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Using Geospatial Data to Generate One-line Diagrams of Electrical Power Systems

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***Abstract.** One-line diagrams are widely used to represent the electrical power system current state and its probable performance in the case of studies and simulations. Hence, its adequate construction is of great importance to avoid inaccurate decisions of the network operators. In order to reduce the human errors and the huge effort in a manual generation technique (usually adopted nowadays), this work proposes a methodology to automatically build these diagrams. The method is based on the usage of the geospatial data related to the network buses and branches with a graph algorithm that permits the elimination of superpositions of buses. The approach was successfully tested with the Institute of Electrical and Electronics Engineers (IEEE) 30 buses standard system and with a portion of the Brazilian network.*

1. Introduction

One-line diagrams consist of the most commonly used form of representation of the electrical network. They are widely employed in a large number of power systems studies and analysis functions, yielding a summary of the performance of the transmission and/or distribution network. Thus, it is crucial to precisely generate these diagrams, since inaccuracies in their construction can lead to unreliable analysis results and have a negative impact on the decisions that must be taken by the systems operators during on-line and off-line operation.

Nowadays, the most frequent way used to build these diagrams is through the usage of CAD (Computer Aided Design) tools that require the manual definition of all network elements positions (buses, branches, transformers, generators, etc.) [CEPEL 2003]. So, considering the huge size of actual networks (as the Brazilian interconnected power system), the application of this kind of method can become unfeasible. Moreover, there are some studies that require topological changes in the electrical network that must be represented by the one-line diagram. Considering the usage of CAD tools, every change in the network topology must be manually set, difficulting its employment in these applications. Besides, it is important to note that the manual generation of the one-line diagrams can lead to human mistakes and consequently to undesireable inaccurate diagrams.

In order to minimize these problems, efforts to develop automatic methods to visualize the power systems one-line diagrams have been done [Mota 2001, Mota 2003, Nagendra Rao 2004]. This work proposes a methodology to automatically construct one-line diagrams of electrical transmission networks based on geospatial information related to some of its elements: towers and substations.

Section 2 describes the basic composition of transmission power systems and presents a conceptual data model of the network components. Section 3 defines with details the two main one-line diagram models related to a power system. Section 4 outlines the proposed approach to automatically visualize the one-line diagrams. Section 5 describes the graph algorithm used to eliminate possible buses superpositions that can occur in the generation of the initial graphical portrayal of the network. Section 6 illustrates the results of the methodology application and, finally, Section 7 presents the conclusions of this work.

2. Transmission Power Systems

The transmission power system is basically constituted by different apparatus and facilities as power plants, substations, generators, transformers, transmission lines, series compensators, reactive banks, synchronous compensators and loads. From a simplified point of view, the generators transform the mechanical energy, yielded by hydro or steam turbines, into electrical energy. The generated electrical power is then injected in the transmission network through transformers. They are responsible for raising the voltage level in order to minimize the power losses in the transmission lines. Thus, the electrical power is transmitted using a high voltage level and alternate current (AC) that permits the usage of such transformers. Finally, the power delivered to the subtransmission and distribution systems is consumed in a lower voltage level (because of practical and security reasons) and so, other transformers are employed to reduce the voltage level at this point of the electrical network [Monticelli and Garcia 1999].

Figure 1 illustrates a conceptual data model for the transmission system components, based on OMT-G [Casanova et al. 2005]. It can be noted that a power plant is composed by generators (synchronous generators) and substations. Each substation can comprise three types of transformers (fixed tap, LTC and phase shifter) and also some regulator devices, responsible for adjustments in the voltage level and for power loss reduction (synchronous compensator, reactive bank and series compensator). From this figure, one can also infer that the transmission network is constituted by transmission lines and different types of loads.

The one-line diagrams, that constitute the focus of this work, can be derived from these network components, as described in Section 3.

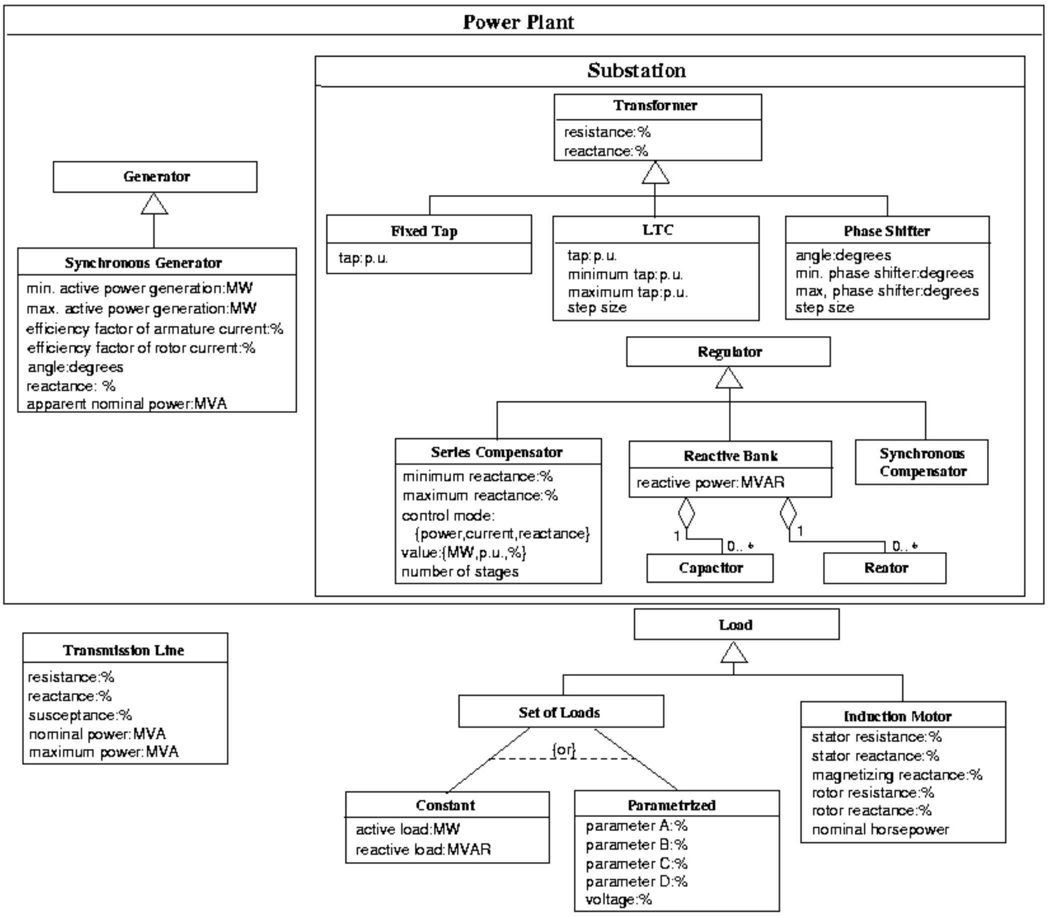


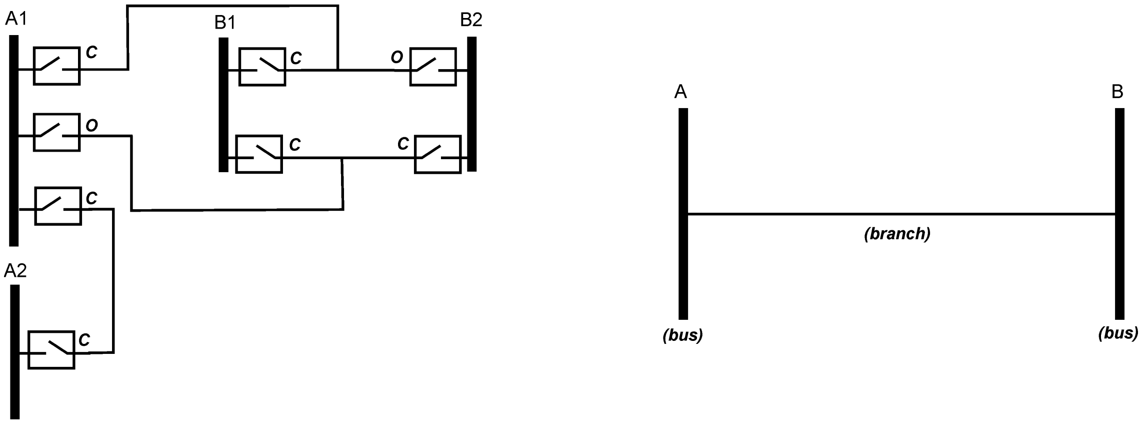
Figure 1. Conceptual Data Model of the Transmission System Components

3. One-line Diagrams

The transmission system is a three-phase network, i.e., the power is transmitted to the load centers through three energy conductors. However, considering normal operation conditions, these three phases are projected to be electrically balanced (what means they have similar electric connections). Thus, it suffices to represent the system using only the connections of one of these phases. In this context, one-line diagrams comprise the one-phase graphical representation of the network elements connections, such as transmission lines, transformers, generators, loads, substations, switching devices, etc. They usually provide an adequate way to get an overview both of the current state of the network and of its performance, showing the electrical network and giving the power system engineer a reasonable idea of what service reliability will be.

These diagrams can represent all the equipment (or some of them) connected to the electrical network, characterizing an equipment/element oriented representation named "bus section/switching devices" model [Monticelli 1999]. This type of one-line diagram is commonly used to permit the visualization of the whole system (or of portions of it) by the electrical network operators. Hence, they can visually identify the equipments involved in a fault condition, allowing a faster isolation of the contingency causes.

Another type of representation of the one-line diagram is the “bus/branch” model [Monticelli 1999]. This kind of diagram yields a graphical representation of the electrical network, comprising only buses and branches. In fact, this corresponds to a simplified representation of the “bus section/switching devices” one-line diagram, since each element depicted in this more detailed representation is modeled by a bus or a branch. This is the case, for instance, of a transformer, that in the second model must be depicted as a branch, or a generator, that must be modeled as a bus. Figure 2 illustrates both types of one-line diagrams for a same network. In this Figure, the index “c” located near the switching devices means that the corresponding switch is closed. Similarly, the index “o” means that the corresponding switch is opened.



Bus section / switching devices model

Bus / branch model

Figure 2. One-line diagram representations

The “bus/branch” one-line diagram can be considered as the most important electrical network representation, because it is widely used in the main power systems studies and analysis functions, such as power flow, state estimation, contingency analysis, voltage sensitivity analysis and network equivalents [CEPEL 2003, Monticelli 1999]. For this reason, it will be the focus of this work. Thus, it is important to formalize the definition of the two components (bus and branch) of this kind of one-line diagram:

1. A bus corresponds to an electrical node, i.e., a node related to a voltage magnitude, and can represent some of the power systems elements, like substations, loads, generators, shunt compensators, etc.
2. A branch yields an electrical way for the current flows and can represent transmission and distribution lines, transformes, series compensators, etc.

So, the conceptual data model of the transmission network components depicted in Figue 1 can be related to its bus/branch representation as illustrated in Figure 3.

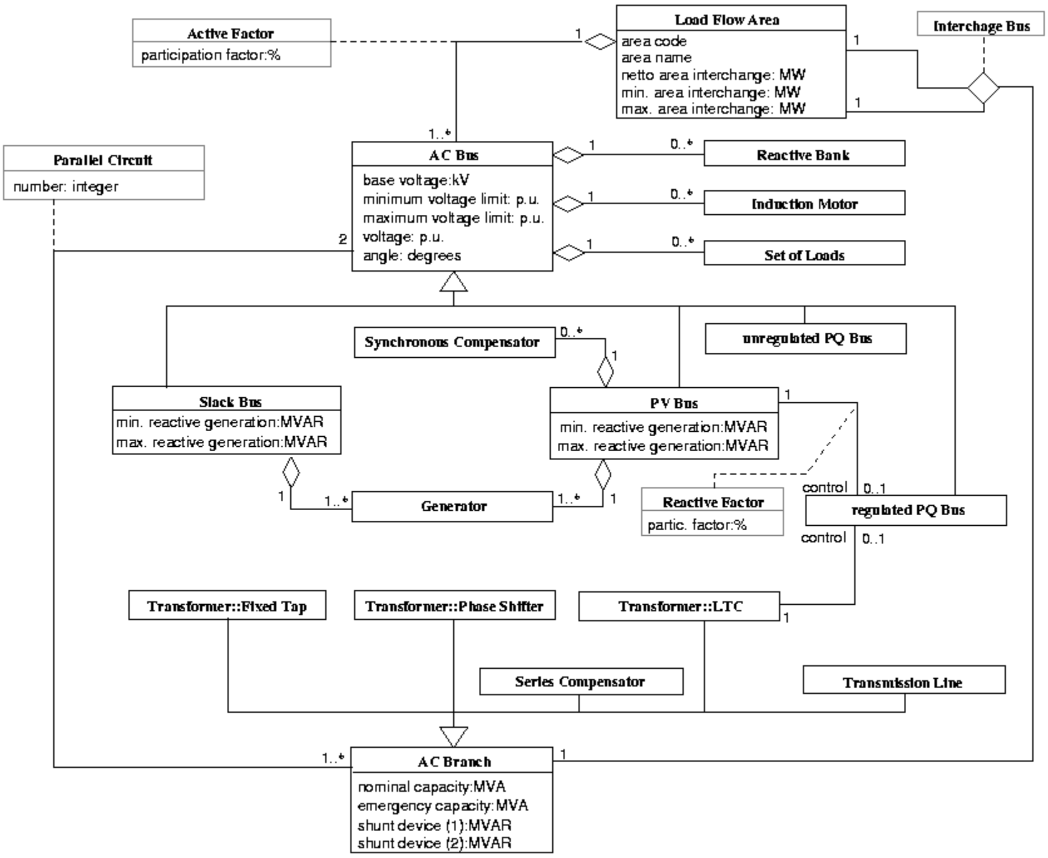


Figure 3. Conceptual Data Model of the Transmission System Components Considering Their Bus/Branch Representation

From Figure 3, it can be noted that transmission lines, transformers and series compensators correspond to branches (AC branches) and all other components can be modeled as buses (AC buses).

The next section describes the outline of the proposed approach to automatically build this type of one-line diagram representation (“bus/branch” model).

4. Outline of the Approach

The main idea of this approach is to construct the one-line diagram of a power system in an automatic fashion. This problem can be reduced to generate a graph (where the network buses correspond to the graph nodes and the system branches correspond to the graph arcs) with minimal crossings, using the connectivity data among buses (topology information). However, this is not a trivial task, especially when thousands of nodes and arcs are involved. One alternative to avoid this problem is to link geographical location (geospatial information) to the electrical data [Siqueira Júnior 2005]. This association is direct, since each physical system equipment has a non-ambiguous correspondence to an element (bus or branch). The system equipments possess an unique geographic position, which can be calculated by the worldwide radio-navigation system GPS (Global Positioning System). The enhancement of the conventional electrical data model by the geographic information is depicted in Figure 4, using the OMT-G notation.

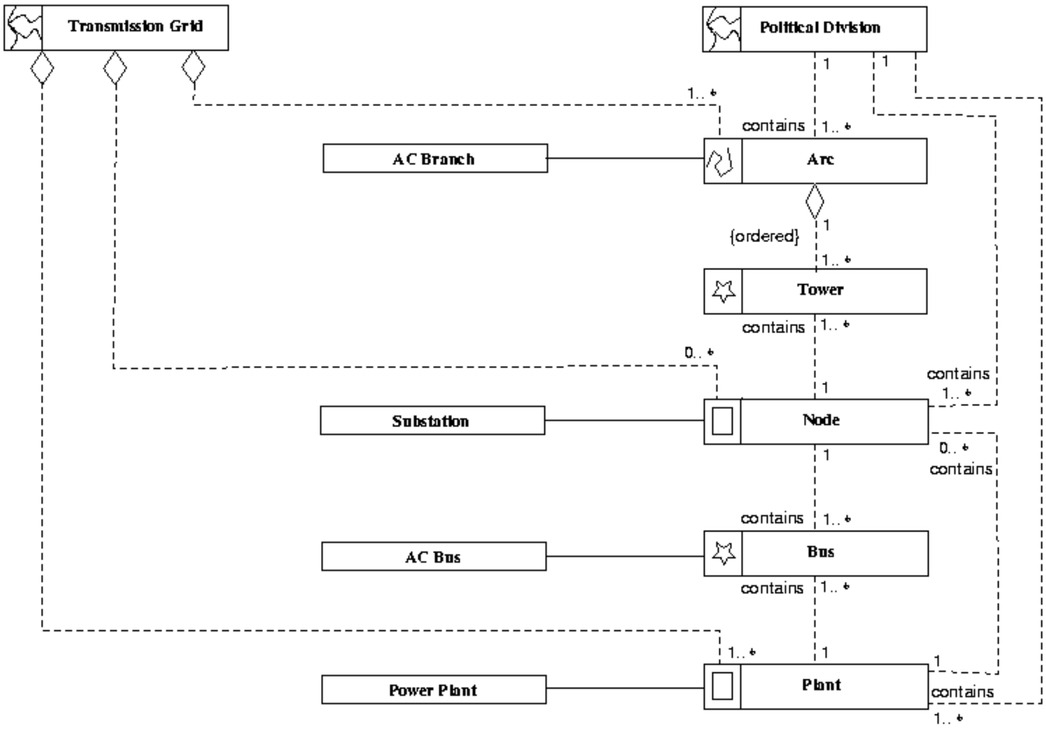


Figure 4. Conceptual Data Model of the Relations Among the Transmission System Components and Geospatial Information

The methodology proposed in this work can be summarized by the following steps:

Step A: Obtain the topology (connections relations) of the power systems elements (buses and branches).

Step B: Add to this topology information, geospatial data related to the network elements (substations, towers, etc.) as depicted in Figure 4.

It is important to note that the steps A and B are based on the conceptual data models described in Figures 1, 3 and 4.

Step C: Generate an initial graphical representation.

This initial network portrayal can be automatically generated considering aleatory positions of buses and branches or taking into account geospatial data related to the power systems components.

Step D: Use an algorithm to eliminate the superpositions of buses

The initial network representation can present some problems associated to the superposition of buses. Ideally, these problems should never occur since each network component possesses an unique geographic position. However, one can encounter some difficulties in obtaining the geospatial data related to all the systems equipments. In this situation, if there is no information about the location of the internal buses of a substation, for instance, one can make use of the geospatial data of the substation itself as a way to localize all its internal buses. Thus, in this case, the initial visualization of the one-line diagram can superpose these buses, yielding a confuse and inadequate representation. The algorithm employed to avoid this problem is described in Section 5.

5. Overview of the Graph Drawing Algorithm

The topology of an one-line diagram resembles very closely the connections of graph elements (nodes and arcs). So, the buses in the one-line diagram can be related to the nodes of a graph. Similarly, the branches in the one-line diagram can be related to the arcs of a graph. That correspondence makes feasible the usage of methods for graphs visualization to generate the one-line diagram of an electrical system.

In this work, the algorithm to generate the final configuration of the one-line diagram uses physical relations to model the graphical interaction among the electric network components. Since the one-line diagram is a graphic representation of a power system with only two dimensions, the objective of the algorithm is to find the graphic coordinates *{**xc, yc**}* associated to each bus. The branches can be depicted using these coordinates as references. This method was adapted from a graph visualization algorithm [Mota 2004], developed to find the coordinates *{**xc, yc**}* associated to the graphical center of each node, as shown in Figure 5.

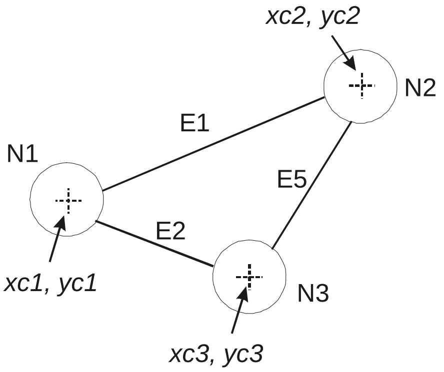


Figure 5. Graph nodes coordinates

Adopting an initial value for these coordinates, a sequence of adjustments is made to find an optimal position for each bus. These adjustments are obtained through an iterative process based on two main hypotheses:

- A bus must repel any other bus with a "graphical force" inversely related to the square of the distance that separate them. This force is calculated in a manner similar to the electrostatic force between two punctiform bodies with charges of same polarity (the Coulomb's law).
- A pair of adjacent buses (connected by a branch or any other device) are mutually repelled or attracted with a "graphical force" proportional to the distance that separate them. This force is calculated in a manner similar to the force that arises in a spring when stretched or compressed (the Hooke's law).

It is not the purpose of this work to further describe the graph algorithm. More details on its formulation can be found in reference [Mota 2004], that explains an object-oriented implementation of it. However, it is important to note that the final representation obtained with this algorithm is strongly dependent of the initial bus positions. In this way, the usage of geospatial data, related to real facilities and devices that exist in the electrical network, can lead to a faster and robust generation of graphical one-line diagrams, giving an excellent initial hint about the positions of the buses and branches. The next section demonstrates this fact, showing one-line representations of actual Brazilian network, in the presence and absence of geospatial information.

6. Case Studies

In order to validate the proposed methodology, two different tests were made: the first on the 30 buses system from IEEE, and the second on a portion of the Brazilian interconnected power system. In both cases, the algorithm was executed at least 50 times and the results obtained are described in the subsequent sections.

6.1. IEEE 30 buses network

The standard IEEE 30 buses network is a well-known test case in the fields of electrical power engineering. Its one-line diagram, using the bus sections/switching devices model, is represented in Figure 6.

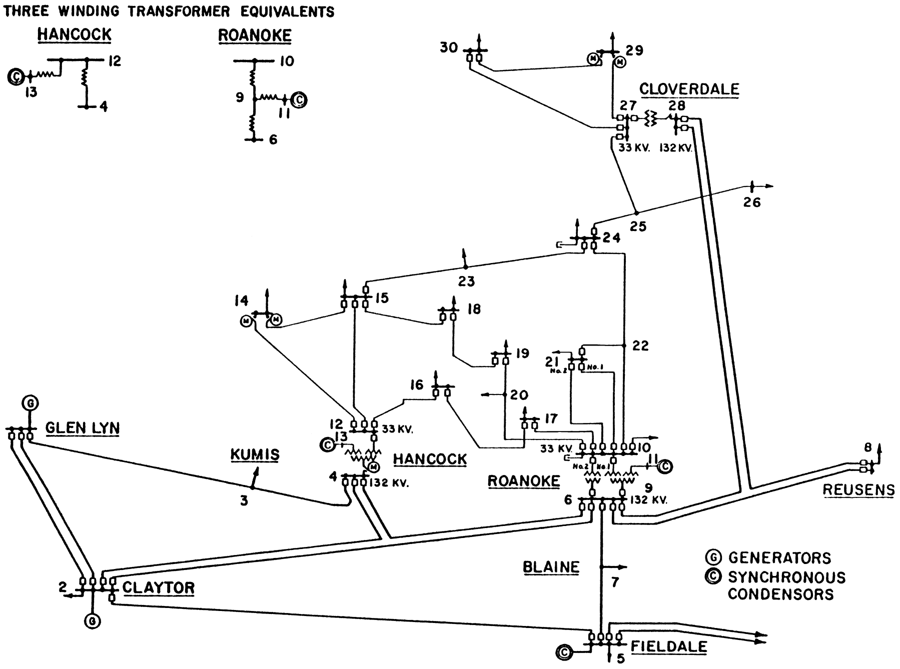


Figure 6. IEEE-30 one-line diagram (bus section/switching devices model)

However, this is not the model used in the studies and simulations. The bus/branch model, adopted for these purposes, is obtained after the elimination of switching devices and the merging of transmission lines. The branches list that corresponds to the bus/branch model for this system is illustrated in Figure 7.

IEEE-30 branches list:
1-3; 1-2; 3-4; 2-4; 2-6; 2-5; 4-12; 4-6; 5-7; 6-7; 6-8; 6-9; 6-28; 8-28; 9-10; 9-11; 10-17; 10-20; 10-21; 10-22; 12-13; 12-14; 12-15; 12-16; 14-15; 15-18; 15-23; 16-17; 18-19; 19-20; 21- 22; 22-24; 23-24; 24-25; 25-26; 25-27; 27-28; 27-29; 27-30; 29-30;

Figure 7. IEEE-30 branches list (bus/branch model)

Each entry in this list represents a branch. The first number is the origin node of the corresponding branch, while the last number represents its destination. One of the one-line representations of this model generated without geospatial information is depicted in Figure 8.

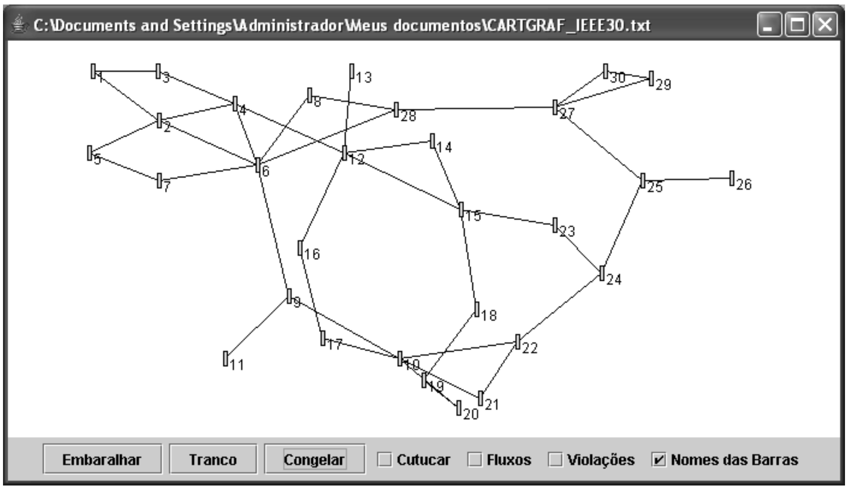


Figure 8. IEEE-30 one-line diagram generated without geospatial information

It can be noted in Figure 8 the occurrence of several branch crossings. This comes from the fact that the buses coordinates were randomly initialized. Another characteristic of adopting these random initial values is the multiplicity of one-line representations provided by the algorithm, i.e., it yields a different diagram every time it is executed.

In order to assess the influence of using geospatial information, the algorithm was executed with previously specified values for the buses coordinates. However, this is a test case, and there is no actual information about the location of electric apparatus and facilities. Thus, these data were emulated through the interpolation of the apparatus graphical positions (generators, substations, transmission lines, transformers and synchronous compensators) in the one-line diagram, previously illustrated in Figure 6. Although this is not the ideal situation, the usage of this kind of information has positive effects in the diagram generation, as illustrated in Figure 9. In this situation, all the branch crossings were eliminated and the graphical representations generated by different executions are very similar.

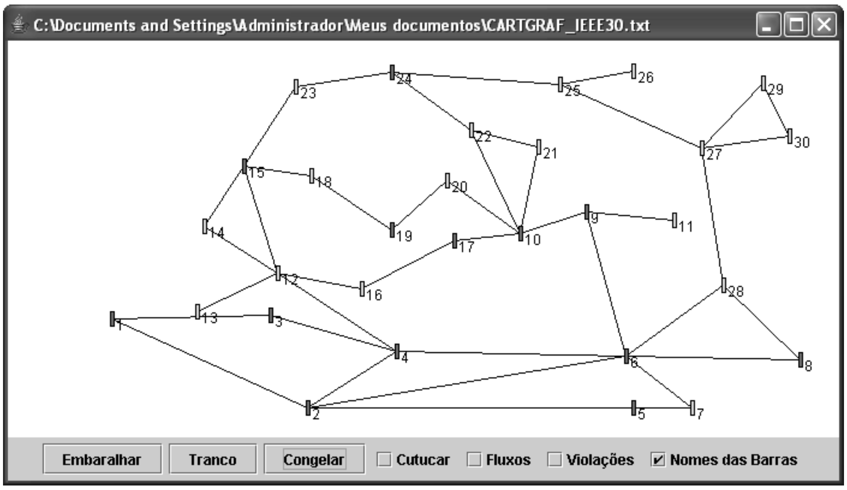

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Figure 9. IEEE-30 one-line diagram generated with geospatial information

6.2. Brazilian electric network

In the second test, a portion of the Brazilian electric network, already represented by its bus/branch model, was employed to generate the corresponding one-line diagram. The branches list associated to this sub-system is illustrated in Figure 10.

Brazilian sub-system branches list:
5401-5402; 5401-5403; 5401-5411; 5403-5406; 5408-5428; 5411-5408; 5411-5410; 5411-5418; 5411-5419; 5411-5421; 5411-5621; 5411-5631; 5413-5417; 5416-5417; 5418-5412; 5418-5413; 5419-5413; 5419-5414; 5421-5422; 5421-5431; 5421-5441; 5421-5452; 5421-5471; 5423-5421; 5423-5424; 5424-5426; 5428-5451; 5431-5433; 5431-5441; 5441-5443; 5441-5461; 5443-5445; 5443-5446; 5452-5450; 5452-5453; 5452-5471; 5452-5651; 5453-5454; 5453-5456; 5453-5473; 5454-5455; 5456-5457; 5458-5451; 5458-5452; 5458-5641; 5458-5651; 5471-5473; 5621-5623; 5623-5624; 5631-5421; 5631-5633; 5641-5643; 5651-5481; 5651-5652; 5651-5653; 5651-5667; 5651-5668; 5652-5654; 5652-5656; 5667-5660; 5667-5661; 5668-5662; 5668-5663; 7029-5653;

Figure 10. Brazilian sub-system branches list (bus/branch model)

This sub-system presents 58 buses and 64 branches. The one-line representation of this model, generated without geospatial information, is depicted in Figure 11.Like in the previous case, it presents several branch crossings and multiplicity of one-line representations, when different executions are considered.

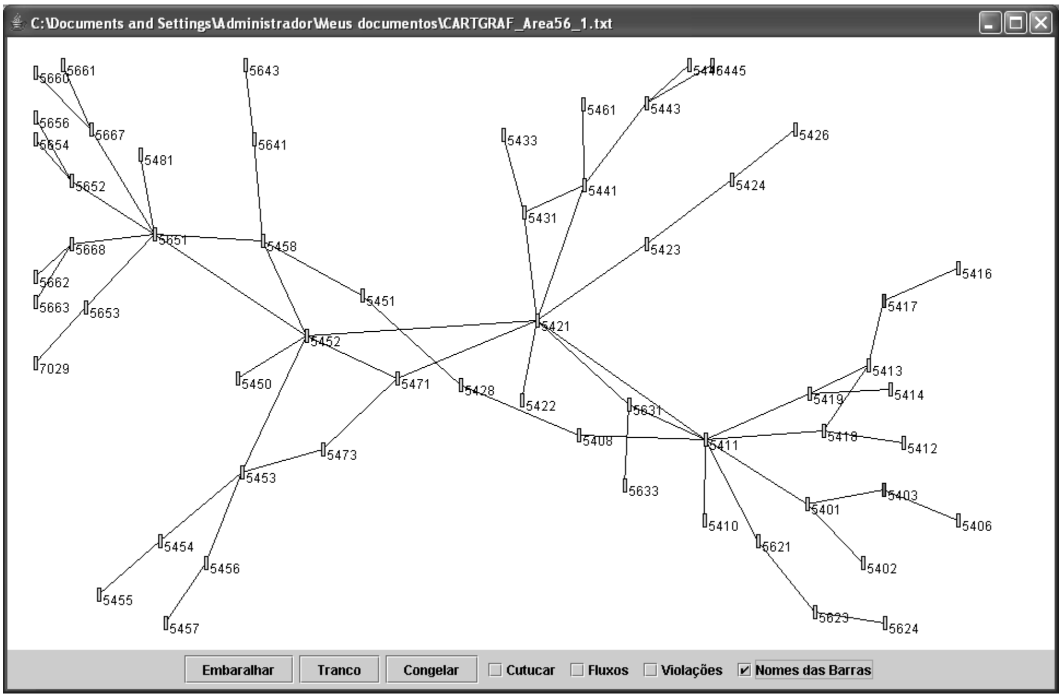

Figure 11. Brazilian sub-system one-line diagram generated without geospatial information

Since this case is based on an actual network, the usage of geospatial information becomes possible. To investigate the efficiency of these data usage, the geographical location were made available only for a few buses. The objective here is to evaluate the method's performance when there is lack of geospatial information. In this test, the information provided for the algorithm is represented in Table 1.

Table 1. Geospatial Information Provided For the Algorithm

Geographical Region	Buses
Northwest	5651, 5652, 5653
North-central	5458, 5428, 5411
Northeast	5621, 5401, 5413
Southwest	5452, 5453
South-central	5421
Not available	All the remaining buses

The initial one-line representation using this information is shown in Figure 12.

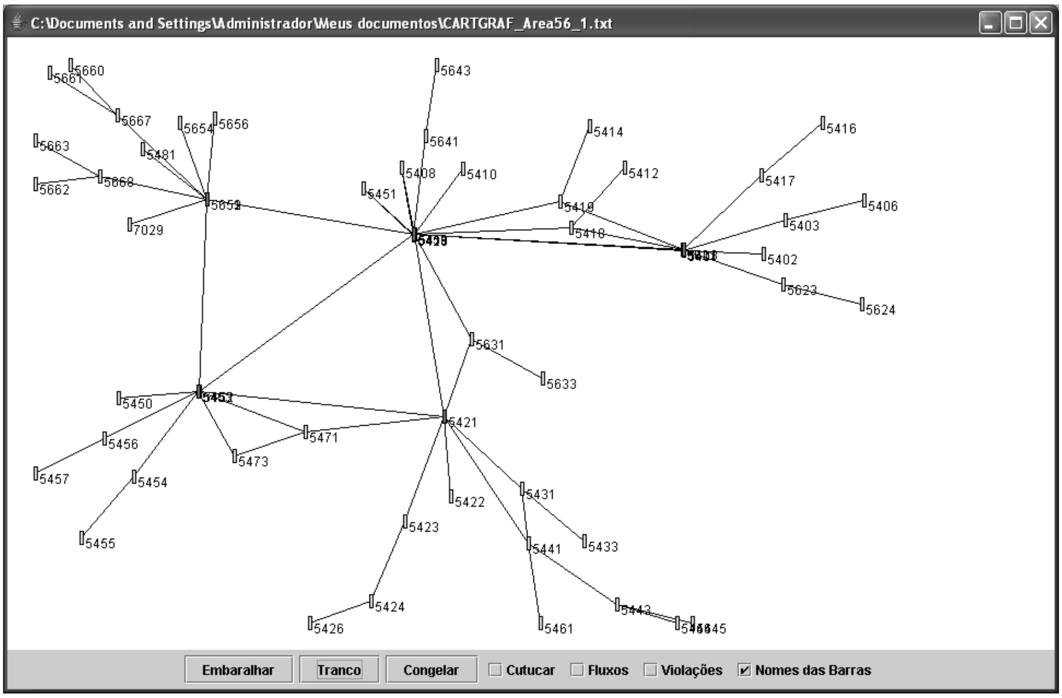

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Figure 12. Brazilian sub-system one-line diagram generated with geospatial information – initial representation

As expected, the buses that pertain to the same region were superposed. After a few iterations, the one-line representation becomes as illustrated in Figure 13.

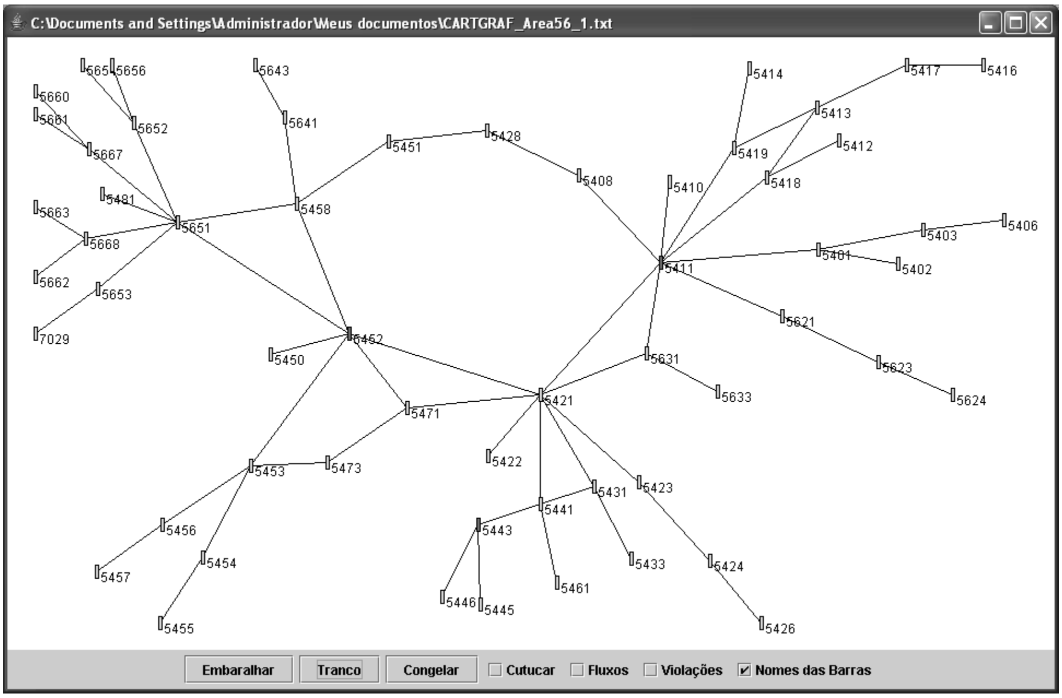

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Figure 13. Brazilian sub-system one-line diagram generated with geospatial information – final representation

It can be observed that the algorithm has eliminated all the branch crossings in the final diagram with only a small amount of geospatial information (available for 12 of 58 buses – approximately 20% from the total).

7. Conclusions

Nowadays, electrical power systems play a critical role in people's life, as evidenced by the recent major blackouts, in Brazil and in the world. All the supervision, maintenance and studies related to electric power generation and transport are based on one-line diagrams. The size of actual electrical power systems makes these diagrams generation and update very complicated tasks. Efforts have been made to apply graph visualization methods to the confection of these diagrams as can be seen in the references; however, the usage of these techniques are inefficient due to the presence of many branch crossings and the multiplicity of graphical representations for a same electric network.

In this context, geospatial data have proved to be a fundamental information, allowing the complete elimination of crossings in many cases, as demonstrated by the results of this work. Its usage has also the benefit of consistent diagram generation for a specific power system, improving the similarity among graphical representations generated in different executions of the graph visualization algorithm described in [Mota 2004].

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