LOAD FLOW METHOD FOR RADIAL SYSTEMS WITH DISTRIBUTING GENERATION[+]

Ali Kadhem Al-Awadi*

Abstract

Electric utilities have historically satisfied customer demand by generating electricity centrally and distributing it through an extensive transmission and distribution network. As demand increases, the utility generates more electricity. But if the capacity of the generation, transmission, or distribution systems is constrained, the traditional utility response to these constraints is to build new facilities. An alternative approach under consideration by utilities is to satisfy demand locally and incrementally by investing in distributed generation. Distributed generation facilities are strategically sited to deliver electricity where it is needed. This can relieve capacity constraints on the generation, transmission, and distribution systems and represents a prompt solution until it is possible to build new facilities.

This paper presents load flow analysis from a distribution radial feeder model of various electrical components including distributing generation units. The load flow analysis uses an evolved ladder load flow iterative technique and is approved by using the well-known Newton-Raphson iterative method to solve for voltage and power unknowns from the algebraic quadratic equations that describe the distribution system network.

The load flow routine is used to calculate bus voltage magnitudes and angles, branch power, losses, voltage drop, current magnitudes and angles, shunt device power, and losses.

In order to test the proposed algorithm, two examples of distribution systems are used. The results show an acceptable validity of the proposed algorithm.

المستخلص

تستخدم الوحدات التوليدية الصغيرة (وحدات الديزل أو الوحدات التوربينية) من قبل المستهلكين عادة كمصادر احتياطية وعند انقطاع مصدر القدرة الكهربائية في الشبكة الوطنية. وفي الوقت الحاضر فإن شركات توليد الطاقة الكهربائية اتجهت إلى ربط مثل هذه الوحدات مع منظوماتها وعلى مستوى جهد التوزيع لتحقيق فوائد عدة منها:

- توفير مصدر معتمد و قريب من الحمل .
- تغطية الأحمال وقت الذروة .
- تقليل الخسائر الناجمة عن نقل الطاقة لمسافات طويلة في خطوط النقل والتوزيع .
- تحسين معامل القدرة .
- تعزيز مستوى الجهود عند العقد .

وفي العراق هناك نقص شديد في مقدار إنتاج الطاقة وعجز في منظومات النقل عن تلبية حاجة الحمل المتزايد لذا فان إدخال مثل هذه الوحدات التي يمكن ربطها مع الشبكة الوطنية عبر المغذيات الشعاعية أصبح مفيدا إذ تمتاز بالسهولة والسرعة في النصب والتشغيل والإدارة ويمكن أن تنصب قرب مصادر الوقود وهذا سوف يساعد في تعزيز وضع المنظومة الكهربائية في الوقت الراهن .

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* B.Sc., M.Sc. Electrical Eng.\Asst . Lecturer\Najaf Technical College,Najaf,Iraq.

في هذا العمل تم إعداد نماذج رياضية لوحدات التوليد الصغيرة ووضع برامج حاسوبية لحساب جهود العقد و تدفق القدرة في المغذيات الشعاعية عند ربط هذه الوحدات ضمن الشبكة الوطنية.
وقد تم اختبار البرامج بتطبيقها على مثالين من المغذيات وقد أعطت النماذج و طريقة الحل المستخدمة نتائج مماثلة لطريقة نيوتن - رافسن المستخدمة لحساب تدفق القدرة وبخطوات وزمن اقل .

1. Introduction

Distributed Generator: a type of electrical generator producing alternating current that has the capability of parallel operation with the utility distribution system, or is designed to operate separately from the utility system and can feed a load that can also be fed by the utility electrical system. In this work distributed generation refers to small-scale electric power generators that produce electricity at a site close to customers and are tied to an electric distribution system. These units are limited to synchronous generators driven by engines or combustion gas turbines.

Introducing distributed generation (DG) to interconnected among the distribution feeder satisfies the following requirements [1]:

1. Voltage support by leveling the voltage profile from substations to loads.
2. Reactive power compensation.
3. Generating capacity relief via reduction in feeder load demand.
4. Feeder loss reduction.

Nowadays there are other important necessities besides above ones for relatively small-scale generation including diesel and small gas turbine units to become more common among the Iraqi Power National Grid at the distribution level, they are:

1. The demand for power is growing and supply is constrained.
2. The transmission lines are unreliable and not able to hold a huge amount of power so it is suitable to serve part of the load locally.
3. Units performed to connect among the grid are easily deployed, transportable, easy to install and relocate in a short time.
4. These units minimize the space requirements and do not require special foundation.
5. They can be installed near the fuel supply, managed, monitored and controlled locally. Modern units are equipped with computerized monitoring and control facilities.
6. They have a lower capital cost because of the small size of the DG (although the investment cost per kVA of a DG can be much higher than that of a large power plant).
7. With latest technologies, they can produce zero or near-zero pollutant emissions over their useful life.

An IEEE working group developed a Draft Standard for Distributed Resources Interconnected with the Electric Power System [2], and received approval by the IEEE Board. The IEEE working group is currently seeking to establish main technology criteria and requirements for interconnection of distributed resources with the electric delivery grid.

In addition to the IEEE working group several utilities put safety requirements for interconnecting distribution generators among radial feeders [3,4,5,6]. Some of these requirements suitable for the scope of this work are discussed here.

The interconnecting process ensuring that the voltage levels at the Point of Common Coupling (PCC) is maintained within the acceptable limits and synchronous generators connected to the distribution system must be equipped with excitation controllers capable of controlling voltage. The generator bus voltage set point shall be stable at, as well as adjustable to, any value between 95% and 105% to maintain voltage with the limits on its system.

The interconnecting process requires that the generator operate in a power factor control mode. This means operating within a constant power factor set point range. The voltage/power factor regulator must be capable of controlling the power factor of the generator between +0.9 and -0.9. In power factor control mode, the voltage regulator must have a voltage override that causes it to reduce excitation if the voltage at the PCC exceeds a specified upper limit. The normal upper limit is 105% of nominal; however, the voltage regulator shall have the provision to adjust this upper limit between 100% and 110% of nominal. The voltage regulator must also have provision for a time delay between sensing an excursion of the upper voltage and initiating control action. The power factor control equipment must have the capability to allow for the adjustment of this time delay between 0 and 180 seconds.

2. <u>Distribution Load Flow</u>

Load flow (or power flow) is the solution of the static operating condition equations of an electric power system under various load demands, source supply, and network configuration, provided that load consumption or demand is known at all busses, the load flow analysis can be used to determine [7,8] :

1. Voltage magnitude and phase angle at each bus.
2. Power flow in each branch (e.g., transformers and lines).
3. Power consumption at each power generation source.
4. Active power and/or reactive volt-amperes generation or consumption of each shunt element.
5. System losses.

Once this information is derived, the model can be adjusted to assure that all loads are supplied with power within specified limits of operation. The adjustments may include:

1. Generator set points.
2. Transformer tap selection.
3. Reactive power compensation.

4. Making emergency power available to satisfy voltage and frequency-operating limits.

The power flow calculations are used to check for under/over voltage, overloads, and assessment of losses.

Conventional distribution load flow methods [9,10] assume that electric power always flows from substations to the end of feeders, but introduction of distributing generation units causes reverse power flow and complicated voltage profiles in the distribution systems [11]. Also traditional load flow calculation methods are oriented to study looped and large systems thus, it is necessary to adopt a load flow calculation method specifically oriented for a radial distribution system with distributing generation that is fast, and uses less memory resources and that has good convergence features.

In this paper the network simulation is done by two different iterative methods, the first is adopted as a proposed distribution method while the second is used in order to approve the proposed method.

2.1 Ladder Load Flow Method:

In this work the power summation iterative method proposed by Baran & Wu [9,10] is extended here with several assumptions to implement distributing generation.

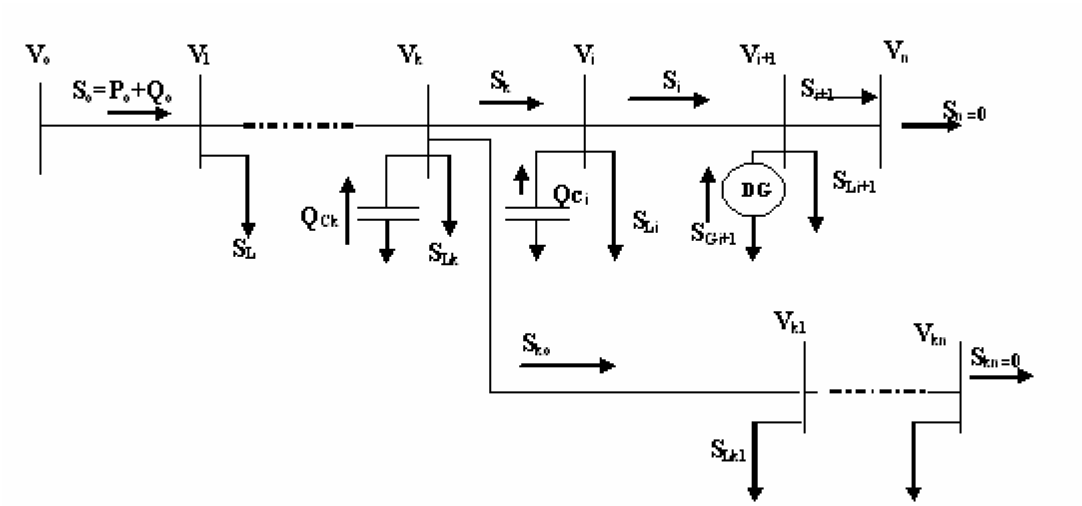

Figure (1) : One- Line Diagram for a Radial Distribution Feeder.

G (n) branches with a lateral branching out from the main feeder as shown in Figure (1). Lateral branching out from node (k) will be referred to as the lateral (k). In the figure, V_o represents the substation bus voltage magnitude and is assumed to be constant. Load flow is performed under the following assumptions:

1. The system is a balanced 3-phase system.

2. The distribution lines are modeled as series impedance, $Z_i = R_i + jX_i$.
3. The load at bus (i) is modeled as a constant power sink, $S_{Li} = P_{Li} + jQ_{Li}$.
4. Shunt capacitors to be placed at the nodes of the system will be represented as reactive power injections.
5. Distribution generator is represented by PQV model as a negative load referred to a PQ model with a constraint power factor. The voltage magnitude is limited to a specified value. Generation at bus (i) is modeled as a constant power source given by , $S_{Gi} = P_{Gi} + jQ_{Gi}$

The reactive generated power is constrained to the generator power factor (between +0.9 and -0.9) and because of the inductive manners of the load the generator power factor is assumed to equal 0.9. This assumption aims to cover the possible reactive power for the load locally.

$$Q_{G(k)} \le P_{G(k)} \times \tan(\cos^{-1} 0.9) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

If the power supplied from the substation $S_o = P_o + jQ_o$ is primarily specified then the active and reactive power and the voltage at the receiving end of the first branch can be calculated as follows:

$$S_1 = S_o - S_{loss1} - z_1 \frac{P_o^2 + Q_o^2}{|V_o|^2} - S_{L1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$V_1 \angle \theta_o = V_o - z_1 \frac{S_o^*}{V_o^*} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Similarly the active and reactive power flowing at the receiving end of branch (i+1), P_{i+1}, and Q_{i+1} and the voltage magnitude at the sending end $|V_{i+1}|$ for the nodes can be expressed by the following equations:

$$P_{i+1} = P_i - R_{i+1} \frac{P_i^2 + Q_i^2}{|V_i|^2} - P_{Li+1} + P_{Gi+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$Q_{i+1} = Q_i - X_{i+1} \frac{P_i^2 + Q_i^2}{|V_i|^2} - Q_{Li+1} + Q_{ci+1} + Q_{Gi+1} \quad \ldots\ldots\ldots\ldots (5)$$

$$|V_{i+1}|^2 = |V_i|^2 - 2(R_{i+1} . P_i + X_{i+1} . Q_i) + (R^2_{i+1} + X^2_{i+1}) \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad \ldots\ldots\ldots (6)$$

And at the end of main feeder $P_n = 0$ and $Q_n = 0$.

where:

P_i, Q_i: active and reactive powers flowing into the sending end of branch (i+1).

$|V_i|$: Bus voltage magnitude at node i.

Equations (4 to 6), are called the branch flow equations.

The process of formulation above can be repeated for the lateral by using the line flow equations and the new terminal conditions,

$V_{ko} = V_k$, $P_{kn} = 0$ and $Q_{kn} = 0$.

An iterative procedure following the flow chart shown in Figure (2) is developed to obtain the unique solution for the node voltages and hence line active and reactive power flow.

2.2 Newton-Raphson Method:

The Newton-Raphson method can be shortly described to be a numerical method used to solve the system of equations that has been formulated following the first law of Kirchhoff. Detailed description of this method is given in the literature [7,8].

Among the other load flow solutions the Newton-Raphson method is found to be more efficient and practical but it is computationally slow and is usually applied only in the case of looped network. The number of iterations required to obtain a solution is independent of the system size, but more functional evaluations are required at each iteration [8].

Because of its confidence and accuracy it is used in this work to check the validity of the proposed algorithm. The distributed generation node is modeled as PV bus and the reactive power is constrained to the limits of power factor control mode while the substation node is modeled as the slack bus.

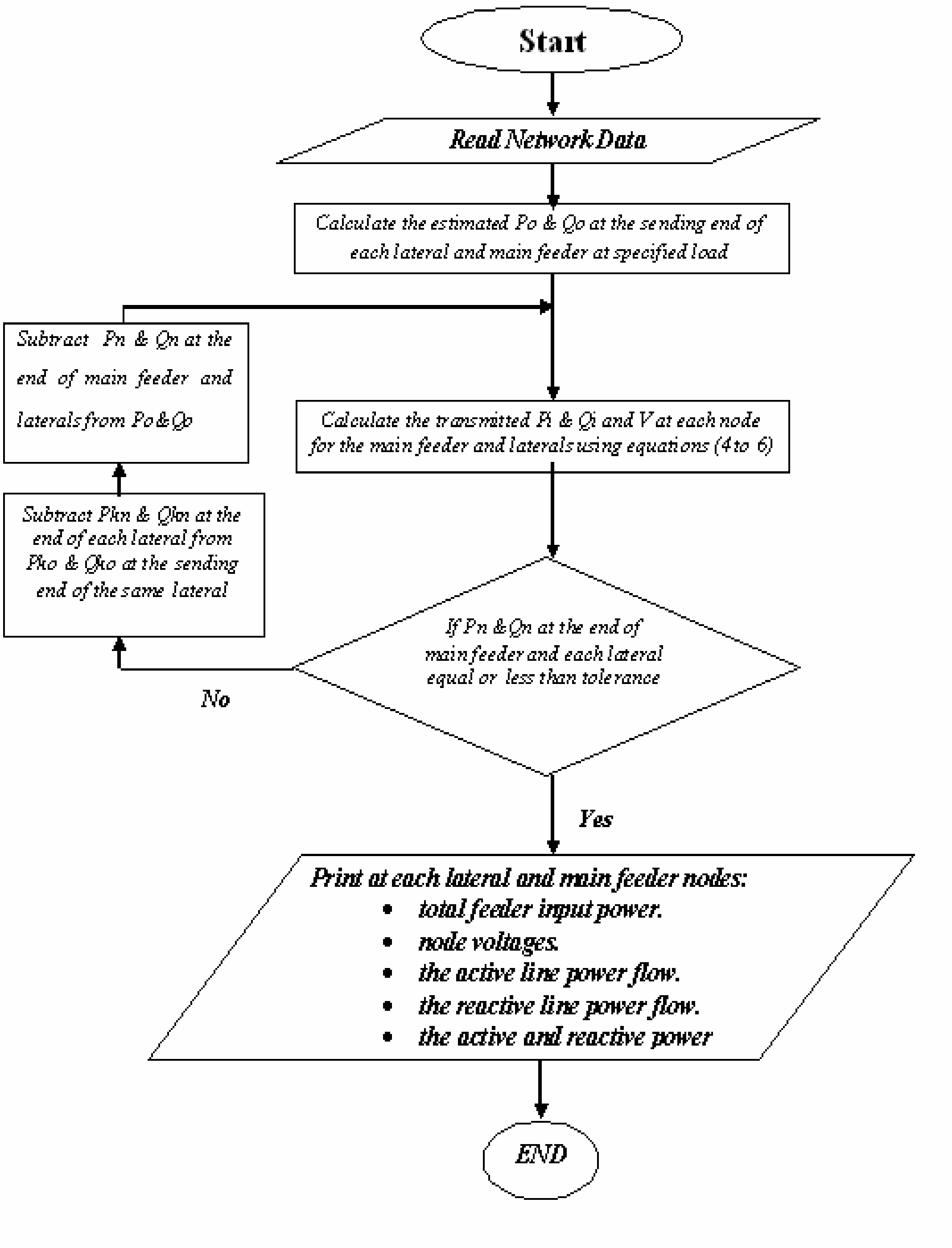

Figure (2): Flowchart for Distribution Load Flow.

3. Test and Results

In order to test the proposed algorithm, two examples of distribution systems are used. The first is a 23 kV radial distribution feeder with thirty sections and six lateral branches. This system is taken from Reference [1٢] and its one-line diagram is represented in Figure (3). The second is a typical 11 kV feeder with twenty-four sections and three laterals. The one-line diagram of this system is shown in Figure(4).

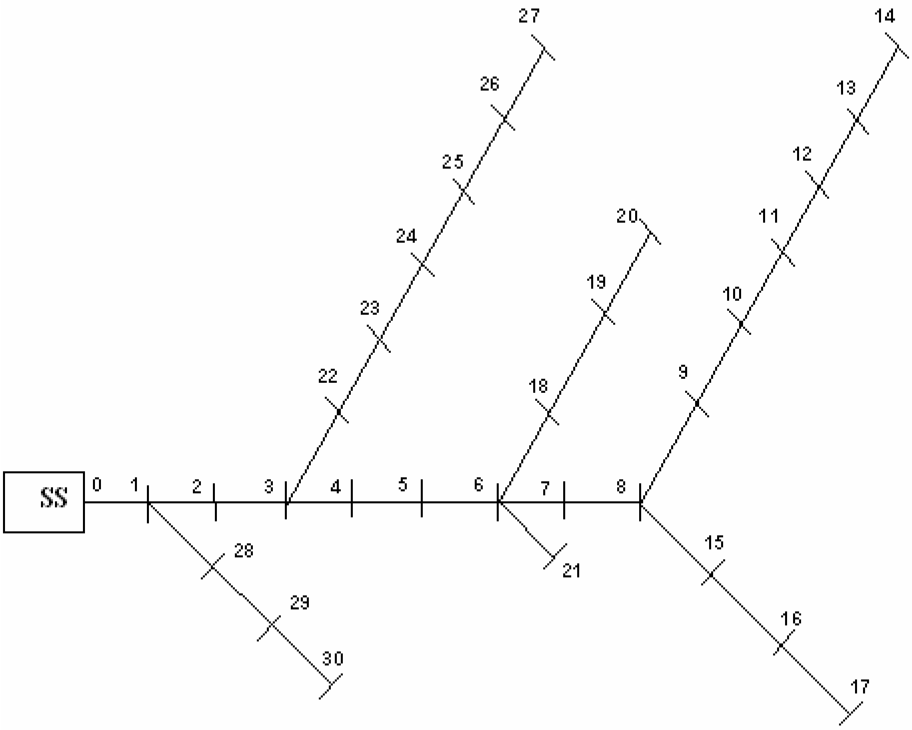

Figure (3) : One- Line Diagram for Test System No.1 .

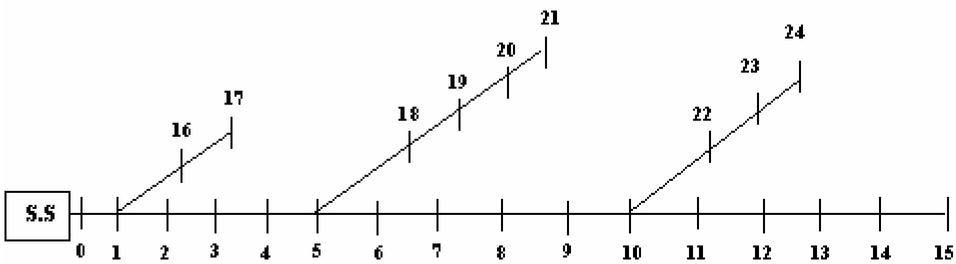

Figure (4): One- Line Diagram for Test System No.2 .

The corresponding technical and load data are given in Tables (A-1) and (A-2) in the Appendix for the first and the second systems respectively.

The load flow study is designed in programs using MATLAB V.6 on a personal computer. Some of the tabulated results using either of the two investigated methods for the tested systems are presented in Tables (1 to 4). There is no significant difference to the fourth digit between the results by using any of the two methods and for the studied cases of the two tested systems. Execution time (solution only) for implementing the two algorithms is shown in Tables (1 & 2) for system No.1 and system No.2 respectively with a tolerance of (0.000001). Other results from the proposed algorithm used to investigate in distributing generation are presented here :

Test System No. 1

The voltage profile under peak load conditions and the system losses for several studied cases are given in the Figures (٥ and ٦) respectively. This system is of high (*R/X*) ratio and the system and load conditions in the base case are chosen such that the voltage profile and the losses are clearly not within acceptable limits.

One distributing synchronous generator with (3.75+j1.25) MVA generation is used first. The DG is equipped with a regulator of 5% droop used here to bring the voltage to 1 P.U. at the nearest node to the substation at which the voltage drops to 0.95 (node No. 5) and seems to be insufficient to retained the voltage profile with the acceptable level. Other similar (of less rating) unit with (2.25+j 0.75) MVA generation is used at node 8 and clearly improves the feeder performance. Using the two units minimizes the system losses as shown in Figure (٦) and all the expected benefits related to leveling the voltage profile, reactive power compensation and feeder loss reduction are maintained.

Test System No. 2

A similar investigation on this system gives the same results in improving the feeder performance. This system contains power factor correction capacitors (Qc=50 kVAr) at each node. Here only one-DG unit is proposed to be as PQ source since all the feeder nodes voltages at the base case is within the acceptable limits as shown in Figure (7). The significant difference being that the DG sharing no longer shows an increasing positive effect on voltage support. Figure (8) shows the effects in the studied cases on the feeder losses.

4. Conclusions

This paper presents an evolved distribution load flow algorithm considering distributing generation. The algorithm is tested using two systems and the load flow results are approved by using the well-known Newton-Raphson iterative method.

Although this study doesn't investigate the advantages of the proposed method among the other solution methods it is clear that load flow calculation method specifically oriented for a radial distribution system is fast, and uses less memory resources and that have good convergence features. This is because for a Newton-Raphson method, high computation memory and time are required related to the functional evaluation to form and invert the Jacobian matrix of the network power values at every iteration step. This is justified through the results and shows the validity of the evolved algorithm.

Other results show that introducing DG to the distribution network presents many benefits related to the feeder performance and reliability.

Table (1): Execution Time for Distribution Load Flow Results (Test System No.1,)

	Without DG		**With DG at node (5).**	
Method	**Iterations**	**Execution Time**	**Iterations**	**Execution Time**
N-R	5	0.16 s	4	0.17 s
Ladder	10	0.11 s	12	0.16 s

Table (2) : Execution Time for Distribution Load Flow Results (Test System No.2,)

	Without DG		**With DG at node (9).**	
Method	**Iterations**	**Execution Time**	**Iterations**	**Execution Time**
N-R	3	0.11 s	4	0.17 s
Ladder	6	0.06 s	5	0.05 s

Table (3) : Distribution Load Flow Results for Test System No.1,
Using the Proposed Method (DG at Node 5).

Vrated =23 kV ***Vo =1.05 P.U.***					***P_G = 5 MW*** ***Q_G = 0.2846 MVAr***				
Feeder section	Rec. Node Voltage		Power Flow		Feeder section	Rec. Node Voltage		Power Flow	
	Mag. (PU)	Ang. (Deg.)	MW	MVAr		Mag. (PU)	Ang. (Deg.)	MW	MVAr
0-1	1.0236	-1.5615	10.7528	5.5330	15-16	0.9443	-2.1515	1.0285	0.3434
1-2	1.0202	-1.4754	7.9602	4.2168	16-17	0.9428	-2.1689	0.4777	0.1594
2-3	1.0129	-1.5953	7.4062	4.0411	6-18	0.9739	-1.8266	1.6075	0.5401
3-4	1.0033	-1.5681	2.3898	2.2946	18-19	0.9692	-1.9407	1.1727	0.3937
4-5	1.0000	-1.5252	1.4300	1.9619	19-20	0.9675	-1.9610	0.4958	0.1655
5-6	0.9759	-1.7793	6.4239	2.2412	6-21	0.9755	-1.7870	0.2071	0.0690
6-7	0.9619	-1.9296	4.4639	1.5501	3-22	1.0059	-1.7879	4.9713	1.7019
7-8	0.9479	-2.0843	4.4040	1.5164	22-23	1.0021	-1.8938	4.4206	1.4996
8-9	0.9390	-2.1843	2.8361	0.9781	23-24	0.9986	-1.9755	2.4897	0.8468
9-10	0.9306	-2.2790	2.6220	0.9009	24-25	0.9897	-2.1862	2.4822	0.8403
10-11	0.9056	-2.5730	2.6002	0.8886	25-26	0.9862	-2.2711	1.3472	0.4518
11-12	0.8955	-2.6966	2.1987	0.7398	26-27	0.9835	-2.3018	0.7941	0.2652
12-13	0.8926	-2.7322	1.5187	0.5078	1-28	1.0212	-1.5255	2.6648	0.8892
13-14	0.8898	-2.7673	0.7312	0.2442	28-29	1.0148	-1.5942	1.7762	0.5949
8-15	0.9461	-2.1306	1.5080	0.5046	29-30	1.0126	-1.6187	0.8838	0.2950

Table (4): Distribution Load Flow Results for Test System No.2, Using the Proposed Method (DG at Node 9).

V rated =11 kV *Vo= 1 P.U.*	*load factor = 1* *load p.f = 0.85 lag.*				*P_G= 3.81 MW* *Q_G= 1.8453 MVAr*				
Feeder section	**Rec.Node Voltage**		**Power Flow**		**Feeder section**	**Rec.Node Voltage**		**Power Flow**	
	Mag. (PU)	Ang. (Deg.)	MW	MVAr		Mag. (PU)	Ang. (Deg.)	MW	MVAr
0-1	0.9991	0.0056	1.1726	1.2406	12-13	0.9963	0.1364	0.6379	0.3949
1-2	0.9978	0.0220	0.4912	0.8195	13-14	0.9959	0.1305	0.4252	0.2632
2-3	0.9975	0.0278	0.2779	0.6871	14-15	0.9958	0.1290	0.2125	0.1315
3-4	0.9972	0.0431	0.0652	0.5554	1-16	0.9989	0.0030	0.6801	0.4201
4-5	0.9970	0.0613	-0.1474	0.4237	16-17	0.9988	0.0017	0.3400	0.2100
5-6	0.9988	0.1513	-0.9978	-0.1027	5-18	0.9968	0.0581	0.8503	0.5263
6-7	0.9992	0.1652	-1.3395	-0.3145	18-19	0.9966	0.0557	0.6376	0.3946
7-8	0.9998	0.1877	-1.5524	-0.4464	19-20	0.9965	0.0540	0.4250	0.2631
8-9	1.0000	0.1930	-1.8933	-0.6573	20-21	0.9965	0.0532	0.2125	0.1315
9-10	0.9989	0.1759	1.7040	1.0562	10-22	0.9987	0.1735	0.6377	0.3947
10-11	0.9972	0.1502	1.0647	0.6598	22-23	0.9985	0.1707	0.4251	0.2631
11-12	0.9967	0.1433	0.8507	0.5268	23-24	0.9985	0.1681	0.2125	0.1315

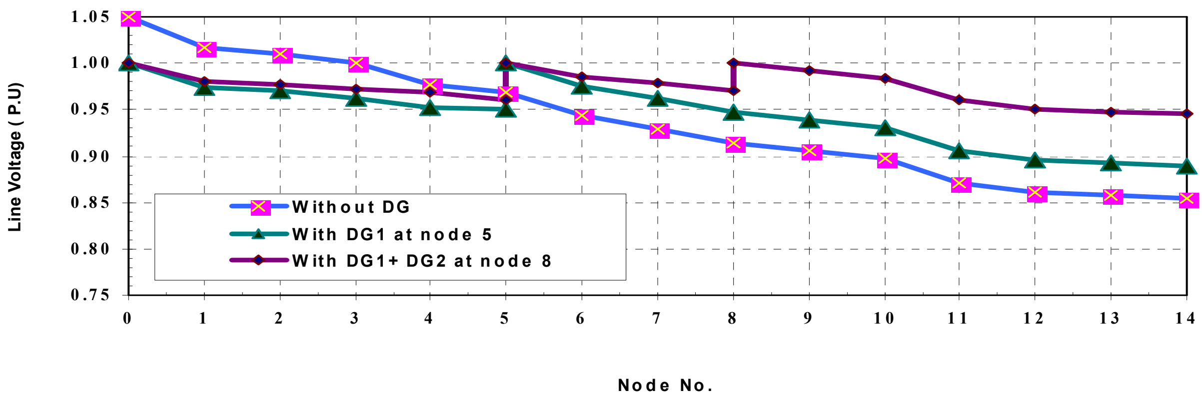

Figure (5) : Voltage Profile for Test System No. 1

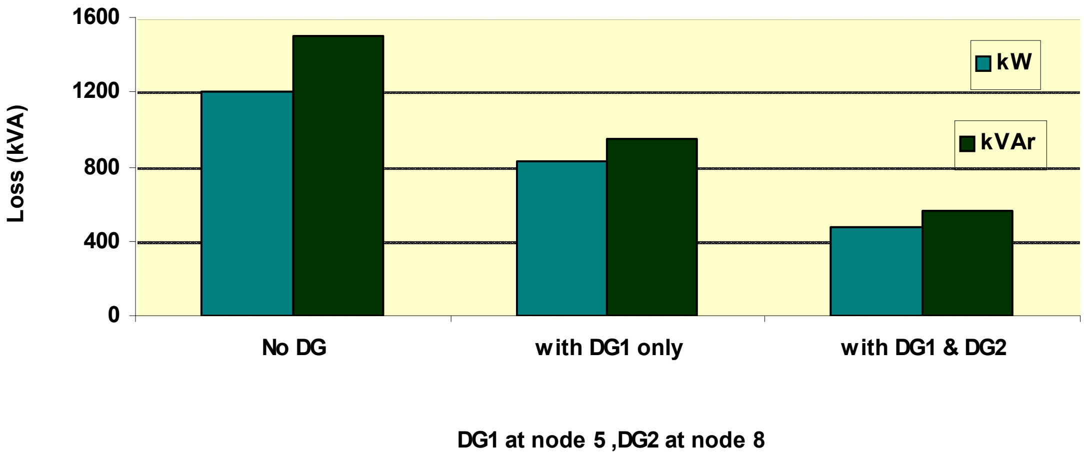

Figure (6): Active and Reactive Power Loss for Test System No. 1.

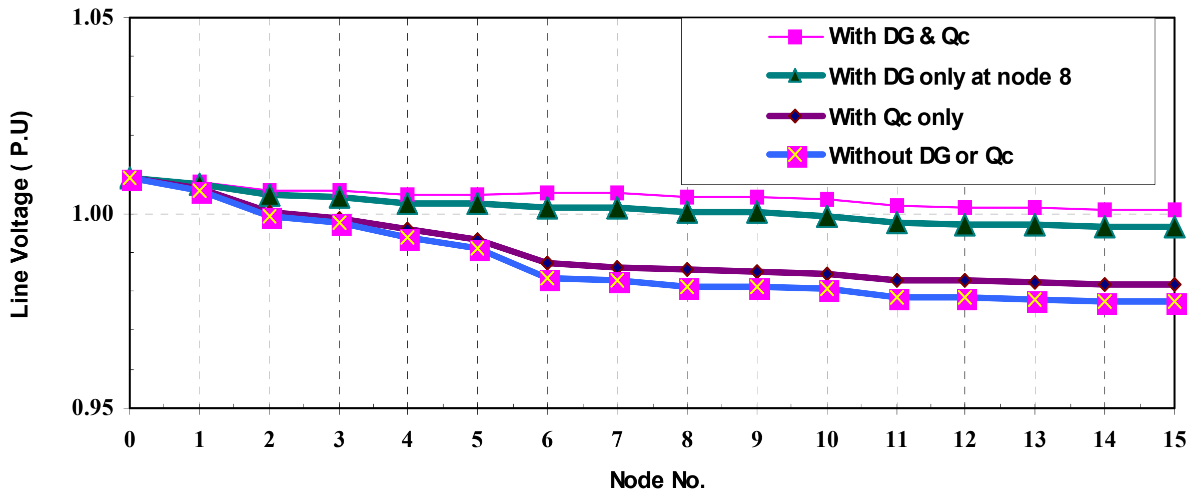

Figure (7) : Voltage Profile for Test System No. 2.

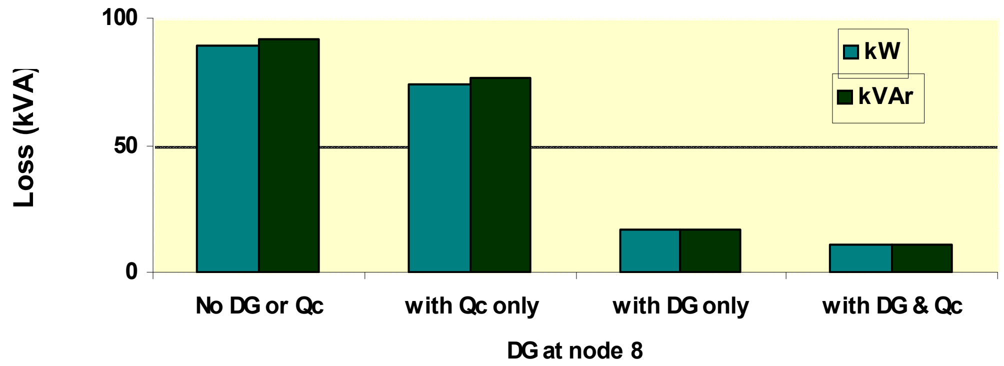

Figure (8) :Active and Reactive Power Loss for Test System No. 2

Vrated =23 kV Vo =1.05 P.U.									
Feeder section	R (Ω)	X (Ω)	Load		Feeder section	R (Ω)	X (Ω)	Load	
			MW	MVAr				MW	MVAr
0-1	0.5096	1.7030	0	0	15-16	0.7282	0.4102	0.549	0.183
1-2	0.2191	0.0118	0.522	0.174	16-17	1.3053	0.7353	0.477	0.159
2-3	0.3485	0.3446	0	0	6-18	0.4838	0.4206	0.432	0.144
3-4	1.1750	1.0214	0.936	0.312	18-19	1.5898	1.3818	0.572	0.224
4-5	0.5530	0.4806	0	0	19-20	1.5389	0.8669	0.495	0.165
5-6	1.6625	0.9365	0	0	6-21	0.6048	0.5257	0.207	0.069
6-7	1.3506	0.7608	0	0	3-22	0.5639	0.5575	0.522	0.174
7-8	1.3506	0.7608	0	0	22-23	0.3432	0.3393	0.2917	0.639
8-9	1.3259	0.7469	0.189	0.063	23-24	0.5728	0.4979	0	0
9-10	1.3259	0.7469	0	0	24-25	1.4602	1.2692	1.116	0.372
10-11	3.9709	2.2369	0.336	0.112	25-26	1.0627	0.9237	0.549	0.183
11-12	1.8549	1.0449	0.657	0.219	26-27	1.5114	0.8514	0.792	0.264
12-13	0.7557	0.4257	0.783	0.261	1-28	0.4659	0.0251	0.882	0.294
13-14	1.5389	0.8669	0.729	0.243	28-29	1.6351	0.9211	0.882	0.294
8-15	0.4752	0.4131	0.477	0.159	29-30	1.1143	0.6277	0.882	0.294

load factor = 1 Vo=11.0 kV load p.f = 0.85 lag.							
Feeder section	R (Ω)	X (Ω)	Load (MVA)	Feeder section	R (Ω)	X (Ω)	Load (MVA)
0-1	0.04960	0.04240	0	12-13	0.05148	0.05460	0.250
1-2	0.11550	0.12250	0.250	13-14	0.06600	0.07000	0.250
2-3	0.03135	0.03325	0.250	14-15	0.03300	0.03500	0.250
3-4	0.06600	0.07000	0.250	1-16	0.01815	0.01925	0.400
4-5	0.06600	0.07000	0	16-17	0.01815	0.01925	0.400
5-6	0.19800	0.21000	0.400	5-18	0.01815	0.01925	0.250
6-7	0.02640	0.02800	0.250	18-19	0.01815	0.01925	0.250
7-8	0.03960	0.04200	0.400	19-20	0.01815	0.01925	0.250
8-9	0.00825	0.00875	0.250	20-21	0.01815	0.01925	0.250
9-10	0.04785	0.05075	0	10-22	0.01815	0.01925	0.250
10-11	0.11550	0.12250	0.250	22-23	0.03120	0.03350	0.250
11-12	0.03828	0.04060	0.250	23-24	0.03120	0.03350	0.250

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