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Mitigating Unbalance Voltage Using STATCOM

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***Abstract*— Power Quality (PQ) is one of the basic requirements of modern power systems. Voltage unbalance is one of the problems of power quality. Different components were used to improve the voltage unbalance in high voltage power system, such as STATCOM, SVC, DVR . . . etc. In the present work, the mitigation of unbalance voltage using three single phase STATCOM is given. Where the standard IEEE 14-bus system was used. First, the weakest bus was identified. The STATCOM was connected to the weakest bus. The cases for different unbalance voltages were been studied. These cases were been studied using three-phase load flow. The proper STATCOM compensation for these cases was found using proper equation of unbalance voltage. The results were been compared, discussed and given in the following paragraphs.**

Keywords **— Power Quality, Voltage unbalance, STATCOM, three-phase load flow.**

I. INTRODUCTION

The quality of power (PQ) is very important now. Sensitive loads need high quality power supply. It contains many issues, such as sag, swell, unbalance, harmonics . . . etc. Power quality can be mitigated using different equipment such as Flexible A.C. Transmission Systems, Dynamic Voltage Restorer, Power Flow Quality Compensator . . . etc. [1,2,3]. In recent years, the study of unbalance voltages represents a vital important issue [4, 5].

The voltage unbalance can be result due to many reasons. Unbalance faults can cause unbalance in system voltages. In addition, non-linear and unbalance loads can cause voltage unbalance. The unbalance in voltages due to unsymmetrical loads is the scope of the study in this work. The system in this case is in steady state conditions. Load flow program is the proper tool to analyze the system. Three-phase load flow program was being proposed for the analyses of the system.

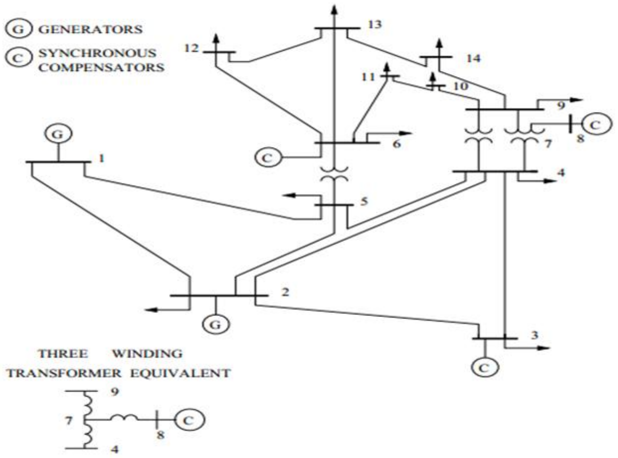

Fig 1 IEEE 14-bus test system

Standard 14-bus IEEE system was used to apply the suggested idea in this work[6]. The system in balance case was been analyzed. Then the case for two-phase symmetric (one phase unbalance) was analyzed. In addition, the three-phase unbalance was analyzed, in the second step. The proper three single phase STATCOM was used to rebalance the voltage in each case. The results show that the addition of the STATCOM can retain the unbalance to be within the standard values. A single line diagram of the IEEE 14-bus standard system is shown in Figure 1.

II. DEFINITION OF UNBALANCE VOLTAGES

The unbalance voltage was been defined using many forms:

A. Symmetrical components.

The basis for the analysis of unbalance in a three-phase power system is bases on the symmetrical positive, negative and zero component. The value of voltage unbalance formula (VUF) is given by [7, 8]:

$$\%VUF = \frac{\text{negative sequence component}}{\text{positive sequence component}}*100 \qquad \text{----------- (1)}$$

$$V_p = \frac{V_{ab}+a.V_{bc}+a^2.V_{ca}}{3} \qquad \text{------------ (2)}$$

$$V_n = \frac{V_{ab}+a^2.V_{bc}+a.V_{ca}}{3} \qquad \text{-------------(3)}$$

B. NEMA definition

This definition was been given by NEMA. It is termed the “line voltage unbalance rate” (*LVUR*). It depends on the average of the three line voltages and the maximum deviation between any of the line-to line voltages from the average line-to-line voltage:

$$\%LVUR=\frac{\text{max voltage deviation from the avg line voltage}}{\text{avg line voltage}}*100 \;\ldots(4)$$

C. IEEE definition

The IEEE definition also approximates VUF. It is similar to the NEMA definition except for the use of the term RMS phase-phase voltages instead of RMS line-line voltages. It depends on the maximum deviation of any of the three-phase phase voltages from the average phase voltage. It is termed the “phase voltage unbalance rate” (*PVUR*). There is another IEEE definition defining unbalance as the ratio of the difference between the maximum and minimum phase voltages and the average phase voltage.

$$\%PVUR=\frac{\text{max voltage deviation from the avg phase voltage}}{\text{avg phase voltage}}*100 \,.\, (5)$$

D. CIGRÉ definition

The CIGRÉ definition employs a simple algebra but gives better approximate results compared with b and c formulas (more accurate):

$$\%VUF=\sqrt{\frac{1-\sqrt{3-6*n}}{1+\sqrt{3-6*n}}}*100\% \qquad \ldots\ldots\ldots..(6)$$

$$n=\frac{V_{ab}^4+V_{bc}^4+V_{ca}^4}{\left(V_{ab}^2+V_{bc}^2+V_{ca}^2\right)^2} \quad \ldots\ldots\ldots..(7)$$

The IEEE definition of voltage unbalance is used in this work. It is simple and give reasonably accurate values. According to IEEE Std. 1547.2 - 2008 the voltage unbalance factor should be below “2% to 3%”. The IEC standard, gives voltage unbalance factor must be below 2% during a long period. It is clear, that an excessive level of voltage unbalance can impose serious impacts on any equipment connected in the grid system [9, 10]. In this work voltage unbalance is calculated (using definition C) before and after compensation.

III. THREE PHASE LOAD FLOWS

The goal of power flow calculation is to calculate the voltage information (magnitude and angle) for each bus for specific load and generation conditions. If this information is known, the real and reactive power flow in each line can be calculated and the reactive power for the generator can be determined [11. 12]. Power flow solution started by identifying the system known and unknown variables. These variables depend on bus type. In the power system, there are three types of buses: Load bus that bus has no generator connect to it, Generator bus that contains at least one generator connected to it and Slack bus. In power flow solution, the real and reactive power are known for the Load bus, called PQ bus. Also for generator bus, the real power and the voltage magnitude are known so that Generator bus called PV bus. While in Slack bus, the voltage level and angle are known.

Depending on bus type, the solution must be considered: for PQ bus the solution must be for voltage magnitude and angle, for PV bus the solution must be for voltage angle and no solution needed for Slack bus. [13]

The Load Flow Program (LFP) is one of the most important programs in the operation and planning of the power system [8]. Therefore, companies and researchers interested in it and prepared the first programs using digital computers. Where the location of the static synchronous compensator (STATCOM) was determined using the power flow program. The same program can also be used to reach the appropriate value of the required reactive power at different loads. Where the three-phase power flow program is used by the digital computers and to evaluate the methods of solution adopted for power flow, the basis of comparison depends on the time needed to solve and the amount of storage needed in addition to access to the appropriate solution.

IV. MITIGATION VOLTAGE UNBALANCE

Many researchers studied voltage unbalance problem as one of power quality problems and many considerations introduced to deal with this problem.

In 2009Y. Xu and others proposed a three-phase IGBT STATCOM for voltage and current unbalance; they introduce an instantaneous power theory for control and calculation. They also compare the simulation results for more than one case of unbalance load and prove that the proposed scheme has good ability for current and voltage unbalance compensation [14].

In 2014 Ana Rodríguez and others studied the implementation of STATCOM for carrying the effect of voltage balance absence in the point of common coupling PCC, the voltage balance absence causes negative sequence currents to be founded in PCC. By means of STATCOM an independent control introduced for positive and negative voltage sequences, an improved controller is added to improve its behavior [15].

In this paper, the proposed method focused on voltage unbalance mitigation by using three single phase STATCOM, that scheme gives the ability to composite the voltage unbalance for each phase separately. The weak bus is selected to connect the STATCOM to it. Single and three-phase unbalance are taken into consideration. The proposed method is applied using MATLAB M-file; the results are discussed and compared to prove the activity of the proposed method.

V. RESULTS AND DISCUSSION

In this research, the IEEE standard 14 Bus system is analyzed. Figure 1 shows the single line diagram of the system. The bus data and line data of the system are given in appendix A. The load on the buses (load buses) is increased gradually, from normal loading in steps of 20 % until 200%. Figure 2 shows the relation between buses voltages and percent loading. It is clear that bus 14 voltage has the lowest value in the system. Which means that bus 14 is the weakest bus in this system. Therefore, the STATCOM will be connected to this bus. Furthermore, other studies reach the same result [9, 10].

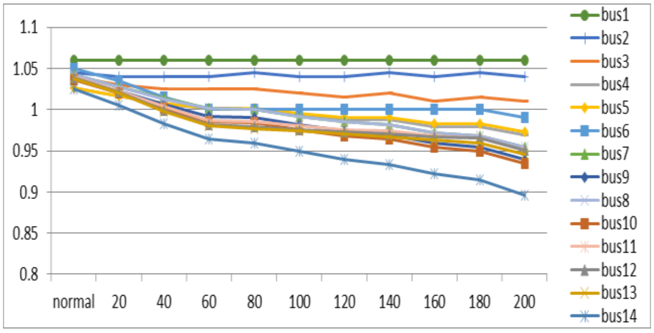

Fig 2 Relation between buses voltages and percent loading.

The study of voltage unbalance was carried out for two general cases. First when two phases are similar and one phase is different. The load on the different phase are taken to be unity, 0.95, 0.9, 0.85, 0.8 0.75 and 0.7. Also the unbalance on the weakest bus and other near and far buses. Furthermore, the cases of 100%, 150% and 200% loading are studied.

When one phase load is different from the two other phases, at bus 14. Figure 3A shows the relation between power factors, of the different phase, with percent voltage unbalance. The figure contains three loading cases 100, 150 and 200% above normal loading. It is clear that voltage unbalance increase as power factor decrease. Furthermore,

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voltage unbalance will increase as percent loading increase. The maximum unbalance, in this case reaches 7.49% at 200% loading and 0.7 power factor. This value is more than the permissible standard value, hence the system need compensation.

The compensation is done according to the following relation:

$$\sum V_{div} = \sqrt{((V_A - V_{av})^2 + (V_B - V_{av})^2 + (V_C - V_{av})^2)} \quad \ldots 8$$

The average phase voltage is found first, using, equation 8, to obtain the minimum unbalance voltage deviation must be minimum, so:

$$V_{O.C} = \frac{\sum V_{div}}{V_{av}} \quad \ldots\ldots\ldots 9$$

This is obtained using trial and error. Since the STATCOM is connected to bus 14, complete voltage rebalancing can be obtained; Since the STATCOM is not connected to this bus. Figure 3B Shows the previous case when the compensation is applied.

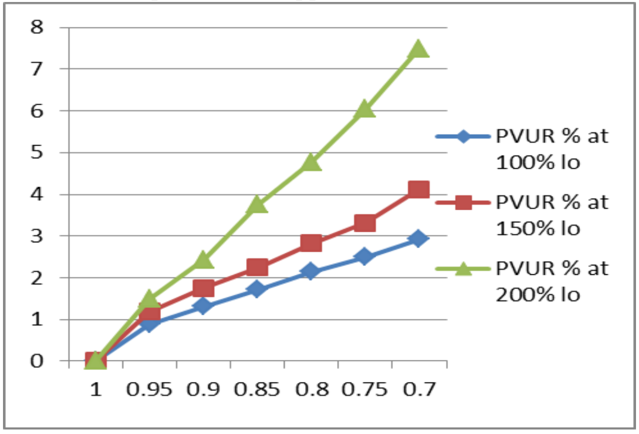

Fig -3A- without compensation.

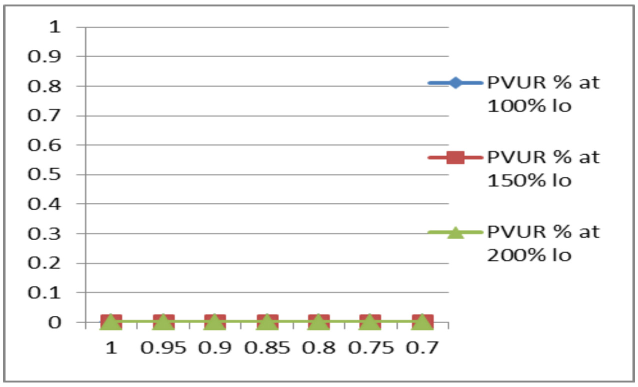

Fig-3B- with compensation.

Figure 3 Relation between power factors, of the different phase, with % voltage unbalance at bus 14 without and with compensation.

The two buses (9 and 13) are connected to bus 14 with one transmission line. The case of voltage unbalance at bus 9 is studied when one phase differ from the other two phases. Three loading condition are studied, 100%, 150% and 200%. Figure 4A shows the relation between power factors and percent voltage unbalance without compensation. The maximum percentage voltage unbalance of 4.98% occurs at 0.7 power factor and 200% loading. This value exceed the standard permissible value. Therefore, compensation is necessary. Equations 8 &9 were used to fine the proper value of STATCOM compensation. Figure 4B shows the percentage voltage unbalance at bus 9, with compensation. The maximum percentage unbalance voltage is 1.6%. This value occurs at 0.7 power factor and 200% loading. This value is within the standard permissible value.

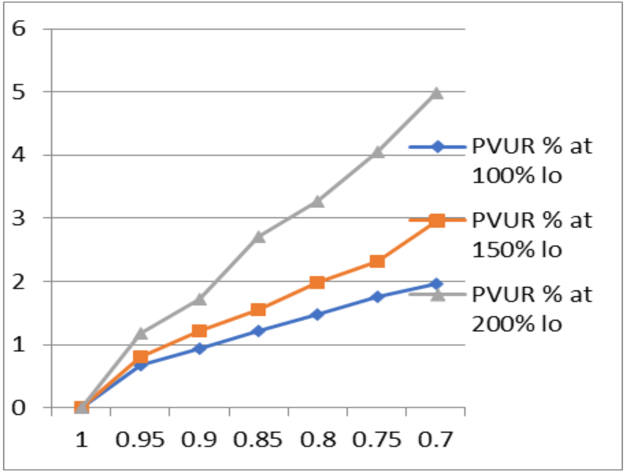

Fig- 4A - without compensation.

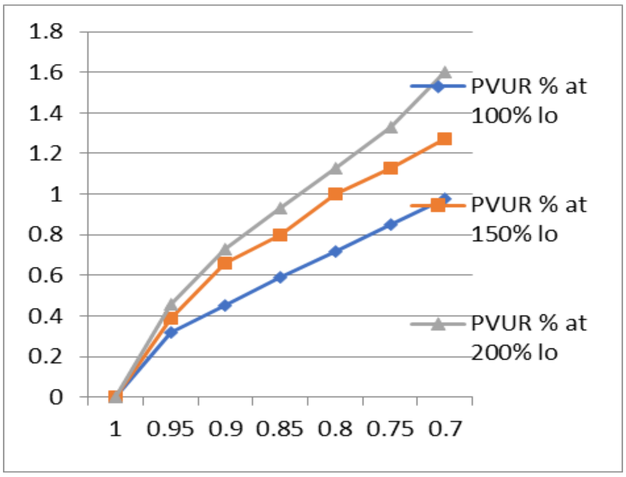

Fig- 4B - with compensation.

Figure 4 relations between power factors and percent voltage unbalance at bus 9 without and with compensation.

The two buses (10 and 12) are connected to bus 14 with two transmission line. The case of voltage unbalance at bus 12 is studied when one phase differs from the other two phases. Three loading condition are studied, 100%, 150% and 200%. Figure 5A shows the relation between power factors and percent voltage unbalance without compensation. The maximum percentage voltage unbalance of 5.45% occurs at 0.7 power factor and 200% loading. This value exceeds the standard permissible value. Therefore, compensation is necessary.

STATCOM addition at bus 14 will reduce voltage unbalance. Figure 5 B shows the percentage voltage unbalance at bus 12, with compensation. The maximum percentage unbalance voltage is 1.43%. This value occurs at 0.7 power factor and 200% loading. This value is within the standard permissible value.

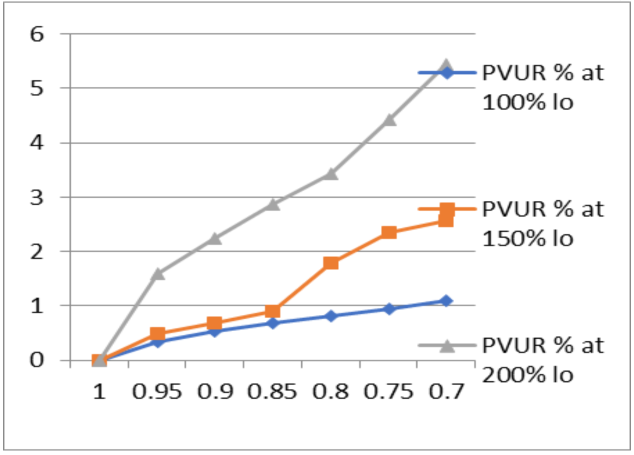

Fig-5A- without compensation.

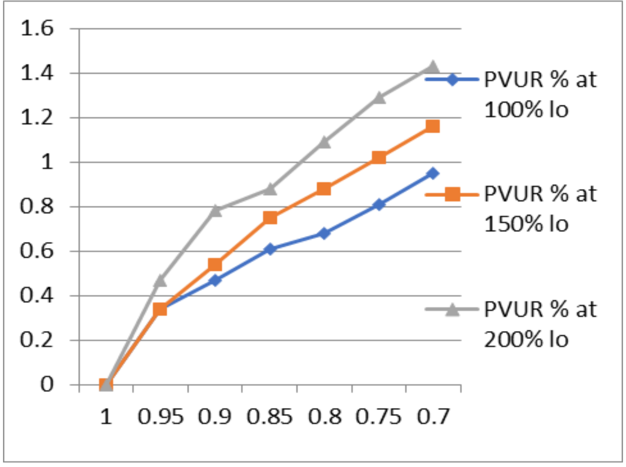

Fig –5B- with compensation.

Figure 5 relation between power factors and percent voltage unbalance at bus 12 without and with compensation.

The second stage of tests, when the unbalance is in the three phases. Phase A was imposed with a lagging power factor 0.95, 0.9, 0.85, 0.75 and 0.7. Phase B was a unity power factor. While phase C was a leading power factor 0.95, 0.9, 0.85, 0.8, 0.75 and 0.7. The test was carried for three loading conditions 100%, 150% and 200% over nominal loading.

The case of three-phase unbalance was applied, first to bus 14. Figure 6 shows the relation between power factors and percent voltage unbalance at bus 14. The maximum percentage unbalance voltage is 9.46%. This value occurs at 0.7 power factor and 200% loading. This value exceed the maximum permissible standard value. Hence, compensation is necessary. Since the STATCOM is connected to bus 14, compensation will result in complete balancing.

Three-phase unbalance was applied to bus 13. Which is one of the nearest buses to compensation bus 14. Figure 7A shows the relation between power factors and percent voltage unbalance at bus 13, without compensation. The maximum percentage unbalance voltage is 6.09%. This value occurs at 0.7 power factor and 200% loading. This value exceed the maximum permissible standard value. Hence, compensation is necessary.

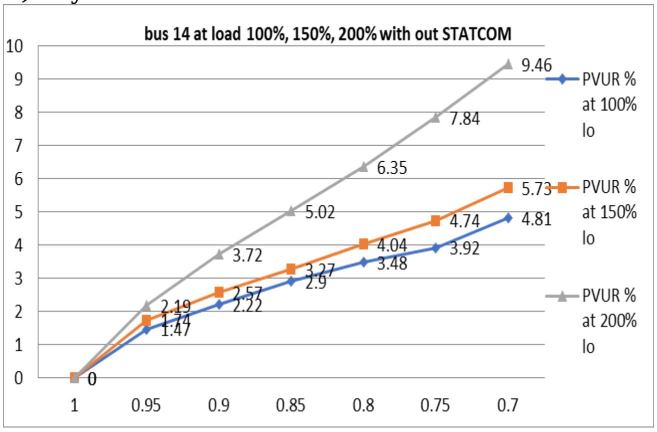

Fig 6 Relation between power factors and percent voltage unbalance.

Figure 7B shows the relation between power factors and percentage voltage unbalance at bus 13, with compensation. The maximum percentage unbalance voltage is 2.02%. This value occurs at 0.7 power factor and 200% loading. This value is within the standard permissible value.

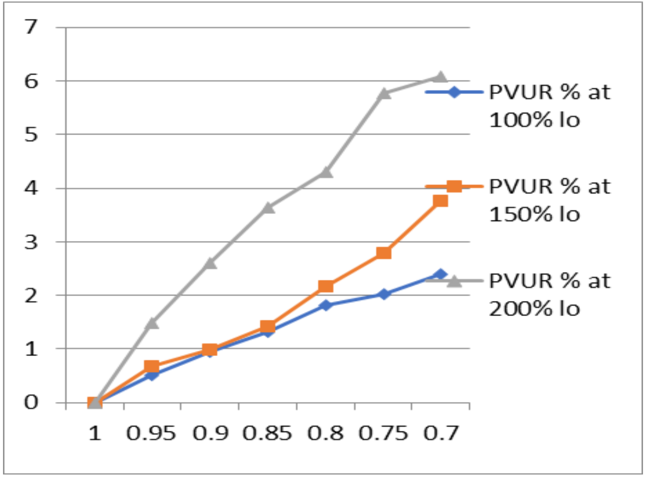

Fig -7A- without compensation.

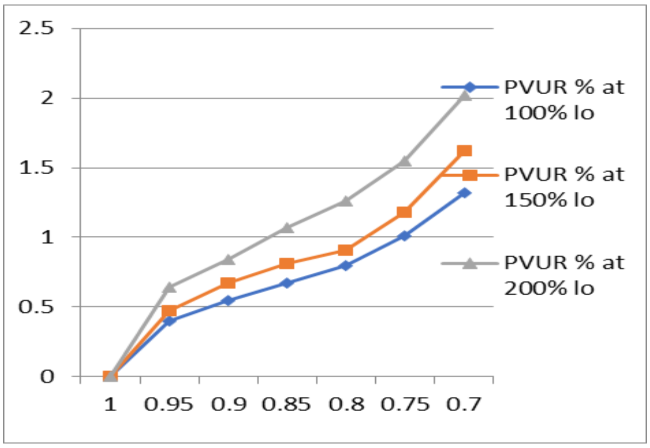

Fig -7B- with compensation.

Fig 7 Relation between power factors and percent voltage unbalance at bus 13, without and with compensation.

Three-phase unbalance was applied to bus 12. Which is one of the two fare buses, two lines from the compensation bus 14. Figure 8A shows the relation between power factors and percent voltage unbalance at bus 12, without compensation. The maximum percentage unbalance voltage is 6.25%. This value occurs at 0.7 power factor and 200% loading. This value exceeds the maximum permissible standard value. Hence, compensation is necessary.

Equation 8&9 were used to fine the proper value of STATCOM compensation. Figure 8B shows the relation between power factors and percentage voltage unbalance at bus 12, with compensation. The maximum percentage unbalance voltage is 2.24%. This value occurs at 0.7 power factor and 200% loading. This value is higher than the standard permissible range by a small value.

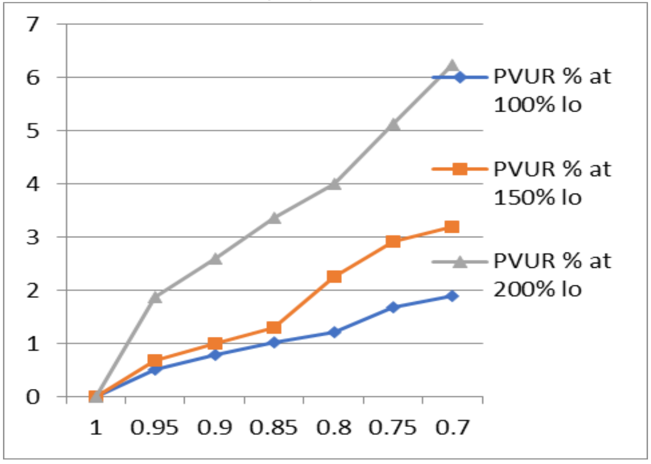

Fig -8A- without compensation.

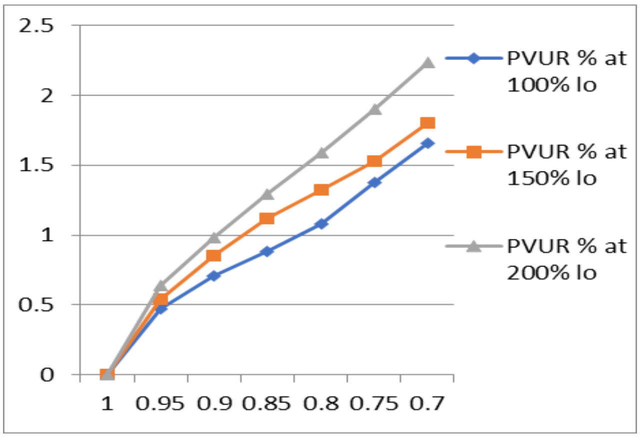

Fig -8B- with compensation.

Figure 8 relations between power factors and percent voltage unbalance at bus 12, without with compensation.

Voltage unbalance due to load unbalance was studied for different cases. The unbalance of one phase is given for three buses. Bus 14 were the compensation is connected. Then bus 9, one transmission line from bus 14. Third bus 12 two transmission lines from bus14. In the second case the unbalance of three-phases are studied. The results of three buses are given. Bus 14 was the compensation is connected. Then bus 13, one transmission line from bus 14. Third bus 10 two transmission lines from bus14. In all these case voltage unbalance without and with compensation are given. Different power factors varies from unity until 0.7 for all cases. The study include three loading condition 100%, 150% and 200% above nominal loading. Table 1 summarizes the results of all cases. It is clear from the table that voltage unbalance of all the cases can be reduce to be within the standard permissible value.

Table 1 Results of studied Cases.

Bus Number	Maximum Voltage Unbalance %	
	Without Compensation	With Compensation
14	7.49	0
9	4.98	1.6
12	5.45	1.43
14	9.46	0
13	6.09	2.02
10	5.8	2.24

VI. CONCLUSION

Unbalance voltage hurts all system components. In this research, unbalance voltage due to load unbalance was studied. IEEE Bus14 standard system was used to verify the idea suggested. First, the weak bus was found, where the compensation is to be added. Three-phase load flow program was used, since the system is unbalance. Different cases of unbalance loading were analyzed. Three loading condition were taken, with different power factors in each case. Unbalance voltages were calculated, for each case, using standard equation. STATCOM compensations for each case were calculated using a suggested formula. The analysis without and with compensation for buses in the zone of weak bus were given. All the results show that compensation can retain voltage unbalance to be within the permissible standard value.

REFERENCES

[1] Reza Sedaghati, Navid Mehdizadeh Afroozi, Yaser Nemati, Ahmad Rohani, AliRezaToorani, Navid Javidtash, Ali Heydarzadegan and HosseinSedaghati “A Survey of Voltage Sags and Voltage Swells Phenomena in Power Quality Problems” International Journal of scientific research and management (IJSRM), Vol. 1, Iss.9, 2013, PP 458-462.

[2] Ganesh K. Budumuru & Biplab K. Mohanty “A comprehensive review on soft computing and signal processing techniques in feature extraction and classification of power quality problems” Journal of Renewable and Sustainable Energy, Vol. 10, Iss.2, 2018.

[3] K. Sheeraz & K. Brijesh “Power quality improvement by using STATCOM control scheme in wind energy generation interface to grid” Earth and Environmental Science, Vol. 114, Iss. 1, 2018

[4] T. E. Seiphetlho, and A. P. J. Rens "On the Assessment of Voltage Unbalance" 14th International Conference on Harmonics and Quality of Power (ICHQP), 26-29 Sept., Bergamo, Italy 2010.

[5] Pushpendra MishraVaishli Holkar, Ashutosh Choubey “Enhancement of voltage profile for IEEE-14 Bus System by

Using STATIC-VAR Compensation (SVC) when Subjected to Various Changes in Load" International Journal of Research Studies in Science, Engineering and Technology [IJRSSET], Volume 1, Issue 2, May 2014, PP27-33.

[6] Hadi Saadat "Power System Analysis" McGraw-Hill, New York, 1999.

[7] Annette von Jouanne and Basudeb (Ben) Banerjee "Assessment of Voltage Unbalance" IEEE TRANS. ON POWER DELIVERY, VOL. 16, NO.4, OCTOBER 2001, PP 782-790.

[8] P. Pillay and M. Manyage "Definitions of Voltage Unbalance" IEEE Power Engineering Review, Vol.21, Iss. 5, May 2001, PP 49-51.

[9] D. Mirabbasi, G. Seifossadat & M. Heidari"Effect of unbalanced voltage on operation of induction motors and its detection" International Conference on Electrical and Electronic Engineering, 5-8 Nov., Bursa, Turkey, 2009.

[10] P.M. Balasubramaniam & S. U. Prabha "Power Quality Issues, Solutions and Standards: A Technology Review" Journal of Applied Science and Engineering, Vol.18, No. 4, 2015, PP 371-380.

[11] Glenn W .Stagg, Ahmed H .El_Abiad "Computer Methods in Power System Analysis" McGraw _ Hill, 1968.

[12] P. Srikanth, O. Rajendra, A. Yesuraj, M. Tilak K.Raja "Load Flow Analysis of IEEE 14 Bus System Using MATLAB" International Journal of Engineering Research & Technology (IJERT), Vol. 2 Issue 5, May – 2013, PP 149-155.

[13] Kriti Singhal "Comparison between Load Flow Analysis Methods in Power System using MATLAB" International Journal of Scientific & Engineering Research (IJSER), Volume 5, Issue 5, May-2014, PP 1412-1419.

[14] Y. Xu1 L.M. Tolbert1, J.D. Kueck1 D.T. Rizy " Voltage and current unbalance compensation using a static var compensator" IET Power Electronics, Vol.3, Iss.6, PP 977-988.

[15] Ana Rodríguez, Emilio J. Bueno, Álvar Mayor, Francisco J. Rodríguez and Aurelio García-Cerrada "Voltage Support Provided by STATCOM in Unbalanced Power Systems" Energies, 24 February 2014, 7, PP 1003-1026.

AUTHOR BIOGRAPHY

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Waleed M. Khalid was born in Iraq in December 1981. He received his B.Sc., In Electrical power engineering techniques from Electrical power engineering techniques of Mosul 2005. He is currently pursuing his M.Sc degree from University of Mosul. His major research interest Include using fixable ac transmission system for enhancement power quality.

APPENDIX

Table 2 Phase data

BUS NO	Generator		Load	
	MW	MVAR	MW	MVAR
1	0	0	0	0
2	13.33	14.13	7.24	4.23
3	13.33	7.8	9	4.85
4	0	0	9.75	1.5
5	0	0	5.85	1.54
6	0	4	8.8	5.54
7	0	0	0	0
8	0	0	0	0
9	0	0	9.84	5.54
10	0	0	6.5	2
11	0	0	4.5	1.3
12	0	0	5.4	1.2
13	0	0	8.3	2.75
14	0	0	8.5	4.85

Table 3 Transformer Data

BUS NO	VOLTAGE MAGNITUDE	REACTIV POWER LIMIT	
	PER-UNIT	MIN MVAR	MAX MVAR
2	1.045	-13.33	13.33
3	1.01	0	13.33
6	1.01	-3	8

Table 4 Regulated Phase Data

BUS	Voltage Magnitude	Reactive Power Limit	
NO	Per Unit	Min	Max
2	1.045	-40	50
3	1.01	0	40
6	1.07	-6	24
8	1.09	-6	24

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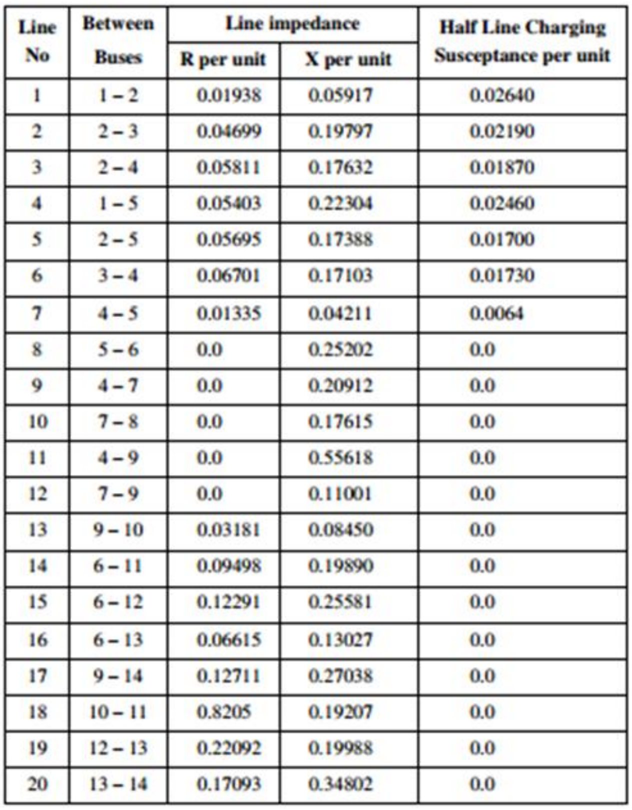
Table 5 Line data



Line No	Between Buses	Line impedance		Half Line Charging Susceptance per unit
		R per unit	X per unit	
1	1 – 2	0.01938	0.05917	0.02640
2	2 – 3	0.04699	0.19797	0.02190
3	2 – 4	0.05811	0.17632	0.01870
4	1 – 5	0.05403	0.22304	0.02460
5	2 – 5	0.05695	0.17388	0.01700
6	3 – 4	0.06701	0.17103	0.01730
7	4 – 5	0.01335	0.04211	0.0064
8	5 – 6	0.0	0.25202	0.0
9	4 – 7	0.0	0.20912	0.0
10	7 – 8	0.0	0.17615	0.0
11	4 – 9	0.0	0.55618	0.0
12	7 – 9	0.0	0.11001	0.0
13	9 – 10	0.03181	0.08450	0.0
14	6 – 11	0.09498	0.19890	0.0
15	6 – 12	0.12291	0.25581	0.0
16	6 – 13	0.06615	0.13027	0.0
17	9 – 14	0.12711	0.27038	0.0
18	10 – 11	0.8205	0.19207	0.0
19	12 – 13	0.22092	0.19988	0.0
20	13 – 14	0.17093	0.34802	0.0