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Load Flow analysis for Moroccan Medium voltage distribution system

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Abstract— **This paper presents an overview of load flow methods existing in transmission and distribution systems, and the current medium voltage system conditions in Morocco. The main aim of this paper is to analyze and compare different load flow methods that are used for distribution systems under the Moroccan Medium voltage networks current conditions. A load flow method is proposed based in 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. The proposed method is tested in the IEEE 15-bus systems, which provides similar structures as Medium voltage system in Morocco. A theoretical proposition of the implementation of this method is developed in this paper with the only use of existing equipment in current MV network in Morocco.**

Keywords— **Load Flow analysis, Radial distribution system, Backward/forward sweep, Medium voltage system in Morocco, Telemetry.**

I. INTRODUCTION

With the publication of Law 58-15 opening access to low- and medium-voltage networks, amending and supplementing Law 13-09, and Decree No. 2-15-772 on access to the national grid of medium voltage, distribution system in Morocco will know radical changes. Integration of renewable energies and the multiplication of actors in a new distribution energy market, will require the introduction of more intelligence into the distribution grid, and the need of more tools for voltage control, demand side management and distribution managements systems … those tools are based in the presence of a strong method of load flow analysis.

Load flow analysis is a critical factor used in transmission system for proper planning of power generating scheduling, to determine the best operation for a power system and exchange of power. Several methods had been developed and used in the transmission system such as Gauss-Seidel, Newton-Raphson and Fast Decoupled methods.

Moroccan Medium voltage distribution systems are radial with large number of nodes, branches, and complex topology configurations that can be changed for maintenance activities, emergency operations or network configurations. 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].

These problems have been revealed in a number of papers, where the authors complained that the classic Jacobien-based methods were not appropriate to solve practical problems presented when analyzing distribution systems [5] [6].

In the literature, various methods of load flow solution techniques are available to carry out radial distribution systems, those methods may be divided into two categories. The first type of methods is utilized by proper modification of existing methods such as, Newton-Raphson. On the other hand, the second group of methods is based on forward-backward sweep processes using Kirchhoff’s formulation.

The main aim of this paper is to compare the different load flow methods that are used for distribution systems under different condition such existed in medium voltage Moroccan distribution system: loadings, X/R ratios, static load models and load growth scenarios. The convergence ability of these methods is evaluated under these conditions. All these load flow methods are evaluated on IEEE 15-bus and IEEE 33-bus radial distribution test system and comparison of voltage profile, total real and reactive power losses, number of iterations and cpu time is provided. And choose a load flow concept that can be used in the current Moroccan context.

In what follows, we present an overview of the medium voltage distribution system in Morocco in section II. Next in Section III we provide the theoretical foundation and the algorithm of Transmission load flow methods and limitation with radial distribution system, In section IV we present the backward/forward sweep algorithms and applications, in section V we discuss the results obtained from a 15-bus test system, and the comparisons, in section VI we present how a simple application of the proposed load flow method in the current Moroccan distribution context. Section VII concludes this paper.

II. OVERVIEW OF MEDIUM VOLTAGE DISTRIBUTION SYSTEM IN MOROCCO

The Moroccan medium voltage distribution system is made of 3 phases, with neutral grounded in the HV/MV substation. Two nominal magnitudes voltages are used 20KV and 22KV.

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Three forms of medium voltage distribution system can be distinguished: 100% overhead lines, 100% underground cables or a combination of both.

The underground networks are made of 3 single-phase cables. The most used topology is the open loop (ring configuration). The loop (or ring) distribution system is one 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.

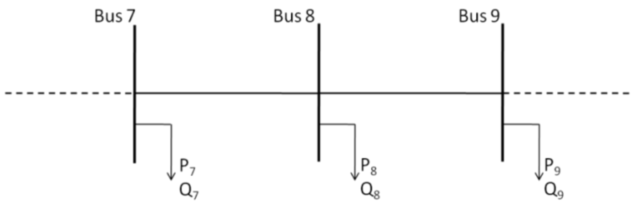

Fig 1: Single line diagram of the open-loop topology

The ring main system has the following advantages:

- There are very less voltage fluctuations at consumer's terminals.
- The system is very reliable as each distributor is fed with two feeders. In case, of fault in any section of feeder, the continuity of supply is maintained.

The overhead networks are made of three bares conductors, the most used topology is the radial configuration, from a main-line, derivations are made to connect MV/LV substations or MV customers, as shown on Fig 2.

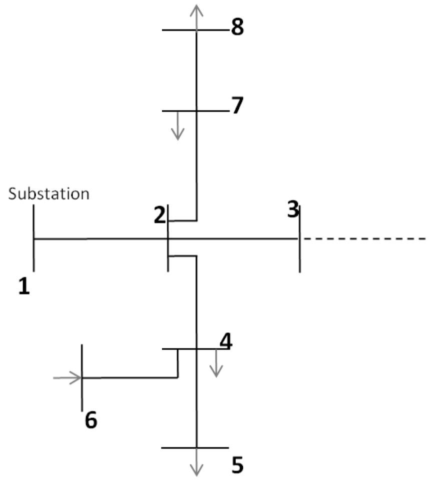

Fig 2: Single line diagram of overhead distribution system

It's to highlight that is recommended to avoid the use of the rake structure (a connection from the main line for each station), which weakens the main-line, and it's preferable to grouping as many station, into cluster, as possible. (Minimize the number of derivations).

According to these several forms of the Medium voltage, it's to separate three types of nodes: Terminal node, common node, and intermediate node.

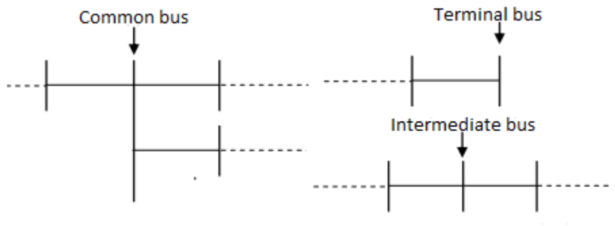

Fig 3 Types of nodes

In Morocco, almost all HV/MV substations had a dedicated SCADA, used as MV network remote control system, to handle network operations and to receive MV/LV substations details.

Digital meter are now available in Moroccan market, and used at almost all MV customers, and utilities started the installation and the use of Advanced Metering Infrastructure (AMI) solutions, as LYDEC in Casablanca and RADEEMA of Marrakech.

III. Power Flow Analysis Methods in transmission system

The most important load flow methods existing in transmission system are: Gauss-Siedel method, Newton-Raphson method and Fast Decoupled method [7].

The first step in performing those load flow analysis is to form an Y-bus admittance using the transmission line and transformer input data. The nodal equation for a power system network using Y bus can be written as follows [8]:

$$I = Y_{bus}\, V \qquad (1)$$

The nodal equation can be written in a generalized form for an n bus system:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad \text{for } i=1,2,3,n \qquad (2)$$

The complex power delivered to a node i is:

$$P_i + jQ_i = V_i I_i^* \Rightarrow I_i = \frac{P_i - j\,Q_i}{V_i^*} \qquad (3)$$

Substituting for I_i:

$$\frac{P_i - j\,Q_i}{V_i^*} = \sum_{j=1}^{n} Y_{ij} V_j \qquad (4)$$

To solve this nonlinear algebraic equations, The Gauss-Seidel load flow method, used an iterative method based on Gauss method, from an initiative value Vi, , the voltage of the $(k+1)^{th}$ iteration is given by:

$$V_i^{k+1} = \frac{\frac{P_i - jQ_i}{V_i^*} - \sum_{j=1}^{n} Y_{ij} V_j}{\sum_{j=1}^{n} Y_{ij}} \text{ With } i \neq j \qquad (5)$$

The Newton-Raphson load flow method, it is also an iterative method, generated from equ (6.1) and (6.2).

$$P_i = \sum_{j=1}^{n} |V_i||V_j| \cos(\theta_{ij} - \delta_i + \delta_i) \qquad (6.1)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j| \sin(\theta_{ij} - \delta_i + \delta_i) \qquad (6.2)$$

Equation (6.1) and (6.2) are expanded in Taylor's series about the initial estimate and the terms are limited to the first approximation of the equations, The element of the Jacobian matrix are obtained after partial derivatives of Equations (6.1) and (6.2) are expressed which gives linearized relationship

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between small changes in voltage magnitude and voltage angle. The equation can be written in matrix form as:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_3\\ J_2 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \qquad (7)$$

The new estimates for bus voltage are:

$$\left|V^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right| \qquad (8.1)$$
$$\delta^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \qquad (8.2)$$

It is the most iterative method used for the load flow because of the quadratic convergence characteristics that are relatively more powerful compared to Gauss-Seidel method.

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. The Jacobian matrix of Equation (7) is reduced to half by ignoring the element of J_2 and J_3. Equation (7) is simplified as:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & 0\\ 0 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \qquad (9)$$

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

```
# Start
# Create Ybus
# Make initial assumptions as the old values
# Substitute the old values into power equations for the next iteration
# Obtain the new value
# New value – Old value
# If (New value – Old value) < specified tolerance; then end otherwise go to step 4.
```

Fig 4: Pseudo-code procedure for analyzing load flow in a power system

The presented methods are successfully and widely used for power system operation, control and planning in transmission system. However, it has repeatedly been shown that these methods may become inefficient in the analysis of distribution systems with high R/X ratios or special network structures [9]-[10].

Distribution systems usually fall into the category of ill-conditioned power systems for generic Newton-Raphson like methods with its special features[11], such as radial topologies, high R/X ratio of the distribution lines, unbalanced operation and loading conditions, non-linear load models and dispersed generation, etc

Numerous efforts have been made to develop power flow algorithms for distribution systems. The backward/forward sweep method is one of the most used ones in scientific literature.

IV. BACKWARD/FORWARD SWEEP METHOD

This method takes advantage of a natural feature of the radial networks; there is a unique path from any node to the source. The general algorithm consists of two basic steps: forward sweep and backward sweep.

From a Line Data specifying the impedance between the sending and the receiving node of each branch, and by supposing that the active power injections and the consumptions of the active / reactive powers at each node are known, and reassembled into a Load Data showing the consumed or injected at each node.

Due to the radial structure of the distribution system, it's possible to determine the direction of the currents in each branch and then calculate its value, and the voltage of each node, with a direct application of Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) [12].

By giving the voltage of the root node and an initial voltage guess of other nodes, the algorithm takes three steps for each iteration:

Step 1: Nodal current calculation:
The current injection at each node i is calculated using Eq 10:

$$I_i^{(k)} = \left(S_i \big/ V_i^{(k)} \right)^* \quad i = 1,2,\ldots,n \qquad (10)$$

Where S_i is the power injection at node i, $V^{(k)}_I$ is the voltage of node i calculated from iteration k.

Step 2: Backward sweep:
Starting from the last ordered branch, current Ji,i+1 in branch from the node i to the node "i+1" is calculated using Eq 11:

$$J_{i,i+1}^{(k)} = -I_i + \sum J_i \qquad (11)$$

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

Step 3: Forward Sweep:
Starting from the root bus, the node voltages are updated using Eq 12:

$$V_i^{(k)} = V_{i-1}^{(k)} - Z_i J_i^{(k)} \;,\; i = 2,3\ldots,n \qquad (12)$$

Where Z_i is the series impedance of branch 'i-1,i"

Those three steps are repeated until voltage magnitudes at each node in present iteration and previous iteration is lower than a tolerance limit ε.

$$\max\left(\left[V^{(k+1)}\right] - \left[V^{(k)}\right]\right) < \varepsilon \qquad (13)$$

V. ALGORITHM DEVELOPMENT

A sample distribution system drawn below is taken on fig-5 to illustrate the methodology chosen to develop a load flow method adapted to Medium voltage distribution in Morocco.

Current injections and relationship between the bus current injections and branch current can be obtained by applying

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Kirchhoff's current law (KCL) to the distribution network. The branch currents can then be formulated as functions of equivalent current injections.

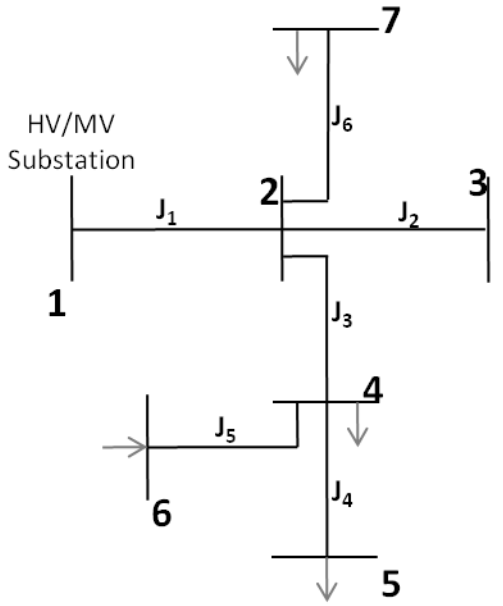

Fig 5: Single line diagram of an distribution network

For example the branch currents J_1, J_2 and J_5 can be expressed by equivalent current injections as:

$$J_1 = I_2 + I_3 + I_4 + I_5 + I_6 + I_7 \quad (14.1)$$
$$J_3 = I_5 + I_6 \quad (14.2)$$
$$J_5 = I_6 \quad (14.3)$$

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

$$\begin{bmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \\ J_6 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \end{bmatrix} \text{ Or } [J] = [BIBC] \times [I] \quad (15)$$

The constant BIBC matrix is an upper triangular matrix and contains values of 0 and +1 only.

The relationship between branch currents and bus voltages can be obtained as follows:

$$V_2 = V_1 - J_1 Z_{12} \quad (16.1)$$
$$V_3 = V_2 - J_2 Z_{23} \quad (16.2)$$
$$V_7 = V_2 - J_6 Z_{26} \quad (16.3)$$

Where V_i is the voltage of bus i, and Z_{ij} is the line impedance between node i and node j. Substituting (16.1) and (16.2) into (16.3), the equation (16.3) can be written as:

$$V_7 = V_1 - J_1 Z_{12} - J_2 Z_{23} - J_6 Z_{26} \quad (17)$$

From (17), it can be seen that the bus voltage can be expressed as a function of branch currents, line parameters and the substation voltage. Similar procedures can be performed on other nodes; therefore the relationship between branch currents and bus voltages can be expressed as:

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 & 0 \\ Z_{12} & 0 & Z_{34} & 0 & 0 & 0 \\ Z_{12} & 0 & Z_{34} & Z_{45} & 0 & 0 \\ Z_{12} & 0 & Z_{34} & 0 & Z_{56} & 0 \\ Z_{12} & 0 & 0 & 0 & 0 & Z_{67} \end{bmatrix} \begin{bmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \\ J_6 \end{bmatrix} \quad (18.1)$$

Or : $$[\Delta V] = [BCBV] \times [J] \quad (18.2)$$

The BCBV matrix represents the relationship between branch current and bus voltages. The corresponding variations at bus voltage, generated by the variations at branch currents can be calculated directly by the BCBV matrix.

The BIBC and BCBV matrices are developed based on the topological structure of distribution systems. The BIBC matrix represents the relationship between bus current injections and branch currents. The corresponding variations at branch currents, generated by the variations at bus current injection can be calculated directly by the BIBC matrix. Combining equation (15) and (18.2), the relationship between bus current injections and bus voltages can be expressed as:

$$[\Delta V] = [BCBV][BIBC][I] = [DLF][I] \quad (19)$$

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 :

$$I_i^{(k)} = \left(S_i / V_i^{(k)} \right)^* \quad (20)$$

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

$$\left[\Delta V^{(k+1)}\right] = [DLF] \times \left[I^{(k)}\right] \quad (22)$$

And the new value of voltage is obtained by equ 23

$$\left[V^{(k+1)}\right] = \left[V^{0}\right] + \left[\Delta V^{(k+1)}\right] \quad (23)$$

This 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.

$$\max(\left[V^{(k+1)}\right] - \left[V^{(k)}\right]) < \varepsilon \quad (24)$$

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VI. FLOW CHART

The flow chart of the method is presented in fig 7.

From a Line Data, indicate the resistance and reactance of each, and the topological structure of network, The BIBC and BCBV matrices are developed.

The next step is to convert the Load-Data into per-unit forms, by choosing a base voltage and a base power.

Voltages of all other nodes are set to nominal voltage, and an iterative process start by calculating currents of branches in a backward sweep using the Kirchhoff's current law, and the node voltages are updating in a forward sweep using the voltage drop calculation, this backward and forward sweep are repeated until voltage magnitudes at each node in present iteration and previous iteration is lower than a tolerance limit..

VII. SIMULATION RESULTS

The proposed method program code is made in MATLBAB and tested on IEEE 15-bus distribution network, which have a similar structure as Moroccan medium voltage distribution system, the Load Data is given in table 1 and the Line Data is presented in table 2, the power factor of load is assumed to be 0.7 [13].

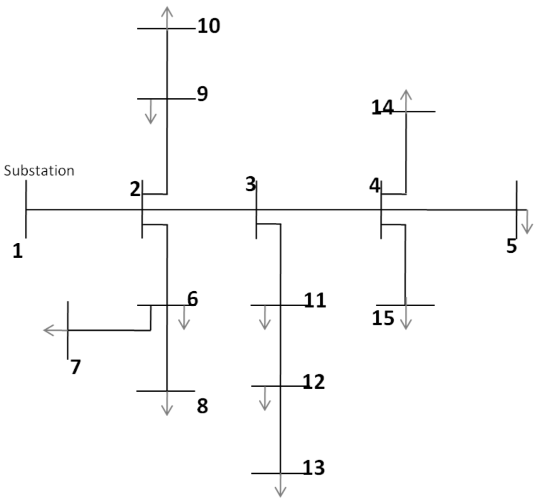

Fig 6 Single phase diagram of 15-bus distribution system

TABLE I
LOAD DATA OF THE 15-BUS SYSTEM

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

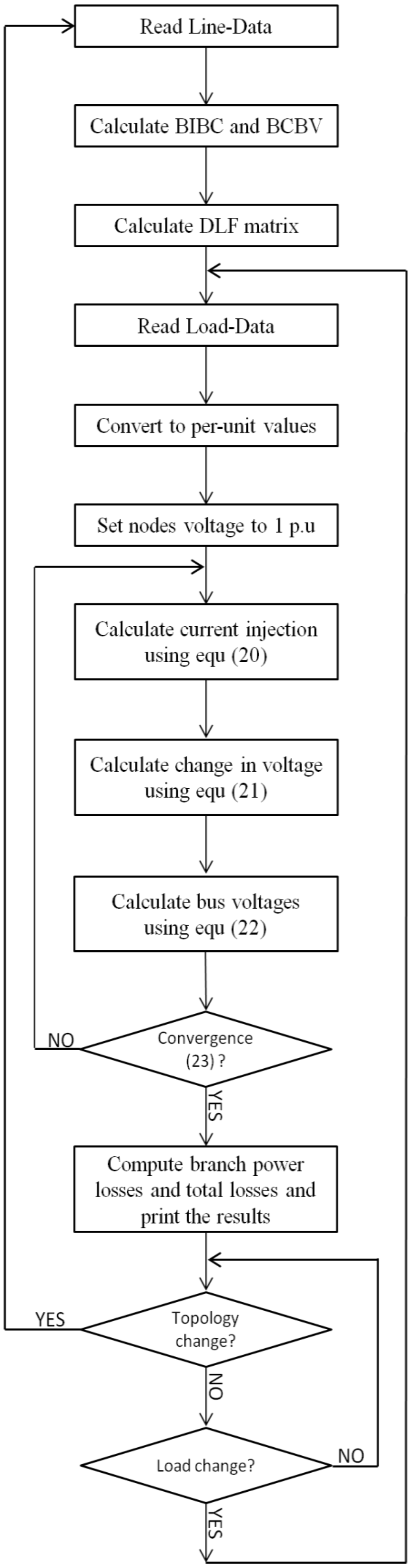

Fig 7: Flow chart of the proposed method

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TABLE II
LINE DATA OF THE 15-BUS SYSTEM

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

From the Line Data, presented in table2, indicate the resistance and reactance of each, and the topological structure of network, The BIBC and BCBV matrices are developed.

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

The results obtained was been compared with others existing load flow methods : Primitive Impedance based Distribution Load Flow (PIDLF), Current Injections based Distribution Load Flow (CIM) and Fast Decoupled Single Matrix Model Distribution Load Flow (SMM). The results are summarized in table N°3.

TABLE 3
RESULTS FOR IEEE 15-BUS SYSTEM

node	CIM	PIDLF	SMM	Proposed method
1	1	1	1	1
2	0.97128	0.96885	0.97031	0.97017
3	0.95667	0.95427	0.95571	0.95657
4	0.9509	0.94852	0.94995	0.95078
5	0.94991	0.94754	0.94896	0.94977
6	0.95822	0.95583	0.95726	0.96267
7	0.95476	0.95237	0.9538	0.95974
8	0.95694	0.95455	0.95599	0.96115
9	0.96797	0.96555	0.967	0.96020
10	0.96689	0.96448	0.96593	0.95936
11	0.94995	0.94757	0.949	0.95202
12	0.94582	0.94346	0.94488	0.95006
13	0.94451	0.94215	0.94357	0.94842
14	0.9486	0.94623	0.94766	0.94926
15	0.94844	0.94606	0.94749	0.94775

VIII. IMPLANTATION OF THE PROPOSED METHOD

The proposed method need two input to perform the load flow analysis, this two inputs are: Line-Data and Load-Data.

Line-Data can be established by collecting the impedance of all the branches constituting the network, Those network information can be assembled in one table, as showing on table IV.

TABLE IV
LINE-DATA TABLE

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

However, the topology structure of the network can be changed for maintenance activities, emergency operations or network configurations.

As mentioned in section II, HV/MV substations in Morocco had a dedicated SCADA, used as MV network remote control system, to handle network operations and to receive MV/LV substations details, this SCADA can remote MV switch status of the MV/LV substation. So any change in the topology structure can be detected by this SCADA, and update the Line-Data table.

Load-Data can be established by collecting the active power injections and the consumptions of the active / reactive powers at each node. Those network information can be assembled in one table, as showing on table V.

TABLE V
LOAD-DATA TABLE

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

The updating of the Load-Data can be obtained by the use of the information by the Advanced Metering Infrastructure (AMI). As mentioned in section II, that the digital meter are available in Moroccan market, and used at MV customers, also utilities started the installation and the use of Advanced Metering Infrastructure (AMI) solutions.

A solution for updating the Load-Data can obtained by equipping the public MV/LV substation by Digital meter, and connects it to the Advanced Metering Infrastructure (AMI).

The implementation of the proposed load flow method is given on fig 8.

IX. CONCLUSIONS

A Load flow method easy to implement in the current Moroccan medium voltage system, has been presented in this paper, The proposed load flow program is based on the backward/forward sweep concept, by forming 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

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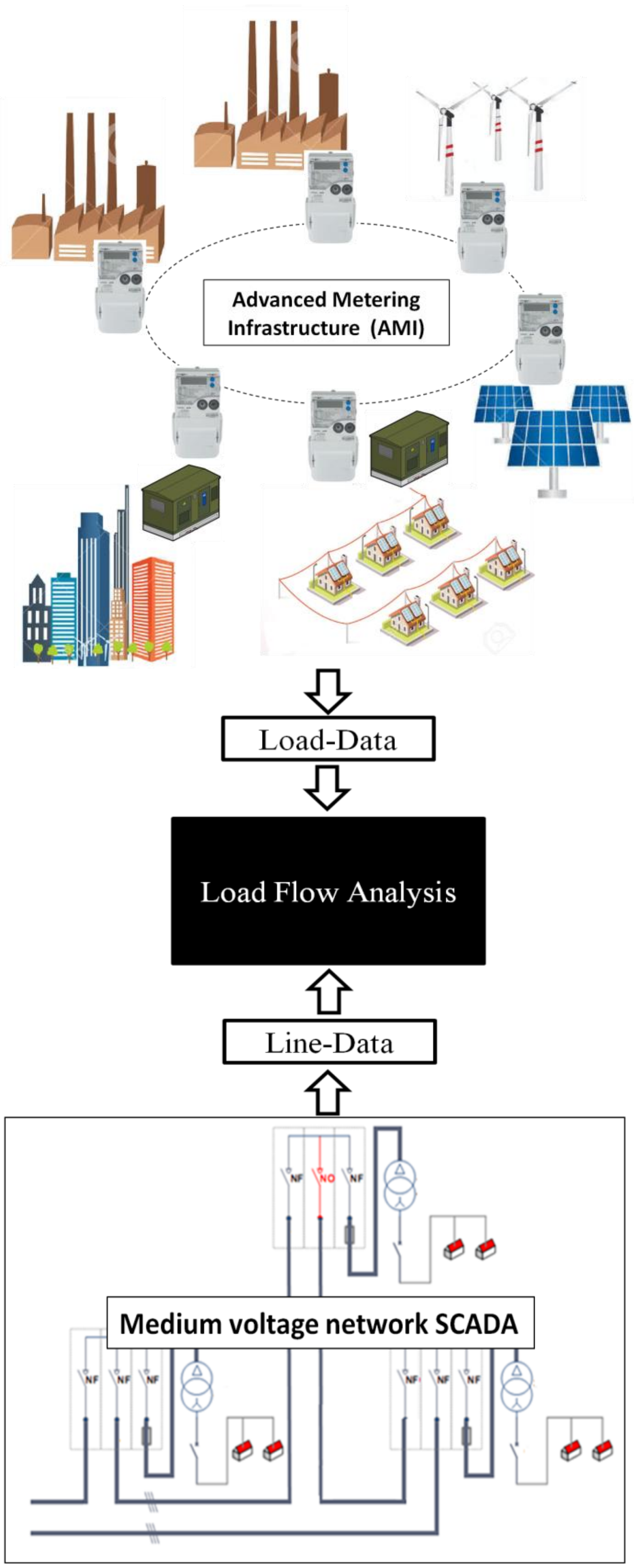

Fig 8: Implemtentation of the proposed method

in the topology structure.

The proposed method can be exploited in several distribution network applications: Voltage control, demand side management, distribution management systems.

Limitation of the proposed method is that it can be used only for the radial distribution system and, not for meshed distribution systems or transmission systems.

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