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# Microgrid System Design Based on Model Based Systems Engineering: the Case Study in the Amazon Region

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**Abstract:** Microgrid is a technically and economically viable opportunity to meet the demands of populations that, for various reasons, do not have access to electricity. The complexity of Smart Grid (SG) systems requires considerable engineering effort in the design process. Designing this type of complex system requires new approaches, methods, concepts and engineering tools. Where, requirements analysis plays a major role in better characterizing, understanding and specifying the domain of application that SG systems should solve. This work presents a systemic proposal based specifically on System Systems (SoS) which anticipates the formalization of requirements, aiming to understand, analyze and design SG within the scope of Model Based Systems Engineering (MBSE). The definition of a microgrid from the SoS perspective is presented in order to provide a complete view of its life cycle. Requirements would be represented in an Objective Oriented Requirements Engineering (GORE) approach, specifically using visual diagrams based on the Keep All Objectives Satisfied (KAOS) method, where network operation and control will be formally represented. A case study for small communities in the equatorial Amazon forest is used as a case study for the proposed method.

**Resumo**: As microgrid surgem como uma oportunidade técnica e economicamente viável de atender a demanda das populações que, por diversos motivos, não têm acesso à energia elétrica. A complexidade de sistemas Smart Grid (SG), 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 os sistemas SG devem resolver. Neste trabalho apresenta-se uma proposta sistêmica baseada especificamente em Sistema de Sistemas (SoS) que antecipa a formalização dos requisitos, visando entender, analisar e projetar SG dentro do escopo de Engenharia de Sistemas Baseados em Modelos (MBSE). Apresenta-se a definição de uma microgrid na perspectiva de SoS no intuito de fornecer uma visão completa do seu ciclo de vida. Os requisitos seriam representados em uma abordagem de Engenharia de Requisitos Orientada a Objetivos (GORE), especificamente usando diagramas visuais com base no método Keep All Objectives Satisfied (KAOS), onde a operação e o controle da rede serão formalmente representados. Um estudo de caso para pequenas comunidades na floresta equatorial da Amazônia é usado como estudo de caso para o método proposto.

*Keywords:* Smart Grid; System Design; MBSE; Requirements Engineering; KAOS.

*Palavras-chaves:* Smart Grid; Projeto de sistemas; MBSE; Engenharia de Requisitos; KAOS.

## 1. INTRODUCTION

Electricity is an indispensable item for the existence of any human being. However, according to the Brazilian Institute of Geography and Statistics (IBGE), in 2010 about 729,000 Brazilian families had no access to any energy resources, mainly due to their location (*IBGE* 2019).

One of the main reasons for the lack of electricity in the lives of thousands of people in Brazil and around the world is the condition of poverty combined with the situation of geographical isolation in which they find themselves. However, despite the criticality, this panorama has been changed over time.

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.

Implementing Smart Grid (SG) 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, Sauter & Hung 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

Recent advances in design concepts, due to the paradigm shift in design from "product" to "service" systems, lead us to think of the SG system as a modern provider of energy services utilizing renewable natural resources that must provide a reliable power system that can be intelligently deployed to facilitate system generation, distribution, and management in this new context, with active user participation (prosumer).

The Basic System Engineering Model (MBSE) method within the scope of Systems of Systems (SoS) can help to understand the new SG landscape, that is, to understand how their main components report and can be shared.These interrelationships need not only consider the distribution and supply of energy, but also consider environmental compatibility, economic impacts, among other factors.

The introduction of a structured requirements phase in the life cycle of SG systems is a recent trend, and has attracted the attention of researchers and designers.Some existing methods even consider a requirements phase in the lifecycle of this type of system, but do not fully meet the requirements phase (consisting of elicitation, analysis, validation, formal modeling, verification), only satisfying some preliminary steps informally.

Through SoS, it's possible to identify SG system requirements that include strategic, financial, and customer experience functions. At the same time, SoS allows the specification of requirements needed to integrate these new technologies with legacy systems.

It is important to note that working with informal requirements, while facilitating the design process outside the academy, can lead to undetected failures during specification requirements (where error costs are lower), encumbering the project as a whole. The difficulty in dealing with a distributed arrangement of subsystems is another important factor in justifying the use of formally closed and consistent methods that can be analyzed and verified prior to implementation.

In this paper we present a method proposal for the formal specification of requirements applied to the domain of microgrid systems.The proposal is based on a systemic approach, specifically Systems of Systems (SoS) that anticipates the formalization of requirements through the use of Objective Requirements Engineering (GORE) method and within the scope of MBSE (Lopes, Lezama & Pineda 2011). The adoption of modeling and formal verification techniques is suggested to ensure efficiency and correctness in the design and development of these types of systems.

## 2. BACKGROUND

The evolution of energy systems, especially smart grids, is directing designers and researchers to produce increasingly powerful and complex energy systems, integrated systems and tightly coupled with many elements belonging to various fields of knowledge, (Gerber 2014).

Several researches related to the design of energy systems have been recently performed, searching for new more robust and consistent (and more flexible) methods, with different objectives, thus, some related published works are shown below:

In this context, Gerber (Gerber 2014) presents a method applied to renewable energy systems proposing a Life Cycle Assessment (LCV) using multi-objective optimization techniques. Other works, such as the one presented by Roboam (Roboam 2012), use a systemic approach to power system design through the use of the "V" type interactive design cycle and the use of formal methods. Frangopoulos (Frangopoulos, Von Spakovsky & Sciubba 2002) used graph theory to model such systems.

Recently proposed models and architectures, such as the IntelliGrid architecture presented by the Electric Power Research Institute (EPRI, USA) (Commission et al. 2008) and the SGAM (Uslar, Specht, Dänekas, Trefke, Rohjans, González, Rosinger & Bleiker 2012) architecture, recognizing the importance of the phase requirements, and including an approach to IEC / PAS 62559 requirements elicitation using Unified Modeling Language (UML), which consists of the development of a Transmission, Distribution, and Integration Requirement Use Cases repository for the design of Smart Grid systems.

### *2.1 New Proposed Approach for SG Systems Design*

Characteristics regarding the complexity and sophistication of SG systems are leading Designers and researchers to look for new systems design methods and, alternatives. In this context, comes the Model Based Systems Engineering (MBSE). According to the International Council for Systems Engineering (INCOSE), (INCOSE 2015) defines MBSE as the formal application of modeling to support system requirements, design, analysis, verification and validation of activities, at all stages of the cycle project life. In addition, MBSE has several frameworks for systematically examining different views of the corporate system, such as business view, system, technology, operations, and service.

From the point of view of the System Design it turns out that the "ideal" design, seeks correctness and completeness, which can only be achieved with formalization. However, the more formal the system, the more difficult is the communication between its elements: requirement (what has to be done and why), design (how to achieve the system and its objectives directly and with less cost and greater efficiency), and implementation (how to do, how to eliminate the system, and how to interact effectively with the end user).

But in most cases a new system is required to “replace” an existing one that has become obsolete. So the process should start by modeling “system-as-is”, that is, the legacy system. The ”new requirements” should then demarcate the differences between ”system-as-is” and ”system-tobe” as shown in Figure 1.

If there is no system-as-is, the recommendation is to build a model with the requirements extracted from the stakeholder. This is going to become system-as-is, whereas system-to-be will be the result of optimization and engineering of the solutions after any negotiation.

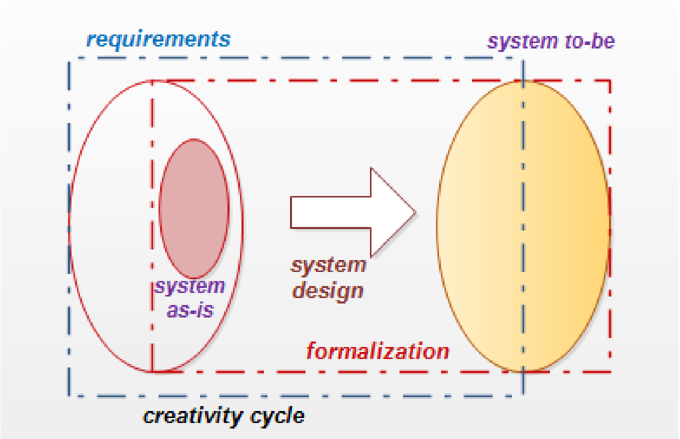


Fig. 1. Creativity cycle

Recent advances in design concepts, due to the paradigm shift in design from “product” systems to service systems, lead us to think of models rather than prototypes, aiming to disconnect us from intrinsic functionality of their parts. One way to structure a complex system is to use the concept of hierarchy, that is, to divide it into parts recursively until we understand them and then reassemble the parts to understand the whole.

However, this approach does not help us understand a complex system, because the emerging properties that really matter disappear when we look at the parts in isolation, that is, we cannot treat this new system as just a junction of parts or small subsystems.

In this scenario, the concept of SoS emerges which is defined as a set of constituent systems that seeks harmony among distributed elements (parts), capable of flexibly and adaptably producing distinct behaviors, whether these are the results of the direct contribution of their components or result of joint action. (Lopes et al. 2011)

However, it is verified that the design of a SG system could not be guaranteed by addressing each constituent subsystem separately, it is necessary that these distributed subsystems combine their features and capabilities in order to generate the SG system which offers greater functionality and performance. For this reason, we consider SG as an SoS (Andrén, Strasser & Kastner 2017) and (Uslar, Rohjans et al. 2019).

In order to establish efficient communication between the parts of the SG, it is proposed to apply (MBSE), a method that prioritizes the formalization of requirements from the early stages of the SoS life cycle. This approach that uses graphical representations begins the end thinking, that is, the future vision of the desired system, and serves as a guide for defining and documenting what will be needed in terms of resources, technology, and other.

Therefore, considering the SG system from the MBSE point of view, and verified the importance of the requirements step, there is a need for a reliable engineering requirements (ER) as an integral component of the proposed method that will lead us to SoS Design. In this context, the proposal is to use the GORE method.

### *2.2 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 multi-source system composed by conventional Renewable Energy Sources (RES), a storage systems and controllable loads (Liserre et al. 2010). The interface between the service network and the microgrid is used to interact with the SG; it provides voltage control, power balancing, and load sharing. A communications infrastructure, provide the transfer and exchange of data, in real time, Figure 2.

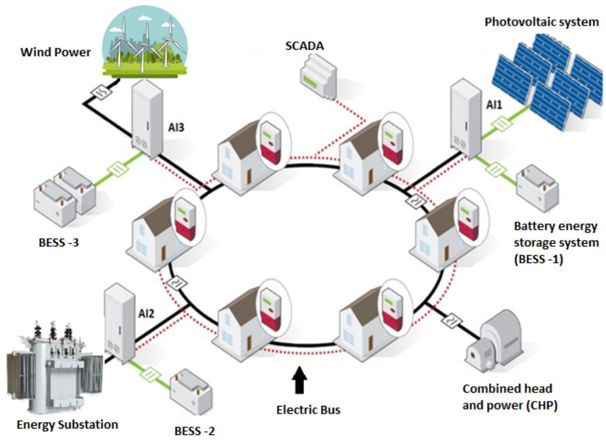


Fig. 2. Proposed scenario for the microgrid

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

### *2.3 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, Aydemir, Cardoso, Li, Maté, Paja, Salnitri, Piras, Mylopoulos & Giorgini 2017).

Functional requirements are more intuitivej, 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 & Tamburrelli 2009).

### *2.4 KAOS modeling and the GORE method*

KAOS (Knowledge Acquisition in Automated Specification) is a GORE method for modeling requirements as objectives (Horkoff, Aydemir, Cardoso, Li, Maté, Paja, Salnitri, Piras, Mylopoulos & Giorgini 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. Fig. 3 show the main elements of a KAOS diagram.

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.

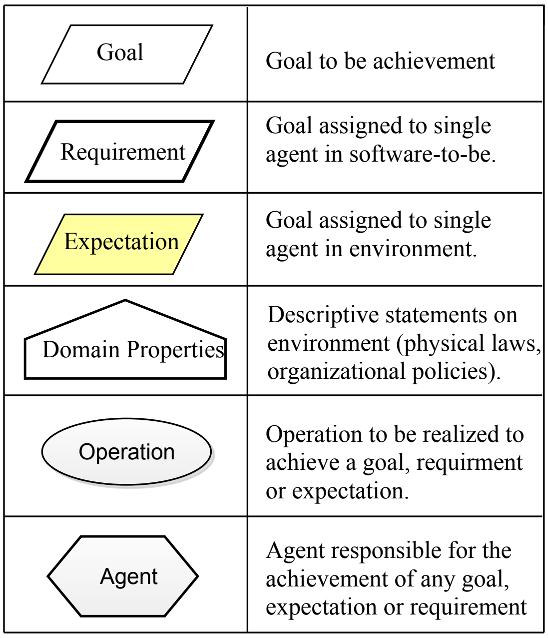


Fig. 3. KAOS Elements

## 3. MICROGRID USE CASE

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, Saidel & Fadigas 2016).

The main objective of this study is, from the legacy system (microgrid), to insert automation, communication, and user participation, and inclusion of other renewable energy resources available in the locale in an efficient and sustainable way, promoting energy quality. In addition, attendance to non-conformities detected in said system.

The process begins by specifying microgrid (legacy system) requirements, applying reverse engineering within the scope of the MBSE and based on the GORE approach. The requirements specification will be refined into two phases, one phase called system As-Is and another called system to-be. In this work we will deal specifically with System As-Is, leaving for future work the elaboration of system To-be.

With the application of Reverse Engineering and through a systemic view is intended to acquire knowledge, it is, collect the functional and non-functional requirements about the legacy system, allowing to identify its functionality the components and their interrelationships. In addition, to delimit the application domain and also to define the scope of development, that is, to define the subsystems of interest (SoS), the system inputs and outputs, the interfaces and the form of communication with external elements, among others.

Using the GORE and KAOS approach will be created representations (models), whose final result will be the documentation of the requirements. This paper intends to make an analysis of the requirements documentation, when compared with the legacy system design information, in order to show the advantages of the proposed method, as well as the importance of the requirements phase in the life cycle of the SG systems.

### *3.1 System Description*

The hybrid microgrid here is the type (photovoltaic-diesel-battery) with a mixed architecture coupled with AC and DC, Figure 4 presents the schematic diagram. This system results from the combination of solar and battery intermittent sources, with diesel generating units, in a single electricity generation system, which takes advantage of the solar resource operating in a combined manner (but not necessarily in parallel) with a diesel generator, with the purpose of meeting a certain load.

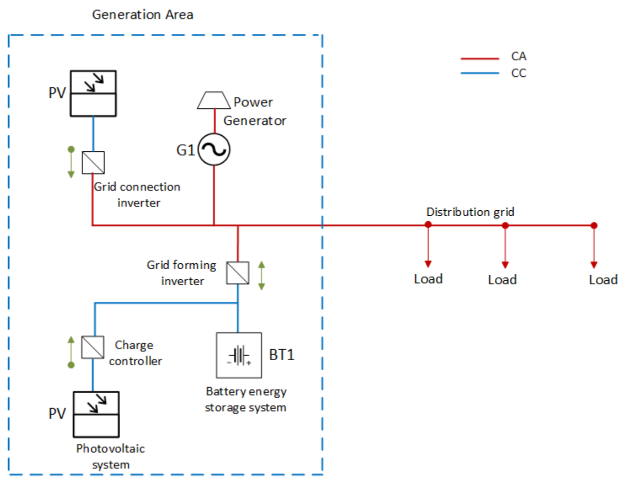


Fig. 4. Microgrid system legacy

In this case, the diesel generator unit may act as the main component when the solar generator is used to save fuel, or it may act as a backup generation unit to ensure microgrid operation during possible periods of unavailability of the solar source.

For monitoring and storing information, the Data Acquisition System (SAD) is used which provides information on system behavior, related to the amount of energy generated and especially that consumed by loads.

Grid inverters are responsible for converting direct current (coming from photovoltaic panels) to alternating current of constant voltage and frequency. In them it is finds the supervisory control of the system, also has the function of managing the battery bank, avoiding overcharging or deep discharges.

## 4. RESULTS AND DISCUSSIONS

The first step of the proposed method is to apply MBSE to "system as-is", the goal of this phase is to collect the legacy system requirements to understand the scenario, in this case the autonomous microgrid. In order to identify its functionality, its components and its interrelationships. As well as the identification of non-conformities this system.

Using MBSE method GORE and KAOS we will capture the requirements of the MSG system, aiming to model the microgrid system with the same functionalities, to understand the system boundaries from the objectives, expectations and constraints.

Table 1. Project Data

| Data | Description |
|---|---|
| Techno-Economic Analysis | Analyzes cost of different technological options;<br>Analyzes cost of diesel or alternative fuel;<br>Analyzes level of technical capacity available on site to perform system operation and maintenance. |
| Calculation of Demand to be Met | Evaluates consumer profile to be served;<br>Analyzes community layout;<br>Performs lifting of loads;<br>Evaluate existing infrastructure. |
| Evaluate availability of energy resources | Evaluates solar radiation index;<br>Evaluates transport logistics of diesel oil. |
| Select architecture type | Selects the type of architecture best suited to local reality, based on IEC 61724; |
| Choice of monitoring equipment | Low power sensors;<br>Avoid current loops;<br>Components that offer system reliability;<br>Evaluate cost of component replacement. |
| Information Handling | Add redundancy in the data acquisition phase to facilitate information processing;<br>Use robust transmission signals;<br>Maintain a system log;<br>Establish the geographic coordinates of the monitoring system. |

The next step of the proposed method is to use Reverse Engineering to extract the information used in project development (legacy system), as shown in Table 1. It is verified that the information collected is very technical, and important for the system implementation, however, information related to the system quality such as safety, reliability, performance, maintainability, scalability and usability are not present. These attributes are important and serve the constraints on system design.

In addition, the analysis of the legacy system revealed the following non-conformities:

- There was a 240 increase in electricity consumption due to excessive energy consumption and the presence of clandestine connections;

- There was an increase in fuel consumption, caused by increased demand, in addition to the quota provided;

Abnormal operation of the battery banks was observed causing the interruption of the power supply by the grid inverters;

Problems communicating Datalogger for collecting microgrid monitoring data.

In order to collect non-functional requirements, we use the GORE and KAOS methodology as shown in Figure 5.

Following the methodological proposal, the following step is to apply GORE and KAOS in order to model the requirements from a functional and non-functional objective perspective, always directed to the problem and the corresponding solution, from a high level view.

Therefore, from the legacy system analysis it verifies that the main objective of the legacy system was: “Design,

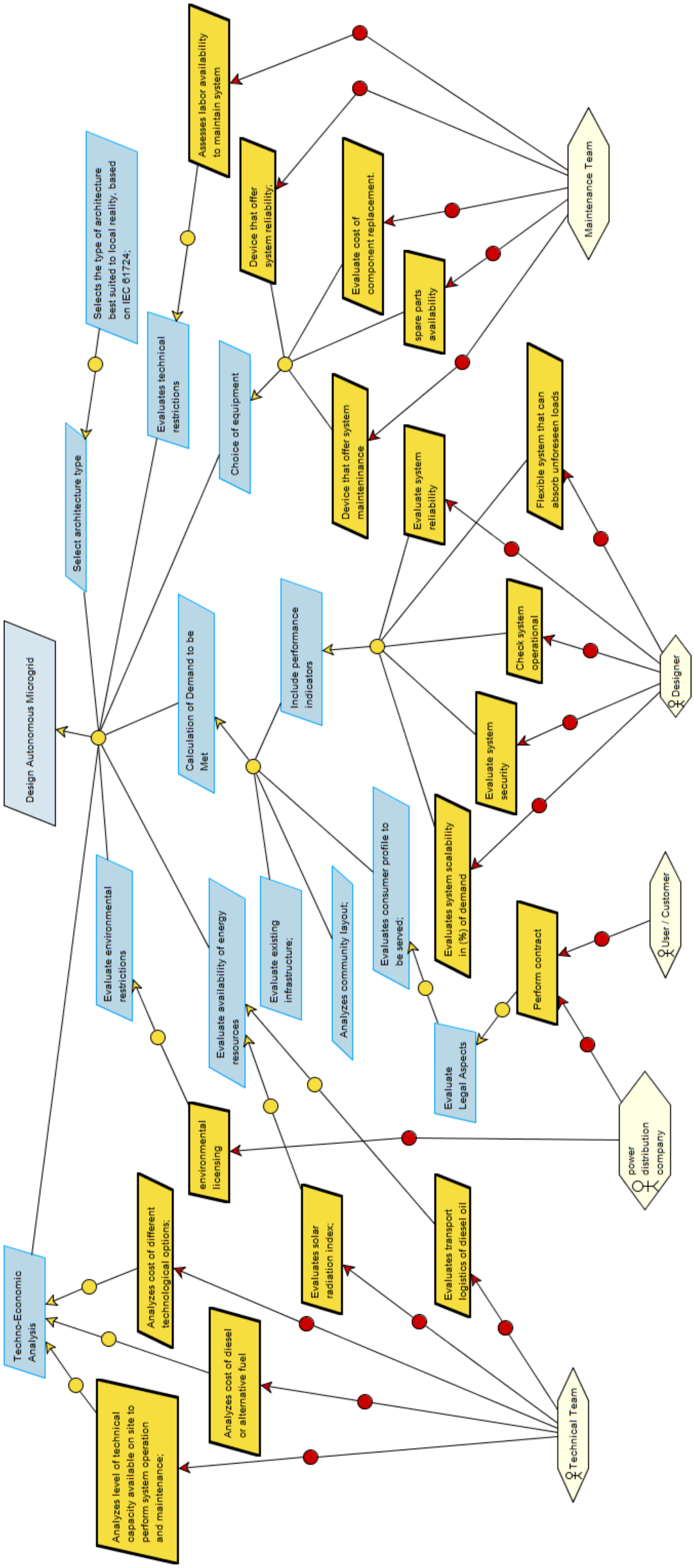


Fig. 5. Goal KAOS Diagram

install and monitor Autonomous microgrid". In this paper we will deal specifically with the part related to the project itself.

In Figure 5 shows the KAOS Objectives Diagram highlighting the main objective "Design Autonomous Microgrid". This main objective is refined into sub-objectives, to know: Techno-economic analysis, environmental advising and technical constraints, selecting equipment, selecting the type of architecture, advising available energy resources, and calculation of demand be met.

These sub-goals will continue to be refined to the level of requirements or expectations. Thus, for example, to calculate demand, it is necessary to evaluate existing infrastructure, community layout, and especially the consumer profile, which represents the following level of refinement. In the legacy system, no objectives related to performance indicators were observed.

Thus, in order to meet certain objectives we have verified the need to include performance attributes such as: Evaluate system scalability in (%) of demand, Evaluate system security, Check operating system, Evaluate system reability, Flexible system that can absorb unforeseen loads, which represent expectations and is responsible for the System Designer. On the other hand, the case of the "Evaluate the consumer profile" sub-objective was added the objective related to the evaluation of legal aspects, important to fulfill the expectation of contracting and has responsible agents, the user and the utility company.

In Table 2 shows the functional requirements and system attributes extracted from the KAOS Goals model, this table is the result of the documentation obtained through the KAOS method. Comparing Table 2 with Table 1, is can identify some missing requirements.

The absence of these requirements meant in non-conformities in the legacy system that could have been addressed from the start of the project. Thus, for example, clandestine connections, which overloaded the grid, increasing the demand, which in turn led to increased fuel consumption and abnormal battery operation, could have been clearly identified by those involved in the project.

Therefore, to address the problem of clandestine connections, Table 2 shows the requirements that would address such non-compliance, which are the Legal Requirements, the evaluated System Security, the evaluated System Reability, the Evaluated System Scalability, and Integrity of System. Therefore, as we can see, a poorly collected requirement can have negative impacts on the system.

In this context, we realize that the importance of the correct specification of the requirements, and we understand that there is a great difficulty in capturing and describing the information raised, an obstacle often caused by misinterpretation of user needs.

In this case, it was also evidence that demand limited to 100kW/h, with automatic shutdown above that consumption. It is verified turns out that this situation could possibly have been the cause for some users to make clandestine connections, causing imbalance in the system.

Table 2. Project Goal

| ID | Type | Description |
|---|---|---|
| G1 | Design Autonomous Microgrid | Represents the main goal |
| G2 | Techno-Economic Analysis | It aims to analyze the viability of the investment, comparing the returns that can be obtained with the investments demanded. |
| G3 | Choice of equipment | Aims to use commercially available technologies / models with cost savings. |
| G4 | Evaluates technical restrictions | It aims to evaluate the technical limitations related to labor, equipment, available technology. |
| G5 | Calculation of Demand to be Met | Aims for correct system sizing, system reliability and appropriate community tariffs. |
| G6 | Evaluate environmental restrictions | It aims to assess the environmental impacts of the project as well as relevant permits. |
| G7 | Evaluate availability of energy resources | It aims to study the system configurations that allow optimizing the use of energy resources in order to ensure security in the supply of electricity and promoting tariff savings. |
| G8 | Include performance indicators | It aims to identify the causes for which goals are not being met and to analyze opportunities for improvement. |
| G9 | Evaluates consumer profile to be served | It aims to analyze social, economic and political aspects, conditions of access to communities. |
| G10 | Evaluate Legal Aspects | Aims to analyze legal aspects related to energy user / supplier contracts |
| E1 | environmental licensing | Performs Environmental Licensing |
| E4 | Assesses labor availability to maintain system | - The System should not be shut down for maintenance more than once in a 24 hour period annually. - Operator should be training in Electrical Installations, NR-10 and programming in Datalogger and Inverters. |
| E7 | Perform contract | - Performs written agreement establishing the consumer shutdown if no power bill payment; -Zero tolerance to power theft |
| E8 | Evaluate system reliability | The system must have an MTBF equivalent to 1 / 10,000 of 1/30 days |
| E9 | Flexible system that can absorb unforeseen loads | Flexible system that can absorb both unforeseen loads and future demands |
| E10 | Check system operational availability | The system must be available at least 99.0% on working days, 24 hours a day. |
| E11 | Evaluate system security | - The system must be capable enough to meet the demand of all users in the communities without affecting their performance. - Users are never allowed to manipulate SmartMeter or external installations. |
| E12 | Evaluates system scalability in (%) of demand | The system will be able to meet peak demand up to (10%) higher than peak hour contracted demand., |

## 5. CONCLUSION

Recent research shows that modern SG Design methods have begun to use a requirements approach in their lifecycle. However, it has been found that all of these methods emphasize functional requirements, leaving non-functional requirements to the background, and none of these methods have a formal requirements step.

Due to the complexity of SG systems, and the importance of the phase requirements in their lifecycle, we understand that it is necessary to provide methods tools and concepts to better characterize, understand and specify the domain of application of these systems. The idea proposed in this paper was to treat SG as a SoS, with the objective of understanding the SG system through a holistic (top-down) view, aiming to avoid delving into some of the aspects before verifying its relation to other aspects of the same or near levels.

To this end, guidelines were provided for the application of a real microgrid-based case study to serve isolated Amazonian communities, the purpose of which was to collect the requirements of the legacy system to enable understanding of the system, in order to identify its functionality , their components and their interrelations, as well as characterize non-conformities in the legacy system.

After applying the proposed methodology, it was found that KAOS turned out to be an effective method to extract objectives from the microgrid, resolving the ambiguity when specifying requirements. It also provided support for their validation and traceability.

With the use of the SoS concept it allowed us greater flexibility in the design, as it made it possible to modify characteristics of the As-Is system without changing what had already been defined, and thus to design the To-Be system.

On the other hand, in the same perspective of complex SoS, the distributed characteristic of the microgrid allowed the sharing of resources between the constituent parts in the context of a larger and evolving system.

Finally, the methodological proposal presented here opens up a promising direction of research for Design and SG systems through a SoS perspective and using modeling and formal verification methods that can be used by designers and researchers of SG systems, contributing to the development of a framework, of practical use.

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