FORMAL REQUIREMENTS SPECIFICATION FOR MICROGRID BASED IN ARCHITECTURE IEC61850

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Abstract— Smart Grid (SG) systems are considered a sustainable alternative to power supply problems all over the world. SG systems are open, distributed and heterogeneous, what raises a huge demand over its design process. At the present, SG projects are usually done by applying deductive methods, where requirement-specifications do not reach a complete model. On the other hand, considering the importance of the requirements phase, it is necessary to provide methods, tools, and concepts to better characterize, understand and specify the application domain of SG systems. This work proposes the introduction of a formal requirements analysis in the SG life cycle that fits IEC61850 architecture. Requirements would be represented in a goal oriented approach (GORE) specifically using visual diagrams based on KAOS method that will be transformed in a extended Petri Nets representation, which enables to manage the modes of operation of a microgrid. Practical results are shown through an example showing the application of GORE methodology and Petri Nets modeling with the corresponding analysis to fit specific requirements associated to microgrid for the Amazon region.

Keywords— Microgrids, Architecture IEC 61850, Petri Nets, Formal modeling, Gore methods.

Resumo— Os sistemas Smart Grid (SG) são considerados uma alternativa sustentável para problemas de fornecimento de energia em todo o mundo. Os sistemas de SG são abertos, distribuídos e heterogêneos, o que aumenta a demanda por seu processo de design. Na atualidade, os projetos de SG geralmente são elaborados aplicando métodos dedutivos, onde a fase de especificação de requisitos não alcançam o modelo completo. Por outro lado, considerando a importância da fase de requisitos, é necessário fornecer métodos, ferramentas e conceitos para melhor caracterizar, compreender e especificar o domínio de aplicação de sistemas SG. Este trabalho propõe a introdução de uma análise de requisitos formais no ciclo de vida SG que se adapta à arquitetura IEC61850. Os requisitos seriam representados em uma abordagem orientada a objetivos (GORE) especificamente usando diagramas visuais baseados no método KAOS que serão transformados em uma representação de Redes de Petri estendida, que possibilite gerenciar os modos de operação de uma microgrid. Os resultados práticos são mostrados através de um exemplo que mostra a aplicação da metodologia GORE e da modelagem de redes Petri com a análise correspondente para atender aos requisitos específicos associados a uma migrogrid para a região Amazônica.

Palavras-chave— Microgrid, Arquitetura IEC 61850, Rede de petri, Modelagem Formal, Metodos GORE.

1 Introduction

Electric power is key issue improve life quality. However, according to (*Brazilian Institute of Geography and Statistics*, 2018), in 2010, approximately 729 thousand Brazilian families lacks any type of electrical energy source.

Thus, the implementation of SG systems with renewable generation has proven to be a feasible alternative to meet power supply needs, specially if based on the integration of different sources in alternative architectures for sustainable distributed generation.

SG systems inherit some complexities from heterogeneous, open and distributed systems (Falcão, 2010). In addition, design and application computer environments are disjoints tacking different phases separately and keeping knowledge from each approach departed, with little or no interaction.

A recent alternative approach to SG systems design is based on use of reference model architectures, as the IEC 61850. This model architecture facilitates the design of automated microgrid systems and is currently being used by many researchers and designers of this area.

Actually, introducing a requirements phase in the life cycle of SG systems is a novelty. Deductive methods are used instead, where the problem is represented by a model, which is analyzed directly to provide a solution that could be verified and tested.

In the academy the systemic approach is more popular as it is shown in the literature:

- Lu et al. (Lu et al., 2014), proposed a microgrid strategic control operation, which analyzes each composite device looking for contradictions about the rapid switching in operation mode or some slowness in the communication with the system management. The proposed control architecture is based on IEC 61850 using adaptive control;

- Deng (Deng et al., 2015) it proposes to improve a plug and play microgrid function each time a new source or equipment is inserted in the system, with different information protocols. He also presents a solution based on IEC 61850 with the extra function ”plug and play”.

- Ustun et al. (Ustun et al., 2012) developed a protection system to communicate with and monitor microgrids in order to update relay failure currents according to the variations in the system. This author also presents a model based on IEC61850 and IEC61850-7-420 communication standards.

In this work, we present a purpose for a method to generate a formal model to analyze requirements elicited by a goal oriented approach and represented in KAOS for microgrid systems based on the architecture IEC 61850.

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.

In the following sections the method based on the reference model IEC 61850 is described and its application to microgrids is illustrated.

2 Conceptual description of the Method

A conceptual description of the method is depicted in Figure 1.

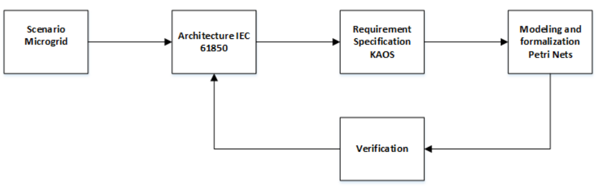

Figure 1: Method flowchart

In the first stage, is defined a scenario, in which the requirements for its operation are first surveyed using the IEC 61850 standard as a reference. Thus, to execute the requirements survey, the operational characteristics, such as forms of energy production, environmental restrictions, and so on, are analyzed. In fact, this is one of the more complicated steps, since much of the information may not be available.

In the second step, the requirements of the microgrid are developed, considering the inherent complexity of the SG systems, in this step the system of IEC 61850 is used for the requirements specification. Therefore, the operation of the microgrid follows the recommendations of IEC 61850 standard.

In the third step requirements will be formalized using the GORE (Goal Oriented Requirement Engineering) method, specifically the KAOS tool. The use of this method introduces a more direct approach, synthesizing functional and non functional requirements aspects, and using the reference model to check the minimal topics to turn on a microgrid service integrating a more general dynamic energy ecosystem.

The fourth step is to model integrated automation in Petri Net. A Petri Net model will be synthesized from the requirement model represented in KAOS diagrams obtained in the previous step. Therefore, KAOS diagrams will be translated to a Petri Nets through a transfer algorithm called ReKPlan (Silva and Silva, 2015).

The main idea is to rely on the reading of Smart Electronic Devices (IDE’s) to feed the developed Petri net which could reproduce the dynamic of the microgrid operation using a system of systems approach.

The final step is validation, through the analysis of the behavioral properties and performance evaluation of the GHENeSys network, aims, to design a control solution for microgrid, considering the particularity and constraints of the Amazon region.

3 The Proposed Approach

The proposed method combines a new approach to Requirements Engineering based on objectives, with the reference model approach frequently used in power systems design. will be applied to microgrid, in which the geographic characteristics, environmental and technical restrictions should be considered.

3.1 Microgrid System

A microgrid can be considered as a low voltage distribution network and interconnected to the utility grid through a common coupling point (PCC). A typical microgrid system consists of a set of components, which include Distributed Energy Resources (DERs), battery energy storage system (BESS), a computerized control to switch among different energy sources and optimize energy supply, and so forth. Therefore, a microgrid can be characterized as an automatized flexible service system.

The characteristics and dynamics regarding DERs operation present a special challenge about the control and operation of the network. Depending on the characteristics of (DERs) and BESS systems within a microgrid, the desired power management system may be significantly different from a conventional power electric system.

A typical microgrid runs in two operating modes (Asmus, 2010): connected network or normal operation. In this first scenario, the microgrid is connected to the main energy distribution resources (DER). In stand-by or isolated mode this scenario happens when some abnormal fault or circumstance occurs in the main network and the microgrid must supply the loads (at least the essential loads) with only the DER.

When the microgrid has only renewable energy sources, additional transition modes are needed to synchronize distributed generation (DG) with and main source or to provide energy locally without the main source. In addition, when demand-response programs are activated, it is considered as another operation mode which combines renewable and main energy source.

Thus, based on the context of the IEC 61850 standard, the DER's were grouped into programmable DER's (DER-P) and non-programmable DER's (DER-NP). The battery power storage system (BESS) and combined heat and power (CHP) are part of the DER-P (Deng et al., 2015). Renewable energy sources such as PV and WP belong to the DER-NP, due to their uncertainty of energy generation, and randomness in energy production, affected by natural factors, so the central management system will be responsible for the reconfiguration of DER's.

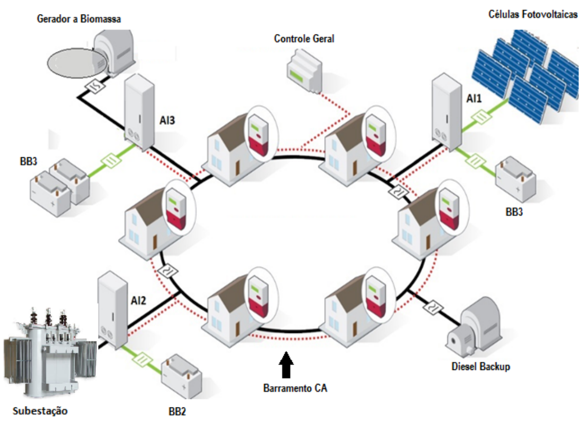

Figure 2: Proposed scenario for the microgrid

The microgrid system, the object of study in this work, comprises two parts: the information system and the power system, as shown in Figure 3. Both parts should be developed using as requirements the reference model included in the standard architecture IEC 61850 which we present succinctly in the next section.

3.2 IEC 61850

The IEC 61850 architecture began to be developed in 1994 by IEEE, UCA, and IEC, technical committee 57. The purpose of IEC 61850 is to specify requirements and provide a framework for achieving interoperability between intelligent electronic devices (IED's). In 2005, all parts of the standard have been published as official IEC standard. In 2010, the United States National Institute of Standards and Technologies (NIST) recognized IEC 61850 as one of the key facilitators for SG implementation, emerging as a standard for future SG implementations(Li, 2014).

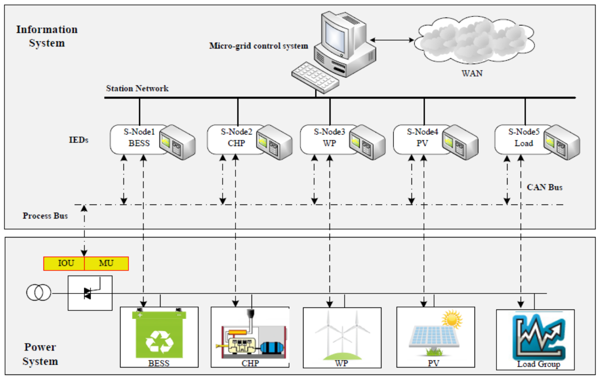

Figure 3: Architecture Microgrid based IEC 61850

Initially, this standard was designed with the objective of providing protection and promoting the automation of substations. Currently, there are already additional information models defined for domains, hydroelectric plants, wind power plants, microgrids and others.

One of the advantages of the IEC 61850 standard is its extensibility characteristic, resulting from the independence of communication and application, specifying services and objects. It allows to design applications in an independent way of specific protocols. Consequently, the data objects defined in the standard can be applied in several communication solutions without having to modify the models.

Moreover, lots of the critical processes of a microgrid, when related to centralized control, suppose a decrease in some capacities and functionalities of the microgrid.

Therefore, direct communication between devices provides to microgrids advanced control capabilities and reduces the amount of information circulating across the network.

The choice of the IEC 61850 standard in this work is due to the fact that this standard has an architecture that allows microgrids automation, through object-oriented tools that allow standardization of the system communication, as well as to fulfill the requirements of interoperability and extensibility between equipment from manufacturers and legacy generation systems in the applications of microgrids (Wen et al., 2014).

On the other hand, IEC 61850 aims to implement protocols with open standards, with an architecture that performs a fast and effective control of microgrid operation modes.t

It is recognized for academy and practitioner communities that the automation process based on IEC 61850 standard allows a reduction of project resources, time, and consequently financial costs.

3.3 *Requirements specification in KAOS*

In this work, a tool called Objectiver (Objectiver, 2015) is utilized to model requirements in goal-oriented KAOS diagrams, that consider relations among user agents and the system environment covering different scenarios(Graa et al., 2012).

Requirements are represented together with IEC 61850 reference architecture (as is done when reference models are used) resulting in the KAOS model shown in Figure 4. It can be observed analyzing the KAOS model that the IDE's of the microgrid, based on the IEC 61850 Architecture, ended up being agents in the KAOS model.

Table 1 describes the requirements corresponding to the operating dynamics based on the IEC 61850 standard.

Table 1: Operating requirements of microgrid based on IEC 610850.

Requirements	Description
Grid mode connected	Normal operation happens when the microgrid is connected to the main grid and distributed energies (DER)
Autonomous Mode	Isolated operation occurs whenever an abnormal fault or circumstance occurs in the main grid and the microgrid is supposed supply the loads (at least the most sensitive loads) with the DER only.
Synchronization Mode	When the microgrid has only renewable energy, additional transition modes are required to synchronize distributed generation (DG) with and without the main grid. In addition, when demand-response programs are active it is considered as another mode of operation that is part of the connected grid mode.
Fault Mode	Each time the main PCC interconnect switch closes the microgrid, it accesses the mains and switches to the connected grid mode and, when the PCC switch is open, the microgrid is separated from the service grid and switches to stand-alone mode.

3.4 *Transforming Requirements in Petri Nets*

From the developed KAOS model, a Petri Net is synthesized by using a transference algorithm proposed by (Silva and Silva, 2015). The Peri Net used here is a Unified model, that is, a modeling environment that implements the standard ISO/IEC 15.909 including basic Place/Transitions nets up to High Level nets and some extensions. Some basic elements used in GHENeSys are illustrated in Figure 6. Similarly, Figure 5 illustrates how basic elements of KAOS model are translated into GHENeSys network and Figure 7 shows how AND/OR refinement of goal-oriented model is translated into structural components. A key operation appears when the microgrid is connected to the main grid sharing excedent energy generated in the local grid with the general (electric) energy provider.

The Petri net model is obtained by the RekPlan (Engineering Requirement for Planning Problems) tool(Martinez Silva, 2016), which automatically transforms KAOS diagrams into Petri Nets. The obtained Petri Nets is suitable to simulate the proper mode of operation, depending on the reading of the IDE's responsible for collecting the microgrid information.

Petri Net was adopted here to model the dynamic of the automated grid system and the information flow associated with the behavior of the microgrid system, i.e., the alow the analysis of relationship, organization, and communication between the components of the microgrid.

Another important issue of using Petri Nets is the possibility to analyze and validate requirements, a process normally neglected in old fashion systems design and regarded as a key issue for automated microgrid design.

3.5 *Validation of Requirements in Petri Nets*

The whole process depicted here is based on the hypothesis that requirements should be formalized before turning out to be specifications. Therefore, requirements are introduced as semi-formal disciplined statements (since we are using reference models) and should be analyzed formally (using Linear Temporal Logic or Petri Nets) and further validated using simulation and property anal-

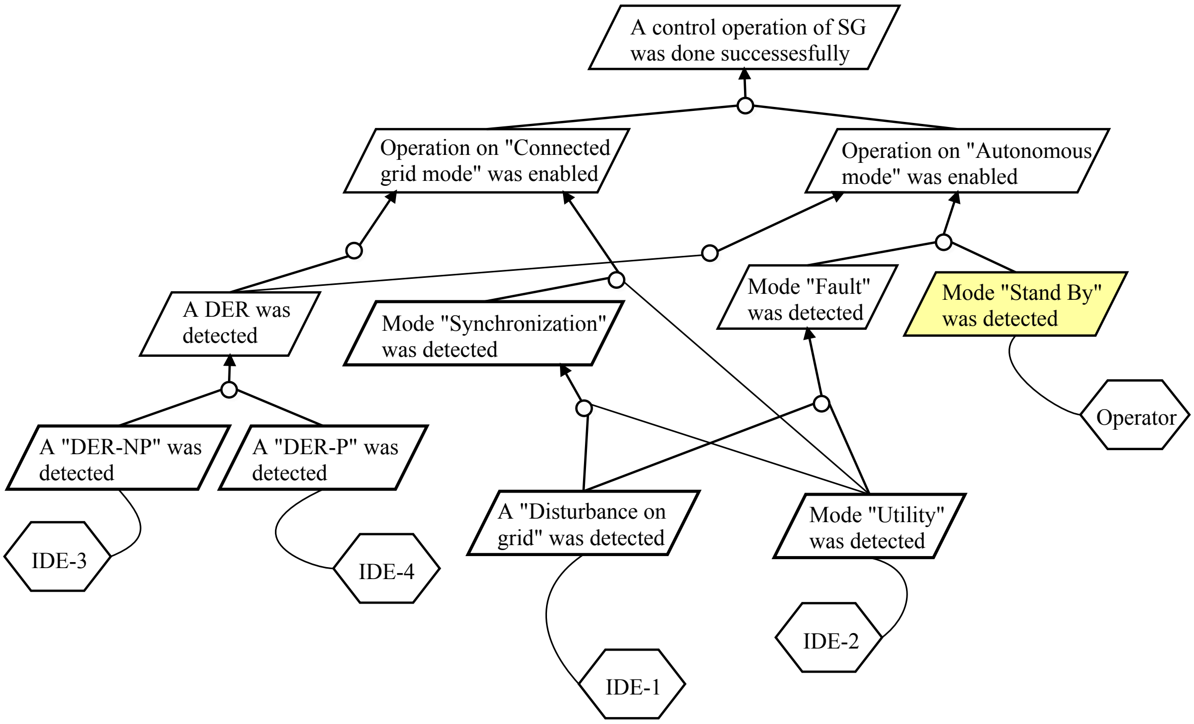

Figure 4: KAOS diagram of the microgrid system

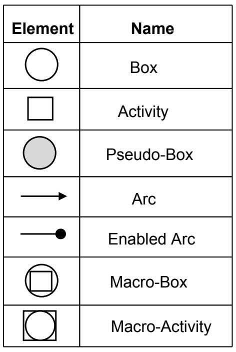

Figure 5: GHENeSys basic Elements

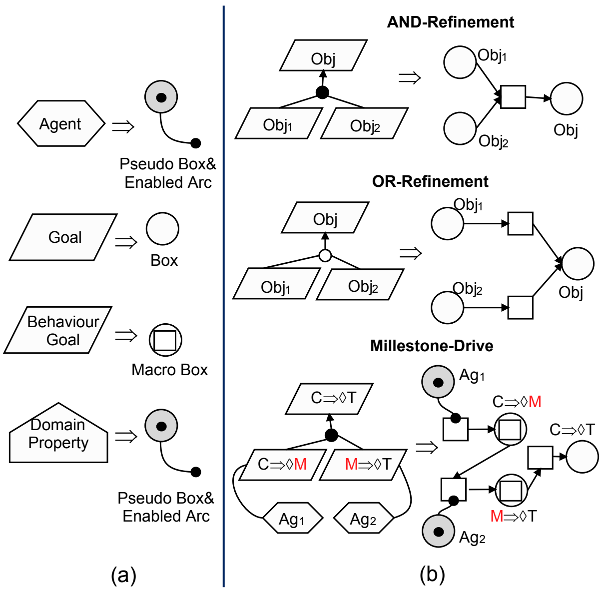

Figure 6: Equivalence for transformation from KAOS to GHENeSys

ysis. That is very important to an automatic system that interacts with electric energy distribution system. Petri Net is used instead of LTL because it is suitable to deal with distributed systems, which is the case of the microgrid and of the overall energy providing system.

Thus the resultant Petri net can indicate the operating modes of the microgrid according to the readings of the IDE's. In the Petri net, the inboxes (or input places) represent the IDE's.

By considering analysis techniques regarding the generated reachability tree, it can be concluded that:

- The Petri Net obtained is deadlock-free
- All markings are reachable from the initial marking (lifeless property), which also indicates that the local grid composes a proper system with the remaining energy distribution system.
- The net is finite (as expected) because the reachability tree in finite too. That also implies the system is closed and controllable.

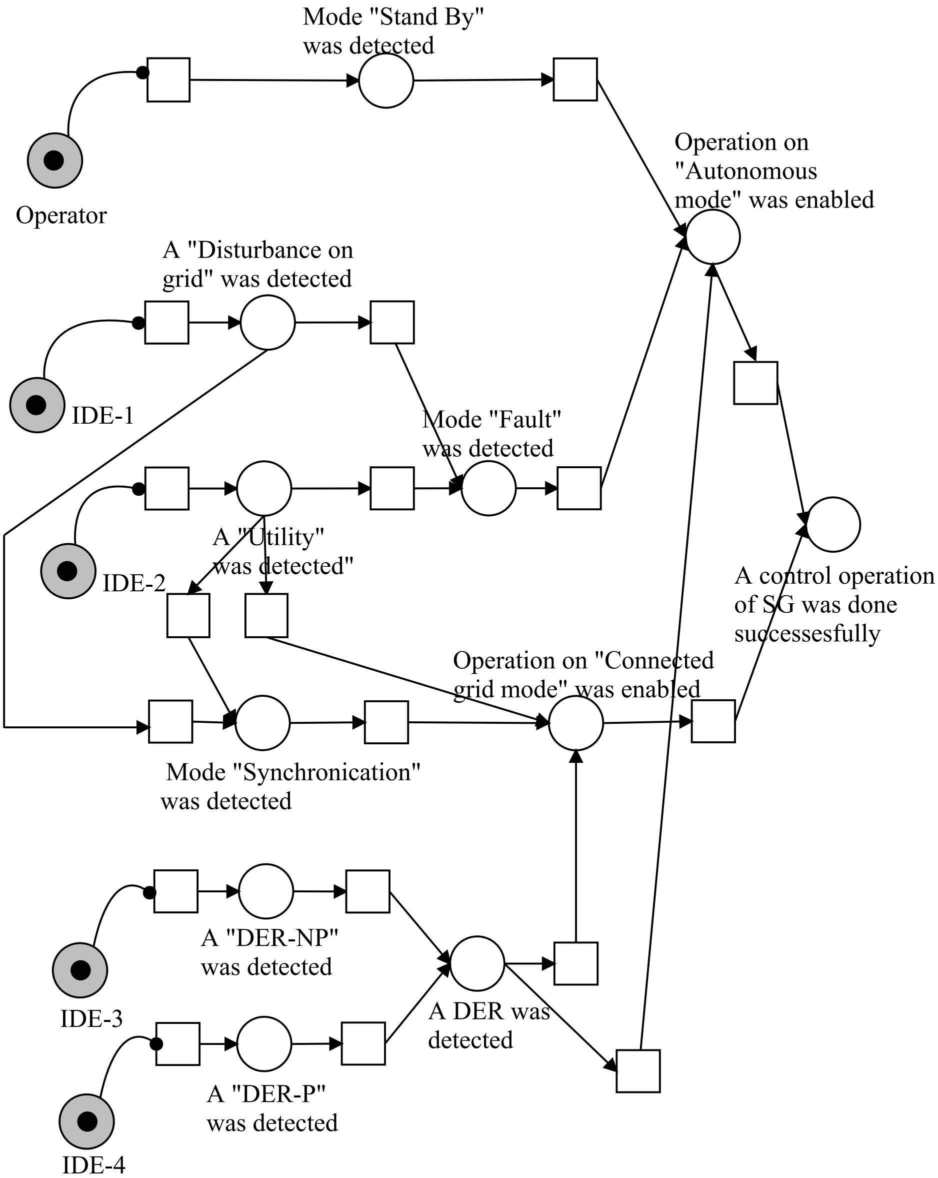

Figure 7: GHENeSys Network

4 Application Scenario

In this section, the proposed method is described, using as a case study the microgrid for communities in the county side of a Brazilian province called Amazonas, which has proper geographical characteristics (it includes the largest tropical forest of the world), as well as environmental technical restrictions.

The first step of the proposed method is to define the scenario, using the IEC 61850 model as a reference. Depending on the locality of Amazonas community we should have a different spectrum of energy sources available (or admissible), such as Biomass, Biogas, solar, hydraulics, wood, natural gas, oil, besides the electrical energy distribution.

In the second step requirements are developed and the microgrid is modeled, in the scope of a system power generation through CHP systems, and BESS, the supply of electricity in low voltage through the energy concessionaire.

Another characteristic of the system is that the DER's would be able to maintain, at the peak of its production, only critical loads. The DER's and diesel generators together must fulfill the energy needs of the community in situations of medium or low production of renewable energies.

In the third step, goal-driven requirements are synthesized, based on the IEC 61850 reference architecture, and considering the geographic, environmental, and technical restrictions, we obtain as results the KAOS model shown in Figure 4.

In the fourth step, a Petri Net is derived from a KAOS model, modeling the automation of the microgrid system operation, as shown in Figure 5.

In this step, when analyzing the readings of the IDE's, the Petri nets developed should switch the most appropriate mode of operation for the microgrid system.

The final step is the validation, through the analysis of behavioral properties and performance evaluation, which support the design of a control solution to the microgrid, considering the particularity and constraints of the Amazon region.

In the Figure 7, it shows the working dynamic of microgrid modeled in Petri Net. The control of the microgrid operation is in charge of receiving the control signals through the IDE's, processing and transmitting the signals for the system. Thus, once the controller receives a signal from the IDE´s, it will enable the triggering of the transition bypassing the system to the Stan-By state, in the autonomous mode.

From the control processing, that is, the evaluation of operations (Available BESS), (Available DG) the system can change to operate with BESS or DG activating or deactivating controllable transitions. Also available from this Stand-By state are two switching possibilities of the Available Utility Grid Supply (U), and Utility Grid Disturbance (UD) control locations which may lead to a possible change or return of the operating state to Synchronization Operation.

Each time the controller detects the PCC circuit breaker the microgrid accesses the grid and switches Grid-Connected mode, the power supply initially happens through the state called Utility, depending on the load demand can switch to the Utility + BESS states, Utiliy + DG or Utility + BESS + DG.

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.

5 Conclusions

The present work is based on the hypothesis that distributed power supply should be diversified and based on harmonic deal with small consumer unities that can also provide energy by local grids (microgrids). Such local facilities should be from different arrangements of renewable energy sources and conventional (electric) energy power supply.

To achieve good performance these systems should be automated and therefore its design should be no longer based on good practices and experience based on intuitive and/or tacit knowledge. Automation would also insert autonomy in control systems which could be a source of problems instead of an advance, if not well managed.

Thus, the proposal presented here combines methods already used and reference architectures with modern gol-oriented methods of requirements modeling, specification and analysis to provide reliable design of microgrids, capable to deal with simple urban problems up to more sophisticated environmental restricted cases, such as the on of small communities in the jungle.

Besides using Goal-oriented Requirements Engineering, the proposal introduces requirements analysis and (formal) validation based on Petri Nets. Preliminary results presented in this work were obtained using classic Place / Transition nets, in which the drives of operation modes depend on the sensing performed by IDE's.

Future steps in this research will look into the possibility of using Petri Nets to model the probabilistic type information that runs through the microgrid. In addition to being an extension of the current job, new features can be introduced, such as time. Besides, the microgrid arrangement supposed here follow the recent tendency to have energy supply as a Service System of Systems open space new ambitious architectures (Silva and Nof, 2015).

The results of this work indicate that it is possible to develop a method for formal specification of requirement which enables to manage the modes of operation of a microgrid based on the IEC 61850 architecture, the use of the GORE methodology and Petri Nets modeling, which allowed to propose a model for the automation of operation of the microgrid system, taking into account adaptations and restrictions.

Acknowledgements

Thanks to the University of Amazon State (UEA), and University of São Paulo (USP) for the support and collaboration in the elaboration of this work.

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