New Load Flow Method S-E Oriented For Large Radial Distribution Networks

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Abstract— **There is a growing interest in the electric utilities to raise their efficiency in the operation and design of transmission and distribution of systems. This work proposes a new, fast, robust and efficient method for the Load Flow solution, in balanced and unbalanced radial distribution systems. It is about a sequential method, based on the S−E load flow algorithm devised for transmission networks by Zaborszky in 1981, which has been adapted to distribution systems, orienting the powervoltage (S−E) iterations, to take advantage of the radial condition of the latter and extending it to handle unbalanced three−phase systems. The iterative process consists of progressively concentrating the load plus network losses at each node, starting from the farend ends nodes and moving toward the substation. Secondly, the nodal complex voltages are calculated from the substation toward the demand nodes, carrying on with this relatively simple procedure, till reaching convergence. The effectiveness of the algorithm is shown when comparing it against other methods widely used in the specialized literature. In particular it is tested against methods proposed by Ardvinson, Shirmohammadi, Ghosh and Das, Jovanovic and Cespedes. The here−in proposed methodology represents a valuable tool that substantially improves the state−of−the−art of the load flow.**

Index Terms — **Distribution System, Load Flow, S-E Oriented (Power and Voltage Oriented), Radial System.**

I. INTRODUCTION

Nowadays, with the opening of the electrical sector and its structural new divided on energy product and energy services, it made appear the needing have to developed competence among the businesses in the generation, transmission and especially distribution of electricity. Therefore, to each day is necessary to know quickly the load behavior and consequently the electrical parameters of the networks. In order to reach these objectives is required to know the state of the network, for all operation interval time. Thus, the businesses can employ the electric rate as a key factor in the load management, that is to say, penalizing with a greater rate to those consumers that they make use of the energy in hours of maximum demand, contributing to the overload of the network, and the entrance of inefficient generating plants in the system [38].

This work has been supported in part by Fundação para a Ciência e a Tecnologia Grant SFRH/ BPD/ 21035/ 2004. [1]

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Inside an open market to the competence are presented to the different businesses the need to implement actions oriented the optimization of electric networks in search of minimum costs of operation guaranteeing adequate service with quality levels [15]. In order to achieve an optimization level of the networks is required the implementation of certain process, so much technical as well as organizing, whose prior step should be that of know the present state of the network in stationary state. It given this growing interest that exists currently among the electric utilities to enlarge its efficacy in the operation and distribution of the electric power, takes special attention the load flow solution of the distribution networks [22] [42].
The load flow to become possible to determine the conditions of stationary state of a power system for a specific generation and demand level [12]. The fundamental task of a load flow algorithm is to obtain the voltages in the bus and the power flows by the lines since the knowledge of the network topology, parameters such as impedances, loads and sources (generation) [38].

Several works have been developed in the load flows research area to distribution networks with different approaches of algorithms solutions and that verifying difficulties when apply on real dimensions systems and normally consumes high time and computational effort. On the other hand these algorithms do not permit to consider one of the main characteristics of the distribution networks like the unbalance existing among the phases. Therefore, it is necessary to carry out efforts to develop new algorithms that improve the actual methods [25].

The classic algorithms of Newton Raphson and Gauss-Seidel have been the base of the generic methods for the load flow solution, especially in transmission networks [5] [6] [10] [21] [26]. Nevertheless, according to the specialists their application in the case of the distribution networks has not been very efficient due mainly to the characteristics networks to be generally of radial structure and to present a high relation (R/X) of lines, when we are making a comparison with the transmission networks [12] [14] [16] [17] [30]. Different research has suggested methods for the solution of loads flow to distribution networks with a high relation R/X [27] [28] [29] [41] [42]. In fact, it has carried to development of algorithms specialized for distribution networks and with characteristics of the greater simplicity has been obtained efficiency in the solution of load flow problem for the Distribution Systems [17].

There are several efficient methods published recently [7] [12] [14] [17] [23] [42]. They are iterative methods, some them need the most computing time, requires evaluating the complex matrix, and in some cases don't insure convergence.

In this paper, is presented a fast and simple method for solving radial single-phase and three-phase distribution networks called S-E Oriented Method. This is a sequential method that uses only two calculation steps. The proposed algorithm can be easily programmed based upon a simple formulation.

II. The Proposed Methodology

The proposed methodology for the solution of the load flow problem in distribution networks, is based on the load flow algorithm S-E oriented for transmission networks, proposed by Zaborszky in 1981 [39], which was adapted to distribution systems orienting the iterations power-tension (S-E), to take advantage of the radial characteristics of these and extended for applied to unbalanced three phase distribution systems.

The proposed method S-E graph oriented for the solution of the load flow problem in distribution networks, consists of a sequential method in which proceeds to determine in a first step the losses in the branches and the active and reactive power equivalent in the same one, supposing in the first iteration known values for the tensions in the nodes (= 1 PU).
In the second step proceeds to calculate the nodes tensions (module and angle), assuming as you known the values of power calculated in the first step. Then it proceeds to repeat the first step, but in this second iteration proceeds to calculate the losses assuming the tensions calculated in the second step of the first iteration until comply the convergence criterion.

A. *Representation of the network*

One of the characteristics of the proposed algorithm is the fact that does not require of a numbering of nodes and branches by layers. For this algorithm the nodes and the branches can be numbered without a predetermined order, characteristic that does it more flexible and strong.
In the revised algorithms in the literature the numbering of the nodes and branches should be performed for layers, in a similar way of the model proposed by Shirmohammadi [32], being had that renumbering the nodes and the branches in the systems whose dates not possess this structure.

B. *Proposed Algorithm for three phase balanced systems*

For the solution of the load flow problem in three phase balanced distribution networks, an algorithm be planted utilizing the single phase equivalent of the network. For each iteration of the methodology, is carried out the calculation of the equivalent power and losses, concentrated on each branch, tension is assumed 1 p.u. in all the buses of the system in the first iteration. After concentrating the power in each bus, the algorithm proceeds to calculation of the currents and voltages in each node, leaving from the power calculated in the first step.

The calculation of the power concentrated on each branch, is carried out from the following equations:

$$P_{Ei} = P_{Loadi} + P_{Lossi} + P_{ECi} \tag{1}$$

$$Q_{Ei} = Q_{Loadi} + Q_{Lossi} + Q_{ECi} \tag{2}$$

The losses in each branch are calculated through the following equations:

$$P_{Lossi} = \left(\frac{S_i}{V_{oi}}\right)^2 .R_{Li}\,, i = n, n-1, ...\ 1 \tag{3}$$

$$Q_{Lossi} = \left(\frac{S_i}{V_{oi}}\right)^2 .X_{Li}\,, i = n, n-1, ...\ 1 \tag{4}$$

Where,
P_{ECi}, Q_{ECi} : Are the equivalent active and reactive load of the branches fed by the branch i.
P_{Lossi}, Q_{Lossi} : Active and Reactive losses of the branches fed by the branch i.
P_{Loadi}, Q_{Loadi} : Active and Reactive load at the node i.
S_i : Apparent power at the node i.
V_{0i} : Voltage of the node i in the first iteration.
R_{Li} : Resistance of the branch i.
X_{Li} : Reactance of the branch i.
n : Number of the branches.

At each iteration of the algorithm totals all the losses of the system and the power that should be supplied by the source. The total losses and the load of the source are calculated by the following equations:

$$P_T = \sum P_{lossi} + \sum P_{ECi} \tag{5}$$

$$Q_T = \sum Q_{lossi} + \sum Q_{ECi} \tag{6}$$

Once known the concentrated power on the receiver extreme of each branch, the branch currents and the nodal tensions are calculated through the following equations:

$$I_i = \left[\frac{P_{Ei} + J.Q_{Ei}}{V_{Ei}}\right]^* \tag{7}$$

$$V_{Ri} = V_{Ei} - I_i.(R_i + J.X_i) \tag{8}$$

V_{Ei} : Voltage of the source node of the Branch i.
V_{Ri} : Voltage of the load node of the branch i.

These calculations are carried out successively until the convergence criterion is comply, that is, that the difference in voltage between the previous iteration and the present one be smaller to a certain defined value, for each nodes.

The S-E oriented Method is applied to single-phase and three-phase radial balanced and unbalanced networks.

C. *Assumptions*

The substation Voltage (V_0), Load Demand at bus i ($S_i = P_i + j.Q_i$), and impedances of distribution lines ($Z_i = R_i + j.X_i$) are specified. The systems can represent by their equivalent single line diagram.
The network is simulated in the program by means of nodes (load concentration in a point of the network) and branches (section of conductor between two nodes). The nodes and branches numbering is the same suggested by Shirmohammadi [6].

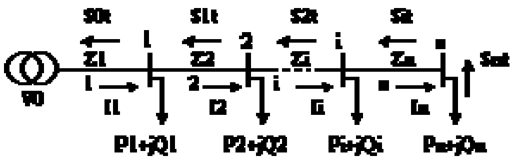

Fig. 1: Single Line Diagram

D. Algorithm Solution

The substation Voltage V_0, Load Demand at bus i $S_i = P_i + j.Q_i$,

Considering the distribution network of the Figure 1:

Step1: Losses and equivalent Power Calculation

The branches current used in the step 1 are calculated considering the nodes voltage equal to the substation voltage. The power losses are calculated from the last branches towards the source:

$$\Delta Sit = Ii^2 Rn + jIi^2 Xn \quad (9)$$

$$\Delta S2t = I2^2 Ri + jI2^2 Xi \quad (10)$$

$$\Delta S1t = I1^2 R2 + jI1^2 X2 \quad (11)$$

$$\Delta S0t = I0^2 R1 + jI0^2 X1 \quad (12)$$

The equivalent power is calculated as:

$$Snt = Pn + jQn \quad (13)$$

$$Sit = \Delta Sit + Pn + jQn \quad (14)$$

$$S2t = \Delta S2t + Pi + jQi + Pn + jQn \quad (15)$$

$$S1t = \Delta S1t + P2 + jQ2 + Pi + jQi + Pn + jQn \quad (16)$$

$$Snt = \Delta S0t + P'1 + jQ1 + P2 + jQ2 + Pi + jQi + Pn + jQn \quad (17)$$

Step 2: Voltage Magnitudes

The branches current used in the step 2 are calculated considering the equivalent power obtained from step 1.The voltage magnitudes are calculated from the source towards the last branches:

$$V1 = V0 - (I1R1 + jI1X1) \quad (18)$$

$$V2 = V1 - (I2R2 + jI2X2) \quad (19)$$

$$Vi = V2 - (IiRi + jIiXi) \quad (20)$$

$$Vn = Vi - (InRn + jInXn) \quad (21)$$

Where,

ΔSit : Power loss injection at node i.

Sit : Power injection at node i.

Si : Load Demand at bus i.

Ii : Branch current that flow through branch i.

Zi : Impedance of branch i.

Step 3: New losses calculations for new voltage value

In this step the new branches current are calculated considering the nodes voltage calculated in the step 2. The new losses power is calculated equal the step 1, but in this case using the calculated voltage in the step 2.

Step 4: Calculations of new voltage magnitudes

Repeat the step 2 using the new values calculated.

This process is repeated until the convergence is comply or the $V^k - V^{k+1} \leq \varepsilon$.

The Flowchart of the proposed method is given in Fig. 3.

III. Testing

A. Case N° 1: 28-bus test Distribution network

Real system of 11 kV and a power base of 100 kVA, whose single phase diagram is shown in the fig.2 and the data, are shown in the Table I.

Five existing load Flow algorithms of the literature were selected, which will be employees like the boss of comparison to validate the proposed method. The advantages were studied and comparative disadvantages of the methods exposed previously, taking into account the experiences reported by the specialists in the literature.

The chosen algorithms are: the method proposed by Shirmohammadi [32], Ardvinson [38], Ghosh and Das [17], Jovanovic [23] and Céspedes [7]. These methods were selected as methods of reference for comparison effects of the behavior by the following reasons:

- In the determined cases of radial distribution networks, the algorithms of Gauss-Seidel and Newton Raphson not convergence is guaranteed.
- With the Gauss-Seidel algorithm is required of greater iterations number and computation time to arrive at the solution that with other algorithms.
- The algorithms of Ardvinson, Ghosh and Das, Shirmohammadi, Jovanovic and Céspedes present good convergence rapidity, simplicity in calculations and facility of programming, when they apply to balanced radial three phase distribution networks.
- They are very efficient methods and they do not require carrying out complex operations with Matrix, facilitating the programming and the time of execution, except for the method proposed by Jovanovic that requires working with Matrix.

These five methods and the proposed in the present work, they were programmed in a same platform in Matlab and test in the solution of five different magnitudes distribution systems, 12 nodes [43], 23 nodes [13], 28 nodes [28], 69 nodes [2] [3] and 201 nodes [4], whose results are found reported in the literature. The results obtained for each one of the studied systems; also they were validated with a commercial program.

To demonstrate the effectiveness of the proposed algorithm, was compared with other algorithms of the specialized literature, the method proposed by Ardvinson [38], Shirmohammadi [32], Ghosh and Das [17], Jovanovic [23] and Céspedes [7], these methods are planned utilizing the same platform of programming and evaluated with the same criterion of convergence. In this phase the behavior of the algorithms was evaluated for five systems taken of literature verifying number of iterations and time of execution for each one of the methodologies. The criterion of convergence utilized corresponds to a ε = 0.0001 p.u. All information regarding of iteration number and executing time are shown in the Fig. 4 and 5.

In the Table III, is observed that the five methodologies give similar results, presenting a variation in the quarter decimal, the methodologies of Jovanovic and Ardvinson alone for the farthest bus away of the substation.

The Fig. 4 and Fig. 5, sample a summary of the iterations number and the execution time for each algorithm to be tested with the 28 nodes system.

It is observed in the Table III, the six methodologies are converged with equal iterations number and the proposed methodology presented the solution in smaller time.

TABLE I
DATA OF 28-NODE DISTRIBUTION NETWORK

Send Bus	End Bus	R (Ω)	X (Ω)	P (kW)	Q (kVAr)
1	2	0.12648	0.05263	140	90
2	3	0.15463	0.06579	80	50
3	4	0.09486	0.03947	80	60
4	5	0.06374	0.02632	100	60
5	6	0.25296	0.10526	80	50
6	7	0.18972	0.07895	90	40
7	8	0.10119	0.04211	90	40
8	9	0.18972	0.07895	80	50
9	10	0.25296	0.10526	90	50
10	11	0.19108	0.05402	80	50
11	12	0.09554	0.02701	80	40
12	13	0.28663	0.08103	90	50
13	14	0.28663	0.05942	70	40
14	15	0.21019	0.05402	70	40
15	16	0.19108	0.08103	70	40
16	17	0.28663	0.05402	60	30
17	18	0.19108	0.05402	60	30
2	19	0.23886	0.06753	70	40
19	20	0.09554	0.02701	50	30
20	21	0.19108	0.05402	50	30
21	22	0.34395	0.09724	40	20
3	23	0.37339	0.07023	50	30
23	24	0.21019	0.05942	50	20
24	25	0.38217	0.10804	60	30
6	26	0.19108	0.05402	40	20
26	27	0.09554	0.02701	40	20
27	28	0.09554	0.02701	40	20

TABLE II
REAL AND REACTIVE POWER LOSSES

Algorithm	Iterations Number	Execution Time (Sec.)
Ghosh and Das	2	0.22
Shirmohammadi	2	0.28
Céspesdes	2	0.49
Jovanovic	2	0.44
Ardvinson	2	0.6
Proposed Method	2	0.19

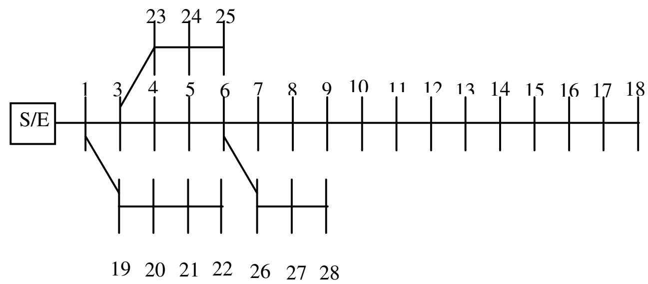

Fig.2. 28-Bus single phase diagram

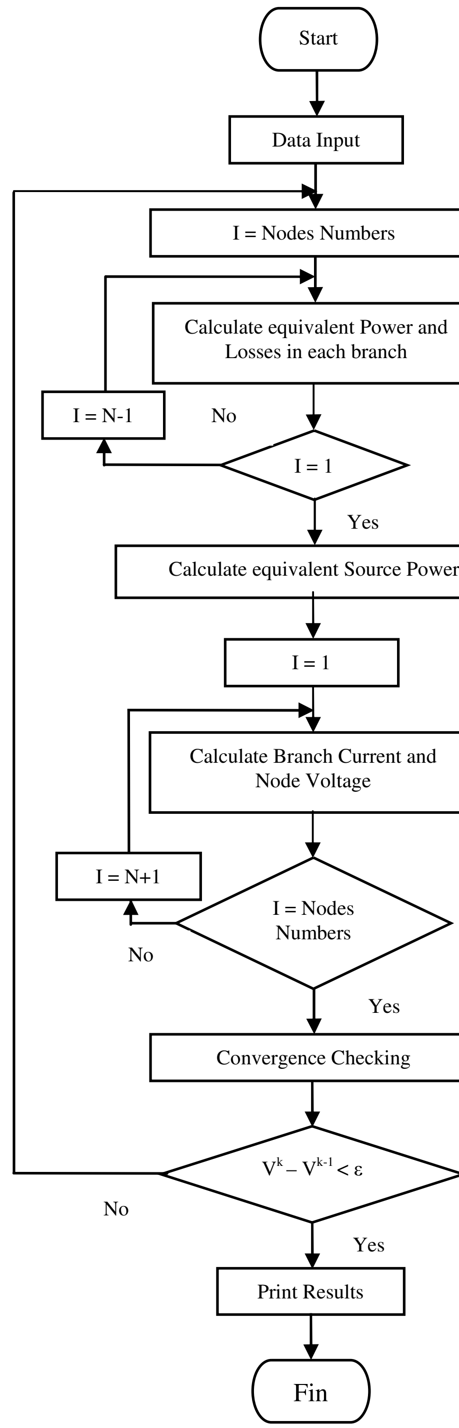

Fig. 3: Flowchart for load flow algorithm

TABLE III
VOLTAGE NODES WITH THE DIFFERENT METHODOLOGY

Node	Ghosh and Das	Céspedes	Shirmohammadi	Jovanovic	Ardvinson	Proposed Methodology
1	1.0	1.0	1.0	1.0	1.0	1.0
2	0.9998	0.9998	0.9998	0.9998	0.9997	0.9998
3	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995
4	0.9994	0.9994	0.9994	0.9993	0.9993	0.9994
5	0.9993	0.9993	0.9993	0.9992	0.9992	0.9993
6	0.9990	0.9990	0.9990	0.9989	0.9989	0.9990
7	0.9988	0.9988	0.9988	0.9986	0.9987	0.9988
8	0.9987	0.9987	0.9987	0.9986	0.9986	0.9987
9	0.9986	0.9986	0.9986	0.9985	0.9985	0.9986
10	0.9984	0.9984	0.9984	0.9983	0.9983	0.9984
11	0.9983	0.9983	0.9983	0.9982	0.9982	0.9983
12	0.9983	0.9983	0.9983	0.9981	0.9981	0.9982
13	0.9981	0.9981	0.9981	0.9980	0.9980	0.9981
14	0.9980	0.9980	0.9980	0.9979	0.9979	0.9980
15	0.9980	0.9980	0.9980	0.9979	0.9979	0.9980
16	0.9980	0.9980	0.9980	0.9978	0.9978	0.9980
17	0.9979	0.9979	0.9979	0.9978	0.9978	0.9979
18	0.9979	0.9979	0.9979	0.9978	0.9978	0.9979
19	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997
20	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997
21	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997
22	0.9997	0.9997	0.9997	0.9996	0.9996	0.9997
23	0.9994	0.9995	0.9994	0.9994	0.9994	0.9994
24	0.9994	0.9994	0.9994	0.9994	0.9994	0.9994
25	0.9994	0.9994	0.9994	0.9994	0.9994	0.9994
26	0.9990	0.9990	0.9990	0.9989	0.9989	0.9990
27	0.9990	0.9990	0.9990	0.9989	0.9989	0.9990
28	0.9990	0.9990	0.9990	0.9989	0.9989	0.9990

IV. CONCLUSION

This work presented a new methodology for the solution of the load flow in radial distribution networks, which turned out to be powerful, fast and efficient, as well as a simple formulation and easy to programming. As before mentioned this method was tested with five different distribution systems, 12-buses, 23-buses, 28-buses, 69-buses and 201-buses commonly used in the technical literature.

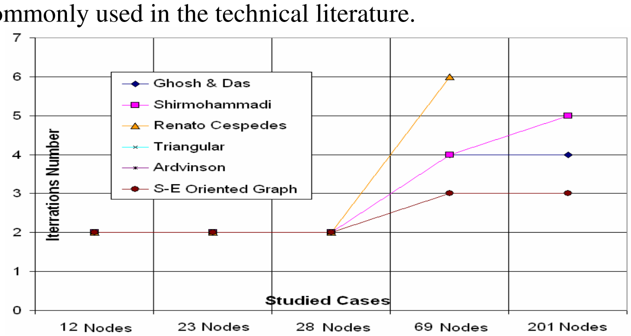

Fig. 4: Iterations Number for the five studied cases

The obtained results were equal to them reported by the authors of the works of which they were extracted the systems of test, and besides they were validated with a commercial program [43] to resolve load flows in distribution systems.

The proposed methodology always converged al turned out expected, in a smaller time that the other methodologies, to a 50% smaller, and in a smaller number of iterations.

These affirmations were more notable for the cases of greater dimension, 69 nodes and 201 nodes, in which there were algorithms that did not converge, being concluded that the proposed methodology can be utilized to solve the load flow problem in large distribution systems and that consumes small computational time and small iterations number.

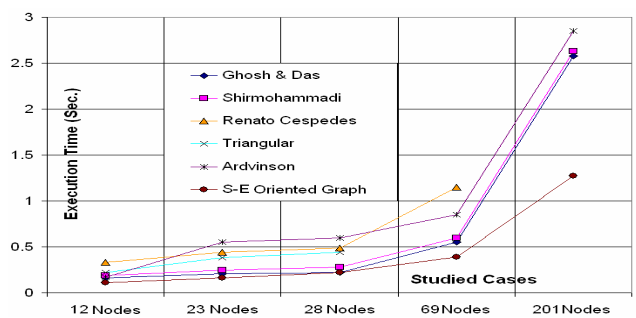

Fig. 5: Execution Time for the five studied cases

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