A Fog Model for Dynamic Load Flow Analysis in Smart Grids

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***Abstract*—In the last 20 years, the amount of energy consumed has grown more than 50% and due to a shortage of energy resources in the future, will not be possible to meet all this demand. The current distribution model transports energy from stations to consumers, but does not consider the use of alternative sources. The smart grids have emerged to allow the inclusion of alternative forms of energy generation in the grid. Yet, to avoid an overload in the system is necessary to calculate the power flow in real time. In this paper, we use Fog Computing as mean to reduce the logical distance between the central distribution and consumption spot. IoT devices in the network edge have more effectiveness and less cost to handle the power flow information. We evaluate the performance of the Newton-Raphson and Gauss-Seidel algorithms with the objective of developing calculations in real time of the load flow problem with the help of fog. Our results have shown that is possible to make a smart grid based on Fog Computing and thus making smart electric networks that react to the environment.**

***Index Terms*—smart grid, fog, cloud, power flow, energy, distribution model, gauss-seidel, newton-raphson, power grid**

I. Introduction

Current power grids follows a conventional model, where power generators transmit unidirectionally the power generated to destinations (residence, commerce or industry). This transmission is made in several stages, through substations, distributors and transmission lines, which makes this transmission inefficient due to the loss of high voltage, especially in transmission lines [6]. In addition, the amount of energy consumed has increased by 2.5% per year in the last 20 years and due to the shortage of energy resources in the future will not be possible to supply all this demand [4].

This distribution model transports power from power plants to consumers, but does not consider alternative energy resources. Thus, smart grids are being studied to propose a new model of energy distribution, allowing the transmission of bidirectional energy (taking advantage of renewable energies also generated by consumers) [9]. To implement the two-way model, the balance between power generation and energy consumption must be achieved. Today, the balance is reached through calculations made in a system with static power generators. Yet, realizing a dynamic power flow project depends on the knowledge about the effects of adding new generators, and consumption variation, a task that could be simulated in the cloud [1].

The distance between the cloud and smart grids' layers can influence the data updating since the communication needs to be done over the internet. Thus, fog is useful in performing real-time power flow calculations because is located at the edge of each smart grids layer. Calculations performed in power flow analysis are complex and the fog servers are not as powerful as the cloud servers. Thus, is necessary to implement the power flow algorithms considering the transmission device characteristics (generation bus and load bus) that the fog server is analyzing. In this way, we carry out the Performance Evaluation of the Gauss-Seidel and Newton-Raphson methods considering mathematical aspects as tolerance, and physical aspects as quantity of load buses and generator buses, verifying the influence that those have on the response variables, voltage and convergence time and thus choose the appropriate power flow algorithms.

The results have shown the Newton-Raphson as the best option in most cases of the analyzed scenarios. Besides, the greatest contribution of this paper is to provide a smart grid based on Fog Computing and thus making smart electric networks with fast react to the environment.

This paper is organized as follows: Section 2 presents the related works and its relation to the proposed work, Section 3 provides the concepts about smart grids. Section 4 describes the evaluation. Section 5 shows the results obtained and Section 6 presents the conclusions.

II. Related work

Expected as the next generation of power grid, Smart Grid uses flows of electricity and information to make a smart distributed energy delivery network. In this context, we have proposed Fog Computing as way to improve the energy flow processing and utilization. Despite the existence of several works exploring the Smart Grid infrastructure, none of them proposed the use of the Fog paradigm as a way to reduce the logical distance between the central distribution and the point of consumption.

Singh and Bala (2016) [14] performed a comparative study between the Gauss-Seidel and Newton-Raphson algorithms

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within the power flow analysis, considering the IEEE 30, IEEE57 and IEEE 118 bus system to determine when these algorithms may be employed. Using Gauss-Seidel the number of iterations increases proportionally according to the number of bus, while the Newton-Raphson method remained practically constant, even with the variation of the number of buses.

Rashmi *et al*. (2016) [10], Chatterjee, S. and Mandal (2017) [2], Dharamjit (2012) [3] and Vijayvargia (2016) [15] developed a MATLAB program to calculate the voltage, angle, active and reactive power of each bus of IEEE9, 14, 30 and 57 systems. The Gauss-Seidel, Newton-Raphson and Fast-Decoupled algorithms were compared and aimed at check the tolerance changes and the number of iterations. As a result was verified that the Newton-Raphson method converges faster than Gauss-Seidel.

Bokka (2010) [1] developed a technique in the analysis of the load flow that alternates between the traditional algorithms Gauss-Seidel and Newton-Raphson with the objective of reducing the execution time of the convergence. To test the new algorithm, the IEEE 39 bus system was used and compared the results with the traditional algorithms executed in isolation. From the results obtained from this comparison it was concluded that the proposed method was faster in convergence time than the traditional methods.

Sedghi and Aliakbar-Golkar (2016) [12] proposed a new approach due to the necessity of the use of matrices, considered the biggest problem of traditional algorithms. It was proposed the use of a diffuse neural network that is trained by the traditional algorithms, as a result the method had greater reliability of convergence and the diffuse neurons were able to overcome the uncertainties of the inputs.

Unlike these works, we have proposed the Fog Computing Paradigm as an extension of Cloud Computing. In our work, Fog Computing performs services directly at the edge of the network, providing low latency and real-time computing, essential in cases where urgent flow changes are required. In addition, these papers do not cover performance evaluation aspects in their analysis.

III. Smart Grids and Power Flow Analysis

Smart grids are designed to save energy, reduce transmission costs, and increase the reliability of power grids, but to achieve these attributes, it is necessary to perform control of consumption and power generation [13]. Thus, is necessary to collect data and interact with all layers of the topology of the power grids, obtaining real-time communication from consumers and generators, see Fig. 1.

Real-time communication has lower latency and shorter application response times when servers are used at the edge of networks. Thus, using fog in smart grids has become critical to achieving the benefits that a smart grid can provide [7], but fog servers do not have the same capacity as servers located in the cloud, so the algorithms created for fog need to be designed considering the economy of processing, memory, and storage. Yet, methods for designing the demand and production capacity of energy are complex and require computational

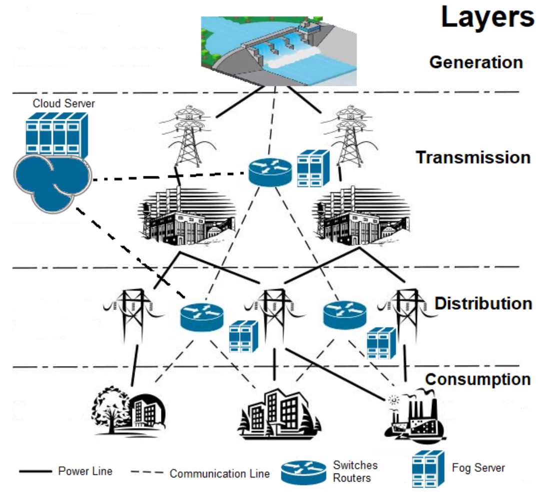

Fig. 1. Fog-aided SmartGrid topology.

power to be executed. These methods are mainly studied by power flow analysis.

The power flow analysis consists of determining the network state (voltages magnitude, phase angles), flow distribution and active and reactive power injection in all system buses, this analysis allows growth planning and monitoring of the best conditions of operation of the electrical networks [14]. To obtain this information, calculations are performed through a set of equations. These equations have the objective of finding four variables: V, θ, P and Q. V represents the voltage magnitude, θ the voltage angle, P the injection of liquid power and Q the injection of reactive power, but for this a static modeling of the system is done, where the variations of the quantities in time are slow so that the transient effect of these systems can be disregarded .

The basic equations of the power flow are obtained by imposing the conservation of the active and reactive powers, where the power injected must be equal to the sum of the powers that flow through the network bus [8]. These equations are $P_k = \sum_{m \epsilon \Omega_k} P_{km}(V_k, V_m, \theta_k, \theta_m)$ and $Q_k + Q_k^{sh}(V_k) = \sum_{m \epsilon \Omega_k} Q_{km}(V_k, V_m, \theta_k,$ where $k = 1, \ldots, NB$, and NB the number of bus in the power grid. Ω_k represents set of bus next to k. V_m is the voltage magnitude of the k-m buses. θ_k, θ_m the voltage angle of the k-m buses. P_{km} active power flow in the k-m buses. Q_{km} reactive power flow in de k-m buses. Q_k^{sh} reactive power injection component due to bus shunt element k ($Q_k^{sh} = b_k^{sh} V_k^2$), where b_k^{sh} is the shunt susceptance connected to the bus k.

The variables which represent the system that is divided into three types of buses: generator bus (where variables P and V are given), load bus (where P and Q variables are given) and reference bus (where variables V and θ), so for each bus is necessary to find the missing variables using the values of the previous bus. In the load flow problem the variable θ is indeterminate, then is adopted an angular reference chosen arbitrarily in the reference bus. Yet, the environment where the power is transmitted offers resistance, so is necessary to represent the resistance and acceptance of the energy in the material used for transmission. This type of consideration is realized through the impedance and admittance of transmission lines [11].

In order to calculate all the variables involved in load flow design, a computational model is required where the system of equations can be represented. The most used model is the matrix, where through the admittance matrix and the voltage array is possible to calculate the current injection array for all the buses. This model is represented by $I = Y.E$, where I is the array of current injections, whose elements are I_k, k = 1, ... NB. Y is admittance matrix. E is the voltages array whose elements are E_k, k = 1, .. NB, where $E_k = V_k e^{j\theta_k}$.

Knowing arbitrarily the variable θ of the reference bus and the current I injected into the system, one can find the voltage magnitude V and the angle θ of all the bus. Thus, is possible to use equation system resolution techniques to determine the values of all system bus variables considering the losses of the environment through the admittance array and the power flow formulas. The techniques studied in this paper are Gauss-Seidel and Newton-Raphson.

A. Gauss-Seidel

Gauss-Seidel is a method of solving the system of equations that follows the model $Ax = b$, where A is an array of size $n \times n$ and x and b are array of size $n \times 1$ as:

$$\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ a_{21} & \cdots & a_{2n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_n \end{pmatrix} = \begin{pmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \\ \vdots \\ \mathbf{b}_n \end{pmatrix},$$

where the multiplication of array using x as reference is made as

$$x_i = \frac{1}{a_{ii}}(b_i - \sum_{j=1, j\neq i}^{n} a_{ij}x_j). \tag{1}$$

If $(m+1)$ iterations and the most recent values of x are used, the Gauss-Seidel model is found

$$x_i^{(m+1)} = \frac{1}{a_{ii}}(b_i - \sum_{j=1}^{i-1} a_{ij}x_j^{(m+1)} \sum_{j=i+1}^{n} a_{ij}x_j^{(m)}). \tag{2}$$

If used the admittance matrix model with the Gauss-Seidel model (2) the load flow problem arises as

$$E_k^{(m+1)} = \frac{1}{Y_{kk}}(\frac{S_k}{E_k^{(m)}} - \sum_{n=1}^{k-1} Y_{kn}E_n^{m+1} - \sum_{n=k+1}^{NB} Y_{kn}E_n^{(m)}), \tag{3}$$

where NB is the total number of buses.

The Gauss-Seidel algorithm begins with the creation of the admittance array and then the choice of the tolerance and initial values for the reference bus variables, in this paper 1 was used for the voltage and 0 for the angle. The initial values are used in (3) and this process only ends when the difference between the new values and the old values is smaller than the specified tolerance. This process is executed for each bus that exists in the system until all variables are found, and the value found previously is used to find the next one.

B. Newton-Raphson

By definition, P and Q are given for load buses P and V for generation buses and V and θ for the reference buses is necessary to calculate V and θ for buses of load, θ and Q for generation buses, and P and Q for reference bus. Once this problem is solved, the state (V, θ) will be known for all buses in the grid, which makes possible to calculate the remaining variables [8]. Since NPQ is the number of load bus and NPV is the number of generating bus, the load flow problem can be decomposed into two equations subsystems.

The first subsystem with $2NPQ + NPV$ equations, where P and Q are given for load bus and P and V for the generating buses. It is necessary to calculate V and Q for the load bus and θ for the generating buses using

$$P_k^{esp} - V_k \sum_{m\epsilon\Omega_k} V_m(G_{km}\cos\theta_{km} + B_{km}\sin\theta_{km}) = 0, \tag{4}$$

where P_k^{esp} is the next generation of power given of the load buses and bus generators and V_k the voltage in the calculation bus source and V_m voltage at their adjacent buses, and

$$Q_k^{esp} - V_k \sum_{m\epsilon\Omega_k} V_m(G_{km}\sin\theta_{km} - B_{km}\cos\theta_{km}) = 0, \tag{5}$$

where Q_k^{esp} is the net injection of reactive power given on the load bus.

After solving the first subsystem, all values V and θ of all buses will be known and will be necessary to calculate P and Q for the reference bus and Q for the generation bus, which is a problem with NPV + 2 equations with the same number of unknowns, in which all the unknowns will appear explicitly, which makes the resolution process trivial and can be found in

$$P_k = V_k \sum_{m\epsilon\Omega_k} V_m(G_{km}\cos\theta_{km} + B_{km}\sin\theta_{km}), \tag{6}$$

and

$$Q_k^{esp} = V_k \sum_{m\epsilon\Omega_k} V_m(G_{km}\sin\theta_{km} - B_{km}\cos\theta_{km}). \tag{7}$$

The second equations subsystem is easily calculated when the first is solved, so the main problem is resolution of the first subsystem, which needs to group the unknowns according to $x = \begin{pmatrix} \theta \\ \mathbf{V} \end{pmatrix}$, where θ is the load buses array of voltage angles and generation buses with size NPV + NPQ and V is the load buses voltage array of with size NPQ. The equations (4) and (5) can be rewritten as a function of V and θ and are respectively represented as (8) and (9):

$$\Delta P_k = P_k^{esp} - P_k(V, \theta) = 0, \tag{8}$$

$$\Delta Q_k = Q_k^{esp} - Q_k(V, \theta) = 0. \tag{9}$$

Considering the new representation can be affirmed that:

$$g(x) = \begin{pmatrix} \mathbf{\Delta P} \\ \mathbf{\Delta Q} \end{pmatrix}, \tag{10}$$

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and

$$g(x) = 0. \tag{11}$$

So, is possible to linearize the function $g(x)$ around the point $(x, g(x))$ by Taylor series as $g(x + \Delta x) \cong g(x) + J(x)\Delta x$, where $J(x)$ is the Jacobian matrix given by the derivatives of the equations of $g(x)$ that are defined in (10),

$$J(x) = \begin{pmatrix} \frac{\delta(\Delta P)}{\delta \theta} & \frac{\delta(\Delta P)}{\delta V} \\ \frac{\delta(\Delta Q)}{\delta \theta} & \frac{\delta(\Delta Q)}{\delta V} \end{pmatrix}, \tag{12}$$

finding Δx such that $g(x) + J(x)\Delta x = 0$, where

$$\Delta x = \frac{-g(x)}{J(x)}, \tag{13}$$

so

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \begin{pmatrix} \frac{\delta(\Delta P)}{\delta \theta} & \frac{\delta(\Delta P)}{\delta V} \\ \frac{\delta(\Delta Q)}{\delta \theta} & \frac{\delta(\Delta Q)}{\delta V} \end{pmatrix} \begin{pmatrix} \Delta \theta \\ \Delta V \end{pmatrix}. \tag{14}$$

The Newton-Raphson algorithm starts with the choice of voltages, reference bus voltage angles and tolerance to be adopted, then $P(V, \theta)$ is calculated for the load bus and and $Q(V, \theta)$ for the load bus and checking if the difference between the found value and the previous value is less than the specified tolerance. If smaller, the process converges and the best solution for (V, θ) was found, otherwise the Jacobian matrix is calculated and the found values are updated. This process is repeated until $P(V, \theta)$ and $Q(V, \theta)$ reduced from previous value is found to be less than the tolerance.

C. Using Fog on the Power Flow Analysis

The power flow analysis has as characteristics the capacity to perform the monitoring of the power grid. Thus, it is possible to predict the overloads in the system and help in changing the distribution topology through changes in generation buses and load buses according to demand. [14].

Today, this analysis is static and requires human intervention, where the generators and distributors of energy need to be in constant communication to maintain the balance of the network, but with the emergence of smart cities and smart grids, the trend in modern life is to automate tasks and seek the use of renewable resources.

This work proposes an architecture that use fog to monitor and interact with power grids. This architecture uses the data obtained through the performance evaluation to suggest the amount of buses that each fog server located at the edge of the smart grids can monitor and interact. The buses number limitation is because the current algorithms cannot process a very large number of buses in their execution.

The substations can be a load bus or a generation bus depending on the calculation that will be performed on the load flow problem, see fig. 2. The distribution substation will be considered a generation bus when the circuit breakers distributed by the city are considered as the load buses, but in relation to the transmission substations, the distribution substations will be considered as load buses, in which case the transmission substations are considered generation buses.

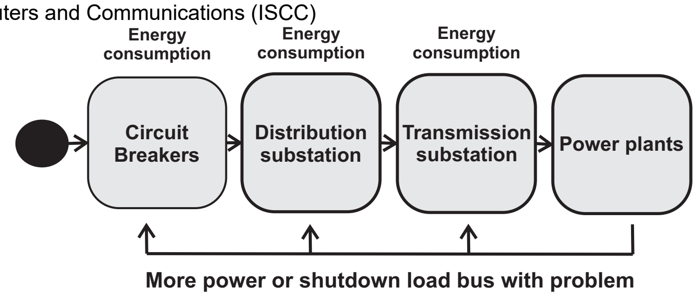

Fig. 2. FeedBack of power flow balance cycle

Transmission substations will be considered load buses when power plants are considered as generation buses.

Thus, every substation will also be edge of the network that will receive the fog server responsible for the calculations of the load flow and sending the information found to other fogs and to the cloud.

The voltage of the load buses are transmitted to the fog servers and it is then decided whether the values are suitable in relation to the rated voltage, whether it is necessary to transmit more power or if it is not possible to increase the power, shutdown the load buses that affect the transmission system.

As the load buses number may vary according to the city growth and considering that the equipment at the edge of the data network is limited, this work presents an algorithm that mixes the 2 studied algorithms and can be used in fog to calculate the voltage of the load bus and through simulations to detect possible overloads in the system.

Algorithm 1: *Using Fog on the Power Flow Analysis.*

```
dataconsumption ← receivedatasmartgrid ();
if host.cpu > 50% then
    if dataconsumption.amountbus < 10 then
        busvalue ← gaussseidel (dataconsumption)
    else
        busvalue ← newtonraphson (dataconsumption)
    end
else
    if dataconsumption.amountbus < 15 then
        busvalue ← gaussseidel (dataconsumption)
    else
        busvalue ← newtonraphson (dataconsumption)
    end
end
```

The algorithm receives the data from the smart grid and verifies the server processing, depending on the value, it is chosen the best model to be used and the best number of buses for the moment.

IV. Performance evaluation

Performance is a fundamental criterion in the design, acquisition and use of computerized systems. In this paper, Performance Evaluation is used to select appropriate power flow algorithms. Performance Evaluation is a very important technique for the academic and industry, because it allows for more reliable results, by saving money and time. In addition, it serves to evaluate any system. Performance Evaluation turns possible find a metric that indicates quantity or quality. It is verified the accuracy, validity, and meaning of the magnitude

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produced during the evaluation. Also, it is used to obtain the highest statistical accuracy as possible, providing the maximum information with a minimum number of experiments. Besides, it shows the effects of various factors on the observed result, presenting the effect of a factor on the result observed.

Thus, within energy distribution systems that are becoming increasingly computerized, a performance assessment is required to understand the key factors influencing voltage and voltage variations, and how computer systems can help to avoid such problems with lowest cost possible.

A. *Experiment planning*

In order to evaluate the performance of the load flow algorithms in the power grids, the MATLAB program was used to perform simulated experiments on the 39 bus system adapted from IEEE 39. Four factors were considered with two levels each, where the chosen factors were: algorithms, tolerance, load buses and generation bus.

The factorial model 2^k, presented by [5], was used in which the levels were defined as in the table I.

TABLE I
FACTORS AND LEVELS

Factors	Levels	
Algorithm	*Gauss-Seidel*	*Newton-Raphson*
Tolerance	0,0001	0,1
Load Bus	1	10
Generation Bus	1	29

The objective of these experiments is to extract how much the related factors influence the response variables, which are the voltage accuracy and the convergence time. For this, combinations were made between the levels specified as directed [5], where a model with arrangement 2^4 is realized. The factors and levels of the experimental design were defined through the most probable values and used in the literature, allowing to evaluate the completeness of the effect that these variables cause to the environment.

In this experiment, the system generation buses are transmitting nominal voltage 1 pu. Combinations with 11 buses are considering the closest buses, and disregarding the influence that the distance between the buses could exert on the results, because the greater the distance the greater the resistance that the power will receive. In addition, the objective is to provide an algorithm that can be used in fog, which makes it possible to consider the buses closer. To guarantee the dynamics of the experiments, the power consumption in the load buses were randomly generated for each experiment.

Ten replications were performed for each experiment that had little variation, so was considered that the amount of replications was sufficient for data analysis. The 95% confidence interval obtained through the t-student table was used for each experiment. Thus the data dispersion interval can be added to bar graphs with probability equal to the adopted index. From the values obtained for each response variable were calculated their total variations, in addition to the influence of each of the factors on their values, as described in section III-B.

As can be seen in Fig. 3, the algorithm (18.29%), load bus (35.90%) and generator bus (23,07%) are the factors with the highest percentage when considering the voltage influence. This is because the higher the number of buses, the worse the performance of the Gauss-Seidel algorithm. Was also possible to realize that the number of generation buses influences the voltage when are 30% of the total buses considering the Newton-Raphson algorithm for more than 30 buses buses or Gauss-Seidel for systems with less buses. The Fig. 3 shows the influence factors in the convergence times of the algorithms. This influence is stronger in the factors, load bus (41.83%) and tolerance (17.75%). This behavior occurs because the larger the number of load buses, the greater the admittance (Gauss-Seidel) or Jacobian (Newton-Raphson) matrix and the large array processing will consume longer computational time. In addition, the tolerance factor also contributes to the processing time because that the larger the tolerance, less calculations need to be performed.

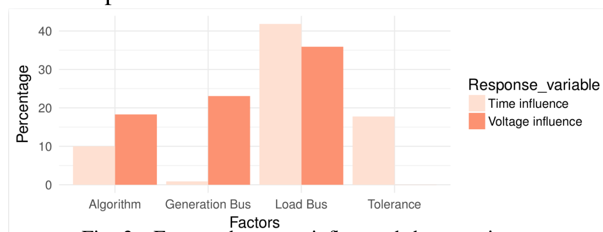

Fig. 3. Factors that most influenced the experiments.

B. *Results Analysis*

In the experiments carried out with the largest number of buses, 29 load buses and 10 generation buses, the Newton-Raphson algorithm nominal voltage was within the 95% suggested by module 8 of the national electric energy agency (NEEA). Yet, the Gauss-Seidel algorithm could not maintain the voltage within this specification for any tolerance tested, and the processing time grew more than half the time than the Newton-Raphson method, as can be seen in the Fig. 4 and Fig. 5

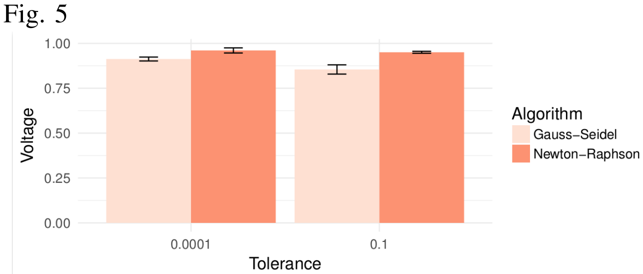

Fig. 4. Results of the voltages obtained from the experiments with 29 load buses and 10 generation buses.

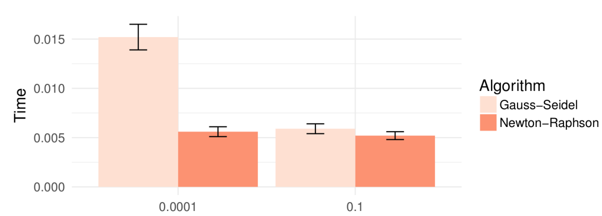

Fig. 5. Results of the times obtained from the experiments with 29 load buses and 10 generation buses.

The relation voltage by buses can be observed in Fig. 6, where a comparison was made between the buses and voltage accuracy. When considering the smallest number of buses, like environment 1, where two buses are used, 1 load and 1 generator, tests done were within the expected range. If considered, case 1 load bus, and 10 generator bus, like the environment 2, the voltage being much higher than 95%. When increases to 30 buses, 1 generator bus, and 29 load bus, as can be seen in environment 3, the voltage tends to fall mainly in the Gauss-Seidel algorithm. Finally, when the number of generator buses increases, the system with 29 load buses and 10 generator buses the voltage grows becoming acceptable for the Newton-Raphson algorithm, see environment 4.

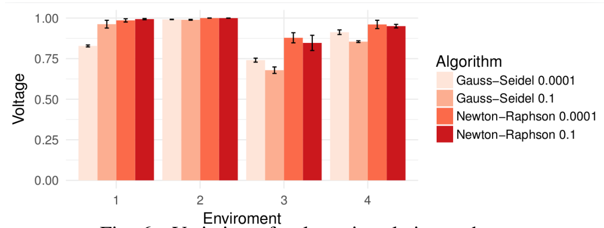

Fig. 6. Variation of voltage in relation to buses.

Fig.7 shows the convergence time by bus, when the number of buses and the tolerance increases, the Gauss-Seidel algorithm tends to take longer to converge, as seen in environments 3 and 4 which have 30 and 39 buses respectively.

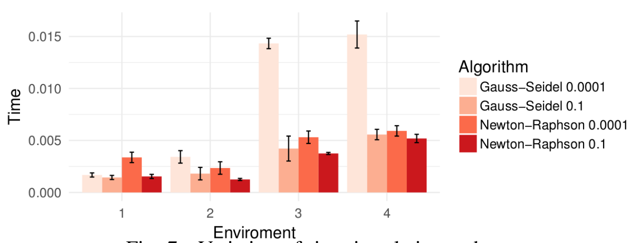

Fig. 7. Variation of time in relation to buses.

V. Conclusion

This paper presents the use of the Fog Computing paradigm as an extension of Cloud Computing. Our proposed approach can reduce the logical distance between the central distribution and the point of consumption, providing low latency and real-time computing. In our work, Fog stores and processes the data for decision making, even autonomously, regardless of the state of the Cloud infrastructure. In this way, our essential services are not affected if a device has problems connecting to the Cloud, because Fog will guarantee the integrity of the data and the continuity of services in those situations.

Also, we have used a statistical model to carry out a performance evaluation of Gauss-Seidel and Newton-Raphson load flow techniques. By analyzing the results obtained for the adopted response variables, it was possible to verify the behavior of the distribution networks. Through this behavior, an algorithm was developed to configure in the fog with the objective of monitoring the smart grids and acting on their components in order to maintain the balance of the load distribution networks. In order to give faster answers to the environment, the best algorithm is executed according to the situation of the servers fog. Thus, the lighter algorithm such as Gauss-Seildei can be executed when the number of buses is adequate and the processing of the server is high.

The Newton-Raphson method, although it can be used in the great majority of the cases of the analysis of the load flow, its implementation consumes a lot of memory and processing due to the use of the jacobiana matrix, being thus, in a fog environment, where the servers can have low memory, and processing, the use of this technique should only be required as a last resort.

VI. Acknowledgment

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