All markings are reachable from the initial marking. Indicating that the network adequately represents the microgrid, which is part of the rest of the energy system;
- The net is finite (as expected) because the reachability tree is finite too. That also implies the system is closed and controllable.

Analysis of structural properties using invariants, can also be used to obtain mathematical information on the structure of the network, which enables the analysis and verification of Petri Net and will be the subject of a further study.

Finally, a method and guidelines for the design of a microgrid was established, applied in a case study for small communities in the Amazon rainforest. The results of this study were shown in the Design of the system itself, composed of the KAOS diagrams Figure 5, the Petri Net model Figure 6 and the verification of the network Figure 7.

5 Conclusions

The balance between energy production and distribution points to an evolution of microgrid systems with the characteristics of being open, distributed, heterogeneous and scalable. These systems will require sophisticated multidisciplinary design approaches, which required a revision in old (functional) methods. Old approaches tend to be replaced by systemic model based methods, starting with the requirements. Prospective methods can be objective-oriented; system-oriented and holistic - not just focused on components - distributed, and resource sharing. That imposes a discipline oriented to service, more than to products. Such approaches have also the advantage to couple with users in a client-server flavor.

In this paper, we proposed a method to explore an alternative approach, based on goal-oriented requirements and a formal modeling based on Petri nets to model micrograms. Some guidelines were introduced that were applied to a microgrid-based case study in small communities in Amazon equatorial forest. Besides the formal requirements modeling and verification techniques the case study serve to evaluate applicability of the proposed method in a critical situation.

Our conclusion is that, using GORE methods, a reference model to the architecture (based on the standard IEC 61850), and a formal representation based on Petri nets can lead to more flexible analysis, including regional constraints and valeu co-creation in the coupling with users. That can improve the efficient of the system that will be implemented. We noticed that this case study is real and was already implemented. Therefore, the analysis and its new prescriptions could be compared with the real system.

Further work points to the improvement of the formal method, to improve the transference between KAOS diagrams to Petri Nets - in this work just focused in objective diagrams - to include object, operation and responsibility diagrams as well. That will allow to reinforce the concept of traceability and the applicability of the proposed method.

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