CEEL - ISSN 2596-2221
Universidade Federal de Uberlândia
25 a 29 de novembro de 2019

BACKWARD-FORWARD SWEEP LOAD FLOW ALGORITHM FOR A FEEDER WITH HIGH DISTRIBUTED GENERATION INTEGRATION

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***Abstract* -The benefits of distributed generation integration based on alternative sources in distribution systems, have promoted a large increase of this type of source in the world's power electrical system. However, this growth causes several modifications in the dynamics of the electric power flow, being possible to highlight the electric current bidirectionality. In this context, it is possible to use several simulation software, such as simulink, in order to analyze many scenarios with the distributed generation insertion. Nevertheless, the operating time in these softwares can be high depending on the application, such as in real-time analysis. For this reason, this paper applies the Back-Forward Sweep method to solve three-phase power flow of a feeder with unbalanced loads and considering the high integration of distributed generation. Thirty-one cases were considered, varying the distributed generation integration from 0% to 150% at the nodes that have loads. Finally, from the results, it was possible to conclude that the proposed methodology was able to solve the power flow for all the cases with the operation time 237 faster than the simulink software.**

***Keywords* - Backward-Forward Sweep, Distributed Generation, Power Flow.**

I. INTRODUCTION

Currently, it is important to note that there is a high tendency for high integration of distributed generation (DG) in distribution systems around the world. It should be emphasized that a great part of this integration is made based on the use of renewable sources of energy, and in the Brazilian energy scenario, photovoltaic systems are the most frequently used [1, 2]. It is worth pointing out that these changes in the context of electric power generation promote several impacts on the contemporary power system, such as: postpone large investments in the electricity sector, losses reduction, improved voltage profile, and increased energy efficiency [3, 4, 5, 6].

In addition, it should be noted some negative impacts related to the integration of DG in distribution systems. For example: insertion of harmonic content on account of the inverters, reduction of the indices of the quality of the energy, incorrect operation of the protection devices [7, 8]. In this context, it is necessary to explore three-phase power flow resolution methodologies of distribution systems, considering the high integration of DG. Simulink software is now widely used, being notoriously effective and ensuring good results in electrical systems (including for power flow resolution of distribution systems). However, this tool has as main negative point the operating time, which becomes considerably high for certain tasks.

In that way, some situations a rapid response of the software used to solve the power flow is required, or even the process needs to be repeated several times (making simulink operation time impractical). For this reason, it is easy to notice the importance of developing studies that seek the solution of three-phase power flow in real time. It can be pointed out, for radial distribution systems, the Backward-Forward Sweep (BFS) method.

In [9] it is observed the validation of the BFS methodology to solve the power flow of a distribution system, from the comparison with "Fast Decoupled". Based on the results, a low operating time is observed in these methods due to the reduced number of iterations. In addition, studies carried out in [10] and [11] attempted to demonstrate the impacts caused by the DG insertion into the power system, which is done through the BFS.

Therefore, the present paper presented a methodology of three-phase power flow resolution of a radial system, based on BFS, in order to obtain voltage, voltage phase and current values of all nodes and branches in a distribution system with high DG integration. The feeder used has thirteen nodes, with unbalanced loads. The validation of the methodology was done through the comparison between the reached data in the BFS in relation to those achieved through simulink software. In addition, another point that was considered and compared in this paper was the operating time of both methods.

In Section II the necessary theory of the BFS algorithm was

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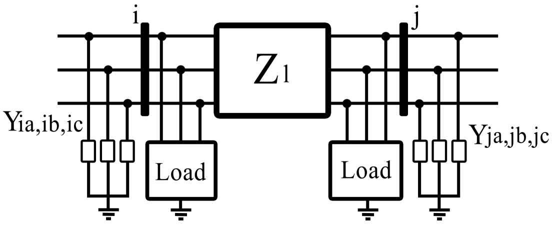
presented, describing in detail the method used. Moreover, the case study of the feeder used was carried out in Section III. Section IV evidenced the results and discussions related to the power flow resolution. Finally, concluding remarks are provided in Section VI.

II. BACK-FORWARD SWEEP

In this section it was presented the 3x3 matrix modeling, in which the neutral and the ground are disregarded, in order to highlight a three-phase power flow solution method, which consists in the Back-Forward Sweep (BFS). For its implementation the method uses a branch-oriented approach to improve numerical performance, based on a layered ordering away from the root node [12, 13].

In Figure 1, it is possible to observe a line section between nodes i and j, with load and admittance in each node. In addition, the impedance between the two nodes is evidenced.

Figure 1: Three-phase line section.



The iterative method starts after the assignment of phase voltages at each node. After that, the nodal currents must be calculated, as shown in (1).

$$\begin{bmatrix} I_{ia} \\ I_{ib} \\ I_{ic} \end{bmatrix}^{(k)} = \begin{bmatrix} \dfrac{S_{ia}}{V_{ia}^{(k-1)}}^{*} \\ \dfrac{S_{ib}}{V_{ib}^{(k-1)}}^{*} \\ \dfrac{S_{ic}}{V_{ic}^{(k-1)}}^{*} \end{bmatrix} - \begin{bmatrix} Y_{iaa}^{*} & Y_{iab}^{*} & Y_{iac}^{*} \\ Y_{iab}^{*} & Y_{ibb}^{*} & Y_{ibc}^{*} \\ Y_{iac}^{*} & Y_{ibc}^{*} & Y_{icc}^{*} \end{bmatrix} \begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix}^{(k-1)} \tag{1}$$

Where:

I_{ia}, I_{ib}, I_{ic} - Current injection at node i.
S_{ia}, S_{ib}, S_{ic} - Power injection at node i.
V_{ia}, V_{ib}, V_{ic} - Voltage at node i.
Y - Admittance at node i.
k - Current iteration.

It is necessary to calculate the line section currents, starting from the lines sections of the furthest layers and moving towards the root node. In (2) it is presented the equation which describes the line section current calculation [12].

$$\begin{bmatrix} J_{la} \\ J_{lb} \\ J_{lc} \end{bmatrix}^{(k)} = - \begin{bmatrix} I_{ja} \\ I_{jb} \\ I_{jc} \end{bmatrix}^{(k)} + \sum_{m \in M} \begin{bmatrix} J_{ma} \\ J_{mb} \\ J_{mc} \end{bmatrix}^{(k)} \tag{2}$$

Where:

J_{la}, J_{lb}, J_{lc} - Current that flows on line l.
I_{ja}, I_{jb}, I_{jc} - Current injection at node j.
J_{ma}, J_{mb}, J_{mc} - Current that flows from m to a, b, c.
M - Set of lines connected to node j.

At that moment, it must be calculated the nodal voltage, from the node of the first layer (root node) to the last layer, as exposed in (3).

$$\begin{bmatrix} V_{ja} \\ V_{jb} \\ V_{jc} \end{bmatrix}^{(k)} = \begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix}^{(k)} - \begin{bmatrix} Z_{iaa,l} & Z_{iab,l} & Z_{iac,l} \\ Z_{iab,l} & Z_{ibb,l} & Z_{ibc,l} \\ Z_{iac,l} & Z_{ibc,l} & Z_{icc,l} \end{bmatrix} \begin{bmatrix} J_{la} \\ J_{lb} \\ J_{lc} \end{bmatrix}^{(k)} \tag{3}$$

Where:

V_{ja} - Downstream node voltage
V_{ia} - Upstream node voltage
Z - Impedance of a line section.

Finally, the stopping criterion was defined in (4), (5) and (6), by calculating the power mismatches at each node for all phases. Thus, if the stopping criterion is lower than a previously determined value, the iterative algorithm must stop and indicates the three-phase power flow solution, because the convergence was achieved. Otherwise, it is necessary to perform another iteration, using (1), (2) and (3), until the error is smaller than the established value [12].

$$\Delta S_{ia}^{(k)} = V_{ia}^{(k)} \left(I_{ia}^{(k)} \right)^{*} - Y_{ia}^{*} |V_{ia}|^{2} - S_{ia} \tag{4}$$

$$\Delta S_{ib}^{(k)} = V_{ib}^{(k)} \left(I_{ib}^{(k)} \right)^{*} - Y_{ib}^{*} |V_{ib}|^{2} - S_{ib} \tag{5}$$

$$\Delta S_{ic}^{(k)} = V_{ic}^{(k)} \left(I_{ic}^{(k)} \right)^{*} - Y_{ic}^{*} |V_{ic}|^{2} - S_{ic} \tag{6}$$

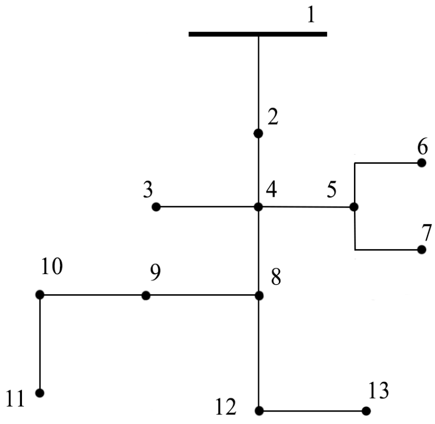
In this paper, it was considered that the dispersed generators, given by photovoltaic (PV) systems, are operating to supply apparent power in a specified power factor. Therefore, it was used in the algorithm PQ nodes to represent the PV systems [12].

III. CASE STUDY

Figure 2 shows the 13-Node distribution feeder that was used in this paper. It is worth noting that node 1 consists in the slack bus, therefore, it provides the angle reference of the voltage. Besides that, this node have the voltage fixed at 13.8

kV, which is a typical value for distribution systems in Brazil.

Figure 2: Feeder used in the case study.



In Table 1 it is possible to observe the load data of the analyzed feeder. Initially, it is stated that nodes 1 and 2 do not have any associated load. In addition, it is worth highlighting the fact that these feeder loads are unbalanced, which promote a greater applicability of the methodology used in this paper, since real systems have this characteristic.

Table 1: Load data.

Node	Active Power [kW]			Reactive Power [kVar]		
	A	B	C	A	B	C
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	160	120	120	110	90	90
4	85	112.5	50	10	38	68
5	120	160	120	90	90	90
6	90	70	110	110	90	90
7	160	120	120	110	90	90
8	385	385	385	220	220	220
9	0	0	180	0	0	130
10	350	200	100	100	70	70
11	200	200	200	70	70	70
12	500	500	500	60	60	60
13	550	220	380	190	60	212

Capacitors were added at nodes 7 and 11, and in Table 2 the respective power values were specified for each phase.

Table 2: Capacitor data.

Node	Reactive Power [kVar]		
	A	B	C
7	200	200	200
11	200	200	200

Moreover, DGs were added on the nodes where there are loads (Figure 3), considering the number of phases of each node, for example, if there is a single-phase load in a node, the PV system inserted in this location will have only one phase. Additionally, DGs with unit power factor were used, that is, they are capable of supplying only active power. Finally, to verify the adaptability of the methodology, the integration of DG was varied with values from 0% to 150%, with a 5% increase, in relation to the active power demanded by each node.

Furthermore, to apply the power flow algorithm, described in Section II, line sections in the studied radial system were ordered by layers away from the root node (node 1), as it can be seen in Figure 4.

IV. RESULTS AND DISCUSSION

In order to demonstrate the importance of the methodology discussed in this paper, simulink software was used to simulate the same feeder addressed in Section III. In this way, it is possible to compare the operating time of the two methods and the accuracy of the results. It is worth noting that the simulink results were adopted as the reference, since it is a software widely used currently and presents satisfactory results. Besides that, it was used the PV distributed generator model proposed in [14] and [15] applied in simulink to reduce the high computational effort demanded by the original PV Array model present in this software.

Initially, to illustrate the results, the graphs of Figure 5 compare the current values obtained through the BFS algorithm and the simulink software, between the nodes 8-9, and 8-12, for the three phases. It should be highlighted that the choices of these lines were made randomly, and that the other lines presented extremely similar results.

Additionally, the voltage values were also compared in Figure 6. In this case, it was chosen the nodes 4 and 6, for all three phases. Again, the results reached in the other nodes were quite similar to the one which was simulated using simulink.

Figure 3: Feeder with high integration of photovoltaic systems.

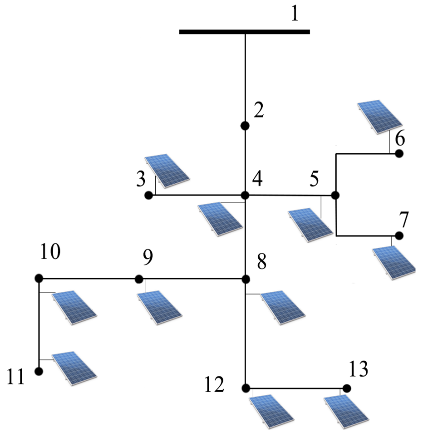


Figure 4: Layer numbering scheme.

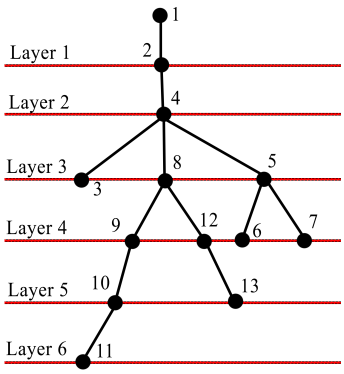


Figure 5: Current values obtained with Simulink and BFS.

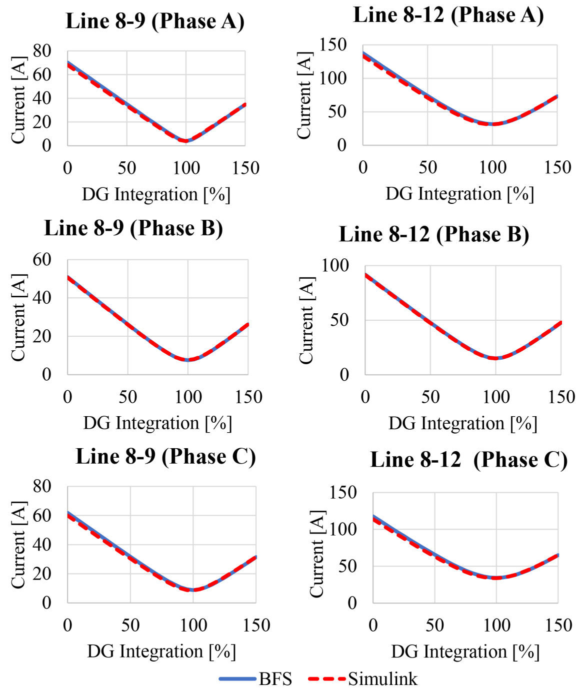
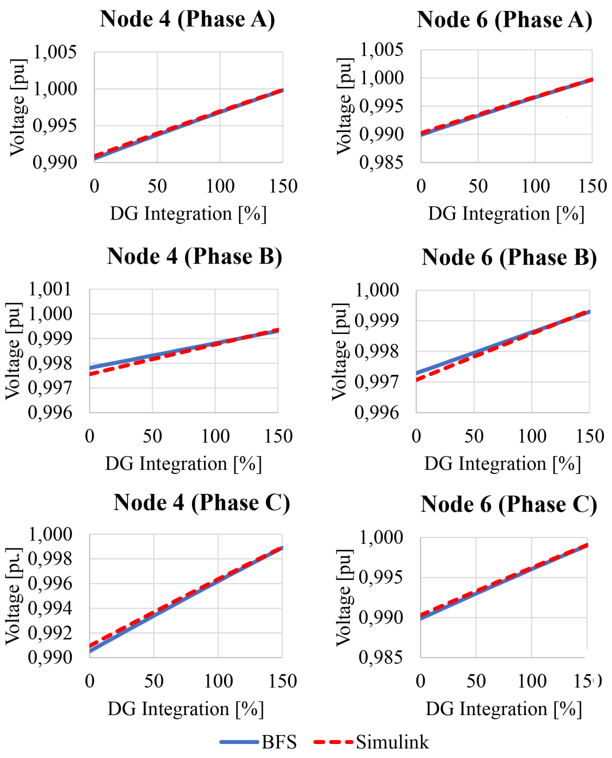
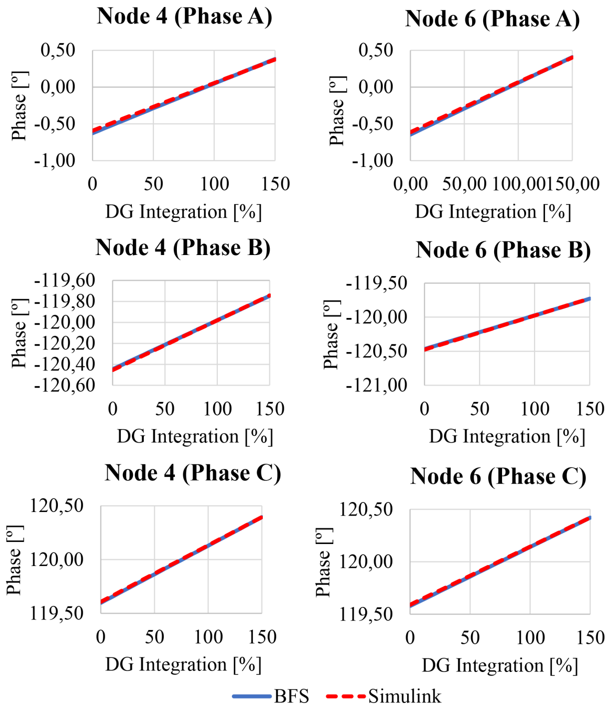


Figure 6: Voltage values obtained with Simulink and BFS.



Finally, the voltage phase values of the nodes 4 and 6 were shown in Figure 7. It is worth noting that the agreement of the curves obtained with simulink and with BFS was repeated for all other nodes.

Figure 7: Voltage phase values obtained with Simulink and BFS.



Analyzing Figures 5, 6 and 7, it is evident that the values obtained through the BFS algorithm approximated considerably of the values reached through the simulink software. This fact remained for all cases of DG integration.

Moreover, as highlighted, the operation time is a fundamental point to be considered when it is necessary to chose a three-phase power flow solution method. Thus, Table 3 shows the operation times for BTS algorithms and simulink software, considering only one case and thirty-one cases. It was used a computer with core i5 processor (2.5 GHz) and 8 GB DDR4 2133 MHz of RAM.

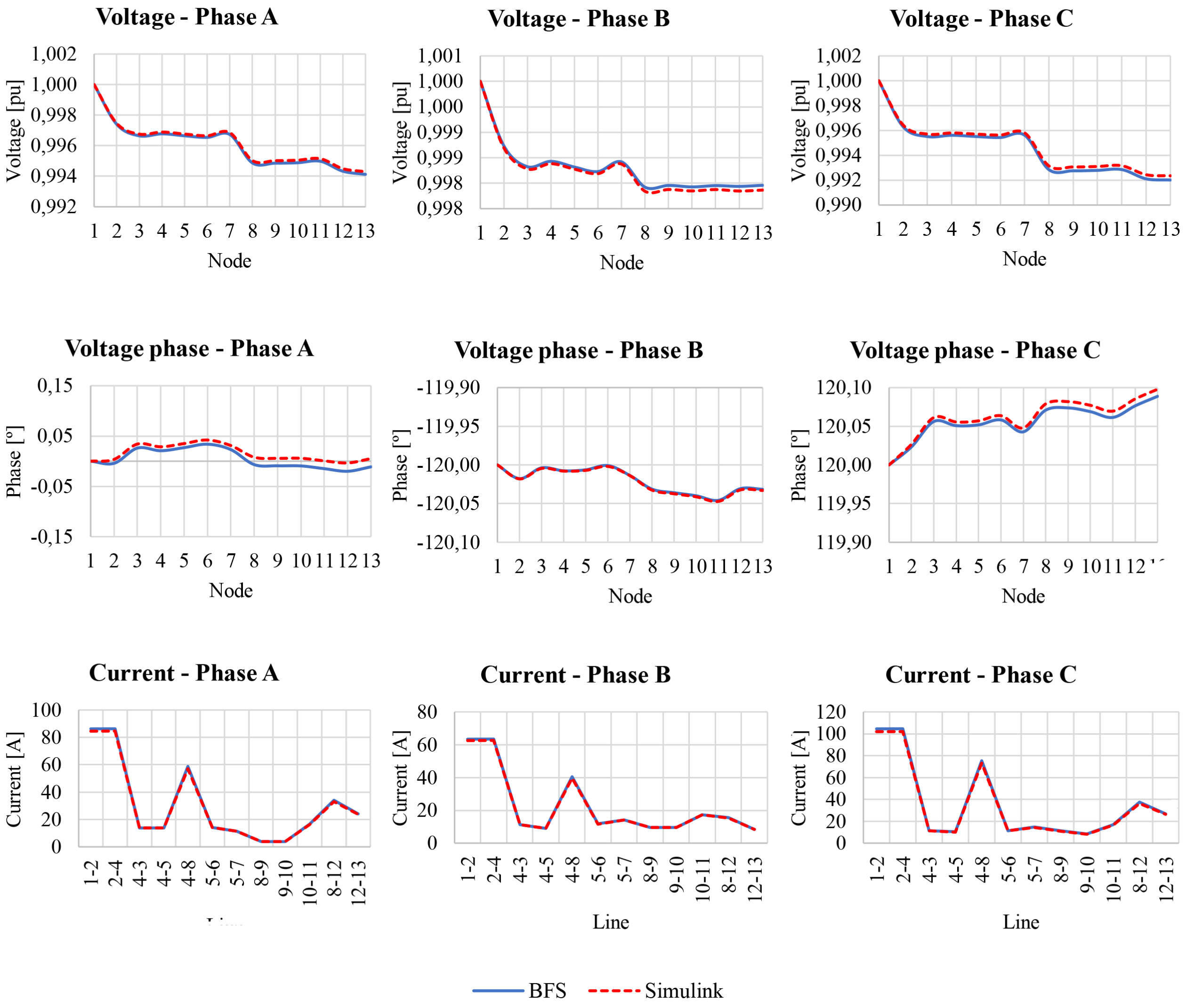
Table 3: Operation time.

Number of cases	Operation Time [s]	
-	BFS	Simulink
1 case	0.062	4.847
31 cases	0.565	134.289

For just one case, the BTS operating time was about 78 times lower than the simulink operating time, while for the thirty-one cases this reduction factor rose to about 237 times. It should be highlighted that this reduction was due to the lower number of variables calculated in the BFS method compared to simulink software.

It is important to evidence that the analyses presented in Figures 5, 6 and 7 considered the same percentage of DG integration for all nodes. However, the methodology approached in this paper is effective in cases where the percentage of DG insertion is not equal for all nodes. So, to illustrate this statement, it was chosen active power values randomly (Table 4) in order to compare the power flow solution from BFS and

Figure 8: Voltage, voltage phase and current values obtained with Simulink and BFS.



simulink software. Then, using the data specified in Table 4, the values of voltage, voltage phase and current was reached from BTS methodology and from simulink, as can be seen in Figure 8.

Table 4: Data related to the DG integration.

Node	DG Active Power [%]		
	A	B	C
1	0	0	0
2	0	0	0
3	99	101	95
4	126	112	108
5	87	89	82
6	125	134	111
7	92	80	71
8	87	78	93
9	0	0	83
10	98	98	104
11	102	78	84
12	83	89	76
13	97	113	101

Analyzing the Figure 8, it is easy to notice the agreement between the reached values, proving the effectiveness of the BFS.

V. CONCLUSION

In this paper it was presented a resolution methodology of three-phase power flow of radial systems, based on BFS, of a distribution system with high DG integration. Analyzing the results, it is evidenced that the BFS solved the power flow problem correctly, when compared to the simulink results.

In addition, the operating time of the BFS in relation to the simulink highlights the importance of this study. This is because, in several engineering problems, it is necessary to perform processes with many iterations, thus solving the power flow several times in the simulink becomes impractical. Besides that, this methodology becomes suitable for real-time applications in distribution automation systems

Finally, it should be noted that in the presented study the DG integration was varied in the same proportions, for example, in the 31th case all nodes with load had 150% of DG. However, it is possible to vary these power freely, since the effectiveness of the results is guaranteed in all cases, as it has been remarked in this paper.

ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) - Brazil - Finance Code 001.

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