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A Graph Theory Based Approach for Voltage Sag Assessment in Distribution Network

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***Abstract*—Voltage sags are the most common power disturbances. In this paper an effective approach for voltage sag assessment has been carried out using network reconfiguration. Network reconfiguration is a method used in graph theory for reducing the complexity of networks. An IEEE 14 bus system is taken as test system. The 14 bus system is reduced to 12 bus system using node elimination technique. Voltage sag was introduced in bus number 9. Load flow analysis was done using Newton-Raphson method. Stability assessment was done for both normal and during voltage sag condition in original 14 bus and reconfigured 12 bus systems. The programs were developed using MATLAB software. The results obtained in the reconfigured systems were encouraging.**

Index terms— voltage sag, node elimination technique, graph theory, network reconfiguration.

I. INTRODUCTION

During the last few decades, voltage stability issues have been received considerable focus primarily due to a number of stability accidents that occurred in some countries [1]. Voltage stability problem has been one of the major problems facing the electric power utilities [2]. Voltage stability is a problem in power system which is lack of reactive power support when heavily loaded or the network transfer capability is reduced due to disturbances [3]. The problem of voltage stability concerns the whole power system, although it usually has a large involvement in one critical area of the power system [4]. The problem is also a main concern in power system operation and planning [5]. It can be characterized by a continuous decrease of the system voltage. In the initial stage the decrease of the system voltage starts gradually and then decreases rapidly [6].

Many researchers define the following terminology related to voltage stability:

"Voltage Stability" is concerned with the ability of a electrical power system to maintain acceptable voltages so that when load admittance is increased, load power will increase and that both power and voltage are controllable [7].Voltage instability" is the absence of voltage stability and results in progressive voltage decrease (or increase). Voltage instability is a dynamic process [7]. A power system is a dynamic system, in contrast to rotor angle stability, the dynamics mainly involve the loads and the means for voltage control.

II. VOLTAGE SAG

Voltage magnitude is one of the parameters that determine the quality of power supply. A decrease in voltage magnitude may result in voltage sag which is currently considered as one of the main power quality problems. Voltage sag is defined as a decrease in magnitude between 0.1 and 0.9 pu in rms voltage at a power frequency of duration from 0.5 cycle to 1 min (IEEE Std 1159, 1995) [8]. Voltage sags are caused by abrupt increase in loads, short circuits or increase in source impedance. Voltage sag may cause sensitive equipment to malfunction and process interruption and therefore are highly undesirable. Researches have been done on voltage sag assessment by means of time-domain simulation tools and stochastic prediction which had been a time consuming process.

A. Causes of Voltage Sags

There are various causes for voltage sags to occur. Major causes among them are due to the following reasons

- Unbalanced load
- Short circuit
- Over load

During unbalanced load condition the bus voltage changes abruptly from high to low values leading to voltage sag condition. When there is any short circuit occurring in any part of the power system there occurs voltage sag condition. Under overload conditions the bus voltage falls down to an extent leading to voltage sag condition [9].

B. Classification of voltage sags

Based on the fault occurring in number of phases of the transmission lines the voltage sags in a power network can be classified into three major types. They are the following

Single phase sags:

The most common voltage sags, over 70%, are single phase events which are typically due to a phase to ground fault occurring somewhere on the system. This phase to ground fault appears as single phase voltage sag on other feeders from the same substation [9]. Typical causes are lightning strikes, tree branches, animal contact etc. It is not uncommon to see single phase voltage sags to 30% of nominal voltage or even lower in industrial plants.

Phase to Phase Sags:

Two Phase, phase to phase sags may be caused by tree branches, adverse weather, animals or vehicle collision with utility poles. The two phase voltage sag will typically appear on other feeders from the same substation [9].

Three Phase Sags:

Symmetrical 3 phase sags account for less than 20% of all sag events and are caused either by switching or tripping of a 3 phase circuit breaker, switch or recloser which will create 3 phase voltage sag on other lines fed from the same substation. 3 phase sags will also be caused by starting large motors but this type of event typically causes voltage sags to approximately 80% of nominal voltage and is usually confined to an industrial plant or its immediate neighbours [9].

C. Characteristics of voltage sag

The power systems faults not only cause a drop in voltage magnitude but also cause change in the phase-angle of the voltage. The parameters used to characterize voltage sag are magnitude, duration, point-on-wave sag initiation and phase angle jump [10].

Voltage Sag Magnitude:

The magnitude of voltage sag can determine in a number of ways. The most common approach to obtain the sag magnitude is to use rms voltage. There are other alternatives, e.g. fundamental rms voltage and peak voltage. Hence the magnitude of the sag is considered as the residual voltage or remaining voltage during the event [11]. In the case of a three phase system, voltage sag can also be characterized by the minimum RMS-voltage during the sag. If the sag is symmetrical i.e. equally deep in all three phases, if the sag is unsymmetrical, i.e. the sag is not equally deep in all three phases, the phase with the lowest remaining voltage is used to characterize the sag [12].

Voltage Sag Duration:

The duration of voltage sag is mainly determined by the fault–clearing time. The duration of voltage sag is the amount of time during which the voltage magnitude is below threshold is typically chosen as 90% of the nominal voltage magnitude [13]. For measurements in the three-phases systems the three rms voltages have to be considered to determine duration of the sag. The voltage sag starts when at least one of the rms voltages drops below the sag-starting threshold. The sag ends when all three voltages have recovered above the sag ending threshold [14].

Phase Angle Jump:

A short circuit in a power system not only causes a drop in voltage magnitude but also a change in the phase angle of the voltage [15]. In a 50 Hz system, voltage is a complex quantity which has magnitude and phase angle. A change in the system, like a short circuit, causes a change in voltage. This change is not limited to the magnitude of the voltage but includes a change in phase angle as well. The phase angle jump manifests itself as a shift in zero crossing of the instantaneous voltage [16]. Phase-angle jumps are not of concern for most equipment. But power electronics converters using phase-angle information for their firing instants may be affected.

III. Load Flow Solutions

Load-flow studies are performed to determine the steady-state operation of an electric power system. It calculates the voltage drop on each feeder, the voltage at each bus, and the power flow in all branch and feeder circuits. Determine if system voltages remain within specified limits under various contingency conditions, and whether equipment such as transformers and conductors are overloaded [17].

The power flow or load flow is widely used in power system analysis. It plays a major role in planning the future expansion of the power system as well as helping to run existing systems to run in the best possible way. The network load flow solution techniques are used for steady state and dynamic analysis programs [18]. The solution of power flow predicts what the electrical state of the network will be when it is subject to a specified loading condition [19]. The result of the power flow is the voltage magnitude and the angle at each of the system nodes [20]. These bus voltage magnitudes and angles are defined as the system state variables.

A. Methods of Calculating Load Flow

The methods of calculating load flow for the system are attained by,

- Classical methods
- Other methods

Classical Methods:

The classical methods of calculating load flow is,

1) Gauss-Seidal method
2) Newton Raphson method
3) Fast Decoupled method

IV. Stability Indices

In this work Newton Raphson method is used for load flow analysis of 14 bus system and reconfigured 12 bus system during normal and voltage sag conditions.

The condition of voltage stability in a power system can be known using voltage stability indices. These indices may be based on static analysis or dynamic models of the power systems [21]. They can either reveal the critical bus of a power system or the stability of each line connected between two buses in an interconnected network or evaluate the voltage stability margins of a system.

A. Types of Stability Indices

1. Loading margin
2. Line stability index
3. Voltage collapse prediction index
4. Power transfer stability index

Loading Margin:

Loading Margin is the most basic and widely accepted method to approximate voltage collapse in the power system. The PV and QV curves shown in Fig. 1. and Fig. 2. are the most used to determine the loading margin of a power system at an individual load bus [22].

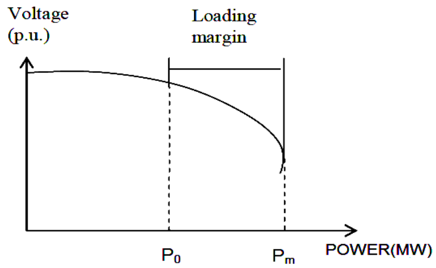

Fig. 1. PV Curve

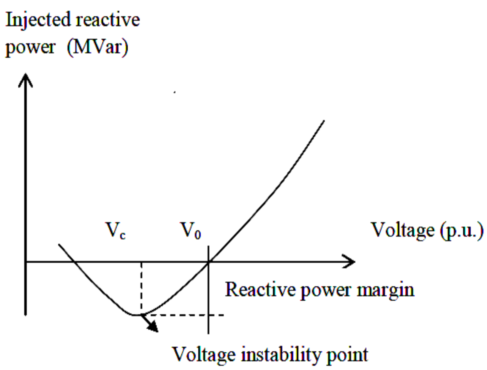

Fig. 2. QV Curve

Line Stability Index:

A line stability index based on the power transmission concept in a single line, in which the discriminator of the voltage quadratic equation is set to be greater or equal than zero to maintain stability [22].

The line stability can be defined as

$$Lmn = \frac{4XQ}{[V_s \sin(\theta - \delta)]^2}$$

Where,

Vs ∠δs,Vr ∠δr are the sending and receiving end voltages.

R+jX is the impedance of the transmission line.

P+jQ is the receiving end apparent power.

θ is the impedance angle.

δ is the angle between the supply voltage and receiving end voltage.

L_{mn} calls the stability index of that line. It is used to find the stability index for each line connected between two bus bars in an interconnected network. Based on the stability indices of lines, voltage collapse can be predicted. When the stability index L_{mn} less than 1, the system is stable and when this index exceeds the value 1, the whole system loses its stability and voltage collapse occurs.

Voltage Collapse Prediction Index:

$$VCPI_k = \left| 1 - \frac{\sum_{m1, m=k}^{N} V'_m}{V_k} \right|$$

$$V'_m = \frac{Y_{km}}{\sum_{j=1, j \neq k}^{N} Y_{kj}}$$

Vk is the voltage phasor at bus k.

Vm is the voltage phasor at bus m.

Ykm is the admittance between bus k and m.δ

Ykj is the admittance between bus k and j.

m is the other bus connected to bus k.

N is the bus set of the system.

The value of VCPI varies between 0 and 1. If the index is zero, the voltage at bus k is considered stable and if the index is unity, a voltage collapse is said to occur [22].

V. ROLE OF RECONFIGURATION

The system configuration can be changed by manual or automatic switching operations. A proper reconfiguration scheme can reduce the power loss in the network. The reconfiguration also tackles the problems of overloading of network components and improves voltage stability [23].

Network reconfiguration is performed by opening sectionalizing (normally closed) and closing tie (normally open) switches of the network [24]. A normally open tie switch is closed to transfer load from one feeder to another while an appropriate sectionalizing switch is opened to restore the radial structure. It has been observed that the voltage Stability of a system can be improved if the overall active power loss in the system is minimized, which comprise of the aggregate of active power losses in each line. Thus, for a given operating condition, if the active power loss in the system can be reduced, the system-wide voltage stability can be improved. In the present case study on the IEEE system, each of the power line is assumed to be connected through series sectionalizing switches. Loss minimization, thus, can be achieved by modifying the switching states of the entire system and converting the system configuration to a radial one. During the course of reconfiguration, the following two important criteria must be maintained:

1. No buses can be left out of service.
2. During each operation, active power flow through a line should be within maximum power transfer capability of the line.

Load Flow solution is not at all a practical solution to the problem. In the proposed method optimum switching state for a given operating condition is obtained by using Graph Theory [25].

VI. RESULTS AND DISCUSSIONS

Improvement of voltage stability in a power network can be achieved by network reconfiguration which involves alteration of the topological structure of power lines [25].

A Graph of a network is a collection of set of points or nodes interconnected by some links [25]. For a power network, the buses may be represented as nodes or vertices [25]. The links those connect any pair of nodes are called the edges. Mathematically, a graph can be defined as a set of nodes or vertices V, and a set of links or edges E, connecting them, as G = {V,E}

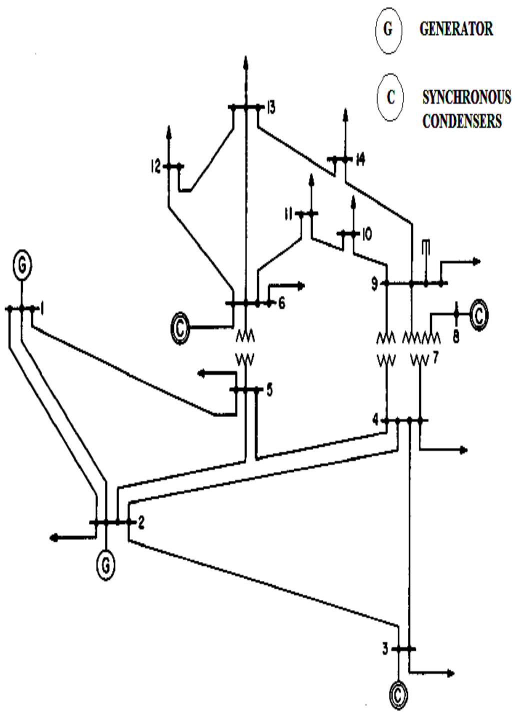

Fig. 3. Test System of 14 Bus System

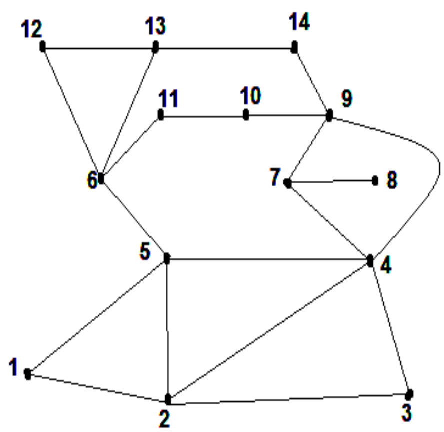

Fig. 4. Graph of an IEEE 14 bus system

The IEEE 14 bus system is reconfigured to a 12 bus system using network reconfiguration technique which is a method in graph theory.

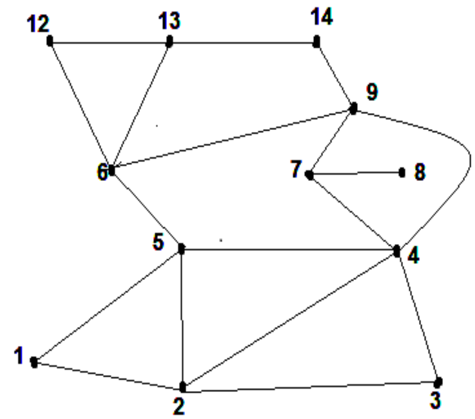

Fig. 5. Reconfigured 12 bus system

The Table I and Table II shows the line index values for 14 bus system and 12 bus system under normal condition. The Table III and Table IV shows the line index values for 14 bus and 12 bus system under voltage sag condition. In both the system, line 4-9 is found to be unstable.

TABLE I. LINE INDEX VALUES FOR 14 BUS SYSTEM

LINE NO	LINE INDEX VALUE
1-2	0.02307
1-5	0.05797
2-3	0.00385
2-4	0.00367
2-5	0.01179
3-4	0.03435
4-5	0.02060
4-7	0.03252
4-9	0.02546
5-6	0.14910
6-12	0.03024
6-11	0.03992
6-13	0.04582
7-8	0.05185
7-9	0.01211
9-14	0.03652
9-10	0.01136
10-11	0.02208
12-13	0.01483
13-14	0.03912

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TABLE II. LINE INDEX VALUES FOR RECONFIGURED 12 BUS SYSTEM

LINE NO	LINE INDEX VALUE
1-2	0.01440
1-5	0.05370
2-3	0.00482
2-4	0.00942
2-5	0.00763
3-4	0.03074
4-5	0.02219
4-7	0.04108
4-9	0.00173
5-6	0.15064
6-9	0.02297
6-12	0.02809
6-13	0.04133
7-8	0.03840
7-9	0.00063
9-14	0.04743
12-13	0.01190
13-14	0.02423

TABLE III. LINE INDEX VALUES FOR 14 BUS SYSTEM DURING VOLTAGE SAG

LINE NO	LINE INDEX VALUE
1-2	0.02160
1-5	0.07891
2-3	0.04149
2-4	0.10745
2-5	0.08895
3-4	0.13906
4-5	0.01610
4-7	0.22648
4-9	1.45265
5-6	0.16925
6-11	0.14614
6-12	0.04084
6-13	0.08540
7-8	0.11789
7-9	0.19312
9-10	0.01032
9-14	0.00671
10-11	0.08371
12-13	0.02661
13-14	0.14483

TABLE IV. LINE INDEX VALUES FOR RECONFIGURED 12 BUS SYSTEM DURING VOLTAGE SAG

LINE NO	LINE INDEX VALUE
1-2	0.02918
1-5	0.10769
2-3	0.02851
2-4	0.09789
2-5	0.08464
3-4	0.13993
4-5	0.00685
4-7	0.18159
4-9	1.42176
5-6	0.17084
6-9	0.29495
6-12	0.04353
6-13	0.08497
7-8	0.13103
7-9	0.17243
9-14	0.02613
12-13	0.03050
13-14	0.14783

TABLE V. POWER LOSS IN LINES FOR 14 BUS SYSTEM

LINE NO.	P_{Loss} (Mw)	Q_{Loss} (MVAr)
4-9	0.000	1.12
7-9	0.000	1.00
9-10	0.015	0.04
9-14	0.131	0.28

TABLE VI. POWER LOSS IN LINES FOR RECONFIGURED 12 BUS SYSTEM

LINE NO.	P_{Loss} (Mw)	Q_{Loss} (MVAr)
4-9	0.000	0.93
6-9	0.012	0.03
7-9	0.000	0.57
9-14	0.140	0.30

The Table V and Table VI gives the power loss in lines connected with bus 9 for 14 bus system and reconfigured 12 bus system. It is found that the reactive power loss in

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reconfigured 12 bus system is quite lesser than original 14 bus system.

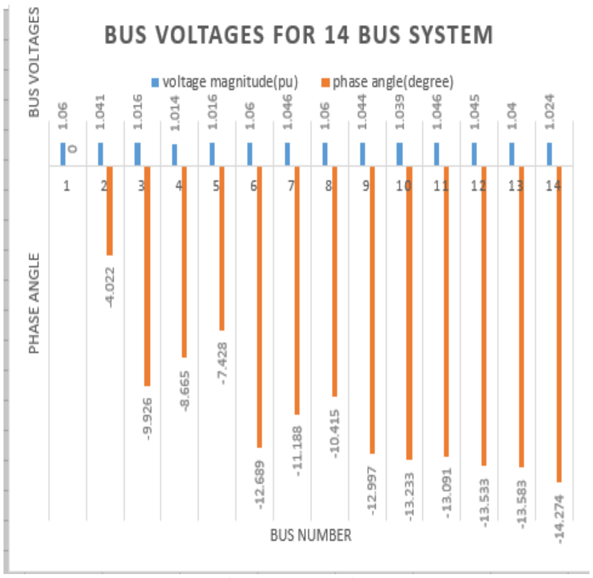


Fig. 6. Graph of bus voltages for 14 bus system

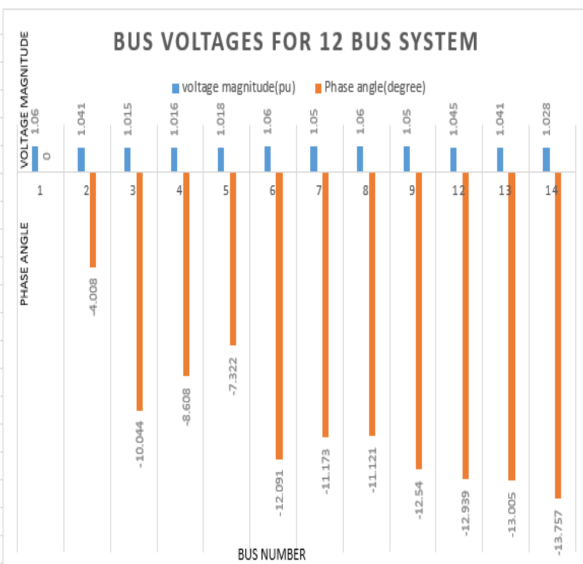


Fig. 7. Graph of bus voltages for 12 bus system

The Fig. 6. and Fig. 7. show the graph of bus voltages for 14 bus system and reconfigured 12 bus system. The graph shows the voltage magnitude and phase angle of all the buses in both the system. In the original 14 bus system all buses are taken into account. Whereas in reconfigured 12 bus system only 12 bus voltages and phase angle are taken into account.

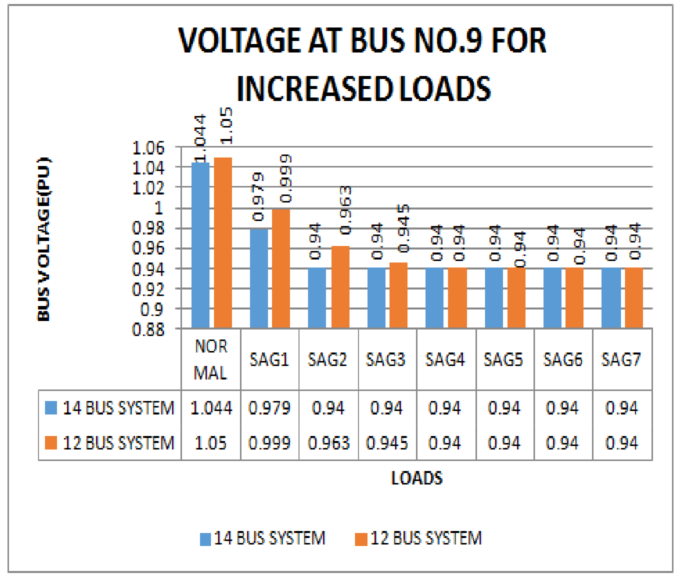


Fig. 8. Voltage at bus no.9 for increased loads

The graph in Fig. 8 shows the voltage at bus number 9 decreases with increase in load. The bus voltages are given in per unit system. The bus voltage at bus number 9 during normal operating condition is indicated as normal in the graph. The bus voltages with respect to sag conditions are due to increase in load are displayed in the graph as sag1 to sag7. Sag1 to sag7 indicates occurrence of voltage sag due to continuous 7 different loading conditions. The load at bus number 9 is increased because bus number 9 is present both in 14 bus system and reconfigured 12 bus system.

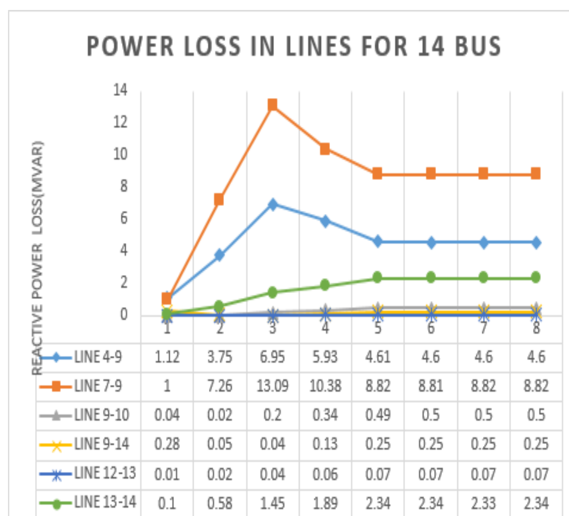
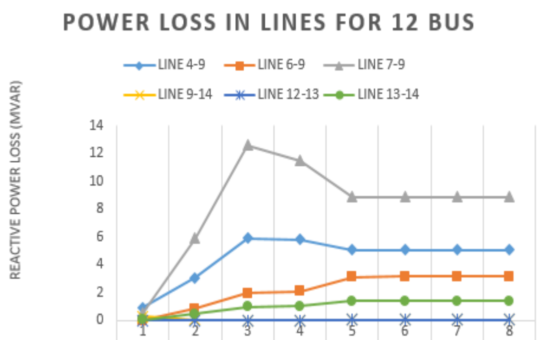


Fig. 9. Power loss in lines for 14 bus system

The power loss in different lines such as 4-9, 7-9, 9-10, 9-14, 12-13, 13-14 is shown in Fig. 9. The power loss curve is drawn for different loads at bus 9 in different lines of a 14 bus system.



	1	2	3	4	5	6	7	8
LINE 4-9	0.93	3.09	5.9	5.82	5.1	5.09	5.09	5.09
LINE 6-9	0.03	0.83	1.97	2.1	3.15	3.18	3.18	3.19
LINE 7-9	0.57	5.91	12.59	11.48	8.9	8.89	8.89	8.89
LINE 9-14	0.3	0.06	0	0.01	0.04	0.04	0.04	0.04
LINE 12-13	0	0.02	0.03	0.03	0.04	0.05	0.05	0.05
LINE 13-14	0.08	0.48	0.97	1.02	1.43	1.43	1.42	1.43

Fig. 10. Power loss in lines for 12 bus system

Similarly in reconfigured 12 bus system also the different loads are applied in bus 9 and power loss in various lines such as 4-9, 6-9, 7-9, 9-14, 12-13, 13-14 are obtained. The power loss in lines for 12 bus system is shown in Fig. 10.

VII. Conclusion

Generally voltage stability is analyzed using load flow method. But in this method, numerous solutions are involved under both normal and abnormal operating condition of power system. The introduction of graph theory reduced the disadvantage of load flow analysis. In this thesis the stability index such as Line index is calculated for the standard IEEE 14 bus system and also for the reconfigured 12 bus system to find out these indices, the output of load flow for IEEE 14 bus and reconfigured 12 bus systems were calculated using Newton–Raphson method. The programs were developed using MATLAB. Voltage sag is introduced in both the original 14 bus and reconfigured 12 bus system. Stability assessment with voltage sag has been done using graph theory and stability indices. The results have proved that the voltage stability assessment can be well determined using Reconfigured systems compare to the actual system. The results show that the power loss and reactive power has been considerably reduced. It is also identified that the analysis can be made for the simple or reconfigured systems instead of the entire complicated system.

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