A Qualitative Agent-Based Approach To Power Quality Monitoring and Diagnosis

Maria J. Santofimia[a*], Xavier del Toro[b], Pedro Roncero[b], Francisco Moya[a], Miguel A. Martinez[a], and Juan C. Lopez[a]
[a]*Computer Architecture and Networks Group. School of Computer Science, University of Castilla-La Mancha, Ciudad Real, Spain*
[b]*School of Industrial Engineering, University of Castilla-La Mancha, Ciudad Real, Spain*

Abstract. Problems derived from the power quality aspects of a power grid are turning the monitoring and diagnosis tasks into an appealing field for electric power researchers. This interest is mainly founded on the great importance of providing highly reliable power grids, but also because of the relatively simple task (computationally speaking) required to accomplish the measurements. Despite its potential importance, efforts are mainly targeted at collecting data and confronting it with quality standards, rather than identifying problems, providing solutions or anticipating power faults. Aware of this shortcoming, this work is intended to bridge the gap that leads to self-sufficient systems, capable of anticipating and reacting to power faults, instead of a simple data gathering. This work also provides a characterization of the power quality domain, proposing a qualitative behavioral model that supports the multi-agent system in its task to anticipate and wisely react to power faults, and improve power quality.

Keywords: Qualitative Reasoning, Power Quality, Multi-Agent Systems

1. Introduction

It is a well known fact that electrical energy is at the core of the developed world activities and economy. Providing reliable electrical power systems is, therefore, a major concern. In this context, power quality monitoring and diagnosis emerges as a hot topic, due to the associated industrial and economic effects of power quality problems in the electrical grid.

Using Multi-Agent Systems (MAS) is the straight forward approach when systems are expected to exhibit an autonomous and intelligent behavior. Nevertheless, this is not the only reason that advocates for an agent-based approach to deal with the power quality problem, as listed underneath:

- Power quality monitoring poses a context where systems have to behave in a robust manner, since the cost associated with a system malfunction, poor power quality, and power faults can be considerable.
- Quick responses are also demanded. If a power fault is detected, a late response will not have the desired effects. Therefore, systems have to respond rapidly.
- The unmanageable number of possible situations makes it unfeasible to code one solution for each possible scenario. Moreover, not only a reactive behavior is expected from the system, but also a proactive, if the system is expected anticipate to faults and mitigate them.
- Finally, distributed and heterogeneous nature of the grid and power quality problems is suitable for using MAS.

All the above features are well addressed by the agent technology. However, while most of the architectures proposed to date for MAS fall into one of these groups, namely, logic-based, reactive, belief-desire-intention or layered architecture agents [57], the architecture proposed in this paper adopts a novel alternative, adapting the Model-Based Reasoning (MBR) approach to be founded on the *qualitative*

* Corresponding author. E-mail: mariajose.santofimia@uclm.es.

behavioral model of the dynamic system. This model describes the behavioral patterns of the system or context, which in this particular case comes in the shape of an electrical power grid. Hence, it is more appropriate to entitle the MAS approach as *qualitative behavioral model-based*.

The use of qualitative reasoning for behavior modeling and generation, as in [58], is proposed as a mean to translate the ambiguous, uncertain, and imprecise information into thorough descriptions of the problem, and the operations or processes that deal with it. While the former sort of information is not well addressed by computing systems, the later is perfectly well managed. Therefore, the qualitative model can be understood as the translation of the human cognitive model of the dynamic system, the electrical grid in this particular case, into a representation understood by computing systems.

The purpose of generating a qualitative behavioral model for the electrical grid is twofold not only it provides a behavioral model, but it also characterizes the power quality problem. Traditionally, problem characterizations have mainly served to support academic purposes [7], to simulation support, or to test systems. Nevertheless, this work resorts to characterizations as a mean to provide the system with human like rationality and understanding capabilities. This domain characterization drives the system behavior in a human-like fashion.

The remainder of this paper is structured as follows. Section 2 revises the previous works that have faced the problem of power quality monitoring and diagnosis, and how the solution proposed here overcomes the identified shortages of previous approaches. Section 3 provides some background about power quality, enumerating some of the most common power quality problems. Section 4 describes the foundations of the qualitative reasoning theory, and how this can be applied to handle the power quality monitoring and diagnosis problem. Section 5 provides the implementation details that support this work and includes an illustrative study case. Finally, the last section presents the main conclusions derived from this work.

2. Previous Works

During the last decade, MAS has gained credit as an efficient approach to address power engineering applications. As cited in [37], MAS have been successfully used for a wide range of applications, such as diagnosis [10], condition monitoring [39], power system restoration [43], market simulation [59] [26], network control [12] [27] and automation [9].

The work in [37] is the first of a two-part paper where the role played by MAS in the field of Power Engineering Applications is analyzed. This work provides an excellent starting point when developing applications for power systems, since it provides a thorough description of the strengths and weaknesses of an agent-based approach. Furthermore, the bibliographic analysis carried out in that work provides a conscientious survey of the wide variety of applications where the MAS technology has been employed in power systems.

Regarding Power Quality Monitoring and Diagnosis, several have been the technologies used to address the problem. The work in [61] presents an online approach to monitor power quality through the Internet. In this line, works in [32][33] resorts to a web-based interface to manage a database system in charge of storing power quality data. Despite the benefits claimed by the author of the previous works, [34][13][14] point out some shortcomings such as high network bandwidth requirements, large storage capabilities, and expensive computational cost. The work in [56] proposes a remote power quality monitoring system, implemented using MATLAB Server Pages. This implementation is also based on a database management system using the Internet network. This work claims to overcome the disadvantages of the aforementioned works by simplifying both, the data stored and transported through the network. Nevertheless, none of them provides any sort of advanced capability to identify fault causes, prevent damages, or provide restoration capabilities.

The implementation of advanced features requires some sort of rationality and autonomous behavior, as provided by MAS. The literature review examines different MAS approaches for power quality monitoring. Some innovative approaches, such as the one in [53], adopts the shape of a Multi-Immune-Agent-Based approach; in [52] a new concept for power quality monitoring is proposed, where the MAS has the capability to automatically reconfigure itself under fault conditions.

However, there is a scarce number of MAS approaches with the ability to characterize, recognize and determine the origin of the power quality faults, and prevent possible damages that it might cause to electronic devices connected to the power grid. These tasks have been traditionally addressed from the optic of the fuzzy logic, such as in [40][55].

Apart from the fuzzy-logic approach, power quality characterization can also be addressed resorting to an ontological approach, as in [28]. The main advantage of doing so is the possibility opened to infer casual explanations to those power quality faults, detected on an electrical grid, following the directions described in [2].

In an isolated manner, systems based on MAS, fuzzy logic or ontologies manage to address some of the features desired in a power quality monitoring and diagnosis system. However, the need for a combined solution that responds to all these requirements motivates the proposal of a qualitative agent-based approach in this work, that grounded on the power grid behavioral model, is capable of reasoning about ongoing scenarios, performing monitoring task, and undertaking those actions that restore the system to its normal state, just after detecting a failure or disturbance.

3. Power Quality Monitoring

The term "*power quality*" refers to the reliability of the supplied electrical energy and the ideal characteristics of the voltage and current magnitudes measured in the electrical transportation and distribution grids. This term also addresses all the undesirable divergences from the ideal behavior that might occur and have negative effects on the costumers and the equipments connected [4].

Power quality has become an important issue, particularly since the beginning of the 90s, and is nowadays a concern for utilities, equipment manufacturers and costumers. Different factors have contributed to increase the interest for power quality:

- Equipments are more sensitive to disturbances (particularly computers, processor and digital electronics).
- Equipments incorporating power electronic converters are causing more disturbances due to their non-linear behavior.
- New regulations are necessary, since the final consumer is not anymore a load but a costumer and electrical energy is a product that must fulfill some quality requirements.
- The electrical grid is increasing in complexity due to the introduction of distributed energy generation systems (such as renewable energy sources), and the market is being liberalized, which implies and increasing number of players.

Power quality problems arise when the voltage and current waveforms differ from their ideal appearance. Ideally, voltage and currents have to be sinusoidal with a fixed amplitude and frequency according to their nominal values. Moreover the voltage and current waveforms have to be in phase, and in three-phase systems they have to be balanced. The main disturbances that lead to poor power quality can be classified and listed as follows [15][19]:

- Transients (duration is less than a fundamental cycle (20 ms)).
  - Pulsed transients.
  - Oscillatory transients.
- Short duration variations (duration is less than 1 minute).
  - Interruptions (amplitude is less than 10% of the nominal value).
  - Dips or Sags (amplitude between 90% and 10%).
  - Swells (amplitude between 110% and 180%).
- Long duration variations (duration is more than 1 minute).
  - Interruptions (black-out).
  - Undervoltages (amplitude is less than 90%).
  - Overvoltages (amplitude is more than 110%).
- Unbalances (in three-phase systems).
- Waveform distortion.
  - Harmonics.
  - Interharmonics.
  - Notches.
  - DC component.
  - High-frequency noise.
- Voltage fluctuations (flicker).
- Frequency deviations.

Some of these disturbances are illustrated in Fig.1.

Power quality is nowadays a requirement as much as some other issues, such as security, reliability, low cost of installation and operation, etc. Since it is not possible to improve something that cannot be measured, power quality monitoring systems, methodologies and regulations are necessary [21][44][15].

Advanced equipment for power quality monitoring is already available in the market, such as power quality analyzers, power analyzers and oscilloscopes with advanced features. The trend on the design of those equipments is moving from a single and costly device for local measurements (operated by a well-trained professional with a strong background on power quality, who is able to understand and manage the information provided by such equipments), towards a global distributed solution with multiple devices spread through the grid and powerful communication capabilities [45][24][41]. Moreover, power-

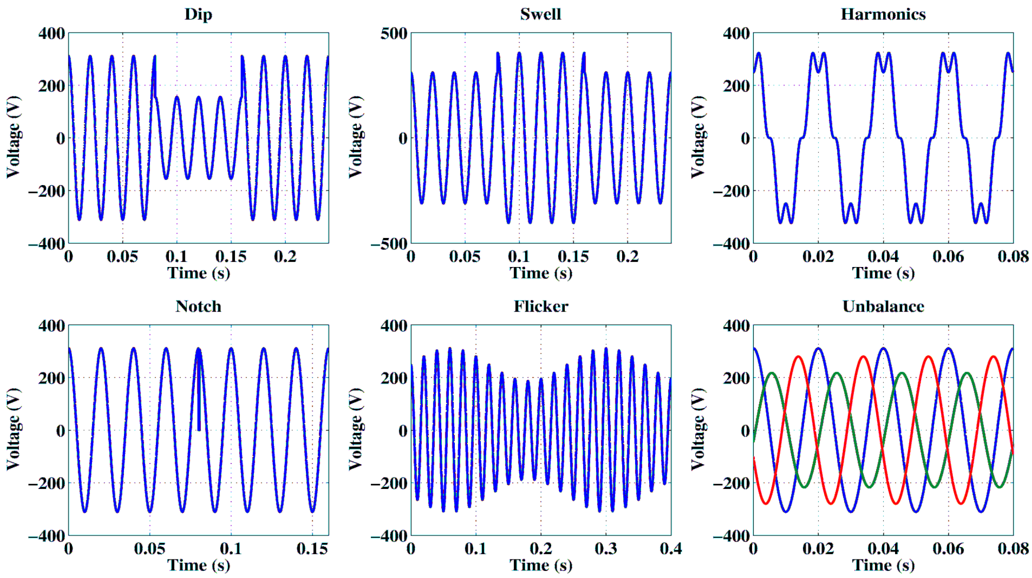

Fig. 1. Typical disturbances in electrical grids.

ful software tools with intelligent algorithms are available in the latest developments to process all the information and provide diagnostics and reports about compliance with the standards, causes and location of problems, negative trends, etc [13]. Due to the importance of communications in those systems, even a standard for electrical system communications, such as the IEC 61850, is being adopted for power quality monitoring applications [35].

In [16] a future vision power quality monitoring systems is provided. In this vision, in ten years time, monitoring and measurement devices will be installed all over the grid and there will exist 100% compatibility between them, failures and faults will be prevented, the location of problems will be possible and ”*power quality data management systems will be automated as will Power Quality data mining, reporting, and analysis*”.

4. The Qualitative Behavioral Model

Describing the world in terms of logical statements using some first-order logic formalism, although desirable from the computer perspective, is not always possible. The modeling, representation, and reasoning about dynamic system behavior are some of those tasks that demand higher level of expressiveness from the formalism used in the knowledge description.

Qualitative reasoning first appears into scene introduced in [11], as a mean to explain and predict the behavior of physical systems. To some extent, qualitative reasoning and physic science only differ in the quantification aspect of the later, since both of them are intended to explain and predict system behavior.

Qualitative models are closely related to the concept of commonsense knowledge. The commonsense knowledge represents the knowledge about the everyday physical world, or as stated in [42] ”*the knowledge of how the world works*”. Commonsense knowledge tells you that when putting a stopper in the kitchen sink, and opening the tap, after a while, the water will overflow. The correlation between commonsense and qualitative reasoning is determined by the fact that the qualitative models provide recipes, such as the one describing that when the liquid contained in a container reaches the container height, if the level increases, the liquid will be spilled out. Meanwhile, the commonsense reasoning applies this qualitative law or model to the ongoing scenario -the open tap- and predicts future effects of it. Basically, qualitative models seem to be the most straightforward approach to provide computing systems with the commonsense reasoning required to exhibit an intelligent and autonomous behavior.

Qualitative reasoning has been addressed from three different perspectives, namely device-centered [25][24], process-centered [17], and constraint-centered [26]. Depending on the modeling perspective, it can be focused on devices, processes or constraints. An extensive analysis about these three approaches can be found in [58].

Among all the attempts found in the literature [31][30][36][3][1] addressing the construction and simulation of qualitative models, this work advocates for GARP3 [7], as the framework supporting the behavioral model generation and simulation. Moreover, due the power quality nature, the theory that better fits its features is the process-centered approach, which is perfectly well addressed by the GARP3 framework. This framework is also able to represent the generated model in the Ontology Web Language (OWL). This is a key issue when it comes to the integration of the behavioral model with the MAS architecture, as it will be described in the following sections.

4.1. The Electrical Grid Behavioral Model

As mentioned above, the generation of the qualitative behavioral model has been supported on the GARP3 framework. This framework provides a structured methodology to undertake the modeling task [46] that is followed here. The qualitative behavioral model of an electrical grid system, which is used to characterize the power quality monitoring and diagnosis problem, is presented here by means of some of the most representative diagrams and artifacts generated by GARP3.

The first step in constructing the qualitative model consists in sketching the entities related to the dynamic system, in the so called entity hierarchy, as depicted in Fig. 2. This step will provide an overall view of the relevant entities for the problem domain.

The next stage models the global behavior of the dynamic system, specifying the typical scenarios, which along with the considered processes compose the causal model of the system. The causal model is intended to provide an image of how each of the considered processes can affect the system.

Fig. 3 shows an example of scenario containing some of the most relevant entities and the relationships between them. Moreover, the quantities[1] that describe the features of an entity are also shown with their quantitative space[2]. The scenario depicted in Fig. 3 shows an electrical grid containing loads and conventional distributed generators. In the state of the system described in that figure, the active power of the loads is equal to the generated active power and therefore, power balance is zero, which is the desired state of equilibrium.

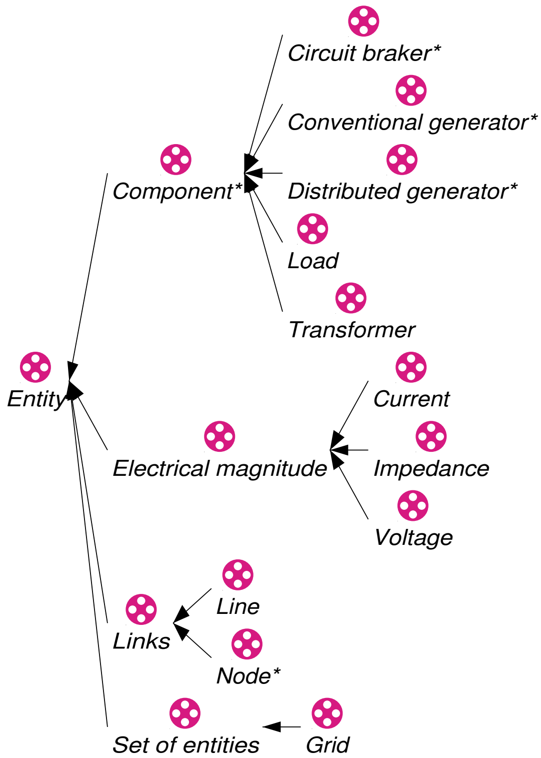

Fig. 2. Entity hierarchy in the electrical grid model.

In order for the MAS to infer behavior, the qualitative model needs a library of model fragments capturing the general knowledge about the system dynamics[3].

Fig. 4 describes frequency deviations, which is one of the power quality problems enumerated in section 3, and it is modeled in GARP3 as a model fragment. Frequency deviations occur when there is no balance between the generated active power and the loads active power. In those situations, for instance, when power demanded by loads is bigger than the power

[1] Quantity is the term used by GARP3 to refer to changeable feature of entities.

[2] Quantity space is the term used by GARP3 to refer to the possible values a quantity might take on. They are ordered set of alternating points and intervals.

[3] Model fragment is the term used by GARP3 to refer to behavioural features for entities. They describe pieces of knowledge that may apply to scenarios.

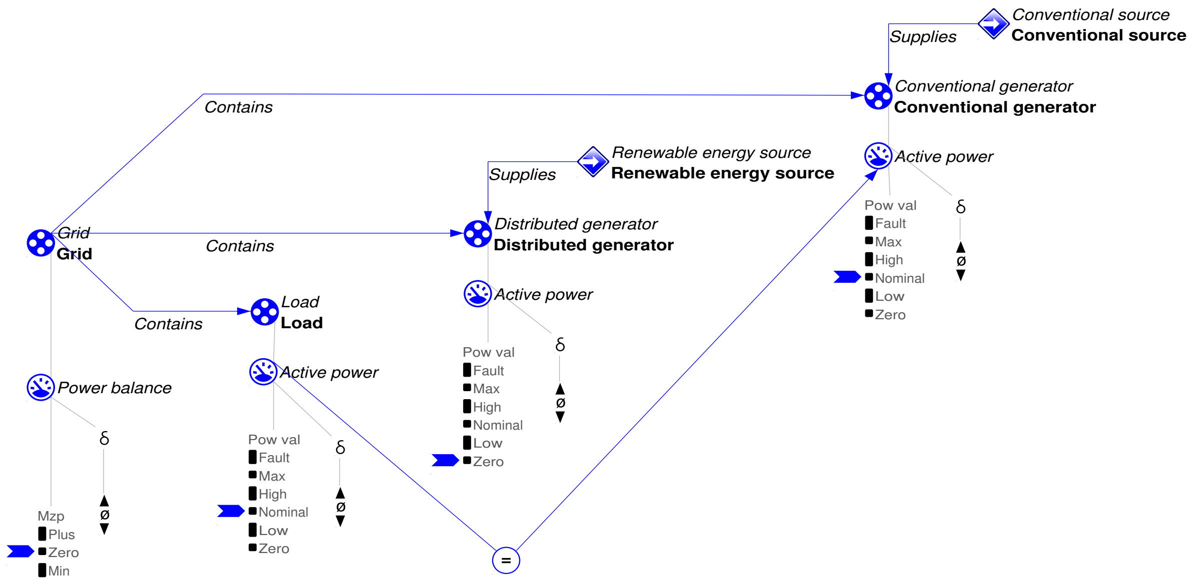

Fig. 3. Example of Scenario.

supplied by the energy sources, the difference in energy demand is compensated by the kinetic energy of conventional generators, which consist on rotating electrical machines. The reduction of kinetic energy reduces the speed of those machines, and consequently the frequency of the generated voltage decreases. The model fragment in Fig. 4 illustrates in a simplified way those relationships.

Fig. 5 depicts the model fragment describing the entities and relationships involved in a voltage dip, which is one of the most frequent power quality problems. Most voltage dips are caused by short-circuits in the grid or the connection of high-power loads, such as big electrical motors. In those situations, the voltage level drops and the event can be classified according to the duration and the reduction of the voltage amplitude as it is briefly described in section 3. The voltage dip model fragment describes the interaction between the active power in the load and the voltage amplitude. A positive increase of the active power in the load produces a reduction of the voltage amplitude (see the relational operator I- used in the GARP3 environment to express a negative influence). Voltage dips are usually mitigated by triggering the circuit breakers for equipment protection and short-circuits. Furthermore, the injection of reactive power can also mitigate and support the grid during voltage dips. This reactive power can be supplied by distributed generation sources such as wind farms, and some grid regulations already demand this action in some countries, such as Spain, where wind power systems have a considerable presence in the electrical grid.

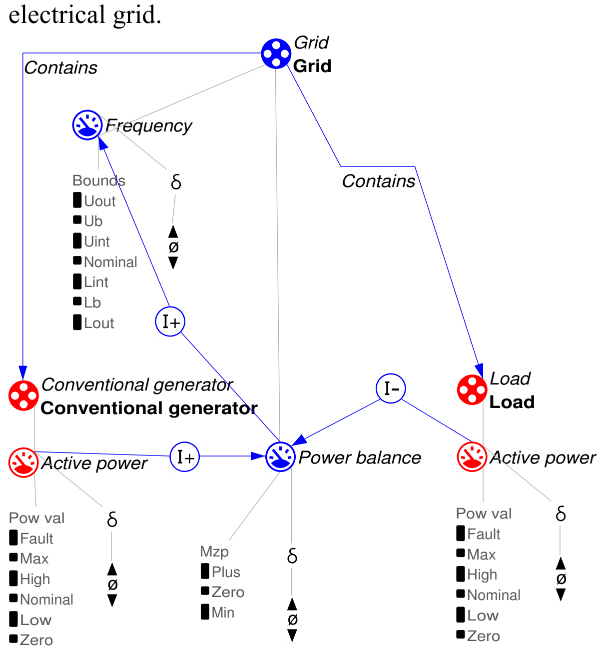

Fig. 4. Frequency deviation model fragment.

The behavioral model of the electrical grid can be enriched by creating additional model fragments (like the ones described in this section) representing the knowledge about the electrical grid dynamics and the related power quality issues.

5. Architecture Description

The proposed qualitative behavioral model provides, not only a characterization of the electrical grid and power quality monitoring and diagnosis problem, but also is the basis for external systems to supervise the power quality of a grid and undertake corrective or preventive actions when required. This section is focused on describing how this second contribution can be achieved, proposing to this end a modular architecture, as the one depicted in Fig. 6.

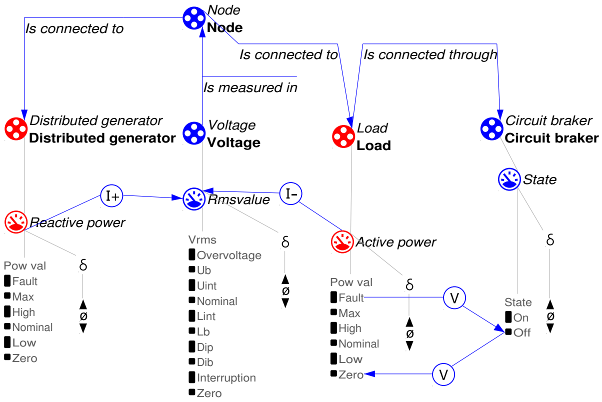

Fig. 5. Voltage dip model fragment.

The following subsections describe the details of the existing architectural elements, paying special attention to the MAS architecture, and also describing how the interactions among these modules are supported.

5.1. The Multi-Agent System Architecture

The qualitative behavioral model plays an important role in driving the behavior of the MAS, in its task to maintain, achieve or satisfy the system's goals. Therefore, this behavioral model-based agent approach is to some extent quite similar to the BDI model of agency [51]. However, despite the fact that behavioral model-based agents can be considered a subset of the BDI model of agency, there exists an important difference in the way how both of them determine the behavior of the agent in its commitment to achieve the stated goals. While BDI agents resort to the concept of *intentions* [6], as the partial plans of action that lead the agent to achieve certain goals, the approach presented here resorts to *courses of actions* or *simulated paths*. They are extracted from the qualitative behavioral model in order to select those actions or processes that lead to the targeted goals. Essentially, the main difference is that the proposed approach does not associate plans to

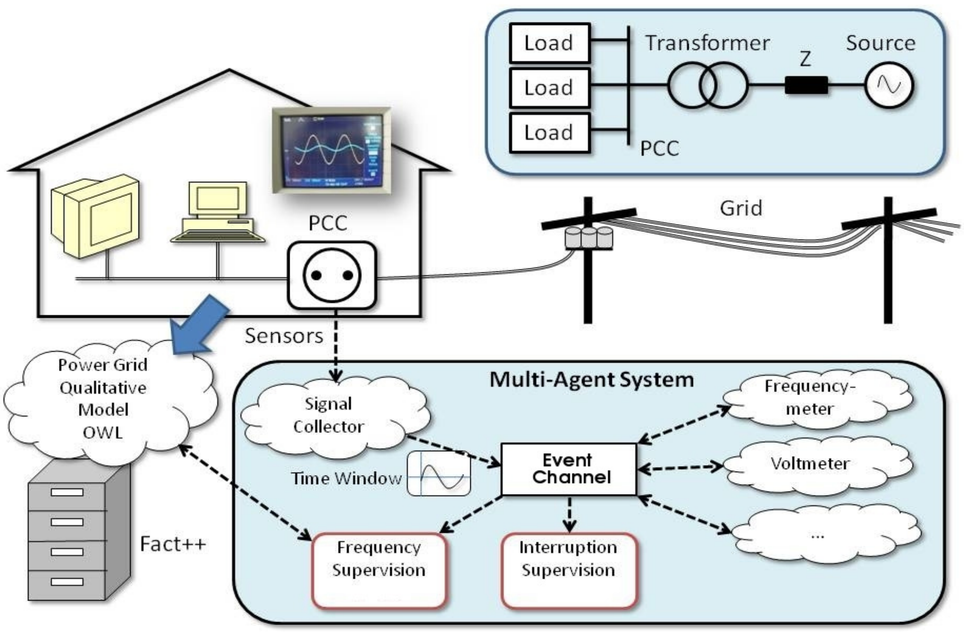

Fig. 6. An overall view of the system.

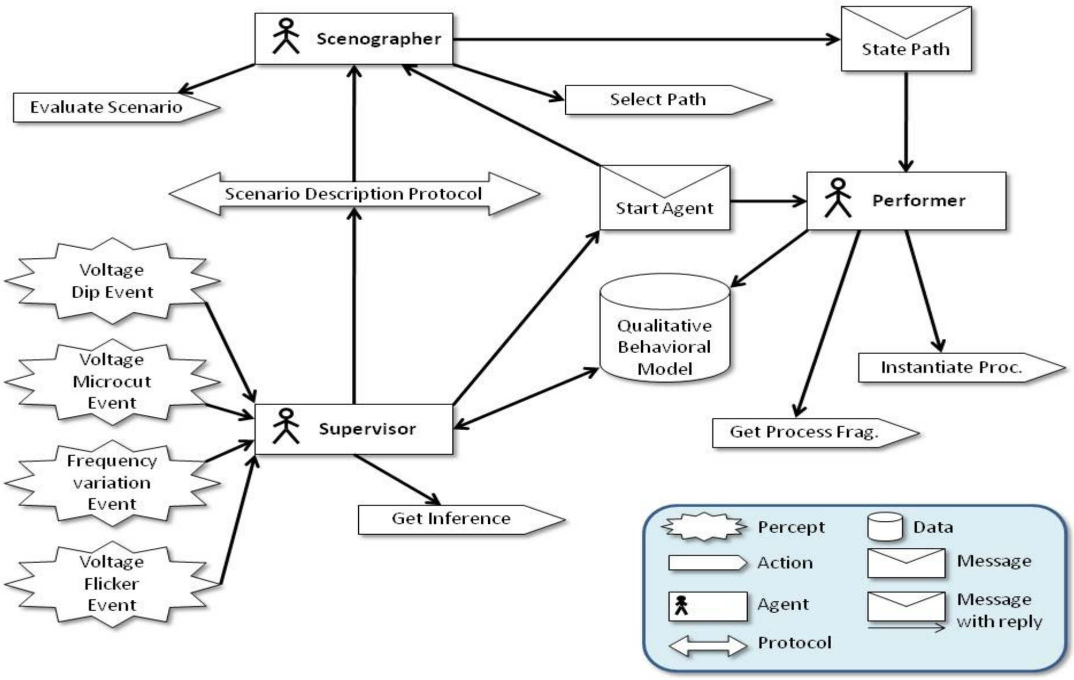

Fig. 7. MAS overview diagram.

goals, but leaves to the behavioral model criteria the selection of plans -here called process fragments- that will lead to the targeted goal. Furthermore, there is a slight hint in how goals are stated in both approaches. Under the behavioral model-based approach, goals are stated in terms of scenarios.

Basically, two examples of system goals are provided by the scenario where the values of the magnitudes being monitored are constrained to their nominal value and the scenario where, given an uncontrolled power fault, the priority is to keep loads safe. These scenarios are held by the *manager agent* as the goal scenarios, and, when some event occurs, deviating the system from those scenarios, the agent will be triggered with the commitment to return to the goal scenarios.

To better understand how plans are selected and undertaken by the MAS in its commitment to achieve the goal scenarios, it has to be remarked that there has to exist a direct mapping from the *process fragments* of the qualitative behavioral model to the methods or processes directly instantiated by the MAS architecture. In this sense, and coming back to the aforementioned set of process fragments for the electrical grid system, some of the most representative model fragments are those describing the dynamic of the frequency or the voltage amplitude of the grid. As described above, these processes are applied to those scenarios that match the requirements, therefore generating a set of new scenarios or states in the graph path. However, in order to be successful, the MAS, and eventually the agent in charge of instantiating processes, the so called *performer agent*, requires the ability to instantiate the methods to perform each of the available process fragments.

In the case of the simplified electrical grid system, scenarios are described in terms of the active power, reactive power, power balance, frequency, current, and voltage values, and their derivative values along the time. These scenarios are similar in concept to those of *beliefs*, as mental state of agents, for the BDI architecture. Therefore, in the behavioral model-based approach, agents do not hold beliefs but scenarios. At each moment in time, agents know the scenario of the qualitative behavioral model that is taking place, and therefore, the process that needs to be performed in order to follow a specific state path that leads to the goal scenario.

Following the representation guidelines provided in [47] to describe a MAS architecture, Fig. 7 provides a comprehensive description of the MAS proposed for the power quality monitoring and diagnosis problem. For simplicity, this diagram only represents some of the most relevant aspects of the system.

Therefore, this diagram does not represent all the events or actions that should be considered in a complete system, since it is not within the scope of the diagram, nor of this work, to list all the events and actions, but to provide a comprehensive overview of the overall architecture, and the MAS in particular.

5.2. Implementation details

The design and implementation of a MAS for power quality monitoring and diagnosis is tackled following the guidelines in [38].

The inherent distributed character of a system for power quality monitoring and diagnosis, deployed in an electrical grid, demands an architectural approach itself distributed. Furthermore, the size and complexity supposed in such a system reinforces the groundings advocating for distribution. Nonetheless, one direct consequence of implementing a distributed architectural approach is the arising need for supporting communication and interaction processes. Moreover, as an addition to these requirements, the particularities of a system for power quality monitoring and diagnosis demand the following requirements:

- It has to be a fast response real-time system. Therefore, the latency of communication and interaction protocols has to be reduced to a minimum.
- Message exchange tasks have to be supported to allow communication among agents.
- Data acquisition and persistence support is required.
- Connectivity for heterogeneous platform has to be supported, since homogeneity cannot be expected regarding the devices plugged to an electrical grid.
- The system has to be scalable.

The need to provide a solution capable of coping with the aforementioned challenges rejects the possibility of resorting to off-the-self frameworks, such as JADE [1] or JADEX [49] for instance. These frameworks have proof to be an excellent solution to implement MAS. However, the MAS presented here is meant to be deployed in a broad network, where sensors collecting the power quality measurements may employ more than a single protocol. Therefore, agents are expected to support the interaction with these devices using different protocols. Instead of being constrained to the Message Transport System provide by frameworks such as JADE or JADEX, the work presented here advocates for a middleware layer, upon which agents, sensors, and actuators can be deployed.

As an additional argument supporting this decision, the work in [54] presents a comparative analysis among some of the available frameworks for MAS. The conclusions derived from that study combined with the requirements stated above, support the selection of a tailor-made architecture, based on the benefits of using a specific middleware technology. Therefore, it is the middleware layer responsibility to support not only the software agents communication and interaction, but also the integration of heterogeneous devices and the scalability of the solution.

The chosen middleware technology is ICE (Internet Communications Engine) [22], a CORBA-like middleware technology. Among the advantages of using the ICE technology to support the MAS architecture, it can be highlighted that it provides a mechanism, called IceStorm, that abstracts the details of implementing a publish/subscribe architecture. Therefore, adopting an event channel implementation provides agents with an architecture where message exchange is supported and is almost straight forward, by simply publishing the messages to one of these channels. Agents subscribed to these channels automatically receive the messages. For the sake of compatibility the agent messages adopt the FIPA-ACL standard [18]. Regarding scalability, ICE provides an implementation of the evictor pattern, as well as mechanisms to automate the object persistence, that ensure the scalability of the system.

Furthermore, among the different models of agency available, the one that better fits the approach presented here, founded on a qualitative behavioral model, is the Model-Based Reasoning as presented in [57]. This approach implements a set of reactive agents, that based on a set of goals, and a model of how things works, resort to a planner in order to achieve a specific goal, given the current state. The model is provided by the qualitative model, developed using the GARP3 frameworks.

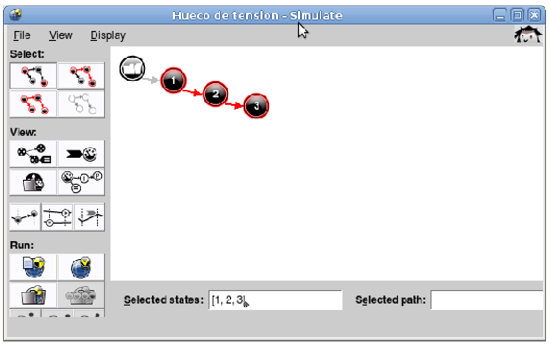

Fig. 8. Simulation path.

Given the fact that the qualitative model itself generates all the simulation paths, identifying the current state in the path allows the identification of the actions that need to be carried out in order to achieved the desired target state. Fig. 8 depicts one of these simulated paths.

Finally, in order to be complete, this architecture requires the services of a reasoning engine, which allows agents to infer the current state, given a set of features. This reasoner can adopt the shape of an OWL-DL reasoner, since, among the many strengths already highlighted in the GARP3 framework, its OWL export utility simplifies the task of performing inferences upon the qualitative model. Given the events taking place in the electrical grid, and the values of the observed magnitudes, the agent queries the OWL Reasoner to identify the current state from a simulated path.

The OWL Reasoner has been implemented as a middleware service, by wrapping the Pellet[4] and Jena[5] API into an ICE server. This service receives SPARQL queries [50] that once evaluated by the Pellet engine allow the identification of the state in the simulated paths. Agent goals are the identification of the power quality fault or disturbances taking place in the electrical grid and when possible, the restoration of the electrical grid to its normal conditions. The use of a simulated path transforms the goal pursuing problem into a search problem. The system seeks the states in the simulated path that lead to failure identification and restoration whenever possible.

Once identified, the reasoning engine extracts from the qualitative behavioral model the path, in terms of process fragments, instantiation that needs to be instantiated to reach the stated goal scenarios. The fact that actuators have also been implemented as middleware services simplifies this instantiation process. Once again, the communication channel supports this task, preventing agents from having to know how to instantiate these processes. Publishing a message to the actuator channels is enough for the corresponding process to interpret the request.

Sharing a common ontology, in terms of concepts of the domain model and their relationships, is at the groundings of this abstraction capability. Agents, middleware services, and the middleware itself hold the same representations for common concepts.

The monitoring results are gathered, saved in a database and showed in the graphical interface depicted in Fig. 11. The GTK Python interface is also designed and deployed on top of the middleware layer. MatPlotLib[6] has been used to show a graphical representation of the detected events.

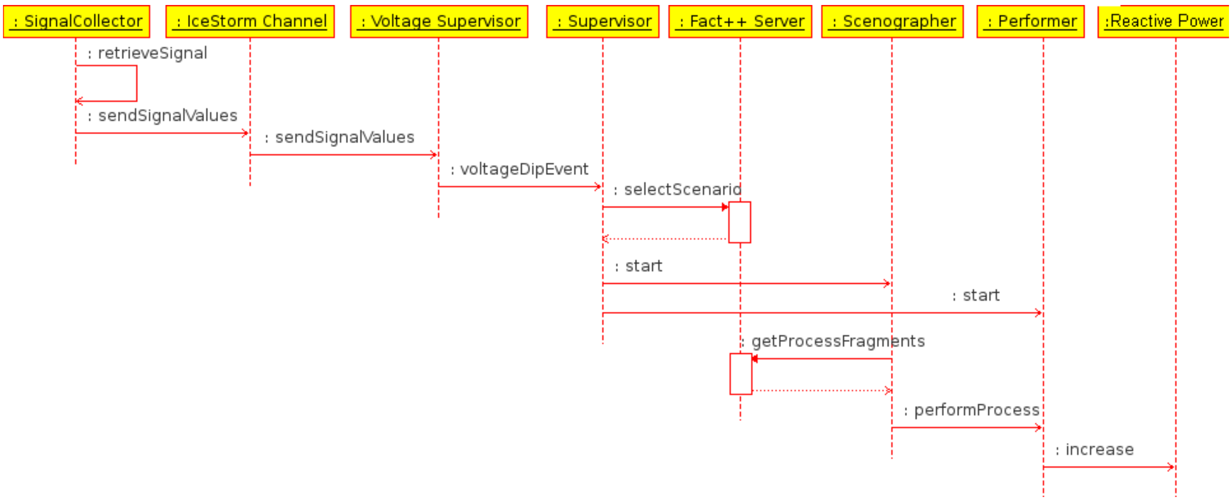

Fig. 9. Sequence diagram for the voltage dip use case.

Fig. 9 provides an overall view on how these different elements interact with each other, by depicting the sequence diagram for the use case of a voltage dip event. The occurrence of such an event is identified by the *Voltage Supervisor*, after the *Signal Collector* publishes the temporal window with the signal values. The voltage supervisor triggers an event an-

[4] Pellet: OWL 2 Reasoner for Java. http://clarkparsia.com/pellet/

[5] Jena – A semantic web framework for Java http://jena.sourceforge.net/

[6] Matplotlib: a Python 2D plotting library. http://matplotlib.sourceforge.net

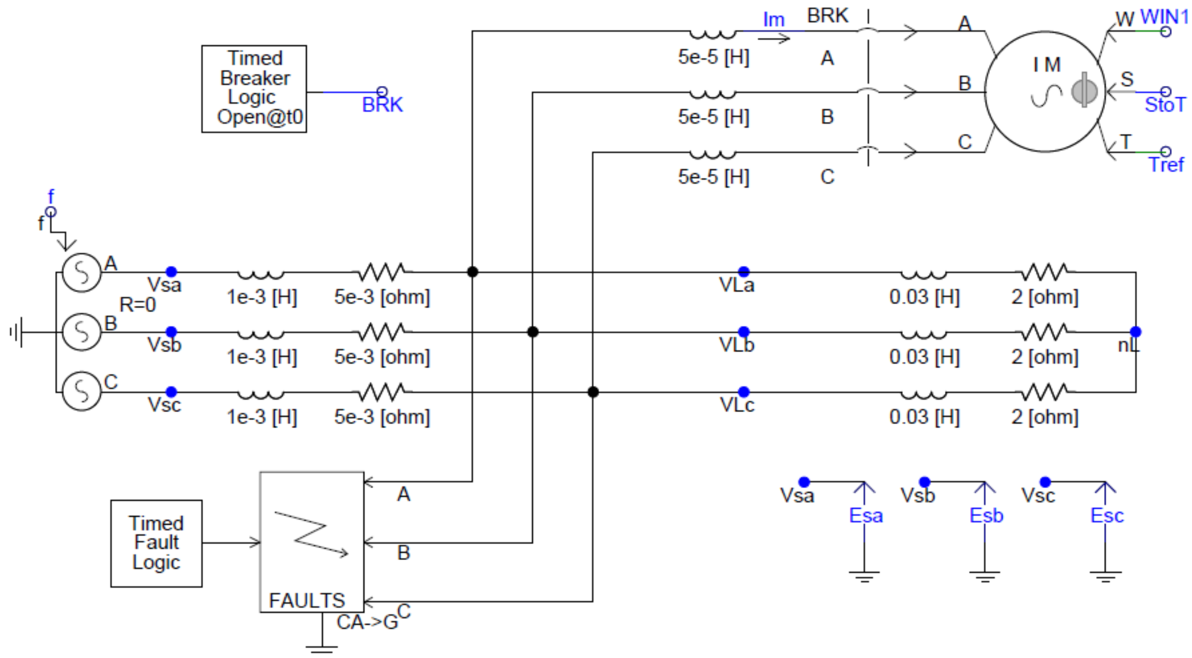

Fig. 10. Electrical diagram of the case study.

nouncing the voltage dip. The *supervisor agent* aware of this goal scenario deviation, queries the reasoning engine about the scenario identification, required as the starting point of the path that leads to lead to the desired state. This agent is also responsible for starting the *scenographer* and the *performer agents*. Both agents are started with the goal of returning the system to a specific state. The scenographer queries the reasoning engine to retrieve the set of process fragments involved. These processes are fed to the performer agents in charge of their instantiation.

5.3. Study Case

This section illustrates the behavior of the system proposed in this work. The scenario of the case study, which is depicted in Fig. 10, has been designed and

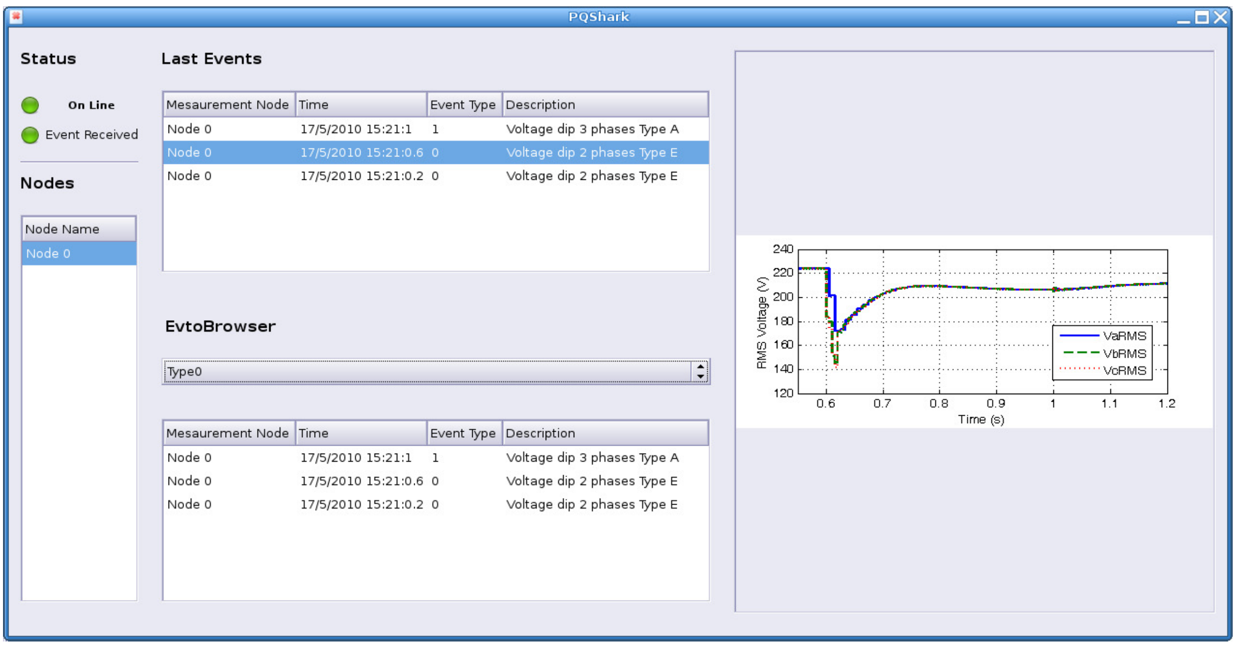

Fig. 11. Screen-shot of the monitoring System.

simulated with PSCAD[7]. This scenario consists of a power generator connected to a three phase electrical grid, and three different loads. One of them is a high power induction motor. There is also an ARL load, and finally, there is a special load devised to produce short-circuits faults.

In this scenario several power quality events have been simulated:

- Two different voltage dips, one of them caused by a short-circuit to ground in two of the phases and the other voltage dip is caused by the connection and start-up of the induction motor. Both events can be observed in Fig. 12 and Fig. 13 at 0.2 and 0.6 seconds, respectively, in the time window.
- A frequency deviation from the nominal value of 50 Hz to 49.4 Hz at 1 second. This event can be observed in Fig. 14.

The values of these temporal windows obtained by simulations have been used to test the proposed behavioral model-based MAS for power quality monitoring and diagnosis.

Fig. 11 shows a screen shot of the front-end design for the prototype in which the aforementioned events have been identified and stored. Moreover the system also generates the response to mitigate the events. These responses have been implemented as messages instantiating the process fragments retrieved from the query to the OWL behavioral model.

Actuators in charge of performing those actions are connected to the message channels provided by the middleware. These messages are correctly interpreted by the receiver in charge of answering the request sent to the channel.

6. Conclusions

Power quality has become an important issue to be addressed in modern electrical grids. Global and distributed solutions will be required to monitor and diagnose power quality with enhanced features to prevent and locate faults. Moreover large quantities of heterogeneous information have to be transferred and processed very fast and in an automated way, to provide useful information and responses to power quality problems. These requirements suggest the suitability of a solution based on a Multi-Agent System.

This work proposes a novel approach to tackle these emerging challenges, based on a Multi-Agent System whose behavior is rationally driven by the qualitative behavioral model of an electrical grid. Moreover, supporting this architecture on a middleware technology such as ICE, enhances the Multi-Agent System with a set of ready to use features such as communication channels, persistence management, scalability support, and a publish-subscribe mechanism, among the most representative features. Finally, combining this architecture with an OWL-DL reasoning engine, such as Pellet, enacts the Multi-Agent System capability to infer the most appropriate behavior, out of the OWL version of the behavioral model. This means that the Multi-Agent System does not count on a set of prefixed plans that lead it to the goals, but instead in a more dynamic and flexible fashion, it resorts to the qualitative behavioral model to determine its behavior.

The fact that the qualitative behavioral model is derived from the dynamic system simulation provides a deterministic way of determining the effects of performing certain actions, under specific circumstances. This characteristic supports the use of this approach for the monitoring and diagnosis tasks, not only for the power quality field as stated here, but with little modifications, and building the corresponding model, to any other dynamic system.

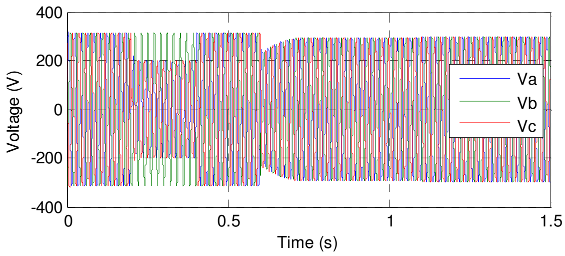

Fig. 12. Temporal window of the voltage waveform measured in the PCC.

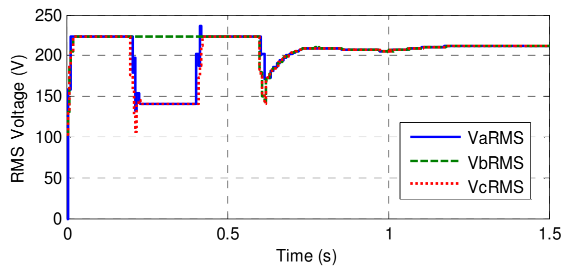

Fig. 13. RMS voltage of the three phases measured in the PCC.

[7] Software package to simulate power systems

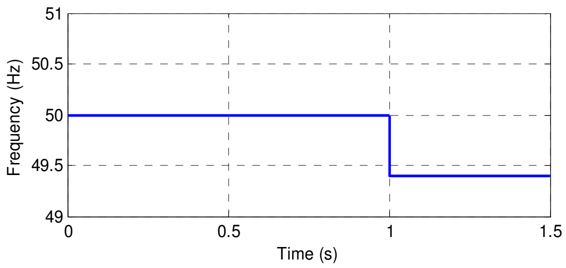

Fig. 14. Measured frequency deviation.

In contrast to the rest of approaches adopted when addressing the power quality monitoring, the qualitative agent-based approach presented here, not only succeed in the monitoring task, but also in the diagnosis and control task. Adopting a MBR strategy, supported on the Power Quality Qualitative Model, allows agents to map current events to model scenarios, and from there to infer the path to be followed in order to achieve the agent objectives.

The design and implementation of the MAS using the ICE middleware technology, provides a common base where agents, sensors and actuators can rest on, easing in this way communication and instantiation aspects.

Finally, providing an ontological model to be shared among all the elements of the system (agents, middleware platform, middleware services, etc.) is an important issue that traditionally has not been taken into account. Adopting this strategy has proved to simplify communication among the system elements, since they all hold the common knowledge of the domain.

Regarding future works, the current prototype has been implemented using a general OWL-DL reasoner, which injects high latency to the system. Due to the fact that the ontological model for the system is available, future works have to be intended to optimize the reasoning task. Adopting an approach as the one described in [48] seems to be a good choice for enhancing the reasoning tasks.

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