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Smart meters measurements data for North African distribution networks analysis with the presence of distributed generation

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Abstract— **This paper presents an analytical method to state estimation of medium and low voltage distribution networks in North Africa, by using smart meters measurements information. The main aim of this paper is to provide electrical characteristics of all distribution network nodes based on the active and reactive power values measured at each network busbars by digital meters. The present analysis method is performed by an algorithm that explore the particular of radial networks characteristics, the exiting of unique road from any network node to the reference node, with the development of two matrices bus injection to bus current (BIBC) and branch current to bus voltage (BCBV) with an improvement in ensuring an automatic updating of the BIBC and BCBV with the change in the topology structure, which will allow getting a flexible load flow method with network configuration, such algorithm are useful to avoid storing or factorizing any matrix which is costly in time and manipulations. Based on the exploration of the network tree structure to calculate the desired variables, the proposed analytical tool is able to facilate the integration of distributed generation into distribution systems in North Africa, with the use of systems currently existing, to allow a harmonic mutation with a lower cost, from the conventional network, to a Smart Grid..**

***Keywords*— Smart meters measurements, network analysis, power summation method, Backward/forward sweep method, radial distribution networks, smart grid.**

I. INTRODUCTION

Power flow is an important tool used in transmission network for power generating planning, the most important load flow methods existing in transmission system are: Gauss-Siedel method, Newton-Raphson method and Fast Decoupled method, for an optimum scheduling between generation plant and exchange of power.

With the introduction of distributed generating into the conventional distribution system in North African countries, and a future mutation to a new active distribution networks, more intelligence should be introduced into the distribution grid, and more of tools for voltage control, demand side management and distribution managements systems should be adopted, those tools are based in the presence of a strong method of a network analysis.

North African distribution grids are strongly radial with complex topology configurations that can be changed for several reasons, and with large number of nodes and branches. Due to the high R/X rations, transmission grid load flow methods are failed with such networks [1][2], even though with some advancements in the Newton-Raphson methods, the robustness of the program is obtained but still the computational time is large [3][4].

The difference between load flow analysis in distribution and transmission networks have been revealed in a number of papers, where the classic transmission methods were not appropriate to solve practical problems presented when analyzing distribution systems [5] [6].

Several works had been presented in the scientific literature, the methods used can be divided into two principals categories: Methods based on the amelioration and adaptation of transmission methods such as fast-decoupled, and others are based on power summation method.

The main aim of this paper is to develop a tool able to analysis distribution networks in North Africa, and provides electrical characteristics of all networks nodes, with the use of only existing information, provided by the smart meters measurements, The proposed method is evaluated on IEEE 15-bus, which presents several similarities as distribution networks in North Africa.

In what follows, we present an overview of the medium and voltage distribution network in North Africa in section II. Next in Section III we provide the theoretical foundation of power summation methods, In section IV we present the information provided by smart meters measurements and how they can used into a power flow analysis, in section V we discuss the results obtained from a 15-bus test system. Section VII concludes this paper.

II. DISTRIBUTION NETWORKS IN NORTH AFRICA

The medium and low voltage distribution systems are made of 3 phases, with neutral grounded in the HV/MV substation for Medium network and a distributed neutral in low voltage distribution system.

In medium voltage distribution system three forms of networks can be distinguished: overhead lines, underground cables and a combination of overhead and undergrounded cables.

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The underground networks are made of three single-phase cables. Ring configuration is the most used topology used, where cables that starts at a distribution substation, runs through or around an area serving one or more distribution transformers or load centre, and returns to the same substation.

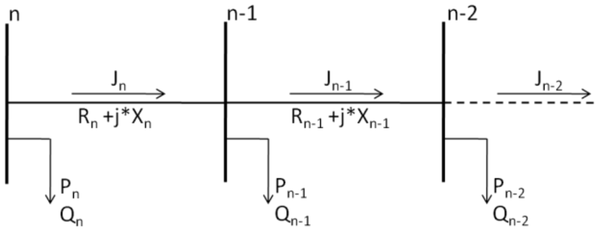


Fig 1: Single line diagram of the open-loop topology

The overhead networks are made of 3 bares conductors, network tree structure is the most used topology, from a main-line, derivations are made to deserve MV consumers and MV/LV substations on Figure2.

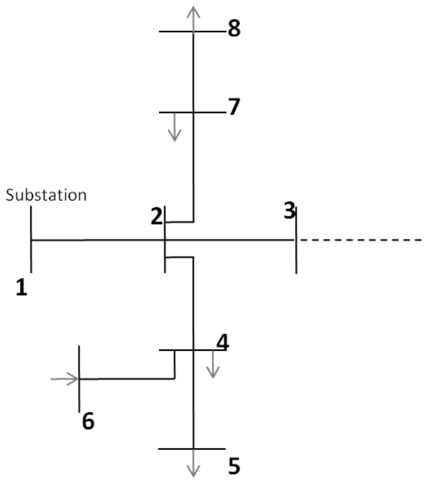


Fig 2: Overhead distribution system structure

In low voltage distribution system also three forms of networks can be distinguished: overhead lines placed on steel or wooden poles or attached to the facade of buildings, underground cables and a combination of overhead and undergrounded cables.

The underground networks are made of four insulated cables. Ring configuration also is the most used topology used, where cables that starts at a MV/LV distribution substation, runs through several LV boxes, and returns to the same substation.

The overhead networks are made of 4 twited conductors, network tree structure is the most used topology, from a main-line, and derivations are made to deserve LV consumers.

According to these several forms of distribution systems, it's to separate three types of busbars: Terminal busbar, common busbar, and intermediate busbar.

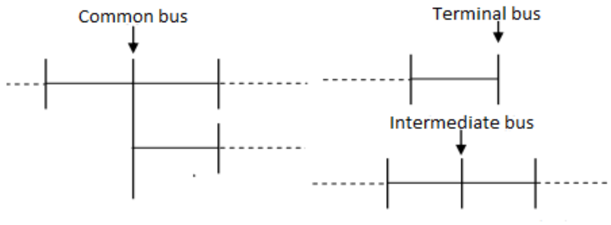


Fig 3: Types of busbars

III. POWER SUMMATION METHOD

The most used power flow methods are: Gauss-Siedel method, Newton-Raphson method and Fast Decoupled method [7].

The first step in performing those load flow analysis is the construction of the Y-bus admittance matrix using the transmission line and transformer input data.

The Gauss-Seidel load flow uses an iterative method based on Gauss equation, the Newton-Raphson is based on the expanding in Taylor's series about the initial estimate the active and reactive power formulation, the terms are limited to the first approximation of the equations. The Fast Decoupled Power Flow Method is one of the improved methods, which is based on a simplification of the Newton-Raphson method, the convergence is geometric.

A common procedure of the three methods, adopted for analysing power flow in a power system is discussed in the pseudo-code shown in Fig.4 [8].

```
# Start
# Construction of the $Y_{bus}$ Matrix
# Make an estimate of the voltage plan
# Substitute the old values into power equations for the next iteration
# Obtain the new value
# compare the new value with Old value
# If (New value – Old value) < specified tolerance; then end otherwise go to step 4.
```

Fig 1: Pseudo-code procedure for analyzing load flow in a power system

But distribution system in North Africa are characterized by a high R/X rations and a strongly radial structure, which leads to ill-conditioned matrices and poor convergence characteristics of those load flow methods.

The problems have been revealed in a number of papers, where the classic transmission methods were not appropriate to solve practical problems presented when analysing distribution systems [6].

Several works had been presented in the scientific literature; the methods used can be divided into two principal categories: Methods based on the amelioration and adaptation of transmission methods such as fast-decoupled, and others are based on power summation method.

In what follow we constrate on the devellopement based on the power summation and the exploration of the radial structure of distribution network in North Africa.

The power summation method may be described in the following steps [9]:

Calculate the current injection at each busbar x using Eq 1:

$$I_x^{(k)} = \left(S_x / V_x^{(k)} \right)^* \quad x = 1,2,\dots,n \qquad (1)$$

Where Si is the power injection at node i, V(k)I is the voltage of node i calculated from iteration k.

- Start from an estimate of the voltage plan: 1 p.u.
- Go from the last busbar of each branch to the HV/MV substation busbar of each branch (backward path), use the estimated voltage values to estimate the branch current : Starting from the last ordered branch, with a direct application of Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) [10], current Jx,x+1 in branch from the node x to the node "x+1" is calculated using Eq 2:

$$J_{x,x+1}^{(k)} = -I_x + \sum J_x \qquad (2)$$

Where Ix is the current injection of node i calculated from step1, $\sum J_x$ are the currents in branches emanating from node "x".

- Go from the leaves to the HV/MV substation busbar to the last busbar of each branch (Forward path), use the branch current values to evaluate a new voltage magnitude using equ3:

$$V_x^{(k)} = V_{x-1}^{(k)} - Z_x J_x^{(k)} \quad , x = 2,3 \dots, n \qquad (3)$$

Where Z_x is the series impedance of branch 'x-1,x"

- Go back to step3.

The algorithms converge when all voltage magnitudes calculated in present iteration and previous iteration remain between a pre-established tolerance.

$$\max([V^{(k+1)}] - [V^{(k)}]) < \varepsilon \qquad (4)$$

Advantages of the power summation method: based on the exploration of the network tree structure to calculate the desired variables, it is not necessary, as newton-raphson or Fact Decoupled algorithms, to store and factorize any matrix.

The power summation method needs two principal informations:

- The active and reactive power of each network node, which can be provided by digital meter, and be collected by the smart metering infrastructure.
- Electrical characteristics between the sending and the receiving node of each branchs, which can be provided by the technical characteristics of each cables and lines used, the topology modification can be detected by the medium voltage remote control or manually by the operator who applied the modification.

IV. ALGORITHM DEVELOPMENT

Let's take a simple radial network as shown in fig-5 to illustrate the methodology chosen to develop a network analysis method adapted to Medium and low voltage distribution in North Africa.

Current injections and relationship between the bus current injections and branch current can be obtained by applying Kirchhoff's current law (KCL) to the distribution network. The branch currents can then be formulated as functions of equivalent current injections.

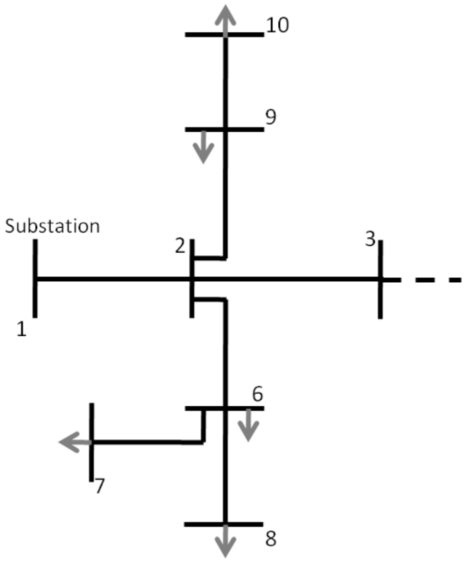


Fig 5: Single line diagram of the proposed distribution network

For example the currents branch 1; 2; 3 and x can be expressed as:

$$J_{x,x+1}^{(k)} = I_x + \sum J_x \qquad (5.1)$$

$$J_1 = I_2 + I_3 + I_4 + I_5 + I_6 + I_7 \qquad (5.2)$$

$$J_3 = I_5 + I_6 \qquad (5.3)$$

$$J_5 = I_6 \qquad (5.4)$$

Therefore the relationship between the branch current and injections or consumptions currents can be expressed as:

$$\begin{bmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \\ J_6 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \end{bmatrix} \qquad (6.1)$$

$$[J] = [BIBC] \times [I] \qquad (6.2)$$

The voltage magnitude of each node can be obtained as follows:

$$V_2 = V_1 - J_1 Z_{12} \qquad (7.1)$$

$$V_3 = V_2 - J_2 Z_{23} \qquad (7.2)$$

$$V_7 = V_2 - J_6 Z_{26} \qquad (7.3)$$

Zxy are the line impedance between node x and node y. From the equations (6) and (7), we can obtain:

$$V_7 = V_1 - J_1Z_{12} - J_2Z_{23} - J_6Z_{26} \qquad (8)$$

The equation (8) shows that the voltage magnitude of each node can be expressed as a function of injections or consumptions currents, line parameters and the root busbar voltage. therefore the relationship between branch currents and bus voltages can be expressed as:

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0_{00} & 0_{00} & 0_{00} & 0_{00} & 0_{00} \\ Z_{12} & Z_{23} & 0_{00} & 0_{00} & 0_{00} & 0_{00} \\ Z_{12} & 0_{00} & Z_{34} & 0_{00} & 0_{00} & 0_{00} \\ Z_{12} & 0_{00} & Z_{34} & Z_{45} & 0_{00} & 0_{00} \\ Z_{12} & 0_{00} & Z_{34} & 0_{00} & Z_{56} & 0_{00} \\ Z_{12} & 0_{00} & 0_{00} & 0_{00} & 0_{00} & Z_{67} \end{bmatrix} \begin{bmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \\ J_6 \end{bmatrix}$$

$$[\Delta V] = [BCBV] \times [J] \qquad (9.2)$$

The two matrices BIBC and BCBV depend on the topological structure of the network. Combining equation (6.2) and (9.2), the relationship between injections or consumptions current injections and bus voltages magnitudes can be expressed as:

$$[\Delta \mathrm{V}] = [\mathrm{BCBV}][\mathrm{BIBC}][\mathrm{I}] = [\mathrm{DLF}][\mathrm{I}] \qquad (10)$$

DLF is a multiplication matrix of BCBV and BIBC matrices

After preparing the BIBC and BCBV matrices, the voltages of all nodes are set to the nominal voltage “1p.u”, as an initial value, an iterative procedure based start:

After the calculation of a $[V^{(k)}]$

The new value of current injection is calculated by :

$$I_i^{(k)} = \left(S_i / V_i^{(k)} \right)^* \qquad (11)$$

The $\Delta V^{(k+1)}$ is:

$$\left[\Delta V^{(k+1)}\right] = [\mathrm{DLF}] \times \left[I^{(k)}\right] \qquad (12)$$

And the new value of voltage is obtained by equ 13

$$\left[V^{(k+1)}\right] = \left[V^0\right] + \left[\Delta V^{(k+1)}\right] \qquad (13)$$

These two steps of computing the current injection, and updating voltage value are repeated until voltage magnitudes at each node in present iteration and previous iteration is lower than a tolerance limit ε.

$$\max\left(\left[V^{(k+1)}\right] - \left[V^{(k)}\right]\right) < \varepsilon \qquad (14)$$

The flow chart of the proposed method is given in fig 6.

V. SMART METER MEASUREMENT DATA AND NETWORK ANALYSIS

The needed information for power summation method can be provided by digital meter installed at consumers, utilities should equip the public busbar with digital meter to provide the active and reactive of all the network nodes.

Those measurements could be collected by an advanced meter infrastructure, already exiting in several medium

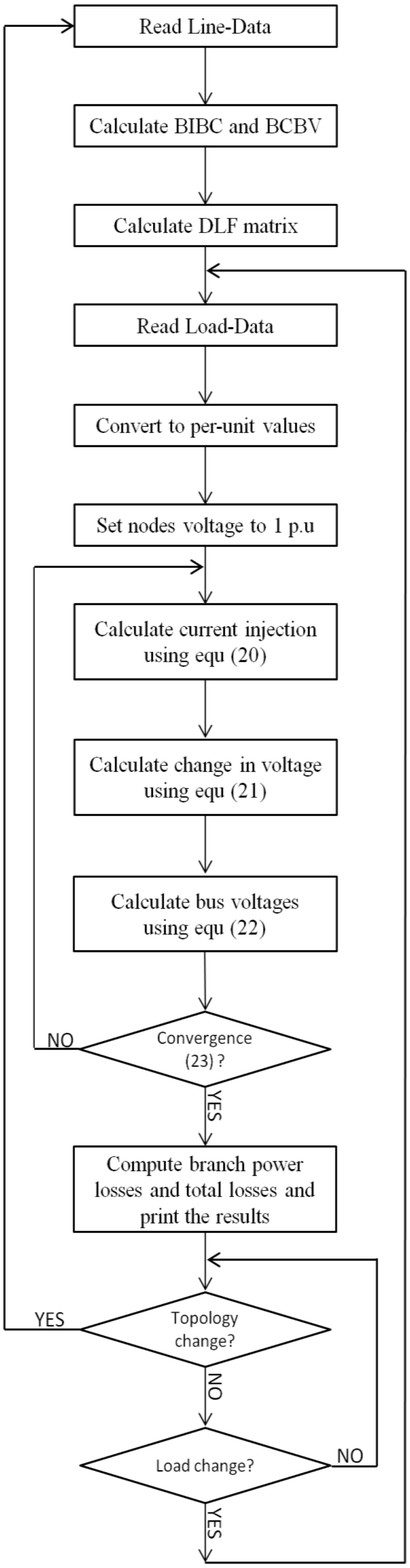


Fig 6: Flow chart of the proposed method

voltage networks in North Africa, and reassembled in a Load-Data table:

TABLE 1: LOAD-DATA TABLE

Node	KVA	KVAr
...	...	...
...	...	...
...	...	...

From a table with all electrical characteristics of each network branch, and table with active and reactive power injected and consumed of each network nodes.

TABLE 2: Line-Data table

Sending node	Receiving node	R (Ohm)	X (Ohm)
...	...	...	...
...	...	...	...
...	...	...	...

By using the proposed scheme, shown in figure 4, and the algorithm developed in section VI, all electrical network characteristics could be provided, as shown in fig 8.

VI. SIMULATION RESULTS

The proposed method program code is made in MATLBAB and tested on the medium voltage radial distribution IEEE 15-bus network, which presents a similar structure as North African distribution networks, the single line diagram of the IEEE 15-bus is presented in fig 7. the Load Data is given in table n°3 and the Line Data is presented in table n°4, the power factor of load is assumed to be 0.7 [11].

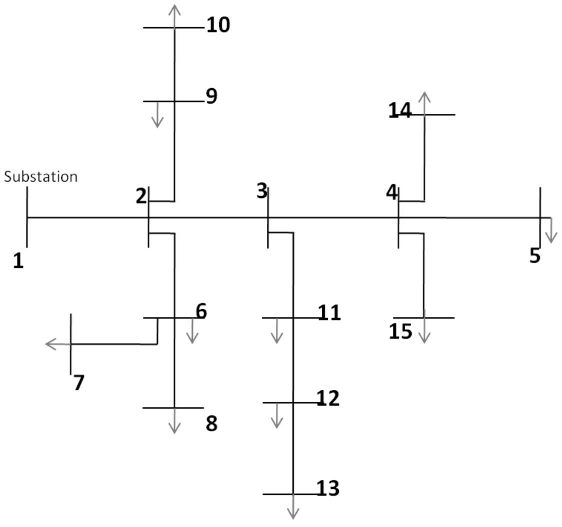


Fig 7 Single phase diagram of 15-bus distribution system

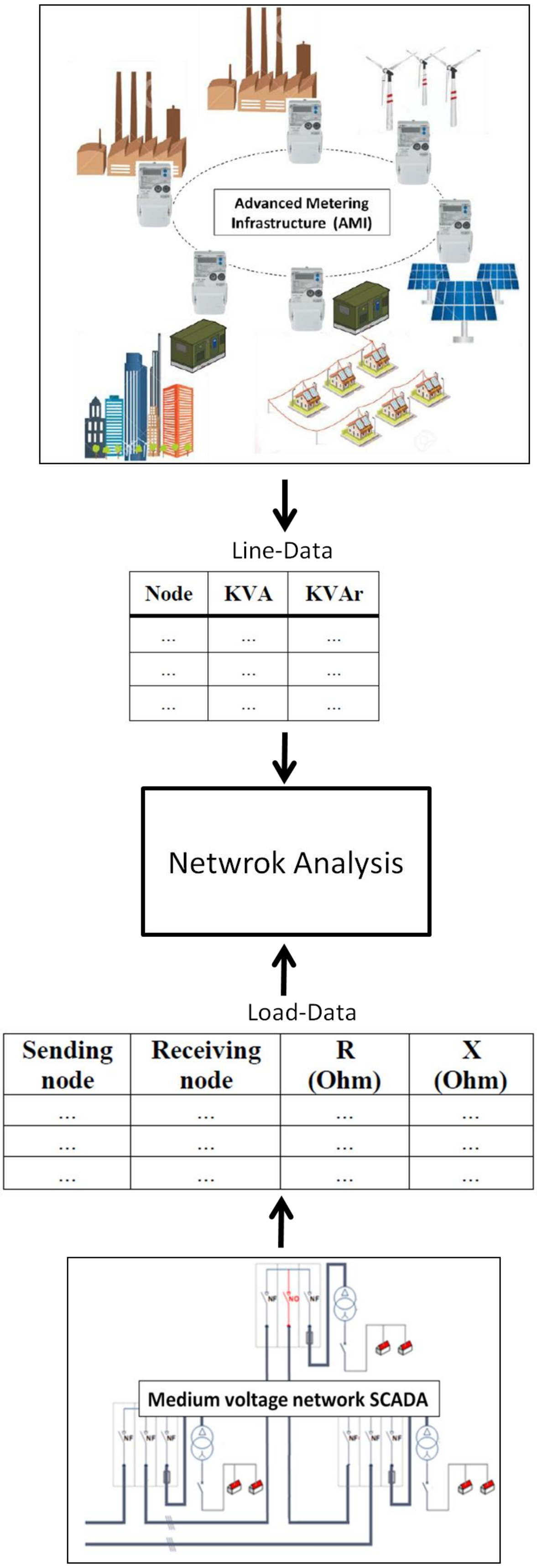


Fig 8: Smart meter measurements and network analysis

TABLE 3: LOAD DATA OF THE 15-BUS SYSTEM [11]

Node	KVA	Node	KVA	Node	KVA
1	00.0	6	200.0	11	200.0
2	63.0	7	200.0	12	20.0
3	100.0	8	100.0	13	100.0
4	200.0	9	100.0	14	100.0
5	63.0	10	63.0	15	200.0

From the Line Data, presented in table N°4, indicate the resistance and reactance of each, and the topological structure of network, The BIBC and BCBV matrices are developed.

TABLE 4: LINE DATA OF THE 15-BUS SYSTEM [11]

Sending node	Receiving node	R (Ohm)	X (Ohm)
1	2	1.530	1.778
2	3	1.037	1.071
3	4	1.224	1.428
4	5	1.262	1.499
2	9	1.176	1.335
9	10	1.100	1.190
2	6	1.174	1.332
6	7	1.174	1.332
6	8	1.174	1.323
3	11	1.150	1.285
11	12	1.274	1.522
12	13	1.274	1.522
4	14	1.075	1.522
4	15	1.075	1.522

An iterative procedure start, the convergent criteria is chosen as 0.0001.

The results obtained were been compared with the result obtained by T. Sathiyanarayanan, M. Sydulu [12], by the use of the Primitive Impedance based Distribution Load Flow method, the result values are presented in table 5.

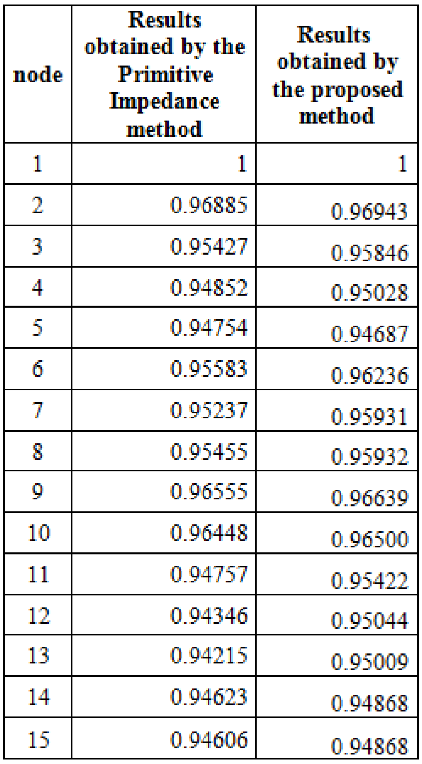
A comparison of the values presented on table 5 confirms the functioning of the proposed algorithm.

The updating of the load data presented on table 3, can be easily obtained from the smart meters measurements, for each significant variation the algorithms is run and the electrical characteristics of all network nodes are updated.

VII. CONCLUSIONS

An analytical tool to provide network characteristics based on the exploration of the information given by the smart meters measurements, and the network tree structure, is presented in this paper. the proposed analytical method is based on the use of the power summation method with the development of two matrices bus injection to bus current (BIBC) and branch current to bus voltage (BCBV) with an improvement in ensuring an automatic updating of the BIBC and BCBV with the change in the topology structure, which will allow getting a flexible power flow method with network configuration. The proposed algorithm is easy to implement and does not requires the use of any complex renumbering of branches and nodes, or any matrix calculation, with the only use of the linear equations based in the Kirchhoff's formulation.

TABLE 5: RESULTS FOR IEEE 15-BUS SYSTEM



node	Results obtained by the Primitive Impedance method	Results obtained by the proposed method
1	1	1
2	0.96885	0.96943
3	0.95427	0.95846
4	0.94852	0.95028
5	0.94754	0.94687
6	0.95583	0.96236
7	0.95237	0.95931
8	0.95455	0.95932
9	0.96555	0.96639
10	0.96448	0.96500
11	0.94757	0.95422
12	0.94346	0.95044
13	0.94215	0.95009
14	0.94623	0.94868
15	0.94606	0.94868

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