Effect of Unbalance Voltage on the Operation and Performance of a Three Phase Distribution Transformers

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Abstract-

Three phase supply system is found to be quite balanced in both magnitude and displacement at the generation levels but it is not so at distribution end. Voltage unbalance which is a common and global phenomenon is found to be very effective in deteriorating the operation and performance of electrical apparatus. Present paper is an attempt to analyze the operation of three phase distribution transformers with unbalance voltage conditions. MATLAB programming based upon symmetrical component approach is adopted to estimate the performance of a three-phase transformer under unbalanced condition. Both under voltage unbalance as well as over voltage unbalance have been considered for analysis purpose. Numerical details study in case of distribution transformer with primary delta connection and secondary star connection with solidly grounded neutral is presented in this paper. The degree of voltage unbalance is represented by the voltage unbalance factor (VUF) derived from symmetrical component.

Key words: Transformer, Abnormal operation, symmetrical components, Voltage unbalance factor

الخلاصة

نظام تجهيز القدرة ثلاثي الطور يكون متزن القيمة و الزاوية عند التوليد ولكن قد لايكون كذلك عند التوزيع . عدم اتزان الفولتية من الظواهر الشائعة التي تؤثر على تدهور عمل و اداء المعدات الكهربائيه . يقدم هذا البحث محاولة لتحليل عمل محولات التوزيع ثلاثية الطور في حالة عدم اتزان الفولتية. تم انشاء برنامج باستخدام لغة البرمجة Matlab بالاعتماد على المركبات المتماثلة لتخمين اداء عمل المحولات ثلاثية الطور في حالة عدم الاتزان. حالة عدم اتزان الفولتية الناتج عن ارتفاع الفولتية وكذلك انخفاض الفولتية كلاهما تمت دراسة تأثيره. قدم البحث دراسة عددية موسعة لمحولة ثلاثية الطور مؤرضة تأريضا مباشرا . استخدم عامل عدم اتزان الفولتية المشتق من المركبات المتماثلة لبيان مقدار عدم اتزان الفولتية.

1. Introduction

Voltage unbalance is the deviation of individual phase voltage magnitudes from the normal/rated values, with the individual phase voltages being not equal to each other either in magnitude and/or in phase displacement. The presence of inequality among the phase voltages can be attributed to the unsymmetrical impedances of transmission and distribution lines, unbalanced or unstable power utilities, unbalanced three phase loads, open delta transformer connections, blown fuses of a three-phase capacitor banks, uneven spread of single-phase loads across the three phases, single-phase traction loads, weak rural power electric systems with long transmission lines, or even unidentified/ uncleared single-phase-to-ground faults [Giridhar Kini, Ramesh C. Bansal, and R. S. Aithal 2007]. Voltage unbalance can affect customer equipment, in particular, three phase induction motors can suffer from temperature rise due to the currents in the windings resulting from negative sequence voltage. Reduced torque and lower full-load speed can also result from voltage unbalance, possible resulting in the motor not being able to adequately fulfill its function. Other affects are an increase in noise and vibration [Neil Browne, Darren Spoor, and Justin Byrnes 2008]. Voltage unbalance can also affect performance of the network. It can result in increased voltage drop on conductors, resulting in the need for larger conductors. It can cause different losses on each phase of transformers, resulting in a rise in hot spot temperature. Unbalance can increase the generation of triplen harmonics, possibly overloading harmonic filters and capacitor banks [Z. Emin and D. Crisford 2006]. In the most practical studies, the method of measuring the voltage unbalanced level is either the percent voltage unbalance (PVU) defined by the (National Electrical Manufactures Association) NEMA or the voltage unbalance factor (VUF) defined by the (International Electrotechnical Commission) IEC. Both of them are positive real quantities which can show the level of voltage unbalance. The PVU is a method calculated by the sampled data of the ratio of the maximum deviation of the average voltage to the average of the three voltages. As for the VUF, it is described by the ratio of the negative sequence to the positive sequence voltage [Guilin Zheng and Yan Xu 2010].

2. Types of Voltage Unbalance

There may be different type of unbalance in a supply system and exists definite possibility of voltage variations above and below the rated value. Thus voltage unbalance can be classified into overvoltage unbalance (OVU) under-voltage unbalance (UVU) unbalance. OVU is a condition when the three phase voltages are not equal to each other, in addition positive sequence component is greater than the rated value while UVU is a condition where the three phase voltages are not equal to each other, and in addition the positive-sequence component is lesser than the rated value. There are many possible voltage unbalance in a power system, here we will study the following six causes, (1) single phase under voltage unbalance (1Φ-UV), (2) two phases under voltage unbalance (2Φ-UV), (3) three phases under voltage unbalance (3Φ-UV), (4) single phase over voltage unbalance (1Φ-OV), (5) two phases over voltage unbalance (2Φ-OV), (6) three phases over voltage unbalance (3Φ-OV) [Knwararjit Singh Sandhu and Vinnet Chaudhary 2009].

3. Unbalance in Three-Phase Distribution Networks

To study the unbalanced operation of a power system, the symmetrical components theory is used. According to Stokvis-Fortescue theorem, every three-phase asymmetrical system of phasors can be decomposed into three symmetrical systems of positive, negative and zero sequence respectively. Every sequence system contains three phasors characterized by equal magnitudes; in the case of positive and negative sequences, components are rotated between them with 120 electrical degrees in counter-clockwise direction and negative clockwise direction, respectively. In the case of zero sequence components, there is no rotation between phasors [Chindriş, A. Cziker, Anca Miron, H.Bălan,and A. Sudria 2007]. If an asymmetrical system of line voltages is taken into consideration, the relationship between the initial system and the symmetrical sequence systems can be written as follows [E. Seiphetlho and A. P. J. Rens 2010]:

$$\begin{bmatrix} V_p \\ V_n \\ V_0 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (1)$$

Where

V_a, V_b and V_c are the unbalanced phase voltage Phasors V_p, V_n and V_0 the positive, negative and zero-sequence voltage phasors respectively (fundamental frequency components).

In the same way, if an asymmetrical system of line currents is taken into consideration, the relationship between the initial system and the symmetrical sequence systems can be written as follows [E. Seiphetlho and A. P. J. Rens 2010]:

$$\begin{bmatrix} I_p \\ I_n \\ I_0 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (2)$$

Where

I_a, I_b and I_c are the unbalanced phase current Phasors I_p, I_n and I_0 the positive, negative and zero-sequence currents phasors respectively (fundamental frequency components).

Where

$a = 1\angle 120$ = - 0.5+ j 0.866

These sequence systems are not only theoretical, they correspond to the reality: the positive sequence components are created by the synchronous or asynchronous generators while the negative and zero sequence components appear at the place of unbalance. Each of them can be separately measured and influence in a different way in power systems. For example, in the case of motors, the positive sequence components produce the useful torque while the negative sequence components produce fields that create braking torques. On other hand, the zero sequence components is the one that get involved in the cases of interferences between the electric and the telecommunication transmission lines [M. Chindriş, A. Cziker, Anca Miron, H.Bălan, and A. Sudria 2007].

4. Unbalance Definition

The two general definitions for voltage unbalance as described are;

4.1 NEMA Definition

The voltage unbalance percentage (VUP) at the terminal of a machine as given by the National Electrical Manufacturer Association Motor and Generator Standard (NEMA MGI) used in most studies is[K.S. Sandhu and Vineet Chaudhary 2008, P.Pillay and M.Manyage 2001]:

$$VUP(\%) = \frac{\max voltage\ deviation\ from\ average\ line\ voltage}{average\ line\ voltage} \times 100 \qquad (3)$$

4.2 Symmetrical Component Definition

The voltage unbalance factor (VUF) is defined by International Electro technical Commission (IEC) as the ratio of negative-sequence voltage component to the positive-sequence voltage component [P.Pillay and M.Manyage 2001, J. M. Apsley 2010].

$$VUF(\%) = \frac{|V_n|}{|V_p|} \times 100\% \qquad (4)$$

Where V_n and V_p are the magnitude of negative and positive sequence voltage components respectively are obtained by symmetrical component transformation.

5. Transformer Modeling Under Unbalance Condition

Steady state analysis of a transformer operating with unbalanced voltage is possible using symmetrical component approach. This requires the development of positive- , negative- and zero sequence equivalent circuit representation. It possible to assume for a transformer that X_1 =X_2 = leakage impedance. As the transformer is a static device, the positive or negative sequence impedances do not change with phase sequence of the applied balanced voltages. The zero sequence impedance can, however, vary from an open circuit to a low value depending on the transformer winding connection, method of neutral grounding [J. C. Das 2002].

The positive and negative sequence equivalent circuit representation of any transformer connection is shown in Fig.1 and Fig.2 respectively.

The zero sequence equivalent representation of transformer is dependent on the type of transformer winding connection .The zero sequence representation for a delta-star transformer with the star neutral solidly grounded is constructed as shown in Fig. 3(a). The grounding of the star neutral allows the zero sequence currents to return through the neutral and circulate in the windings to the source of unbalance. On the delta side, the circuit is open, as no zero sequence currents appear in the lines, though these currents circulate in the delta windings to balance the ampere turns in the star windings. The circuit is open on the delta side line, and the zero sequence impedance of the transformer seen from the delta side is an open circuit [J. C. Das 2002]. If the star winding neutral is left isolated, Fig.3 (b), the circuit will be open on both sides, presenting infinite impedance [John J. Winders and Jr 2002].

In a star – star transformer connection, with both neutrals isolated, no zero sequence currents can flow. The zero sequence equivalent circuit is open on both sides and presents infinite impedance to the flow of zero sequence currents [John J. Winders, Jr, A. C. Franklin, and D. P. Franklin 1983].

For delta–delta connection, no zero currents will pass from one winding to another. On the transformer side, the windings are shown connected to the reference bus, allowing the circulation of currents within the windings [A. C. Franklin and D. P. Franklin 1983].

In star–star connected transformer, with both neutrals grounded the zero sequence equivalent circuit representation shown in Fig.4 [John J. Winders and Jr 2002, A. C. Franklin, and D. P. Franklin 1983].

Where per phase values are defined as:

V_{pp} positive-sequence voltage
V_{np} negative-sequence voltage
V_{0s} zero-sequence voltage
R_{Tp} primary resistance
X_{Tp} primary reactance
R_{Ts} secondary resistance referred to primary
X_{Ts} secondary reactance referred to primary
X_m magnetizing reactance
Z_p positive-sequence impedance of transformer
Z_n negative-sequence impedance of transformer
Z_0 zero-sequence impedance of transformer
I_{pp} primary positive-sequence current phasor
I_{ps} secondary positive-sequence current phasor
I_{np} primary negative-sequence current phasor
I_{ns} secondary negative-sequence current phasor
I_{0p} primary positive-sequence current phasor
I_{0s} secondary positive-sequence current phasor

Let V_{as} , V_{bs} , and V_{cs} be the phase secondary voltages of a delta-star transformer with the star neutral soldely grounded . The corresponding zero-, positive and negative-sequence components (V_{0s} ,V_{ps} and V_{ns}) of the voltages are given by equation[E. Seiphetlho and A. P. J. Rens 2010] :

$$\begin{bmatrix} V_{ps} \\ V_{ns} \\ V_{0s} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad (5)$$

The corresponding zero-, positive and negative-sequence components (I_{0s} ,I_{ps} and I_{ns}) of the currents are given by equation[M. Chindriş, A. Cziker, Anca Miron, H.Bălan, and A. Sudria 2007]:

$$\begin{bmatrix} I_{ps} \\ I_{ns} \\ I_{0s} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} \quad (6)$$

Analysis of equivalent circuits the positive and negative primary phase voltages and currents can be determined from equations [Knwararjit Singh Sandhu, Vinnet Chaudhary 2009, A. C. Franklin, D. P. Franklin 1983]:

$$V_{pp} = ((V_{ps} \times n \times ((Z_{LP} + Z_{Ts}) \times (Z_m + Z_{Tp}) + Z_{Tp} \times Z_m))/((Z_{LP} \times Z_m)) \quad (7)$$

$$V_{np} = ((V_{ns} \times n \times ((Z_{Ln} + Z_{Ts}) \times (Z_m + Z_{Tp}) + Z_{Tp} \times Z_m))/((Z_{Ln} \times Z_m)) \quad (8)$$

$$I_{pp} = \left(V_{pp} \times \frac{Z_m + Z_{Ts} + Z_{Tp}}{(Z_{Lp} + Z_{Ts}) \times (Z_m + Z_{Tp}) + Z_{Tp} \times Z_m}\right) \quad (9)$$

$$I_{np} = \left(V_{np} \times \frac{Z_m + Z_{Ts} + Z_{Tp}}{(Z_{Ln} + Z_{Ts}) \times (Z_m + Z_{Tp}) + Z_{Tp} \times Z_m}\right) \quad (10)$$

Where n is the transformer voltage ratio. The values of n are dependent on transformer connection as shown in Table 1 where N_p represents the primary turn number while N_s has the same meaning for the secondary winding [M. Chindriş, A. Cziker, Anca Miron, H.Bălan, and A. Sudria 2007].

The primary is delta connected. The primary phase voltages and currents can be calculated by as [K.S. Sandhu and Vineet Chaudhary 2008]:

$$\left.\begin{aligned} V_{pa} &= V_{pp} + V_{np} \\ V_{pb} &= a^2 * V_{pp} + a^2 * V_{np} \\ V_{pc} &= a * V_{pp} + a^2 * V_{np} \end{aligned}\right\} \quad (11)$$

$$\left.\begin{aligned} I_{pa} &= I_{pp} + I_{np} \\ I_{pb} &= a^2 * I_{pp} + a * I_{np} \\ I_{pc} &= a * I_{pp} + a^2 * I_{np} \end{aligned}\right\} \quad (12)$$

The transformer input, output power and primary and secondary power factor can be expressed in terms of symmetrical components of the voltage and currents as [E. Seiphetlho and A. P. J. Rens 2010]:

Input active power:

$$P_{in} = Real[3 \times (V_{pp} \times I_{pp}^* + V_{np} \times I_{np}^*)] \quad (13)$$

Input reactive power:

$$Q_{in} = Imaginary[3 \times (V_{pp} \times I_{pp}^{*} + V_{np} \times I_{np}^{*})] \quad (14)$$

Where (*) indicates the conjugate value.

Primary power factor:

$$p.f = \cos[\tan^{-1}(Q_{in}/P_{in})] \quad (15)$$

Output active power:

$$P_{ot} = Real[3 \times (V_{ps} \times I_{ps}^{*} + V_{ns} \times I_{ns}^{*} + V_{0s} \times I_{0s}^{*})] \quad (16)$$

Output reactive power:

$$Q_{ot} = Imaginary[3 \times (V_{ps} \times I_{ps}^{*} + V_{ns} \times I_{ns}^{*} + V_{0s} \times I_{0s}^{*})] \quad (17)$$

Secondary power factor:

$$p.f = \cos[\tan^{-1}(Q_{ot}/P_{ot})] \quad (18)$$

Total losses in watts:

Total losses = P_{in}- P_{ot} (19)

Efficiency of the transformer is defined as:

$$\eta = \frac{P_{ot}}{P_{in}} \times 100\% \quad (20)$$

6. System under study

To facilitate the analysis of unbalance and to understand the effect of unbalance voltage on operation of distribution transformer, a system content of three phase distribution transformer with delta primary winding connected and star secondary winding with solidly grounding neutral. The transformer is loading with unbalance impedances as shown in figure (5).

The transformer and load have the following parameters:

- rated primary voltage V_p =11 Kv, rated secondary voltage V_s=415 V, transformer turn ratio N=45.9, transformer rated power S_T= 250 KVA.
- Primary impedance Z_{Tp} = (17.4 + j 40.3) Ω, secondary impedance reffered to primary Z_{Ts} = (13.4 + j 40.3) Ω.
- Load impedance reffered to primary Z_{La} = (1310 + j 950) Ω, Z_{Lb} = (1010 + j 650) Ω, Z_{Lc} = (1080 + j 450) Ω.

All parameters are on per phase basis

7. Results and Discussion

To study the effects of voltage unbalance on performance of distribution transformer, three causes of unbalancing the secondary voltage included under and over voltage are applied on the system under study.

Case 1: effect of three phase voltage unbalance.

(a) Over voltage unbalance. It can be seen from table 2 that both efficiency and secondary power factor increase with increasing of unbalance factor.
(b) Under voltage unbalance .It is observed from the results listed in table 2 that at under voltage unbalance in secondary voltage. The secondary power factor and transformer efficiency are decreased with increase of unbalance factor (VUF).

It also can be observed from table 3 for under and over voltage cases that the change in VUF is little effect on primary power factor.

The efficiency and total losses at over and under three phase voltage unbalance are 3-D plotted with unbalance factor in figures 6 and 8. The secondary and primary power factors are 3-D plotted with VUF in figures 7 and 9.

Case 2: effect of single phase voltage unbalance.
(a) Over voltage unbalance.

For over voltage unbalance occurs in phase a. It can be seen from the results listed in table 4 that the secondary power factor and transformer efficiency decrease with increasing of VUF.

For over voltage unbalance occurs in phase b the transformer efficiency increases with increasing of VUF, while the secondary power factor decreases with increasing of VUF as shown in table 6.

For under voltage unbalance occurs in phase c the transformer efficiency and secondary power factor increase with increasing of VUF, as shown in table 8.

The efficiency and total losses for single phase over voltage unbalance occurs in phase b is 3-D plotted with VUF in figure 10.The secondary and primary power factor is 3-D plotted with VUF in figure11.

(b) Under voltage unbalance

For under voltage unbalance occurs in phase a. It can be seen from the results listed in tables 4 that the power factor and efficiency increase with increasing of VUF.

For under voltage unbalance occurs in phase b. The transformer efficiency decreases with increasing of VUF until VUF value 6.4518% and return to increases with increasing o VUF as shown in table 6.The secondary power factor increases with increasing of VUF as shown in table 6.

For under voltage unbalance occurs in phase c. The transformer efficiency and secondary power factor decreases with increasing of VUF, as shown in table 8.

The efficiency and total losses for single phase under voltage unbalance occurs in phase b is 3-D plotted with VUF in figure 12.The secondary and primary power factor is 3-D plotted with VUF in figure 13.

Case 3: effect of two phase voltage unbalance.

For unbalance voltage occurs in phase a and c. It can be seen from the results listed in table 10 that the secondary positive – sequence voltage is fixed at V_{SP} =239.0064 volt with different VUF values. It also can be observed that the efficiency and power factor decrease with increase of VUF. The maximum changes in efficiency and secondary power factor are 2.843% and 0.92% respectively.

The efficiency and total losses are 3-D plotted with VUF in figure 14.The secondary and primary power factor is 3-D plotted with VUF in figure 15.

For unbalance voltage occurs in phase a and b. It can be seen from result listed in table 12 that the positive – sequence voltage of the secondary voltage is fixed at the same above value. It also can be seen from results in table 10 that the efficiency and power factor decrease with increase of VUF. The maximum changes in efficiency and secondary power factor are 1.916% and 0.16% respectively. The efficiency and total losses are 3-D plotted with VUF in figure 16. The secondary and primary power factor is 3-D plotted with VUF in figures 17.

It can be seen from tables 10, 12 that the negative sequence voltage component has little effect on the power factor. In other word the transformer power factor affected by the positive sequence voltage component.

8. Conclusion

This paper presents analysis and control the operation of three-phase distribution transformer operating with unbalanced condition.

From the results of this paper it can be concluded the following:

1- The operating characteristics of a three phase distribution transformer will not be as good as in the balance case, but most customers do not know that the unbalance may cause a higher power factor. It is worth that customers usually use capacitors to improve the power factor, but due to ignorance of voltage unbalance, they may over compensate the power factor, thus result in over voltage.

2- The negative sequence voltage component has little effect on the secondary power factor.

3-The values of efficiency and secondary power factor dependent on over or under voltage unbalance for three phase unbalance. For two and single phase voltage unbalance the values of efficiency and secondary power factor dependent on same reason of the three phase unbalance ,further dependent on at which phase or phases the unbalance voltage occurs.

4-The voltage unbalance may causes decrease of transformer efficiency and increase transformer losses.

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Table (1) Transformer ratio dependent on its connection

n	Connection	n	Connection
$\frac{1}{\sqrt{3}}.\frac{N_p}{N_s}$	Dy	$\frac{N_p}{N_s}$	Yy
$\frac{N_p}{N_s}$	Dd	$\sqrt{3}.\frac{N_p}{N_s}$	Yd
$\frac{2}{\sqrt{3}}.\frac{N_p}{N_s}$	Dz	$\frac{2}{\sqrt{3}}.\frac{N_p}{N_s}$	Yz

Table (2) results of transformer secondary circuit for 3 –phases under and over voltage unbalance

	VUF%	Vas	Vbs	Vcs	Ias	Ibs	Ics	Vsp	Vsn	Vso	PF	Total losses Watts	Efficiency %
	0.0000	239.6004	239.6004	239.6004	312.0781	420.4602	431.6304	239.6004	0.0000	0.0000	0.8672	21795	91.6972
U V U	1.5604	237.5169	231.2664	225.0160	309.3644	405.8355	405.3573	231.2664	3.6087	3.6087	0.8652	22026	90.9961
	3.2375	235.4334	222.9325	210.4316	306.6507	391.2108	379.0841	222.9325	7.2174	7.2174	0.8630	22103	90.2853
	5.0448	233.3499	214.5986	195.8473	303.9370	376.5861	352.8109	214.5986	10.8261	10.8261	0.8606	22028	89.5691
	6.9982	231.2664	206.2647	181.2629	301.2232	361.9614	326.5378	206.2647	14.4348	14.4348	0.8580	21801	88.8550
	9.1161	229.1830	197.9307	166.6785	298.5095	347.3367	300.2646	197.9307	18.0435	18.0435	0.8552	21422	88.1526
O V U	1.4555	241.6838	247.9343	254.1847	314.7918	435.0849	457.9036	247.9343	3.6087	3.6087	0.8691	21413	92.3839
	2.6962	244.8091	256.2682	268.7691	318.8624	449.7097	484.1767	256.6155	6.9188	6.9188	0.8708	21134	92.9871
	3.9731	246.8925	264.6021	283.3535	321.5761	464.3344	510.4499	264.9494	10.5268	10.5268	0.8724	20457	93.6381
	5.1723	248.9760	272.9361	297.9378	324.2899	478.9591	536.7230	273.2833	14.1351	14.1351	0.8739	19628	94.2696
	6.3006	251.0595	281.2700	312.5222	327.0036	493.5838	562.9962	281.6172	17.7436	17.7436	0.8752	18647	94.8810
	7.3641	253.1430	289.6039	327.1066	329.7173	508.2085	589.2693	289.9512	21.3522	21.3522	0.8765	17513	95.4720
	8.4786	254.1847	297.9378	341.6910	331.0742	522.8332	615.5425	297.9378	25.2609	25.2609	0.8778	15917	96.1100

Table (3) results of transformer primary circuit for 3 –phases under and over voltage unbalance

	VUF %	Vap	Vbp	Vcp	Iap	Ibp	Icp	Vpp	Vpn	PF
	0.0000	11655	11655	11655	9.1735	9.1735	9.1735	11655	0.0000	0.8184
U V U	1.5604	11402	11251	11098	8.9649	8.8792	8.7208	11250	175.5455	0.8184
	3.2174	11146	10854	10542	8.7541	8.5898	8.2691	10845	348.9089	0.8185
	5.0135	10893	10458	9986	8.5459	8.3018	7.8174	10439	523.3634	0.8186
	6.9547	10640	10065	9432	8.3389	8.0166	7.3661	10034	697.8179	0.8189
	9.0594	10389	9677	8879	8.1331	7.7346	6.9153	09628	872.2723	0.8192
O V U	1.4465	11911	12060	12213	9.3846	9.4686	9.6261	12061	174.5	0.8184
	2.6794	12201	12476	12780	9.6232	9.7740	10.0833	12483	334.5	0.8185
	3.9484	12458	12885	13338	9.8359	10.0726	10.5363	12888	508.9	0.8185
	5.1402	12715	13296	13897	10.0494	10.3729	10.9894	13294	683.3	0.8186
	6.2615	12973	13709	14457	10.2636	10.6746	11.4427	13699	857.8	0.8188
	7.3183	13231	14123	15016	10.4784	10.9777	11.8961	14105	1032.2	0.8189
	8.4259	13457	14532	15569	10.6673	11.2746	12.3454	14493	1221.2	0.8191

Table (4) results of transformer secondary circuit for 1 –phase under and over voltage unbalance in phase a

	VUF%	Vas	Vbs	Vcs	Ias	Ibs	Ics	Vsp	Vsn	Vso	PF	Total losses Watts	Efficiency%
	0.0000	239.6004	239.6004	239.6004	312.0781	420.4602	431.6304	239.6004	0.0000	0.0000	0.8672	21795	91.6972
U V U	2.0710	225.0160	239.6004	239.6004	293.0821	420.4602	431.6304	234.7389	4.8615	4.8615	0.8690	18519	92.6537
	4.2296	210.4316	239.6004	239.6004	274.0860	420.4602	431.6304	229.8774	9.7229	9.7229	0.8707	15250	93.7014
	6.4815	195.8473	239.6004	239.6004	255.0899	420.4602	431.6304	225.0160	14.5844	14.5844	0.8724	11994	94.8440
	8.8328	181.2629	239.6004	239.6004	236.0939	420.4602	431.6304	220.1545	19.4458	19.4458	0.8740	8748	96.0873
	11.2903	166.6785	239.6004	239.6004	217.0978	420.4602	431.6304	215.2931	24.3073	24.3073	0.8756	5512	97.4359
O V U	1.9886	254.1847	239.6004	239.6004	331.0742	420.4602	431.6304	244.4618	4.8615	4.8615	0.8655	25084	90.8248
	3.8997	268.7691	239.6004	239.6004	350.0702	420.4602	431.6304	249.3233	9.7229	9.7229	0.8638	28383	90.0315
	5.7377	283.3535	239.6004	239.6004	369.0663	420.4602	431.6304	254.1847	14.5844	14.5844	0.8621	31693	89.3120
	7.5067	297.9378	239.6004	239.6004	388.0624	420.4602	431.6304	259.0462	19.4458	19.4458	0.8604	35014	88.6609
	9.2105	312.5222	239.6004	239.6004	407.0584	420.4602	431.6304	263.9076	24.3073	24.3073	0.8587	38345	88.0733
	10.8527	327.1066	239.6004	239.6004	426.0545	420.4602	431.6304	268.7691	29.1687	29.1687	0.8571	41687	87.5444
	12.4365	341.6910	239.6004	239.6004	445.0505	420.4602	431.6304	273.6306	34.0302	34.0302	0.8555	45040	87.0695

Table (5) results of transformer primary circuit for 1 –phase under and over voltage unbalance in phase a

	VUF%	Vap	Vbp	Vcp	Iap	Ibp	Icp	Vpp	Vpn	PF
	0.0000	11655	11655	11655	9.1735	9.1735	9.1735	11655	0.0000	0.8184
UVU	2.0710	11182	11539	11539	8.7978	9.0564	9.1109	11419	236.5	0.8184
	4.2033	10712	11420	11429	8.4253	8.9382	9.0523	11182	470	0.8186
	6.4412	10241	11309	11321	8.0515	8.8263	8.9953	10946	705	0.8188
	8.7779	9769	11201	11217	7.6778	8.7182	8.9408	10709	940.1	0.8191
	11.2202	9298	11097	11117	7.3043	8.6143	8.8888	10473	1175.1	0.8196
OVU	1.9763	12127	11778	11774	9.5477	9.2964	9.1735	11892	235	0.8184
	3.8755	12598	11905	11896	9.9221	9.4228	9.2376	12128	470	0.8185
	5.7020	13070	12035	12021	10.2966	9.5524	9.3039	12365	705	0.8187
	7.4600	13541	12168	12150	10.6712	9.6851	9.3725	12601	940.1	0.8189
	9.1533	14013	12304	12281	11.0458	9.8208	9.4433	12838	1175.1	0.8192
	10.7853	14484	12443	12416	11.4205	9.9594	9.5162	13074	1410.1	0.8195
	12.3593	14956	12585	12553	11.7953	10.1007	9.5912	13311	1645.1	0.8199

Table (6) results of transformer secondary circuit for 1 –phase under and over voltage unbalance in phase b

	VUF%	Vas	Vbs	Vcs	Ias	Ibs	Ics	Vsp	Vsn	Vso	PF	Total losses Watts	Efficiency %
	0.0000	239.6004	239.6004	239.6004	312.0781	420.4602	431.6304	239.6004	0.0000	0.0000	0.8672	21795	91.6972
UVU	2.0710	239.6004	225.0160	239.6004	312.0781	394.8670	431.6304	234.7389	4.8615	4.8615	0.8684	21373	91.5214
	4.2296	239.6004	210.4316	239.6004	312.0781	369.2738	431.6304	229.8774	9.7229	9.7229	0.8695	20780	91.4176
	6.4815	239.6004	195.8473	239.6004	312.0781	343.6805	431.6304	225.0160	14.5844	14.5844	0.8707	20019	91.3939
	8.8328	239.6004	181.2629	239.6004	312.0781	318.0873	431.6304	220.1545	19.4458	19.4458	0.8718	19090	91.4613
	11.2903	239.6004	166.6785	239.6004	312.0781	292.4941	431.6304	215.2931	24.3073	24.3073	0.8730	17992	92.5623
OVU	1.9886	239.6004	254.1847	239.6004	312.0781	446.0535	431.6304	244.4618	4.8615	4.8615	0.8661	22050	91.9344
	3.8997	239.6004	268.7691	239.6004	312.0781	471.6467	431.6304	249.3233	9.7229	9.7229	0.8651	22137	92.2253
	5.7377	239.6004	283.3535	239.6004	312.0781	497.2399	431.6304	254.1847	14.5844	14.5844	0.8640	22055	92.5623
	7.5067	239.6004	297.9378	239.6004	312.0781	522.8332	431.6304	259.0462	19.4458	19.4458	0.8630	21804	92.9388
	9.2105	239.6004	312.5222	239.6004	312.0781	548.4264	431.6304	263.9076	24.3073	24.3073	0.8621	21385	93.3485
	10.8527	239.6004	327.1066	239.6004	312.0781	574.0196	431.6304	268.7691	29.1687	29.1687	0.8612	20798	93.7859
	12.4365	239.6004	341.6910	239.6004	312.0781	599.6129	431.6304	273.6306	34.0302	34.0302	0.8603	20042	94.2463

Table (7) results of transformer primary circuit for 1 –phase under and over voltage unbalance in phase b

	VUF%	Vap	Vbp	Vcp	Iap	Ibp	Icp	Vpp	Vpn	PF
	0.0000	11655	11655	11655	9.1735	9.1735	9.1735	11655	0.0000	0.8184
UVU	2.0710	11182	11539	11539	8.7978	9.0564	9.1109	11419	236.5	0.8184
	4.2033	10712	11420	11429	8.4253	8.9382	9.0523	11182	470	0.8186
	6.4412	10241	11309	11321	8.0515	8.8263	8.9953	10946	705	0.8188
	8.7779	9769	11201	11217	7.6778	8.7182	8.9408	10709	940.1	0.8191
	11.2202	9298	11097	11117	7.3043	8.6143	8.8888	10473	1175.1	0.8196
OVU	1.9763	12127	11778	11774	9.5477	9.2964	9.1735	11892	235	0.8184
	3.8755	12598	11905	11896	9.9221	9.4228	9.2376	12128	470	0.8185
	5.7020	13070	12035	12021	10.2966	9.5524	9.3039	12365	705	0.8187
	7.4600	13541	12168	12150	10.6712	9.6851	9.3725	12601	940.1	0.8189
	9.1533	14013	12304	12281	11.0458	9.8208	9.4433	12838	1175.1	0.8192
	10.7853	14484	12443	12416	11.4205	9.9594	9.5162	13074	1410.1	0.8195
	12.3593	14956	12585	12553	11.7953	10.1007	9.5912	13311	1645.1	0.8199

Table (8) results of transformer secondary circuit for 1 –phase under and over voltage unbalance in phase c

	VUF%	Vas	Vbs	Vcs	Ias	Ibs	Ics	Vsp	Vsn	Vso	PF	Total losses Watts	Efficiency %
	0.0000	239.6004	239.6004	239.6004	312.0781	420.4602	431.6304	239.6004	0.0000	0.0000	0.8672	21795	91.6972
UVU	2.0710	239.6004	239.6004	225.0160	312.0781	420.4602	405.3573	234.7389	4.8615	4.8615	0.8643	22642	91.0181
	4.2296	239.6004	239.6004	210.4316	312.0781	420.4602	379.0841	229.8774	9.7229	9.7229	0.8613	23237	90.4025
	6.4815	239.6004	239.6004	195.8473	312.0781	420.4602	352.8109	225.0160	14.5844	14.5844	0.8583	23586	89.8604
	8.8328	239.6004	239.6004	181.2629	312.0781	420.4602	326.5378	220.1545	19.4458	19.4458	0.8551	23687	89.4052
	11.2903	239.6004	239.6004	166.6785	312.0781	420.4602	300.2646	215.2931	24.3073	24.3073	0.8519	23539	89.0507
OVU	1.9886	239.6004	239.6004	254.1847	312.0781	420.4602	457.9036	244.4618	4.8615	4.8615	0.8700	20702	92.4276
	3.8997	239.6004	239.6004	268.7691	312.0781	420.4602	484.1767	249.3233	9.7229	9.7229	0.8727	19361	93.2004
	5.7377	239.6004	239.6004	283.3535	312.0781	420.4602	510.4499	254.1847	14.5844	14.5844	0.8752	17771	94.0070
	7.5067	239.6004	239.6004	297.9378	312.0781	420.4602	536.7230	259.0462	19.4458	19.4458	0.8777	15933	94.8401
	9.2105	239.6004	239.6004	312.5222	312.0781	420.4602	562.9962	263.9076	24.3073	24.3073	0.8800	13847	95.6931

Table (9) results of transformer primary circuit for 1 –phase under and over voltage unbalance in phase c

	VUF%	Vap	Vbp	Vcp	Iap	Ibp	Icp	Vpp	Vpn	PF
	0.0000	11655	11655	11655	9.1735	9.1735	9.1735	11655	0.0000	0.8184
UVU	2.0710	11539	11539	11182	9.0564	9.1109	8.7978	11419	236.5	0.8184
	4.2033	11420	11429	10712	8.9382	9.0523	8.4253	11182	470	0.8186
	6.4412	11309	11321	10241	8.8263	8.9953	8.0515	10946	705	0.8188
	8.7779	11201	11217	9769	8.7182	8.9408	7.6778	10709	940.1	0.8191
	11.2202	11097	11117	9298	8.6143	8.8888	7.3043	10473	1175.1	0.8196
OVU	1.9763	11778	11774	12127	9.2964	9.2376	9.5477	11892	235	0.8184
	3.8755	11905	11896	12598	9.4228	9.3039	9.9221	12128	470	0.8185
	5.7020	12035	12021	13070	9.5524	9.3725	10.2966	12365	705	0.8187
	7.4600	12168	12150	13541	9.6851	9.4433	10.6712	12601	940.1	0.8189
	9.1533	12304	12281	14013	9.8208	9.5162	11.0458	12838	1175.1	0.8192
	10.7853	12443	12416	14484	9.9594	9.5912	11.4205	13074	1410.1	0.8195
	12.3593	12585	12553	14956	10.1007	9.6683	11.7953	13311	1645.1	0.8199

Table (10) results of transformer secondary circuit for 2 –phases voltage unbalance in phase a and c

VUF%	Vas	Vbs	Vcs	Ias	Ibs	Ics	Vsp	Vsn	Vso	PF	Total losses Watts	Efficiency%
0.0000	239.6004	239.6004	239.6004	312.0781	420.4602	431.6304	239.6004	0.0000	0.0000	0.8672	21795	91.6972
1.0001	243.7509	239.6004	235.4498	317.4842	420.4602	424.1534	239.6004	2.3963	2.3963	0.8659	22988	91.2437
2.0003	247.9015	239.6004	231.2992	322.8903	420.4602	416.6763	239.6004	4.7927	4.7927	0.8646	24147	90.8056
3.0004	252.0520	239.6004	227.1487	328.2964	420.4602	409.1992	239.6004	7.1890	7.1890	0.8633	25271	90.3831
4.0005	256.2026	239.6004	222.9981	333.7024	420.4602	401.7222	239.6004	9.5853	9.5853	0.8620	26360	89.9765
5.0007	260.3531	239.6004	218.8476	339.1085	420.4602	394.2451	239.6004	11.9816	11.9816	0.8606	27414	89.5859
6.0008	264.5037	239.6004	214.6970	344.5146	420.4602	386.7680	239.6004	14.3780	14.3780	0.8593	28435	89.2117
7.0009	268.6543	239.6004	210.5465	349.9207	420.4602	379.2910	239.6004	16.7743	16.7743	0.8580	29420	88.8540

Table (11) results of transformer primary circuit for 2 –phases voltage unbalance in phase a and c

VUF %	Vap	Vbp	Vcp	Iap	Ibp	Icp	Vpp	Vpn	PF
0.0000	11655	11655	11655	9.1735	9.1735	9.1735	11655	0.0000	0.8184
0.9939	11755	11657	11555	9.2457	9.1905	9.0849	11655	115.8451	0.8184
1.9878	11855	11660	11454	9.3183	9.2085	8.9965	11655	231.6902	0.8184
2.9818	11956	11664	11354	9.3912	9.2274	8.9082	11655	347.5353	0.8185
3.9757	12057	11670	11254	9.4646	9.2473	8.8201	11655	463.3804	0.8185
4.9696	12157	11676	11154	9.5383	9.2680	8.7320	11655	579.2255	0.8186
5.9635	12259	11683	11055	9.6124	9.2897	8.6441	11655	695.0706	0.8187
6.9574	12360	11692	10956	9.6868	9.3122	8.5563	11655	810.9157	0.8189

Table (12) results of transformer secondary circuit for 2 –phases voltage unbalance in phase a and b

VUF%	Vas	Vbs	Vcs	Ias	Ibs	Ics	Vsp	Vsn	Vso	PF	Total lossesWatts	Efficiency %
0.0000	239.6004	239.6004	239.6004	312.0781	420.4602	431.6304	239.6004	0.0000	0.0000	0.8672	21795	91.6972
1.0001	243.7509	235.4498	239.6004	317.4842	413.1767	431.6304	239.6004	2.3963	2.3963	0.8671	22619	91.3844
2.0003	247.9015	231.2992	239.6004	322.8903	405.8931	431.6304	239.6004	4.7927	4.7927	0.8669	23415	91.0843
3.0004	252.0520	227.1487	239.6004	328.2964	398.6096	431.6304	239.6004	7.1890	7.1890	0.8666	24182	90.7972
4.0005	256.2026	222.9981	239.6004	333.7024	391.3260	431.6304	239.6004	9.5853	9.5853	0.8664	24922	90.5233
5.0007	260.3531	218.8476	239.6004	339.1085	384.0424	431.6304	239.6004	11.9816	11.9816	0.8662	25633	90.2626
6.0008	264.5037	214.6970	239.6004	344.5146	376.7589	431.6304	239.6004	14.3780	14.3780	0.8659	26316	90.0154
7.0009	268.6543	210.5465	239.6004	349.9207	369.4753	431.6304	239.6004	16.7743	16.7743	0.8656	26972	89.7817

Table (13) results of transformer secondary circuit for 2 –phases voltage unbalance in phase a and b

VUF %	Vap	Vbp	Vcp	Iap	Ibp	Icp	Vpp	Vpn	PF
0.0000	11655	11655	11655	9.1735	9.1735	9.1735	11655	0.0000	0.8184
0.9939	11755	11657	11555	9.2457	9.1905	9.0849	11655	115.8451	0.8184
1.9878	11855	11660	11454	9.3183	9.2085	8.9965	11655	231.6902	0.8184
2.9818	11956	11664	11354	9.3912	9.2274	8.9082	11655	347.5353	0.8185
3.9757	12057	11670	11254	9.4646	9.2473	8.8201	11655	463.3804	0.8185
4.9696	12157	11676	11154	9.5383	9.2680	8.7320	11655	579.2255	0.8186
5.9635	12259	11683	11055	9.6124	9.2897	8.6441	11655	695.0706	0.8187
6.9574	12360	11692	10956	9.6868	9.3122	8.5563	11655	810.9157	0.8189

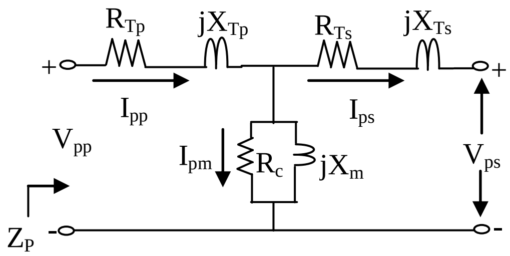


Fig.1 Per-phase positive sequence representation

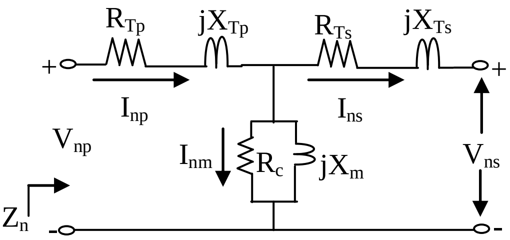
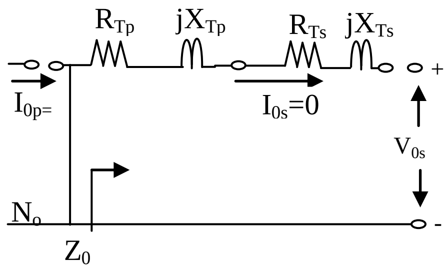
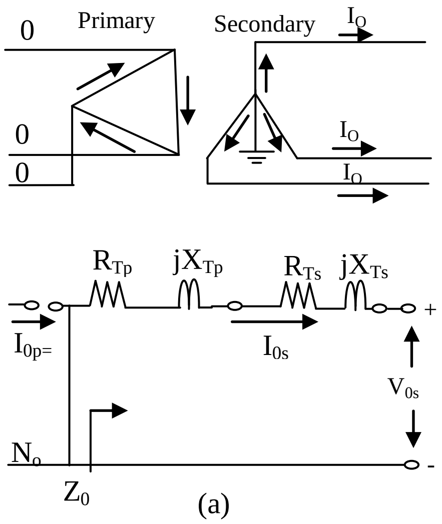


Fig.2 Per-phase negative sequence representation



(b)



(a)

Fig.3 (a) Derivations of equivalent zero sequence circuit for a delta–star transformer, star neutral solidly grounded; (b) zero sequence circuit of a delta–star transformer, star neutral isolated.

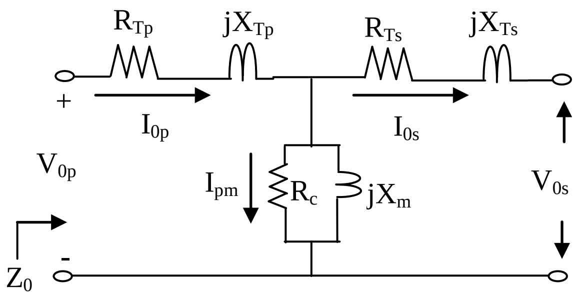
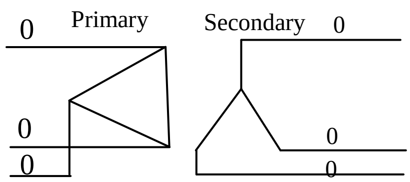


Fig.4 Per-phase zero sequence representation of a wye–wye transformer, both neutrals grounded.



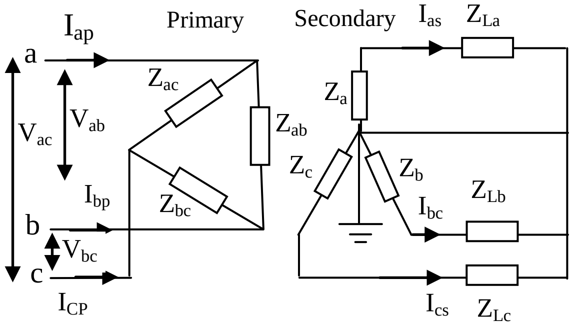


Fig.5 system under study

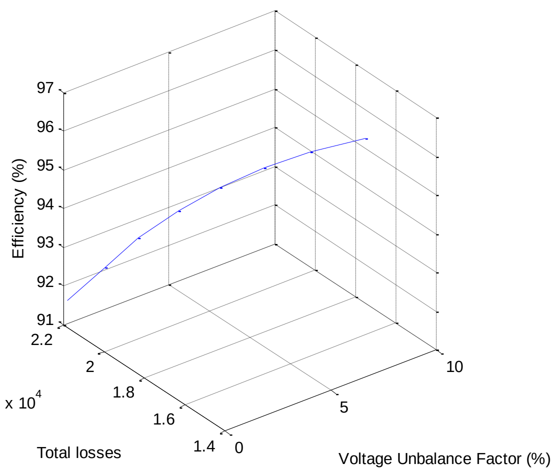


Fig.6. 3-D plot of VUF, total losses and efficiency for 3-phases over voltage unbalance

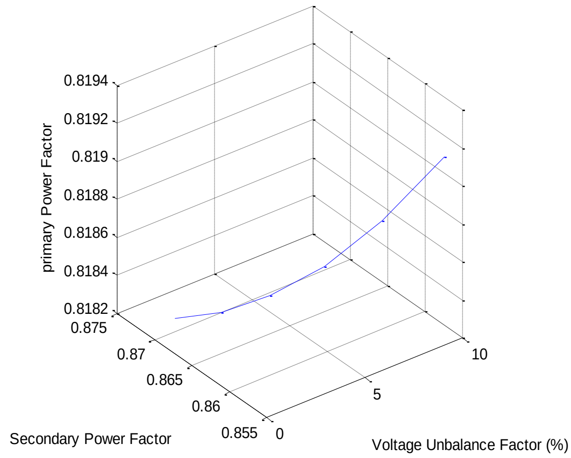


Fig.9. 3-D plot of VUF, secondary and primary power factor for 3-phases under voltage unbalance

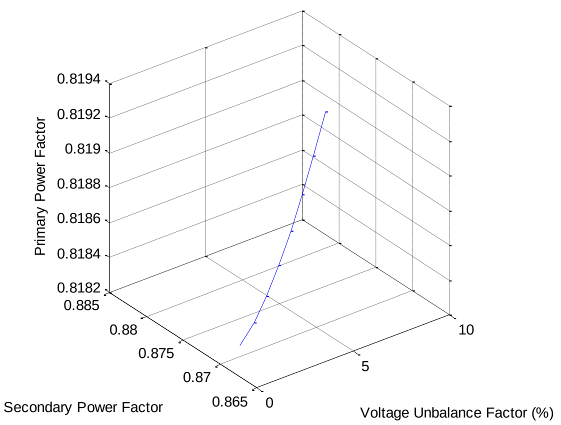


Fig.7. 3-D plot of VUF, secondary and primary power factor for 3-phases over voltage unbalance

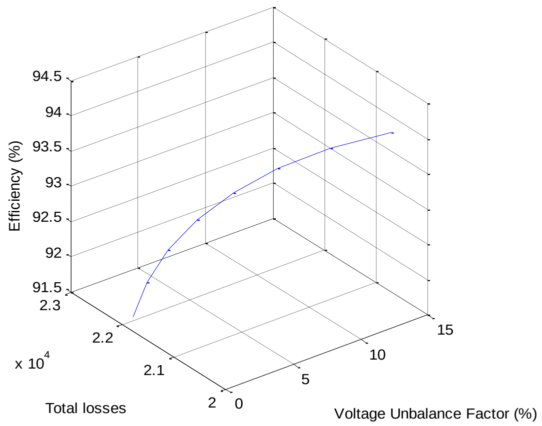
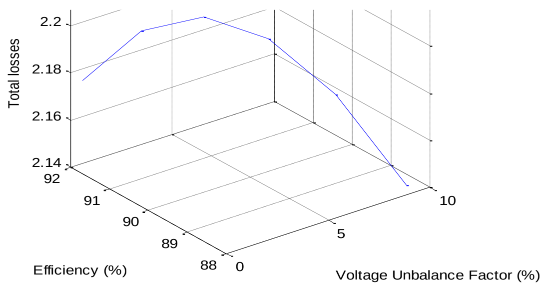


Fig.10. 3-D plot of VUF, total losses and efficiency for 1-phase over voltage unbalance in phase b



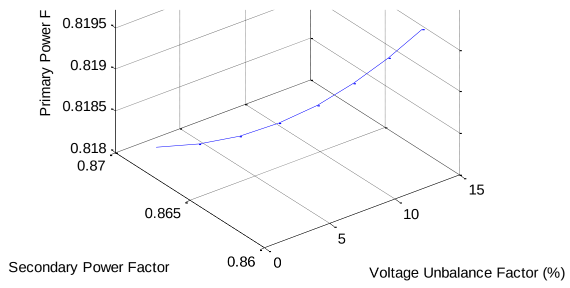


Fig.8. 3-D plot of VUF, total losses and efficiency for 3-phases under voltage unbalance

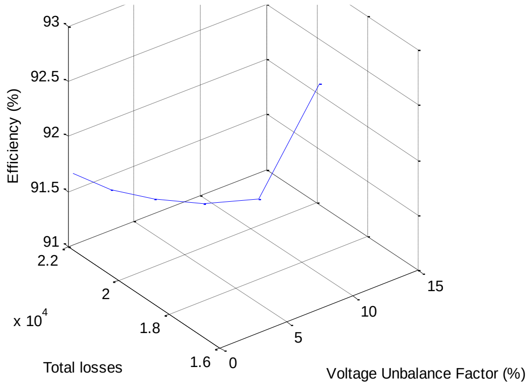


Fig.11. 3-D plot of VUF, secondary and primary power factor for 1-phase over voltage unbalance in phase b

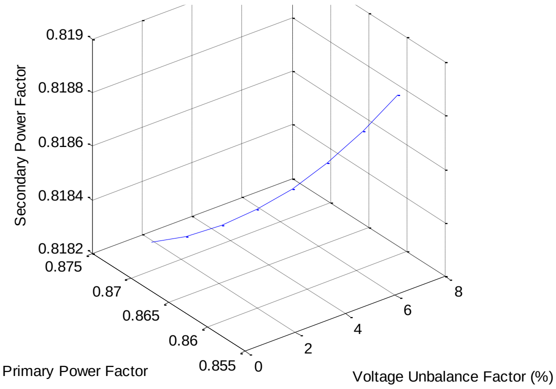
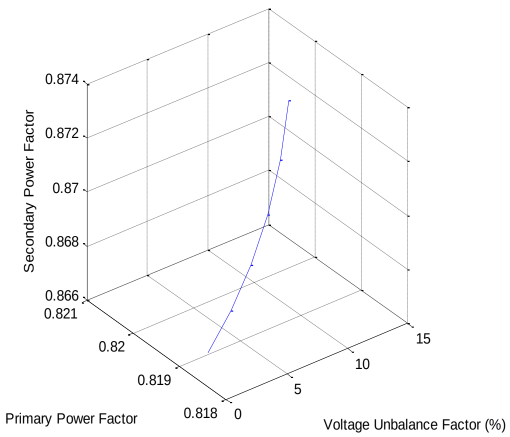


Fig.12. 3-D plot of VUF, total losses and efficiency for 1-phase under voltage unbalance in phase b

Fig.15. 3-D plot of VUF, secondary and primary power factor for 2-phase voltage unbalance in phase a and c



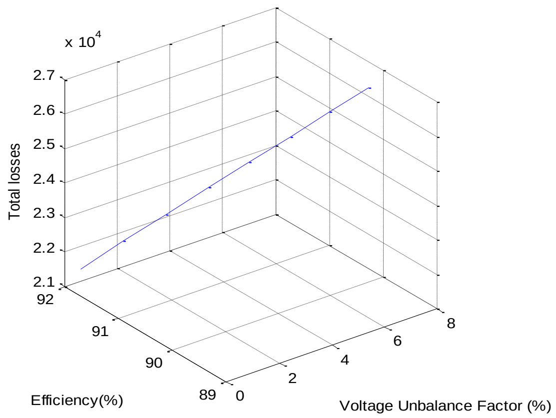


Fig.13. 3-D plot of VUF, secondary and primary power factor for 1-phase under voltage unbalance in phase b

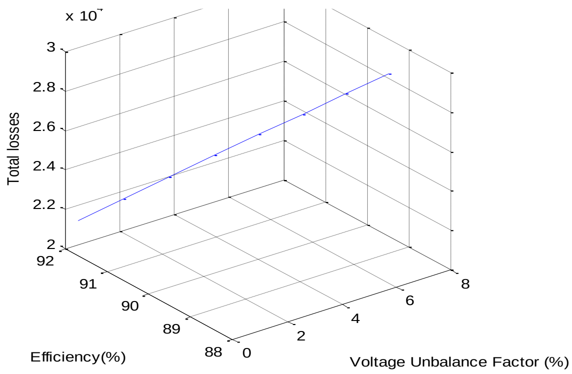


Fig.16. 3-D plot of VUF, total losses and efficiency for 2-phases voltage unbalance in phase a and b

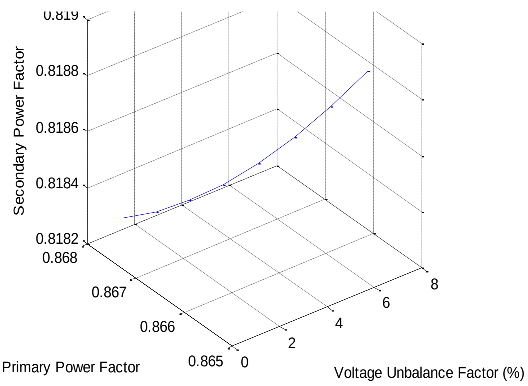


Fig.14. 3-D plot of VUF, total losses and efficiency for 2-phases voltage unbalance in phase a and c

Fig.17. 3-D plot of VUF, secondary and primary power factor for 2-phases voltage unbalance in phase a and b