Analysis of Unbalanced Radial Distribution System with Summer Time Varying Load and Growth

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Abstract—In this paper the analysis of unbalanced radial distribution system (ubrds) is carried out under type A and type B unbalances. Impact of these unbalances on the system performances is investigated in terms of voltage profile, total power losses, cost of energy loss, and voltage stability index (VSI). This paper includes identifying the closeness critical bus which is the most sensitive to the voltage collapse in ubrds. Node having minimum value of voltage stability index is the most sensitive node. VSI values are computed for distribution network with and without consideration of the load unbalances. The most sensitive bus in terms of voltage stability is determined under these unbalanced scenarios. Majority of the existing research papers are designed for radial balanced distribution feeders with time invariant load. In this paper, the impact of time varying load flow with realistic load model is considered. The load growth factor has also been considered which is essential for the planning and expansion of the existing systems. The impact of the realistic load model as ZIP load model consists of residential, industrial and commercial has been considered for study of the test system. The analysis is carried out on 25 bus ubrds.

Keywords: Unbalanced Radial Distribution Systems, Voltage Stability Index, ZIP load model, Seasonal load and load growth.

I. INTRODUCTION

The deregulated market requires a great deal of attention to satisfy reliability, security and optimization objectives. As is well known, the voltage stability problem may become more and more frequent in this new scenario. Voltage stability has become a critical issue for electrical power transmission and distribution systems because of: (i) continuing increases in demand; (ii) the transfer of high powers between several interconnected areas; (iii) economic and environmental constraints, that have resulted in investment delays; and (iv) high penetration of emerging new and renewable energy sources in both distribution and transmission systems.

Voltage stability of a distribution system is one of the keen interests of industry and research sectors around the world. It concerns stable load operation, and acceptable voltage levels all over the distribution system buses. The distribution system in a power system is loaded more heavily than ever before and operates closer to the limit to avoid the capital cost of building new lines. When a power system approaches the voltage stability limit, the voltage of some buses reduces rapidly for small increments in load and the controls or operators may not be able to prevent the voltage decay. In some cases, the response of controls or operators may aggravate the situation and the ultimate result is voltage collapse. Voltage collapse has become an increasing threat to power system security and reliability. Many incidents of system blackouts because of voltage stability problems have been reported worldwide [1-2]. In order to prevent the occurrence of voltage collapse, it is essential to accurately predict the operating condition of a power system. So electrical engineers need a fast and accurate voltage stability index (VSI) to help them monitoring the system condition. Nowadays, a proper analysis of the voltage stability problem has become one of the major concerns in distribution power system operation and planning studies.

Currently, most electrical power systems operate very close to their stability limits and it is crucial to keep both efficiency and security at appropriate levels [3]. The objective in power systems operation is to serve energy with acceptable voltage and frequency to consumers at minimum cost. Thus, an accurate knowledge of how far the current system's operating point is from the voltage instability limit is crucial to system operators, which often need to assess if the system has a secure and feasible operation point following a given disturbance, such as a line outage or sudden change in system loading [4]. Voltage stability analyses can be assessed by obtaining voltage profiles of critical buses as a function of their loading conditions. These voltage profiles, or shortly PV curves, provide considerable

insight into the system's behavior and operating conditions for different loading levels, and have been used by the electric power industry for assessing voltage stability margins and the areas prone to voltage collapse. The methods [5-13] and [14-17] are adopted for the voltage stability analysis of radial balanced and unbalanced distribution systems respectively. A fast method to determine the voltage stability limit of power system was proposed by Haque [5]. Analytical approach to voltage collapse proximity determination is proposed for radial networks by Gubina, et al. [6]. Moghavvemi, et al. [7] proposed bus/line stability indices which is obtained from the solution of the line receiving end reactive power equation (Qr) and the line receiving end active power equation (Pr) of the reduced two-bus equivalent network. In [8], Chakravorty, et al. proposed a new stability index based on well-known bi-quadratic equation relating the voltage magnitudes at the sending and receiving ends and power at the receiving end of the branch. Two simple methods to evaluate two efficient voltage collapse proximity indicators are presented in [9] by Augugliaro, et al. to find the the weakest node, where voltage instability phenomenon can occur bringing the whole system to the voltage collapse, and evaluate the maximum loading capability of the entire system or of the weakest node, beyond which voltage collapse takes place. A new bus stability index is developed by Chaturvedi, et al. [10] from the line receiving bus voltage equation of Kirchoff's voltage law for a particular branch section. A new static voltage stability index of a RDS is developed [12] by Hamada et al., to faithfully evaluate the severity of the loading situation, thereby predicting for voltage instability at definite load value. A new VSI for all the buses proposed [13] for radial distribution networks by Mahmoud using the catastrophe theory. Investigation of different load models on voltage stability of unbalanced radial distribution system is presented by Gunalan, et al. in [14]. Xiao Ping Zhang, et al. a CTPFlow approach for voltage stability analysis of unbalanced three-phase power systems is presented in [15]. G. Carpinelli, et al. a three-phase constrained optimal power flow is proposed to analyse voltage stability in an unbalanced power system [16]. The voltage stability analysis in unbalanced radial distribution systems using secant predictor is given in [17] by Mamdouh Abdel-Akher.

The load on a power system is constantly changing. There is no such thing as a "steady state" load. Seasonal effects, weekly/daily, and legal/religious holidays, play an important role in load patterns. Most electric utilities serve customers of different types such as residential, commercial, and industrial. To study the system more realistic we have to consider these different load models together along with load curve variation. The time varying load models impact needs to be addressed for voltage stability analysis in unbalanced distribution network. Distribution networks comprise of loads like industrial, commercial, residential and lightning loads are generally weak in nature because of high resistance to reactance ratio. Each of these loads is at its maximum

at different times of the day and this may cause feeder overloading which may result in voltage collapse. Voltage stability is one of the important factors that dictate the maximum permissible loading of a distribution system. Using this VSI, the buses of the system which are weak in nature can be identified. Voltage stability of a system depends on load model, the network topology and settings of reactive compensation devices.

Researchers have paid very little attention on the voltage stability analysis of unbalanced radial distribution network and they carry the analysis under time invariant load conditions.

In this paper the analyses are performed in order to capture the dependence of voltage stability on the load unbalance and load growth. Also the system performance is evaluated for 24 hours seasonal (summer) load curve variation. In this paper we considered the impact of time varying load flow with realistic load model. The load growth factor has also been considered in the study which is essential for the planning and expansion of the existing systems. The impact of the realistic load model as ZIP load model has been considered for study of the systems. The results have been obtained for unbalanced distribution network of 25 buses [21].

The main contribution of the paper is: (i) Analysis of unbalanced radial distribution network with load growth and seasonal load variations, (ii) Impact of type A and type B unbalances in ubrds with load growth and seasonal load variations, (iii) impact of unbalances, ZIP load model, load variation, and load growth on voltage stability index, (iv) total power losses, voltage profiles and VSI, and cost of energy loss are determined.

II. ANALYSIS OF UNBALANCED DISTRIBUTION SYSTEM UNDER TYPE A AND B UNBALANCE [18]

Unbalance Type A: Firstly the overall network load is balanced for the three phases. Subsequently, a percentage of the c-phase load is increased, while the same value is decreased in phase b. In this way, the total network load remains constant under type A unbalance scenario. The new three-phase loads in type A unbalance operation become as follows:

$$SL_a = SL_a$$

$$SL_b = SL_b * (1 - lub)$$

$$SL_c = SL_c * (1 + lub)$$

Unbalance Type B: Firstly the overall network load is balanced for the three phases. Afterward, a percentage of the load of phase b is decreased, while the decrease is twice this value in phase c. This kind of unbalance reduces the total network load under type B unbalanced scenario. The new three-phase loads in type B unbalance operation become as follows:

$$SL_a = SL_a$$

$$SL_b = SL_b * (1 - lub)$$

$$SL_c = SL_c * (1 - 2 * lub)$$

where lub is the load unbalance factor which determines unbalance in the loads at all nodes in the study system, lub = 0.0 represents the balanced system base case study. In this paper work lub is taken as 20%. The objective of this section is to study the system behavior under type A and type B unbalance. In the type A unbalance system load in a-phase remains same, but in c-phase it is increasing and in b-phase it decreasing. Due to increased load demand, voltage magnitudes will decrease and total power losses also increase in phase c. Due to decreased load demand, voltage magnitudes will increase and total power losses also decrease in phase b.

In the type B unbalance the decrement in c-phase load is twice that of decrement in phase-b. Due to decreased load demand, voltage magnitudes will increase and total power losses also decrease in phase b and c. However the decrement in total power losses and improvement in voltage is more in phase c than phase b. The main objective of this section is to study the effect of the system unbalance on system performance at different unbalance scenarios.

	Case 0	Case 1	Case 2
unbalance	0%	20% of type A	20% of type B

III. VOLTAGE STABILITY INDEX (VSI)

Modern distribution networks are being operated closer to their voltage stability limits due to many factors such as increasing load levels, lack of reactive power sources, high installation of single-phase shunt capacitors and reverse action of voltage control devices. Under these stressed operating conditions, voltage instability and voltage collapse may occur if suitable monitoring and control measures are not engaged. Voltage instability has become a challenging problem in distribution networks. Voltage stability is the ability of a system to maintain voltage in acceptable level so that when system nominal load is increased. The driving force for voltage instability is increased load. Accurate modeling of load and the pattern of load increase is very important since the voltage stability is load driven parameter. The voltage stability index is a parameter that identifies the near collapse nodes. The node with small stability indices are called weak nodes and then should be reinforced by injecting reactive power.

In addition, the best location for reactive power compensation to improve voltage stability margins is the weakest bus in the network. Therefore, the best locations to install compensation devices for voltage stability enhancement are the buses with the minimum voltage stability index. Unbalanced operation of distribution networks significantly decreases the voltage stability

margins. This analysis will help researchers to identify the weakest bus for voltage stability enhancement under unbalance scenarios.

In the present analysis voltage stability index is calculated for time variant realistic ZIP load model. Type A and type B load unbalances are considered while calculating VSI. Also the impact of load growth on voltage stability indices is determined. Voltage stability index [11] is determined for each bus using Eq. (1) and the bus with minimum VSI is determined. VSI of each bus is a number between 0 and 1.

$$SI(re(i)) = V(se(i))^4 - 4(P(i)x(i) - Q(I)r(i))^2 - 4(V(se(i))^2(P(i)r(i) + Q(i)x(i)) \qquad (1)$$

$$for\ i = 1,2,\dots Number\ of\ buses$$

Where,

P = is the sum of the real power loads of all the nodes beyond each node , plus the real power load at each node itself, plus the sum of real power losses of all branches beyond each node.

Q = is the sum of the reactive power loads of all the nodes beyond each node , plus the reactive power load at each node itself, plus the sum of reactive power losses of all branches beyond each node.

Cost of Energy Loss (CL): The cost of energy losses [19] has been calculated based on the mathematical model represented as: The annual cost of energy loss is given by

$$CL= (Total\ Real\ power\ Loss)*(E_c * 8760)\ \$ \qquad (2)$$

E_c : Energy rate (\$/kWh)

Where, E_c = 0.06 \$/kWh

Model of Load Growth and ZIP load:

$$Load_i = Load \times (1 + rare)^m \qquad (3)$$

rate=annual load growth rate, m= plan period up to which feeder can take the load. In this paper work, rate=0.07 and m=5.

Time varying load [20] as a combination of residential, industrial and commercial has been considered. Seasonal (summer) variation of load has also been considered taking suitable exponential components in the ZIP load model. Let α, β and γ are the percentages of residential, commercial and industrial loads at each node respectively.

$$P = P_o\left[\alpha\left(\frac{V}{V_o}\right)^{npr} + \beta\left(\frac{V}{V_o}\right)^{npc} + \gamma\left(\frac{V}{V_o}\right)^{npi}\right] \qquad (4)$$

$$Q = Q_o\left[\alpha\left(\frac{V}{V_o}\right)^{nqr} + \beta\left(\frac{V}{V_o}\right)^{nqc} + \gamma\left(\frac{V}{V_o}\right)^{nqi}\right] \qquad (5)$$

IV. RESULTS AND DISCUSSIONS

The results have been obtained for 25 bus ubrds considering load growth and realistic ZIP load model. Daily load curve which is more practical to real distribution system is considered. Type A and type B

unbalances have been considered for study and load growth has also been considered to study the impact on voltage profile, VSI, losses, and cost of energy loss. Peak demand occurred at 18th hour and minimum peak occurred at 7th hour in a day as shown in Fig. 16. A detailed voltage dependent load model has been considered for this paper work, and the three categories of loads considered are: residential, industrial and commercial. The percentage of these loads is also considered as varying with respect to time. The plots of voltage profiles and VSI profiles for two types of unbalance scenarios considering load growth, with 24 hours seasonal (summer) load variation is presented. The voltage and VSI profiles are depicted for all three phases. Voltage stability index (VSI) profiles for all three phases without load growth for 24 hours load variation are presented in Figs. 1-3, Figs. 4-6 and Figs. 7-9 for case 0 (no unbalance), case 1 (type A unbalance) and case 2 (type B unbalance) respectively.

It is observed from the figures of voltage profiles that phase A voltage is higher in case 1 (type A unbalance), phase B and phase C voltage is higher in case 2 (type B unbalance). It is observed from the figures of voltage stability index profiles that phase A VSI is higher in case 1 (type A unbalance), phase B and phase C VSI is higher in case 2 (type B unbalance). With the load growth, the real and reactive powers drawn from the substation increases since total load increases and thereby the losses and cost of energy losses will increase. Minimum bus voltage and minimum VSI values with load growth are less than without load growth. The minimum voltage profile obtained with and without load growth is also shown in Fig. 10 and Fig. 11 respectively. The minimum VSI profile obtained with and without load growth is also shown in Fig. 12 and Fig. 13 respectively. It is observed that the minimum voltage and minimum VSI in phase B and C improved in case 2 (type B unbalance). It is observed that minimum voltage occurs at bus 12th and VSI is minimum at bus 16th. So, 16th bus is the most critical bus in point of voltage stability. The total real power loss variation and cost of energy loss for 24 hours load variation is shown in Figs. 14-15. The load curve is shown in Fig. 16.
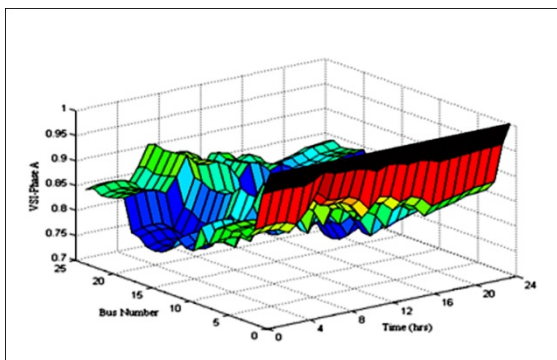

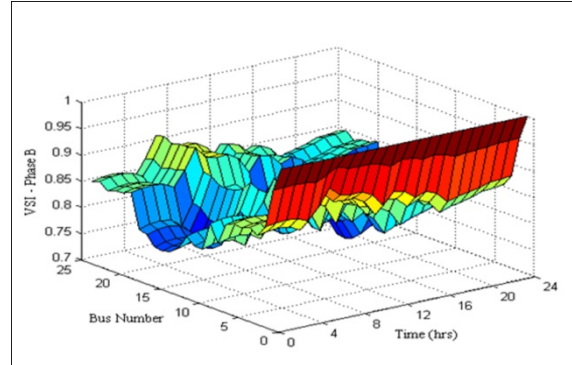Figure 1. VSI profile of phase A in case 0.

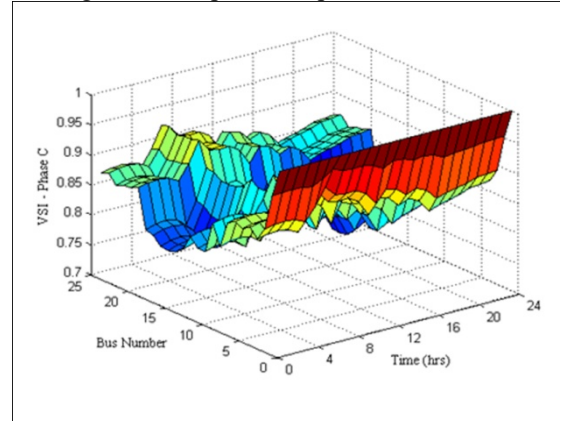Figure 2. VSI profile of phase B in case 0.
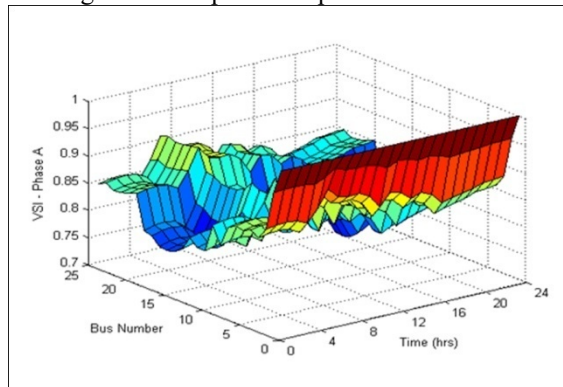

Figure 3. VSI profile of phase C in case 0.

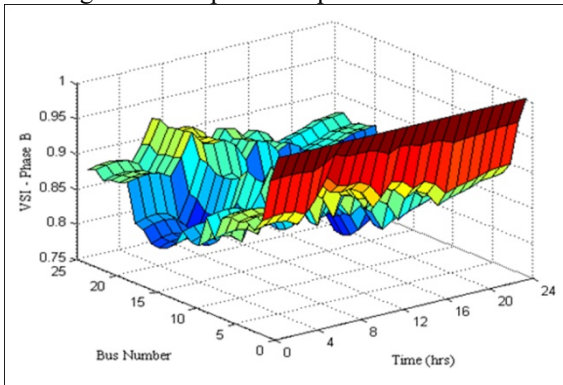Figure 4. VSI profile of phase A in case 1.
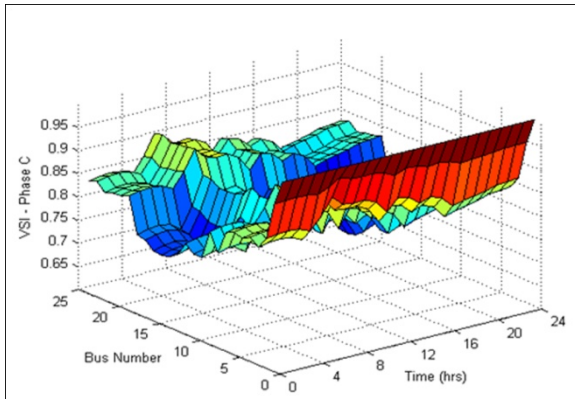

Figure 5. VSI profile of phase B in case 1

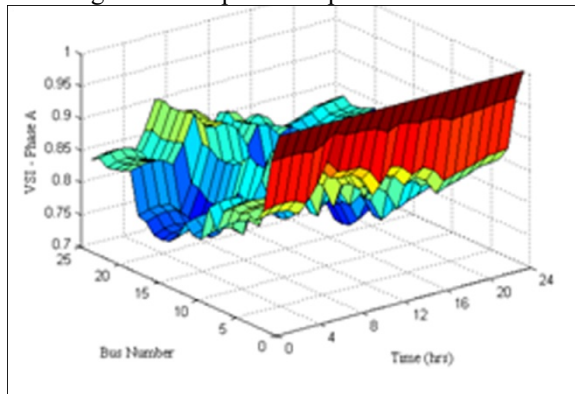Figure 6. VSI profile of phase C in case 1

Figure 7. VSI profile of phase A in case 2
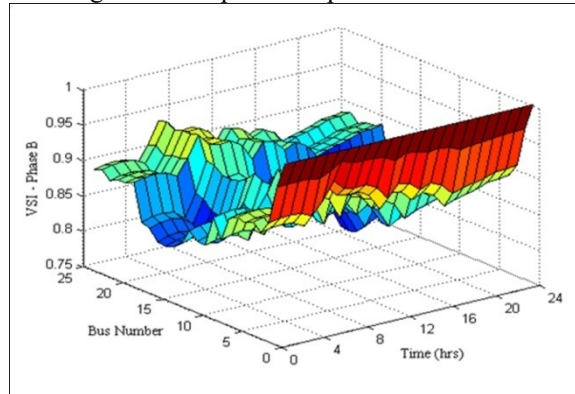

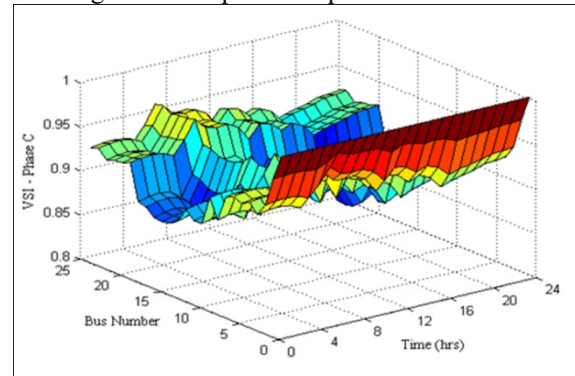Figure 8. VSI profile of phase B in case 2

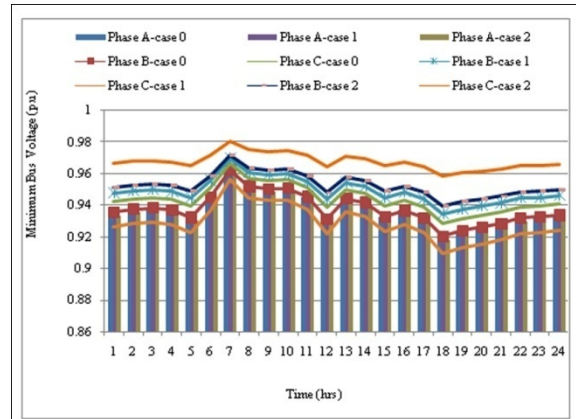Figure 9. VSI profile of phase C in case 2

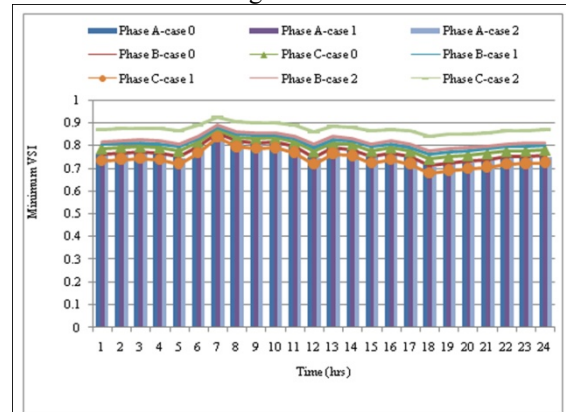Figure 10. Minimum voltage profile without load growth.

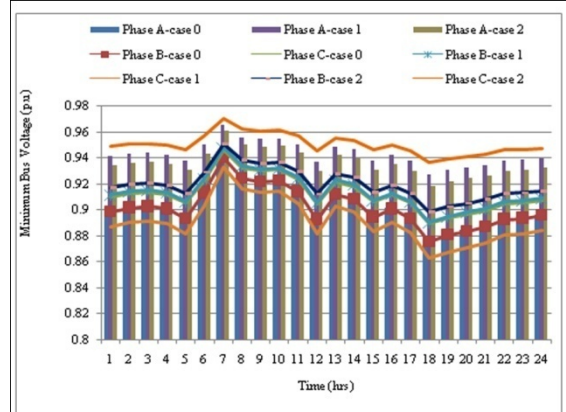Figure 11. Minimum VSI without load growth.

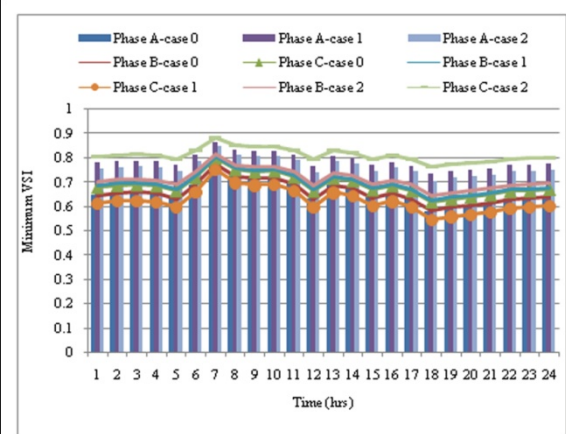Figure 12. Minimum voltage profile with load growth.
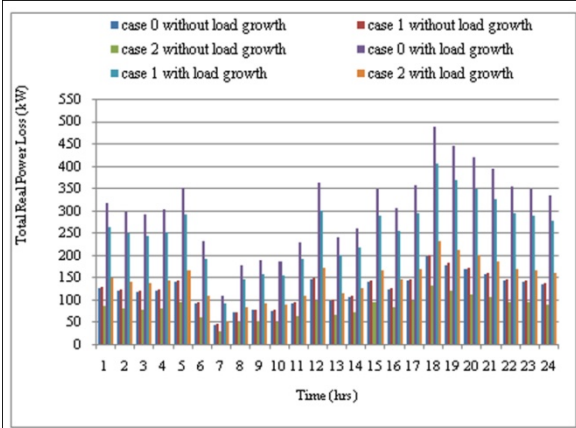
Figure 13. Minimum VSI with load growth.

Figure 14. Total real power loss profile with and without load growth.
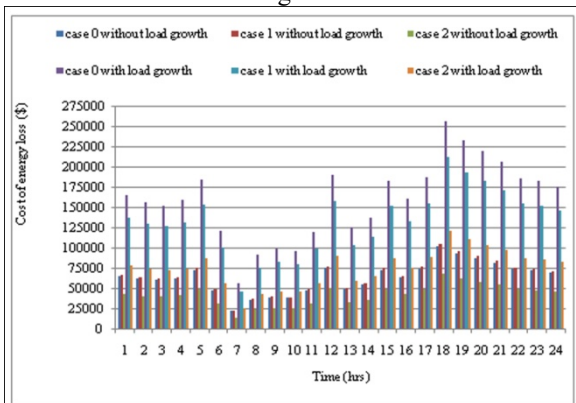

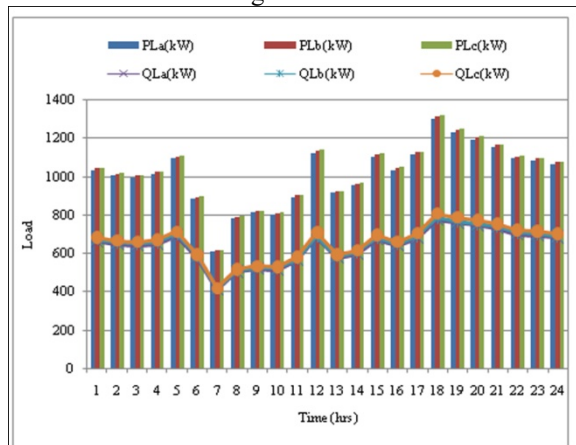Figure 15. Cost of energy loss with and without load growth.

Figure 16. Load curve for 25 bus ubrds with summer load in case 0.

V. CONCLUSION

In this paper, analysis of ubrds has been carried out taking into consideration impact of different unbalances and realistic ZIP load model considering load growth also. Voltage instability has become a challenging problem in unbalanced distribution networks. This paper presents voltage stability analysis to identify the weakest bus in unbalanced distribution network with realistic ZIP load over 24 hour period considering active and reactive daily loads curves. The impact of unbalances in unbalanced radial distribution network has also been determined for identifying the critical buses from voltage stability point of view. It is observed from analysis that unbalanced distribution network with type B unbalance have better voltage profile, lower total power losses and cost of energy losses. If we consider the load growth, the real and reactive powers drew from the substation increases since total load increases, losses also increase. Minimum bus voltage with load growth is low than without load growth for all load models. However minimum bus voltage is better, lower total power losses and cost of energy losses in type B unbalance. Voltage stability index is found better for type B unbalanced scenario. The results show that the unbalance factor is greatly affecting the voltage stability index of the study system.

This study may help for the better planning of unbalanced distribution systems taking the impact of different types of load unbalance, load growth and voltage stability index. VSI will provide planning better locations for reactive power sources and better management of reactive power deployment.

Observations:

a) Minimum voltage in phase A is lower in case 2 than case 0 and case 1.

b) Minimum voltage in phase B is lower in case 0 than case 1 and case 2.

c) Minimum voltage in phase C is lower in case 1 than case 0 and case 2.

d) Total real power loss in case 2 is lower than case 0 and case 1.

e) Cost of energy loss in case 2 is lower than case 0 and case 1.

f) Minimum VSI in phase A is lower in case 2 than case 0 and case 1.

g) Minimum VSI in phase B is lower in case 0 than case 1 and case 2.

h) Minimum VSI in phase C is lower in case 1 than case 0 and case 2.

i) The total load is minimum at 7th hour and is high at 18th hour. So total power losses and cost of energy losses are also minimum at 7th hour and high at 18th hour. Power losses and cost of energy losses will follow the load curve variation pattern.

j) With load growth the voltage profile is reduced, total power losses is increased and cost of energy losses is also increased due to increased load.

VI. ACKNOWLEDGMENT

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