A Novel Extended Graph Strategy to Model Microgrids

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***Abstract*—Microgrids with renewable distributed generation appears to be a good alternative to provide electricity for rural areas and isolated zones. However, these microgrids presents relatively low robustness due to their distributed generation topology with lack of dominant nodes to absorb and compensate instabilities, and intermittent energy availability. This work presents a novel strategy to model microgrids in an extended graph model, generating additional model embedded information, essential for optimization processes in the quest of robustness and economy, among other objectives. The traditional impedance model of microgrid is complemented by an extended graph integrating additional information of grids elements such as saturation, current and voltage limits or energy resource availability. This paper presents the extended graph developed model, which yields to a concise representation of an entire microgrid system, as well as a set of graph metrics usable for electrical grid evaluation. The presented model and metrics show to be useful to store, in a single and simple model, valuable information for design, evaluation and operation of microgrid systems.**

***Index Terms*—Microgrid, network, graph theory, renewable energy**

I. Introduction

Microgrids have become a promising solution to supply local energy demand, to promote the renewable energy sources penetration, and to improve the quality, reliability and efficiency of power systems [1]. Some of the reasons to adopt microgrids are the difficulties to expand the transmission and distribution infrastructure to isolated sites and the possibility to use distributed small energetic resources. However, they present new challenges as they are constraint to unpredictable environmental conditions, to the low-capacity of generators to follow the demand, to the lack of dominant nodes in the network structure [2], to the scarcity of energetic resources and to the small economic margins. These issues from microgrids impose the need to analyze the system as a whole in order to be able to make better decisions, optimize design, and dispatch planning and control of the grid, while keeping its environmental impacts within acceptable limits. In order to accomplish these goals, it is important to integrate social, economic, environmental and technical information and to analyze the system using multi-criteria evaluation [3], [4].

In its simplest form, a power grid can be represented as a graph, in which nodes are stations generators, transmission substations and loads, while edges correspond to the transmission lines between the nodes [5]. However, simple graph models cannot provide a meaningful complexity analysis of power networks [6], [7]. The principal shortcoming of electrical graph measures lie in their inability to identify and to explicitly incorporate different types of information and rules [3]. This work proposes a novel modelling strategy using an extended graph model to overcome some of these limitations. The traditional impedance model of microgrid is complemented by an extended graph, integrating additional technical, economic, environmental, and social information. The presented model and metrics showed to be useful to store, in a single and multilayer model and metrics, valuable information for the design, evaluation and operation of microgrids, and how they can be implemented using graph-oriented databases [8] [9]. This paper is structured as follows: in section two a theoretical framework considering graph theory, graph oriented databases and microgrid systems is presented, in section three, the modelling considerations and strategy, as well as some implementation aspects is presented. In section four an implementation example is presented, and finally section four present conclusions and future work perspectives.

II. Theoretical Framework

It is well-accepted that topology analysis is useful for defining and understanding the behavior of electrical networks [10]–[12]; thus, it is possible to obtain some useful topological metrics from its graph structure, to define behavior indicators [5], [13]. In this section, we review the analysis of the microgrid as a graph, centrality measures, as well as multilayer analysis and graph databases, which are fundamental for our model.

A. The microgrid as a graph

Like all power grids, microgrids can be modeled as a network [14]. Therefore, a graph $G = (V, E)$ is a set of vertices V, and set of edges E, where edge properties may represent the impedance value in a traditional impedance model [15]. In an extensive approach, V is a set of vertices

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representing power stations, buses, generators, loads, etc. and E is a set of edges representing power lines connecting the vertices. This type of representation can extract, from the graph structure, some topological features that are useful to understand the behavior of the grid, by the means of network metrics. In a simple impedance model, the available information fails to capture important physical, operational, environmental, economic and social features of the power grid [6], [7].

Previous researches have also described power network via extended graphs and using network measures based on the traditional electrical properties of the power system [5]. The model proposed in this paper uses electrical topological measures adapted from the ones proposed in [16]. The most common of those measures is *Degree centrality*, which measures the importance or influence of a node in the network via its degree [17]. An adapted degree centrality measure C_{dy} for power grids has been proposed by [16] as presented in equation (1).

$$C_{dy}(v) = \frac{\| Y(v,v) \|}{n-1}, \tag{1}$$

where v is the node, Y the admittance matrix and n the number of nodes in the grid.

Other common centrality measures are *Eigenvector centrality*, *Closeness centrality*, *Betweenness centrality*, *Current-Flow Betweenness Centrality* [18] and *Communicability* [19].

B. Multilayer graphs

Network science is commonly applied for describing the structure of a large variety of complex systems. Power grids contains electrical interactions, which can model a single type relationship. However, when we want to include different types of interactions a multilayer model is needed to find relevant emergent phenomena [20]. In power systems, this approach has been applied to design the control architecture for microgrids [21]. These layers have a specific responsibility to regulate the current, voltage, or frequency in a wide range of operating points. This distributed hierarchal control can minimize the uncertainty by exchanging information and power within the microgrids. Traditional approaches for the study of networks based on adjacency matrices were useful to describe networks of one layer; however, those approaches are insufficient to study multilayer networks. For this reason, a tensor approach is commonly used [20].

C. Graph databases in power system

Data analysis and processing technology are evolving rapidly, and non-relational databases are leading the database technology revolution [8]. Graph database is a system that uses the structure of graphs, nodes and edges to model and to store information. Compared with a relational database, it permits managing data in its natural structure, where the nodes and edges can contain properties and attributes. Edges represent the relationship between two nodes, which can be unidirectional or bidirectional, and they can have more than one relationship for the same pair of nodes. Relationships may have properties such as weight, cost, distance, rating or time intervals [22].

The focused studies on complex network analysis based on No-SQL databases have made it possible to shift away from the conventional paradigm of relational databases, where it is impossible to process and to scale the analytic studies on technical aspects of power systems [9]. Based on the graph databases concept (using the open source graph database Neo4j), the researchers in [23] showed a new method for storing, modeling, and analyzing power grid data.

All these previous works confirmed the advantages of using graph databases. Moreover, these strategies, as they are applied to conventional or large-scale networks, are necessarily adequate for the performance evaluation of microgrids, since microgrids have important differences in their structure and operation [24].

III. Methodology

A model is intended to represent three different aspects of the system: constituent elements, relevant information and element interactions. The model presented in this work integrates all three aspects in a multilayer graph model as a simple representation allowing to integrate information from different nature. From a multilayer graph approach, each layer of the graph is intended to represent some aspect of the system or a specific type of information. Four main sets of information: economic, technical, environmental and social, were identified and defined as information classes that define the different layers of the multilayer graph model.

The economic layer is conceived to represent flow of capital and to give useful indicators such as value generation, profit, costs, incomes among others. The technical layer and information class are intended to give useful information about the operational state of the grid, using four sets of relevant information containing equipment or infrastructure specifications, energetic resources, power delivery, regulations and general constraints. The environmental class is intended to manage information to evaluate environmental impacts of the microgrid. The social class layer groups information about population and the community. The main purpose of a microgrid is to provide a welfare to the community either as life quality assurance or as a productivity facilitator. Thus, the purpose of this layer is to evaluate the relation between the microgrid and the community, and the related impacts. The resulting four layer graph model structure is presented in Figure 1, where elements are common to all layers, but interactions differ. Power flow will be the linking element between all layers.

The information of each layer is presented in a structure having two components, base information and layer indicators. Base information is considered the minimum set of relevant information that can be obtained directly from the grid and that is necessary to obtain composite information. Base information is either obtained by metering or supplied by the infrastructure or equipment providers. Layer indicators are considered, for the means of this article, composite information that can be

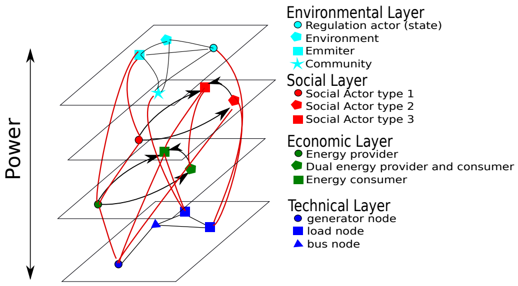

Fig. 1. General structure for the microgrid multilayer graph model

obtained by operating with base information. Base information and layers indicators are considered attributes of the microgrid elements and represented as arrays of multidimensional vectors as shown in Figure 2 and described in equation (2), where the dimension of each vector is determined by the user needs.

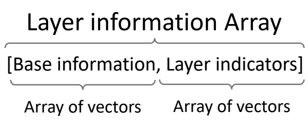

Fig. 2. Layer information general structure

$$
\begin{aligned}
Ec_x &= [ec_1, ec_2, \dots ec_{n_e c}] \\
T_x &= [t_1, t_2, \dots t_{n_t}] \\
En_x &= [en_1, en_2, \dots en_{k_e n}] \\
S_x &= [S_1, S_2, \dots S_{l_s}]
\end{aligned}
\tag{2}
$$

Considering Ec, T, En, S, the arrays representing the economic, technical, environmental and social layers, respectively, index x can represent "base" and "indicator" data and $n_e c$, n_t, $k_e n$, l_s corresponds to the number of vectors in the corresponding arrays. Vectors dimension is to be set according to the model's application requirements. Layers indicators are obtained by applying layers defined methods to layers base information, as illustrated in Figure 3.

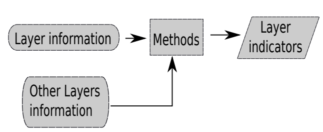

Fig. 3. Achievement of layer indicators from base information

For the case of the model presented, the four layers base information is defined as shown in Figure 4.

It should be noted that the vectors presented in this paper illustrate the modelling strategy, but vector elements can change and adapt to the user's needs.

A. Grid element identification and classification

All constituent elements of a microgrid were listed, and a compilation of their attributes acquired. The universe of elements was then clustered according to their functionality

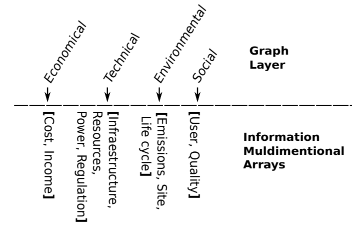

Fig. 4. Layer and layer vector structure

and the set of attributes describing them. From an object oriented analysis, the resulting clusters of elements, each containing similar elements, will define classes; the element class attributes are given according to the relevant information associated to the elements of the corresponding class, and class methods are defined as operations between attributes to obtain appropriate indicators as needed.

Three main grid element clusters were identified: Generator-load, Energy storage, and coupling element clusters as shown in Table I. Energy storage elements are to be understood as any piece of equipment or infrastructure capable of storing energy that can be transferred from/to the grid. Coupling elements are considered to be all elements having input and output power flow simultaneously. Transmission lines, transformers, bars, switching and protection elements are some of the grid elements that can be considered part of this class. Table I show some of the possible attributes associated with each of the element classes.

B. Class methods definition

Methods in this model, are conceived to transform layers' base information onto layer indicators; they can use information from other layers as illustrated in Figure 3. The number of possible methods is infinite as it is possible to create as many different indicators as needed in accordance to the user requirements. This paper presents a global strategy and some examples of methods and their associated indicators, but an exhaustive definition is out of the scope of this work. Methods definition takes advantage of graph metrics to operate with element attributes and uses power flow as the linkage element between the four layers. Some examples for the four layers are presented next.

Economic layer methods: Generation income $G_i(v)$ (equation (3)) will use attributes from the generation-load classes and is defined either for a node as equation (1) or for the global grid. When defined for a node, it is defined as the directional weighted degree [16] of the node v, where the weight w_v is the dot product of delivered energy and the energy sell price considering the delivered energy a vector in a two dimensional space with orthonormal base $\hat{p}, \hat{p}$, with active component $\hat{p}E_P$ and reactive component $\hat{q}E_Q$ and the energy sell price defined as a vector in the same space with active component $\hat{p}E_{dp}$ and reactive component $\hat{q}E_{dq}$.

$$
\begin{aligned}
G_I(v) &= \sum a_{vj} w_{vj} \ \ \forall j \\
w_{vj} &= \vec{E}_d(v,j) \cdot \vec{E}_{dp}(v) \\
\vec{E}_d(v,j) &= \hat{p} E_P(v,j) + \hat{q} E_Q(v,j) \\
\vec{E}_{dp}(v) &= \hat{p} E_{dp}(v) + \hat{q} E_{dq}(v),
\end{aligned} \tag{3}
$$

where $\vec{E}_d(v,j)$ represents the delivered energy by node v to node j in the study time interval, $\vec{E}_{dp}(v)$ represents energy delivery price, from node v to any node j, and a_{vj} has a value of 1 if the link exists between node v and node j, and 0 in the opposite case. The correspondent method for the whole microgrid is defined as presented in equation (4).

$$
G_I = \sum G_I(v) \ \ \forall v \tag{4}
$$

As a more general indicator, the energy profit method can be defined as an extension of equation (5) but considering both delivered and received energy instead of only delivered energy in an oriented graph where received energy is assumed entering the node and delivered energy exiting the node.

$$
\begin{aligned}
G_I(v) &= \sum a_{vj} w_{vj} - a_{jv} w_{jv} \ \ \forall j, \\
w_{vj} &= \vec{E}_d(v,j) \cdot \vec{E}_{dp}(v) \\
w_{jv} &= \vec{E}_d(j,v) \cdot \vec{E}_{dp}(j)
\end{aligned} \tag{5}
$$

where $a_{vj} = 1$ denotes the existence of a vertex oriented from node v to node j, $a_{jv} = 1$ denotes the existence of a vertex oriented from j to v, w_{vj} the earns for delivering energy to node j and w_{jv} costs for receiving energy from node j. More complex indicators can be obtained from more complex graph metrics such as centrality measures, shortest or longest paths, clustering measures and others. As an illustrative example, a method using centrality measures can be used to analyze and visualize the importance of a node in relation with an indicator. In this way, centrality measures are used by calculating weighted centrality while assigning the element weights corresponding to the desired indicator. A cost centrality measure will calculate centrality when the layer weights are set to be energy costs [17] in a modified from equation (1).

Technical layer methods: Technical layer methods and indicators are intended to give useful information about the operational state of the grid. Some of the most common technical indicators are derived directly from power flow. As an illustrative example, estimated transmission power losses can be found from information associated to transfer elements. The transfer power losses can be found as the difference between input and output power from a transfer node, measures that can be represented through weighted grade graph measures. In this way, the transmission loss of a transfer element can be written as equation:

$$
S_l(v) = (1 - Eff(v)) G_w(v), \tag{6}
$$

where *Eff* correspond to the element efficiency of element v and the weighted grade is $G_w(v)$ the complex power of element v:

$$
\begin{aligned}
G_w(v) &= \sum a_{vj} w_{vj} \ \ \forall j \\
w_{vj} &= \sum S_{vj}(v) \forall j,
\end{aligned} \tag{7}
$$

and $S_{vj}(v)$ defined as the power flow between node v and node j.

More complex analysis can be achieved with other methods, stability or quality features such as oscillation modes, or harmonic distortion can be also achieved using adequate graph metrics. From power harmonic decomposition as an attribute of the grid elements represented as an n dimensional weight vector, the path length graph measure in equation (8), indicates how harmonics are distributed in the graph. The longest paths contain the largest number of harmonics and nodes having critical oscillation modes are more suitable to be located within those paths. Moreover, centrality measures using the harmonic decomposition for weighted grade measure, will indicate the relevance of the node and its contribution to oscillation modes as a variation of equation (1).

$$
C_{cz}(v) = \frac{n-1}{\sum_{t \in V/\ v} d_Z(v,t)}, \tag{8}
$$

where $C_{cz}(v)$ is the closeness centrality measure, v the node, and $d_Z(v,t)$ denotes the length of the shortest path between nodes v and t as presented in equation (9).

$$
d_Z(v,t) = \| \sum_{(i,j) \in E \cap path(v \to t)} z_{pr}(i,j) \|, \tag{9}
$$

given $Z_{pr}(i,j)$ the impedance between nodes i and j.

Social layer methods: As previously stated, the impact in society of an electric power project is of great importance; however, social indicators are not easy to define, neither to obtain. The social layer methods should include these social models as direct measurement of social variables is not available. This paper presents the strategy of how methods can be constructed based in social hypothesis, but these hypothesis should be taken as illustrative examples, and further validation of them is necessary. The validation of social hypothesis is out of the scope of this study. For the illustrative purpose of this work several hypothesis are presented:

Hypothesis 1 (H1): *Energy consumers can be clustered according to their energy consuming habits.*

Hypothesis 2 (H2): *Energy consuming habits are related to life quality and consuming site.*

Hypothesis 3 (H3): *Energy consumption is related to human activities and similar activities will use similar amount of energy.*

Hypothesis 4 (H4): *Energy consumption of a typical user (cluster centroid), can be characterized in a demand curve, which is known.*

Given that the number of energy users remains constant in the study time interval, and that every user is accomplishing an activity, it can be stated that total power P can be distributed into a number n of activities $P = P_{t1} + P_{t2} + \cdots + P_{tn}$, where P_{ti} is the power needed to accomplish task i, and the derivative of P can be expressed as:

$$\frac{dP}{dt} = \frac{dP_{t1}}{dt} + \frac{dP_{t2}}{dt} + \cdots + \frac{dP_{tn}}{dt} \tag{10}$$

From $P_{ti} = K_i n_i$ and *H1* to *H4*, it is possible to relate the number of users to the consumed power for a task. Modelling the population as a vector $n = [n_1, n_2, \ldots, n_n]$ with orthonormal base $\hat{n} = [\hat{n_1}, \hat{n_2}, \ldots, \hat{n_n}]$ its derivative, which is in fact a representation of the population flow, can be written as:

$$\frac{dn}{dt} = \sum_{i=1}^{n} \frac{1}{k_i} \frac{dP_i}{dt} \hat{n}_i \tag{11}$$

Considering that energy consumption occurs in load nodes, and that tasks are related to sites *H2*, the weighted degree measure of a node defining weight as power can be used to estimate the population flow within the influence perimeter of the microgrid. Thus, the population flow can be expressed in terms of the node degree G_i as:

$$\frac{dn}{dt} = \sum_{i=1}^{n} \frac{1}{k_i} G_i \tag{12}$$

Methods in the graph database should have integrity restrictions to assure the preservation of the structure of the model [25].There are some tools available to implement graph databases; *Neo4j* for example, is an open code graph oriented database that officially accepts *.Net, Java, JavaScript, Go* and *Python* drivers. One of the important features of *Neo4j* is that it does not have a defined data base structure, it deals with ACID transactions and contain an enormous amount of nodes and relations that can be swept with its language *Cypher*. The main benefit obtained from *Neo4j* consists in its ability to sweep relationships in a large data set int the native graph structure.

IV. Modelling Strategy implementation example

The developed modelling strategy is used to represent a hypothetical highly distributed microgrid located in Málaga, a small community in Santander, Colombia. The model includes renewable generation resources as solar, wind and micro-hydraulic, as well as diesel generators, distributed geographically according to the resource availability. Some sustainability assessment indicators corresponding to economic, technical, environmental and social evaluation were considered to test for the model capability to store, relate and manage the chosen relevant information.

TABLE I
Labels and node attributes

Class	Attribute	Notes
Generator and Load System	S_n, Z	Power rating, impedance
	V_{max}, V_{min}	Voltage bounds
	P_s, Q_s	Active, reactive power
	Q_{max}, Q_{min}	Reactive power bounds
	P_{max}, P_{min}	Active power bounds
	V, f, θ_v	Amplitude, frequency, angle
	$Energy_s$	Energy
	$Energy_{cost},$	Energy cost
	$Energy_{Av}$	Energy availability
	$Inertia$	Inertia
Energy Storage System	S_n, Z	Power rating, impedance
	V_{max}, V_{min}	Voltage bounds
	P_d, Q_d	Active, reactive power
	Q_{max}, Q_{min}	Reactive power bounds
	P_{max}, P_{min}	Active power bounds
	V_g, f	Voltage amplitude, frequency
	SOC	State of charge
Coupling Element	TTR	Transformer turns ratio
	Z	Impedance
	V, f	Voltage amplitude, frequency
	V_{max}, V_{min}	Voltage limits
	P, Q	Active, reactive power
	I, I_{max}	Current, maximum current

Figure 5 illustrates the single-line diagram of a prototype low voltage network, designed from energy information available in the location. This network is composed of two photovoltaic generation systems G_i, a small hydroelectric power station, a Diesel generator, a storage system, 5 transmission lines and 5 user residential groups distributed at various points in the network (loads). Each load is modelled from an average daily demand curve. The total system load is $100kW$ and generation capacity is $120kW$.

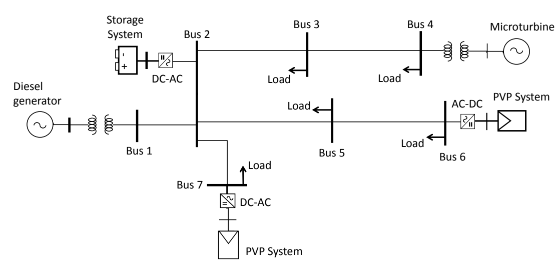

Fig. 5. Single line diagram of the test network system

Table I, shows the list of node types that are taken into account for the model of the microgrid. The elements such as generation systems and loads are grouped in the class called *generator and load system*, because it was analyzed that they contain similar attributes, and that sometimes the generators work as loads. Moreover, this type of node will have the label *load* in order to differentiate the elements that are loads corresponding to the demand and end users.

A. The detailed description of the proposed model

A schematic representation of the multilayer graph is shown in Figure 1 where colors codify the different classes or layers.

Red for the social layer, green for the economic layer, cyan for the environmental layer and blue for the technical layer. Nodes represent elements or actors and edges represent relations as lines, and transformers in the technical layer or commercial transactions in the economic layer. It can be observed the existence of edges either in between nodes of the same layer as edges between nodes of different layers, conforming a complex system where complex relations between nodes, represented by paths, can involve edges of different nature. This representations allows the natural complexity of the system to naturally arise in the model, making possible to study and analyze the emergent behavior of the system through graph metrics.

V. Conclusions and perspectives

The model developed in this work demonstrate that a multilayer graph structure is suitable to model a power microgrid. This strategy integrates in a coherent way, different types of information that with the inclusion of synergic relations, can lead to both, simple and complex indicators. Therefore, this novel strategy can be considered as a useful tool, in all processes concerning microgrids, from feasibility studies to grid's operation. The presented model allows to a more efficient work from multidisciplinary collaborative teams, since the model considers and relates, in a formal but intuitive way, interdisciplinary interactions between the grid elements through the model layers.

The presented model eases the access to structured information for any decision maker in every part of the life cycle of the grid, from design engineers, to microgrid's management personnel. This fact, and the possibility of analyzing the grid as a complex system with an important set of existent mathematical tools intended for this purpose, give the proposed model unique features to facilitate well-informed based decision-making procedures.

Moreover, existent computational tools and open access codes makes feasible the implementation of this modelling strategy, which can provide an extremely customizing model that adapts to almost any user requirement and can interact with existing specialized software.

The presented model strategy and the model derived from it can have a maximum potential benefit when incorporated to a smart grid that assures the availability of required information. The model can integrate all the smart grid layer structure, including metering and hardware, communication infrastructure in the lower layers, and analysis and decision making in the upper layers. Time as an important variable, and appropriate periodical refreshment of all information is important to maximize the possibilities of the model.

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