



Analysis and Comparison of Load Flow Methods for Distribution Networks Considering Distributed Generation

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Abstract

Conventional passive distribution networks are changing to modern active distribution networks which are not radial. Conventional load flow methods should be modified for new distribution networks analysis. In modern distribution networks distributed generation (DG) units are embedded with conventional and/or renewable resources. DG units are generally modeled as PV or PQ nodes which inject active power electricity to the network. Modeling of a DG unit is dependent on the operation and its type of connection to the grid. This paper considers the most important new load flow methods for DG integrated distribution networks. The methods are analyzed and compared with each other. Every method has advantages and disadvantages in different conditions. So, comparison of these methods can be useful to select the best method for a typical network. As a result, some suggestions are proposed to apply the new methods.

Keywords: Load flow, modern distribution networks, distributed generation.

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1. Introduction

Load flow is one of the most important tools to analyze the power systems for both planning and operation stages. Load flow is used to determine the static performance of the system. The conventional load flow methods used for power systems are as follows.

1. Gauss-Seidel method with admittance matrix (YGS)
2. Gauss-Seidel method with impedance matrix (ZGS)
3. Newton-Raphson (NR) method
4. Decoupled Newton-Raphson (DNR)
5. Fast Decoupled Newton-Raphson (FDNR)

The mentioned methods usually fail to analyze distribution networks, because the admittance matrix (Y_{Bus}) of the network is sparse and R/X ratio and loading of the feeders is higher. As a result,

Backward/Forward Sweep (BFS) methods are usually used in practice. BFS methods do not need Jacobian matrix unlike NR methods. However, conventional BFS is not useful for modern active distribution networks. Future distribution networks as smart grids are integrated with high penetration DG units. Moreover, modern networks are not radial unlike the conventional ones. In fact, to increase the penetration of DG units, modern distribution networks shall include several loops [2]. Therefore, simultaneous mesh and DG modelling is the main challenge for new distribution networks load flow.

DG units are modelled regarding operation and their type of connection to the grid. They are generally modelled as PQ or PV nodes in load flow studies [3]. The conventional BFS methods fail, if DG units are modelled as PV nodes. Thus some modifications are needed to update the BFS methods. Recently several new methods are proposed for power flow studies considering DG units. Every method has advantages and disadvantages. Comparison of these methods can be useful to select the best method for a typical network. This paper analyzes and compares the most important methods for load flow studies of new distribution networks considering DG units. The methods are firstly introduced and analyzed in the second section. Then, helpful suggestions and conclusion remarks are presented in the third section.

2. Load flow methods

The most important load flow methods, which can be applied to new distribution networks, are categorized to six groups: NR based methods, Gauss-Seidel based methods, super position based methods, compensated backward/forward sweep methods, optimization based methods and artificial intelligence based methods. This arrangement is shown in Fig.1.

The methods are analyzed in the following.

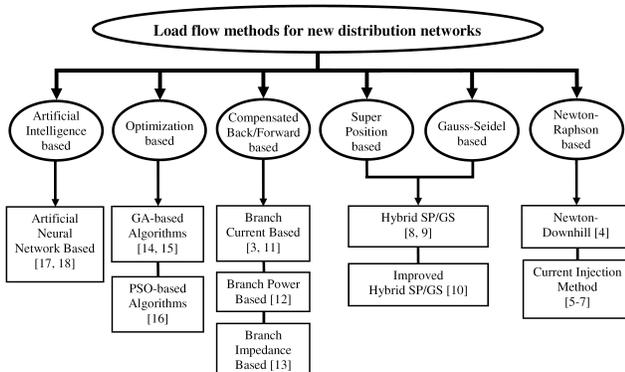


Fig.1. Classification of load flow methods for new distribution networks

2.1. Newton-Downhill (ND) load flow

A disadvantage of the NR method is the dependence of final result on the initial point. The initial point is usually one for voltage magnitude and zero for voltage angle. However, this initial point may not be suitable for distribution networks load flow and NR may not be converged to the solution. ND method includes two phases. In the first phase, some linear searches are used to find a good initial solution for the second phase [4]. As a result, the solution of the ND method is independent of the initial point. In the second phase NR method is run, in which a down-hill factor (λ) is used as follows.

$$x^{k+1} = x^k - \lambda.[f'(x^k)]^{-1}.f(x^k) \tag{1}$$

Firstly $\lambda = 1$ and Eq. (1) is used to find a new solution. If $\|f(x^{k+1})\| \geq \|f(x^k)\|$, λ will be halved, x^{k+1} is recalculated until $\|f(x^{k+1})\| < \|f(x^k)\|$ or $\lambda \leq \epsilon_\lambda$, where ϵ_λ is the lower bound of Down-hill factor. As a result, convergence order of ND is less than two. Although the convergence rate of ND is more, it can not solve the singular and morbidity of Jacobian matrix.

2.2. Current Injection Method (CIM) load flow

In CIM, the power flow equations are written in terms of the current injections in rectangular form, and the resulting set of nonlinear equations is solved using NR. New very efficient routines have been developed to perform matrix ordering and factorization and CIM is competitive with BFS. The elements of Jacobian matrix in CIM do not include sine and cosine parts. Moreover, the off-diagonal terms are equal to the corresponding elements of nodal admittance matrix and thus remain constant throughout iterative procedure. CIM is more successful than NR when the network has many loops, load is heavy or R/X ratio is high [5, 7]. The convergence of NR and CIM is compared in Table 1 for a typical distribution network. However, experimental results show that CIM does not converge if the number of PV DG nodes increases [6].

Table 1: Number of iteration for NR and CIM load flows in different conditions [7]

Loading factor	NR	CIM	R/X ratio	NR	CIM
1	2	3	1	2	3
2	-	3	2	2	3
3	-	4	3	-	3
4	-	4	4	-	6
5	-	-	5	-	-

2.3. Hybrid Super Position/ Gauss-Seidel (HSP/GS) load flow

HSP/GS method is based on super position theorem. PQ load nodes and PQ DG nodes are modeled as current sources and slack node and PV DG nodes are modeled as voltage sources. In the first stage, all the voltage sources are taken as zero. Then in the k -th iteration, the voltage deviations (VD^k) due to current injections (I^k) are computed by the factorization of admittance matrix (Y_{Bus}) as follows.

$$[I]^k = [Y_{Bus}] \cdot [VD]^k \quad (2)$$

The voltage deviation can be calculated more easily by impedance matrix (Z_{Bus}) and Gauss-Seidel method for three phase load flow [9].

In the second stage, all the current sources are taken as zero. Then no load bus voltages (V_{NL}) are calculated. The no load bus voltages are superimposed on voltage deviations as follows.

$$[V]^{k+1} = [VD]^k + [V_{NL}] \quad (3)$$

The mentioned steps are repeated until the stop criterion is satisfied. The HSP/GS method is sensitive to the number of PV DG nodes. In practice, HSP/GS method will not converge if the number of PV nodes is high [3].

2.4. Improved Hybrid Super Position/ Gauss-Seidel (IHSP/GS) load flow

If the number of PV DG units is high, to improve the performance of HSP/GS method a sensitivity matrix (M) is introduced. Unlike in HSP/GS method, PV DG units are modeled as current sources. The reactive power injected by these current sources is initialized in the first iteration. Then it is updated during iterations using the following equation.

$$M \cdot \Delta Q = \Delta V \quad (4)$$

Where ΔV is the mismatch of voltage magnitude in PV DG nodes. M is the constant sensitivity matrix which is obtained from impedance matrix [10]. Eq. (4) is acceptable while the voltage magnitude and voltage angle are near the one and zero respectively. As a

result, IHSP/GS method may not be successful for large radial distribution networks with high impedance or heavy load. On the other hand, increasing of the loops number and DG units can keep the Eq. (4) in acceptable conditions.

2.5. Compensated Branch Current Based Backward/Forward Sweep (CBCBB/FS)

In BCBB/FS method active and reactive power of loads are modeled as electricity currents and backward/forward sweep is done. This method is suitable for only passive radial networks. It needs some modifications to apply to new distribution networks. In CBCBB/FS, PV DG nodes are modeled as break points which inject active and reactive power to the network [3]. Similarly the loops are broken at break points to make the network radial. Then, BCBB/FS is run to converge. After every convergence of BCBB/FS, active (P) and reactive (Q) power in break points are updated using sensitivity matrix as follows [12].

$$\begin{bmatrix} X & R \\ -R & X \end{bmatrix} \begin{bmatrix} \Delta Q \\ \Delta P \end{bmatrix} = \begin{bmatrix} \Delta V \\ \Delta \delta \end{bmatrix} \quad (5)$$

Where V and δ are the magnitude and angle of voltage, respectively.

Eq. (5) is acceptable if the magnitude and angle of voltage in all nodes are near to one and zero respectively. As a result, CBCBB/FS will not be successful for heavy load or large scale radial networks. On the other hand, increasing of loops number and DG units can improve the accuracy of Eq. (5).

2.6. Compensated Branch Power Based Backward/Forward Sweep (CBPBB/FS)

CBPBB/FS load flow method is similar to CBCBB/FS, but power equations are used for backward/forward sweep instead of current equations [12]. The sensitivity matrix is used similar to Eq. (5). Then CBPBB/FS properties will be similar to CBCBB/FS.

2.7. Compensated Branch Impedance Based Backward/Forward Sweep (CBIBB/FS)

In CBIBB/FS load flow method, PQ load nodes are modelled as shunt impedances. The impedances are variable and are corrected during iterations. Using impedances (instead of current or power) in backward/forward sweep makes the equations linear. The forward sweep equations become especially simple. To model PV DG units in load flow, an additional reactance (X_c) is inserted in the network. The additional reactance should keep the voltage magnitude at specified value (V_{sp}) in PV DG node. As

a result, the value of reactance is given by the following equation [13].

$$X_c = \frac{-X - \sqrt{X^2 + Z^2(E^2/V_{sp}^2 - 1)}}{E^2/V_{sp}^2 - 1} \quad (6)$$

Where E and Z are the parameters of the equivalent Thévenin network at the node where X_c is installed. X is the imaginary part of Z .

At the end of each iteration and for each PV DG, the Thévenin scheme must be built. Moreover, this method can not consider loops in the network.

2.8. Genetic Algorithm Based (GAB) load flow

In this method, firstly the magnitude and angle of voltages of PQ load nodes and PQ DG nodes are initialized randomly. Then the initial values are used to calculate the active and reactive power of PQ nodes. An objective function to be minimized is defined as follows.

$$\text{Min.} \left\{ \sum_{p=1}^n (P_p^{cal} - P_p^{sp})^2 + (Q_p^{cal} - Q_p^{sp})^2 \right\} \quad (7)$$

Where P^{sp} and Q^{sp} are the specified values of active and reactive power in PQ nodes, P^{cal} and Q^{cal} are the calculated active and reactive power in PQ nodes and n is the number of all PQ nodes.

In the next step, crossover, mutation and selection operators are applied to the magnitude and angle of voltages. The above steps are repeated while the GA converges to the optimal solution.

PV DG nodes can be easily modelled as optimization problem constraints. However, the crossover and mutation operators are intelligently modified to improve the optimization procedure [14].

In this method, singular Jacobian matrix can not disable the algorithm. However, computation time is more than in other methods. The GAB load flow is a trick when other methods are disabled. So it is suitable for offline computations where the problem is hard to solve.

2.9. Particle Swarm Optimization Based (PSOB) load flow

In this method, similar to GAB load flow, the objective function is defined as Eq. (7). The load flow problem becomes a restricted optimization problem. Then PSO algorithm is applied to solve the problem. In practice, PSO algorithm is modified by some methods such as chaotic local search to be more efficient [16]. PSOB load flow properties are very similar to GAB method properties, but PSO algorithm is naturally

faster than GA. However, PSOB load flow is still suitable for offline problems.

2.10. Artificial Neural Network Based (ANNB) load flow

This method is based on a three-layered neural network. The inputs of the neural network are active and reactive power of loads and PQ DG units, voltage magnitude of PV DG units and their active power injected. The outputs of the third layer are the magnitude and angle of PQ nodes voltages, reactive power and voltage angle of PV DG units and power loss of the distribution network. To train the neural network, a load flow method which mentioned in sections 2.1-2.9 can be used. For example, a modified NR load flow is run for several times to give various input-output patterns. Then the neural network is trained by back propagation method. As a result, the trained neural network can model the nonlinear load flow system and obtain the results of load flow for other different inputs.

The advantage of ANNB load flow is its less computation time cost for online problems. On the other hand, ANNB method is more flexible. Experimental tests show that capability of ANNB load flow allows it to produce a correct output even when it is given an input vector that is partially incomplete or partially incorrect [17]. It is suitable for online modern distribution network management as a challenge in smart grid. However, if the injected power by DG units changes in a wide range, ANNB is not useful. So it may not be helpful in renewable DG integrated networks. Moreover, selecting of initial patterns to train the neural network is a challenge in this method. Using chaotic neurons controlled by heuristic methods in ANN can improve the disadvantages of ANNB load flow [18].

3. Conclusions and suggestions

Whereas conventional distribution networks are changing to modern distribution networks, new load flow methods are needed. In this field, the most important challenges are simultaneous meshed and DG integration and fast online network management. DG units can be modeled as either PQ or PV nodes, regarding their control system. In this paper, 10 superior load flow methods for new distribution networks are analyzed and compared. The properties of the methods are summarized in Table 2 for comparison. Among these, more methods have some limitations to use.

NR based methods fail if the Jacobian matrix becomes singular. As a result, they diverge for heavy load operation of networks which include large number of PV nodes. Increasing of the PQ DG units and mesh numbers decreases feeders loading level which makes the NR based methods more suitable. However, NR based methods are not efficient for new distribution networks with large number of PV DG units.

Unlike NR based methods, super position based methods do not need Jacobian matrix. Modified super position based methods are efficient even if the number of PV DG units is high. However, they are not successful in heavy load conditions. Moreover, the approximation used in the method fails if the voltage magnitude set point of PV nodes is not enough near to 1 p.u. So they have limitations to be used.

Compensated back/forward sweep methods do not use Jacobian matrix either. They are suitable for weakly meshed networks with PV DG units. However, they do not converge accurately in heavy load conditions and high R/X ratio. Increasing of mesh number decreases the loading level of feeders, but unlike in the NR based methods, it makes the back/forward sweep methods more complex and time consuming. So they may not be useful for new modern networks.

Optimization based methods are not sensitive to the network properties (i.e. number of meshes and PV DG units), but they need excessive computation time for large scale networks. Moreover, they are too sensitive to controller parameters of the optimization algorithm (e.g. GA). However, optimization based methods are the most reliable methods among all. Modified intelligent operators are needed to improve the performance of these methods. On the other hand, fast modern computers technologies can make these methods more suitable in the future.

Neural network based methods are very fast in computation, but they are sensitive to the inputs range. Moreover, they need the other load flow methods for training. Here, optimization techniques are needed to make the training process more efficient.

In this paper, it is proposed to use a fuzzy-neural network which is trained by optimization based load flow methods in offline. As a result, the method has the highest convergence reliability and fuzzy-neural network can overcome uncertainties of the inputs. Then it can be used for online load flow studies where computation time is the least.

Table 2:

Comparison of load flow methods for new distribution networks

Load flow method	Advantage	Disadvantage
Newton-Downhill	<ul style="list-style-type: none"> • Independent of initial solution • Higher convergence rate than NR 	<ul style="list-style-type: none"> • Convergence order less than 2 • Fails if Jacobian matrix is singular
Current Injection Method	<ul style="list-style-type: none"> • Good convergence even in heavy load • Less sensitive to R/X ratio 	<ul style="list-style-type: none"> • Fails if PV DG number becomes high
Hybrid SP/GS	<ul style="list-style-type: none"> • Needless of Jacobian matrix 	<ul style="list-style-type: none"> • Fails if PV DG number becomes high
Improved Hybrid SP/GS	<ul style="list-style-type: none"> • Independent of PV DG number 	<ul style="list-style-type: none"> • Unsuccessful in heavy load
Branch Current /Power Based Back/Forward	<ul style="list-style-type: none"> • Needless of Jacobian matrix • Independent of PV DG number 	<ul style="list-style-type: none"> • Unsuccessful for heavy load large scale networks
Branch Impedance Based Back/Forward	<ul style="list-style-type: none"> • Needless of Jacobian matrix • Linear back/forward sweep equations 	<ul style="list-style-type: none"> • Disable for meshed networks • Excessive computation for high PV DG number in large scale networks
GA Based Load Flow	<ul style="list-style-type: none"> • Simple implementation • Reliable in convergence • Suitable for offline problems 	<ul style="list-style-type: none"> • Excessive computation time for large scale networks • Sensitive to controller parameters of GA
PSO Based Load Flow	<ul style="list-style-type: none"> • Reliable in convergence • Suitable for offline problems • Faster than GA 	<ul style="list-style-type: none"> • Slower convergence than all the others except GA • Unsuccessful for large scale networks
ANN Based Load Flow	<ul style="list-style-type: none"> • Having the least computation time • Suitable for online problems 	<ul style="list-style-type: none"> • Needy to the other methods • Limited to specified inputs range

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