Analysis for Integration of Solar PV Fed Three-Phase Grid to Five-Phase Drive System under unbalance condition

Ahmed Riyaz
Department of Electrical Engineering
Baba Ghulam Shah Badshah University
Rajouri, India
riyazamu@gmail.com

Samar Jeet Singh
Department of Electronics & Communication Engineering
Integral University
Lucknow, India
samarbnd@gmail.com

Shailendra Kumar
Department of Electronics & Communication Engineering
Integral University
Lucknow, India
skumar@iul.ac.in

Mohammed Asim
Department of Electrical Engineering
Integral University
Lucknow, India
asimamu@gmail.com,

Asim Rahman Ansari
Department of Electrical Engineering, FET
MJP Rohilkhand University
Bareilly, India
ashi0786ansari@gmail.com

Abstract—Multi-phase (more than three phase) is being increasingly used in many applications. Due to higher phase numbers, there is more possibility for a multi-phase system to have unbalancing between different phase voltages in comparison to a three-phase system. Performance and behaviour of a multi-phase system under unbalance condition is of much importance. Conversion of an unbalanced system to a balanced system was proposed by C. L. Fortescue and balanced components was given the name "symmetrical components". In this paper three-to-five phase transformation has been analysed under various unbalanced conditions using simulation and experimental analysis. Symmetrical components transformation of a five-phase system is presented and determination of active and reactive power with the help of symmetrical components is developed. Furthermore, sequence circuit of three-to-five phase transformation is developed to model various operating conditions. With this modelling, the degree and nature of different unbalances and their effects on the system can be predicted in advance. Both simulation and laboratory tests results for a three-to-five-phase transformation is presented. It has been concluded that experimental results are well in line with the analytical results.

Keywords—Multiphase Transformer, Passive phase transformation, Winding Connection, symmetrical components, sequence networks.

I. INTRODUCTION

Multi-phase machines are usually considered for high-power applications. With the help of power electronic converters any number of phases of AC power can be obtained. By employing higher order phase system over traditional three-phase system, the amount of power per phase reduces along with many inherent advantages. Multiphase system was initially introduced in the late 1960s [1] and they are significantly helpful in the area of power and in applications like electric vehicles and ship propulsion [2-8]. Generally, the five and six phase systems have been explored in literature. The most logical extension of a three-phase system is a five-phase system.

For power input to a multi-phase machine, multi-phase supply is required. Multi-phase supply may be obtained by power electronic converters using rectifier-inverter combination while the voltage/current obtained contains harmonics and ripples. For most of the applications this kind of supply is satisfactory. However, high performance motor drives need precise motor parameters. Sinusoidal supply is required to perform various tests on the motor in order to know the motor parameters. Hence, there is need of static transformers to obtain multi-phase supply while the input is three-phase. In literature, various transformer connection schemes have been reported recently to convert the available three phase supply into multiphase supply. By using these connection schemes five-phase generator output can be transformed into three-phase economically in wind energy applications [9]. Various connection schemes are reported in the literature for three-to-five phase transformer [9-10]. Available three-phase supply from the grid may have some unbalancing and the windings of the transformers may also have some unbalance. A case study of three-phase transformer with unequal winding impedances is done in [11]. In [12] a three-phase distribution transformer with unbalance supply has been analyzed. Performance of Multi-phase transformers is affected more under unbalance conditions [13]. Behaviour of three-phase transformer under unbalance supply is discussed in detail in the literature, however, not enough focus has been given for unbalancing in systems having more than three-phase.

A complete symmetrical analysis of five-phase system is presented in this paper. The operation of three-phase to five-phase transformer with unbalance voltage conditions is also discussed. The proposed system is described in Section II. Different prevalent voltage unbalance definitions are discussed in Section III; these definitions is applied here for a five-phase system using simulation and experimental analysis. Determination of symmetrical component, calculation of active power and reactive power in a five-phase system is discussed in Section IV. Development of sequence circuit for a three-to-five multiphase transformer is discussed in section V. Simulation and experimental analysis and their results along with discussion are presented in Section VI and VII. The paper is concluded in Section VIII.

979-8-3503-9976-9/23/$31.00 ©2023 IEEE.

II. SYSTEM DESCRIPTION

Source power generated from solar photo-voltaic cell is given to the three-phase inverter, the output of the inverter is fed to the three to five phase transformer via grid. Five phase drive is powered by the three to five phase transformer. The proposed scheme is presented in Fig. 1.

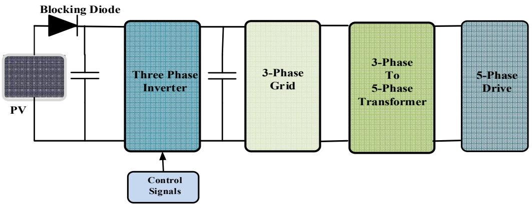

Fig. 1: Proposed system for Five-Phase Drive.

III. VOLTAGE UNBALANCE IN MULTIPHASE SYSTEMS

For a multi-phase transformer, a common problem is impedance mismatch due to different number of turns in various phase winding. Mismatch in impedance may also be present due to transmission lines, unbalanced loads and various faults in system. Impedance mismatch result in voltage unbalance and affect machines adversely. Increased noise, vibration, less torque and de-rated speed in machines are mainly due to voltage unbalance. Voltage unbalance causes disturbance in multiphase distribution networks also and may cause power losses of transformers and lines.

In literature, various methods have been adopted to define the term voltage/current unbalance [14]. PVUR (phase voltage unbalance ratio), MPVUR (mean phase voltage unbalance ratio) and VUF (voltage unbalance factor) are defined by IEEE, while LVUR (line voltage unbalance ratio) is adapted by NEMA (National Electrical Manufactures Association). While analysing any system the definition of voltage unbalance is very important. As defined by IEEE, it is the ratio of difference of maximum voltage from the average phase voltage and average phase voltage. For analysis purpose in this paper IEEE definition of voltage unbalancing is considered as mentioned in Eq. (1).

$$PVUR = \frac{\max\left[|V_a - V_{\text{avg}}|,|V_b - V_{\text{avg}}|,|V_c - V_{\text{avg}}|,|V_d - V_{\text{avg}}|,|V_e - V_{\text{avg}}|\right]}{V_{avg}} \times 100$$

$$\text{Where, } V_{avg} = \frac{V_a + V_b + V_c + V_d + V_e}{5} \qquad (1)$$

IV. DETERMINATION OF SYMMETRICAL COMPONENT OF FIVE PHASE SYSTEM

A multiphase system is more prone to unbalancing due to a greater number of phases. Under unbalance condition voltage and current magnitudes are not equal in different phases and the transformer fails to deliver rated power output of nominal ratings. Unbalanced operation of a network can be analysed with the help of the symmetrical component. Symmetrical component is a technique discovered in 1913 by Charles Legeyt Fortescue. According to Stokvis-Fortescue theorem [15], any asymmetrical system can be transformed into symmetrical balanced system called the symmetrical components of the system. In this paper the symmetrical component of a five -phase system has been calculated.

According to Fortescue, a perfectly balanced system as in Fig. 2 will have only positive sequence currents and voltages; and there will be no negative or zero sequence components. Similarly, the currents also have equal magnitudes and phase angles, which would produce a result of only positive sequence and no negative or zero sequence currents for a balanced system. For unbalanced systems as in Fig. 2, there will be positive, negative and possibly zero-sequence currents.

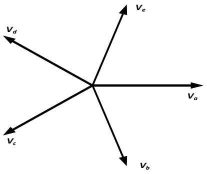

Fig. 2: Balanced five-phase system phasor.

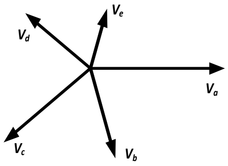

Fig. 3 (a): Unbalanced five-phase system phasor with different magnitude.

Fig. 3(a) shows five-phase unbalanced phasors and its transformation to five sequence components. The original set of five unbalanced phasors are represented by V_a, V_b, V_c, V_d and V_e while their two set of positive, two sets each of negative sequence component and zero sequence component are shown in Fig. 3 (b), (c) and (d). The positive sequence component, negative sequence component and zero sequence component of phase-a are denoted by V_{a1},V_{a2}, V_{a3}, V_{a4} and V_{a0}. Similarly, the unbalanced current phasors may be resolved into five symmetrical components [16].

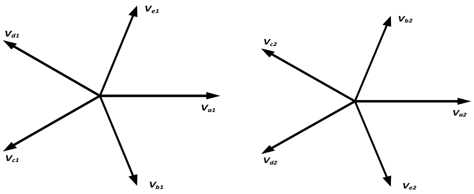

Fig. 3 (b): Set of positive sequence component of unbalanced five-phase system.

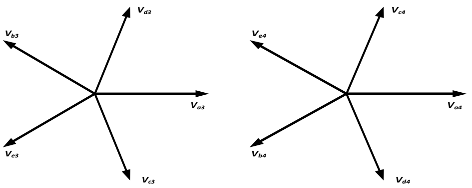

Fig. 3 (c): Set negative sequence component of unbalanced five-phase system.

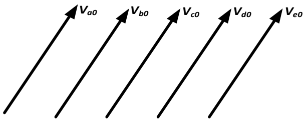

Fig. 3 (d): Zero sequence component of a five-phase system.

The $\alpha - o$perator may be defined as follows:

$$\alpha = e^{j\frac{2\pi}{5}} = \cos\frac{2\pi}{5} + j\cos\frac{2\pi}{5}$$

then, $\alpha^2 = e^{j\frac{4\pi}{5}} = \cos\frac{4\pi}{5} + j\cos\frac{4\pi}{5}$

and, $\alpha^3 = e^{j\frac{6\pi}{5}} = \cos\frac{6\pi}{5} + j\cos\frac{6\pi}{5}$

$$\alpha^4 = e^{j\frac{8\pi}{5}} = \cos\frac{8\pi}{5} + j\cos\frac{8\pi}{5}$$

$$\alpha^5 = e^{j\frac{10\pi}{5}} = e^{j2\pi} = 1$$

$$\alpha^6 = e^{j\frac{12\pi}{5}} = e^{j\frac{10\pi}{5}}e^{j\frac{2\pi}{5}} = e^{j2\pi}.e^{j\frac{2\pi}{5}} = 1.e^{j\frac{2\pi}{5}} = \alpha$$

$$\alpha^7 = e^{j\frac{14\pi}{5}} = e^{j\frac{10\pi}{5}}e^{j\frac{4\pi}{5}} = e^{j2\pi}.e^{j\frac{4\pi}{5}} = 1.e^{j\frac{4\pi}{5}} = \alpha^2 \quad (2)$$

Using the $\alpha - o$perator from Eq. (2) and Fig. 3 (b), we can derive the positive sequence voltages of different phases as follows:

$$V_{b1} = \alpha^4 V_{a1}; V_{c1} = \alpha^3 V_{a1}; V_{d1} = \alpha^2 V_{a1};\ V_{e1} = \alpha V_{a1}$$

Similarly, other sequence components of all phases may be derived from Fig. 3 (c), (d), (e) and (f) with the help of α - operator:

$$V_{b2} = \alpha V_{a2}; V_{c2} = \alpha^2 V_{a2}; V_{d2} = \alpha^3 V_{a2};\ V_{e2} = \alpha^4 V_{a2}$$

$$V_{b3} = \alpha^2 V_{a3}; V_{c3} = \alpha^4 V_{a3}; V_{d3} = \alpha V_{a3};\ V_{e3} = \alpha^3 V_{a3}$$

$$V_{b4} = \alpha^3 V_{a4}; V_{c4} = \alpha V_{a4}; V_{d4} = \alpha^4 V_{a4};\ V_{e4} = \alpha^2 V_{a4}$$

$$V_{a0} = V_{b0} = V_{c0} = V_{d0} = V_{e0} \quad (4)$$

Hence, the phase voltages may be written as follows using Eq. (4) and by arithmetic addition of all sequence components of corresponding phase:

For phase a:

$$V_a = V_{a0} + V_{a1} + V_{a2} + V_{a3} + V_{a4}$$

Similarly:

$$V_b = V_{a0} + \alpha^4 V_{a1} + \alpha V_{a2} + \alpha^2 V_{a3} + \alpha^3 V_{a4}$$

$$V_c = V_{a0} + \alpha^3 V_{a1} + \alpha^2 V_{a2} + \alpha^4 V_{a3} + \alpha V_{a4}$$

$$V_d = V_{a0} + \alpha^2 V_{a1} + \alpha^3 V_{a2} + \alpha V_{a3} + \alpha^4 V_{a4}$$

$$V_e = V_{e0} + \alpha V_{a1} + \alpha^4 V_{a2} + \alpha^3 V_{a3} + \alpha^2 V_{a4} \quad (5)$$

From Eq. (5), phase voltages may be presented in matrix form:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & \alpha^4 & \alpha & \alpha^2 & \alpha^3 \\ 1 & \alpha^3 & \alpha^2 & \alpha^4 & \alpha \\ 1 & \alpha^2 & \alpha^3 & \alpha & \alpha^4 \\ 1 & \alpha & \alpha^4 & \alpha^3 & \alpha^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \\ V_{a3} \\ V_{a4} \end{bmatrix} \quad (6)$$

or, $V_{abcde} = \mathrm{A} V_{a01234}$

Where:

$$V_{abcde} = \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix};\ V_{a01234} = \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \\ V_{a3} \\ V_{a4} \end{bmatrix}$$

$$\mathrm{A} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & \alpha^4 & \alpha & \alpha^2 & \alpha^3 \\ 1 & \alpha^3 & \alpha^2 & \alpha^4 & \alpha \\ 1 & \alpha^2 & \alpha^3 & \alpha & \alpha^4 \\ 1 & \alpha & \alpha^4 & \alpha^3 & \alpha^2 \end{bmatrix} \quad (7)$$

From Eq. (6):

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \\ V_{a3} \\ V_{a4} \end{bmatrix} = \frac{1}{5} \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 & \alpha^3 & \alpha^4 \\ 1 & \alpha^4 & \alpha^3 & \alpha^2 & \alpha \\ 1 & \alpha^3 & \alpha & \alpha^4 & \alpha^2 \\ 1 & \alpha^2 & \alpha^4 & \alpha & \alpha^3 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} \quad (8)$$

or, $V_{a01234} = \mathrm{A}^{-1} V_{abcde}$

$$\mathrm{A}^{-1} = \frac{1}{5} \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 & \alpha^3 & \alpha^4 \\ 1 & \alpha^4 & \alpha^3 & \alpha^2 & \alpha \\ 1 & \alpha^3 & \alpha & \alpha^4 & \alpha^2 \\ 1 & \alpha^2 & \alpha^4 & \alpha & \alpha^3 \end{bmatrix} \quad (9)$$

Now, $I_{abcde} = \mathrm{A} I_{a01234}$ (10)

$$I_{a01234} = \mathrm{A}^{-1} I_{abcde}$$

Real and Reactive Power for an unbalanced five-phase system: The five-phase power in an unbalanced system is given by:

$$P_{abcde} + \mathrm{j}Q_{abcde} = V_a I_a^* + V_b I_b^* + V_c I_c^* + V_d I_d^* + V_e I_e^*$$

or, $P_{abcde} + \mathrm{j}Q_{abcde} = V_{abcde}^T I_{abcde}^*$

Using above equations, five-phase power can be expressed as follows:

$$P_{abcde} + \mathrm{j}Q_{abcde} = V_{a01234}^T A^{-T} A^{-1*} I_{a01234}^*$$

Since,

$$A^{-T} A^{-1*} = 5 \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

We may write,

$$P_{abcde} + \mathrm{j}Q_{abcde} = 5(V_{a0} I_{a0}^* + V_{a1} I_{a1}^* + V_{a2} I_{a2}^* + V_{a3} I_{a3}^* + V_{a4} I_{a4}^*) \quad (11)$$

From Eq. (11), it may be observed that the complex power is five times the summation of the complex power of the five-phase sequences.

V. DETERMINATION OF SEQUENCE CIRCUIT AND PARAMETERS OF THREE TO FIVE PHASE TRANSFORMER

Considering the case when transformer primary and secondary are Y-Y connected. Total kVA at both the sides of the transformer is same, the relation for the same is given by: $$3V_P I_P = 5V_S I_S \quad (12)$$

Primary Side of the transformer: If the impedance of each phase is Z_P and the neutral point (N) of the windings are grounded through an impedance Z_N and. The neutral current can be expressed as Eq. (13):

$$I_N = I_A + I_B + I_C \quad (13)$$

$$i.e., I_N = 3\, I_{A0} + (I_{A1} + I_{B1} + I_{C1}) + (I_{B2} + I_{B2} + I_{C2})$$

or, $$I_N = 3I_{A0} \quad (14)$$

Hence, as observed from Eq. (14), neutral current is three times of zero sequence current for a three-phase system. Therefore: $$V_N = 3Z_N I_{A0}$$

$$V_A = V_{AN} + V_N = V_{AN} + 3Z_N I_{A0}$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} + \begin{bmatrix} V_N \\ V_N \\ V_N \end{bmatrix} = Z_P \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} + 3Z_N I_{A0} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

For three-phase system [14]:

$$\begin{bmatrix} V_{A0} \\ V_{A1} \\ V_{A2} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & b & b^2 \\ 1 & b^2 & b \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}$$

i.e.,

$$V_{A012} = BV_{ABC} \quad (15)$$

Hence,

$$V_{A012} = Z_N I_{A012} + 3Z_N I_{A0} B \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

Since, $$B \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

Hence, $$\begin{bmatrix} V_{A0} \\ V_{A1} \\ V_{A2} \end{bmatrix} = Z_P \begin{bmatrix} I_{A0} \\ I_{A1} \\ I_{A2} \end{bmatrix} + 3Z_N \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad (16)$$

Therefore, $$Z_0 = Z_P + 3Z_N \quad (17)$$

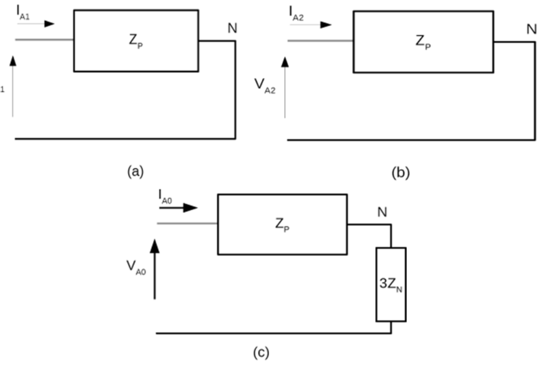

Fig. 4: Sequence Network of three-phase side of the three-to-five phase transformer: (a) Positive, (b) Negative and (c) Zero sequence.

Secondary Side of the transformer: The neutral current at secondary side is given by:

$$I_n = I_a + I_b + I_c + I_d + I_e$$

So, $$I_n = 5I_{a0} \quad (18)$$

Hence, as observed from Eq. (18), neutral current is five times of zero sequence current for a five-phase system. Then, the voltage-drop between the neutral and ground is

$$V_n = 5Z_n I_{a0}$$

$$V_a = V_{an} + V_n = V_{an} + 5Z_n I_{a0}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \\ V_{dn} \\ V_{en} \end{bmatrix} + \begin{bmatrix} V_n \\ V_n \\ V_n \\ V_n \\ V_n \end{bmatrix} = Z_S \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ I_e \end{bmatrix} + 5Z_a I_{a0} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \quad (19)$$

Pre-multiplying both sides of the Eq. (19) by the matrix *C* and using Eq. (9) and (10), we get:

$$V_{a01234} = Z_n I_{a01234} + 5Z_n I_{a0} \mathrm{A} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

Since, $$\mathrm{A} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \\ V_{a3} \\ V_{a4} \end{bmatrix} = Z_S \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \\ I_{a3} \\ I_{a4} \end{bmatrix} + 5Z_n \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (20)$$

So, $$Z_0' = Z_s + 5Z_n \quad (21)$$

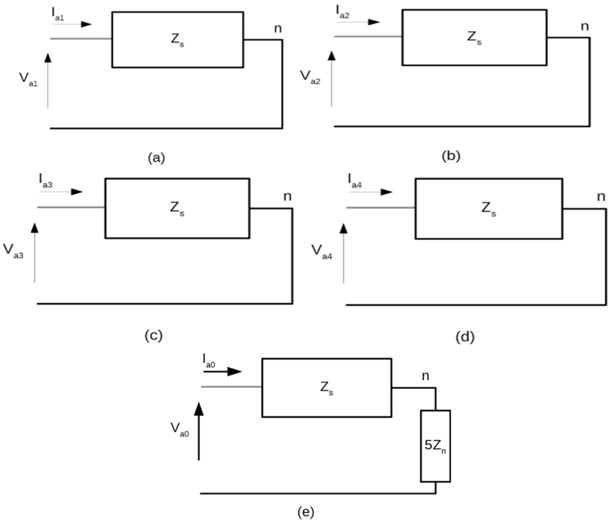

Fig. 5: Sequence Network of three-phase side of the three-to-five phase transformer: (a) Positive 1, (b) Negative 1, (c) Positive 2, (d) Negative 2 and (e) Zero sequence.

VI. ANALYSIS OF 3-TO-5 PHASE TRANSFORMER UNDER VARIOUS OPERATING CONDITIONS USING SIMULINK

The analysis of chosen transformer scheme has been carried out in Simulink environment of MATLAB. The transformer is analysed under various operating conditions. In Fig. 6 balanced input is given to the transformer and corresponding to this case balanced output is available and that is depicted in Fig. 7. The output of the 3-to-5 Phase Transformer has been analysed for various input conditions.

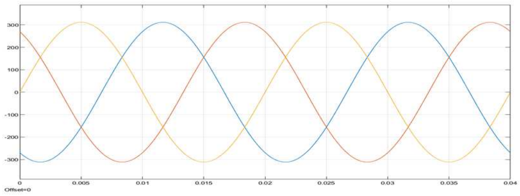

Fig. 6: Balanced input to the three- to-five phase transformer.

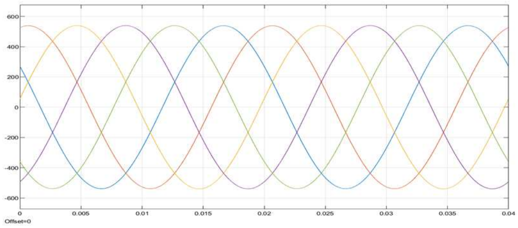

Fig. 7: Output of the three- to-five phase transformer with balanced three-phase input.

In Fig. 8 unbalanced input is given to the transformer and corresponding to this case balanced output is available and that is depicted in Fig. 9. The output of the 3-to-5 Phase Transformer has been analysed for various input conditions.

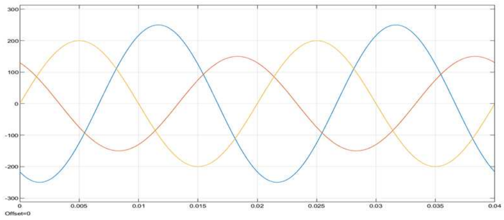

Fig. 8: Input with unbalancing to the three- to-five phase transformer.

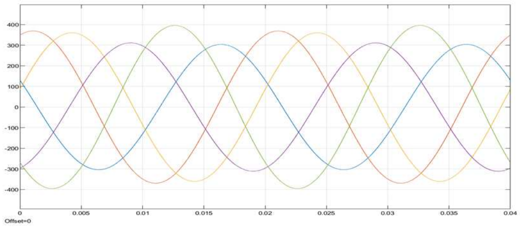

Fig. 9: Output of the three- to-five phase transformer with unbalanced three-phase input.

From the above Simulink results shown by waveform of Fig. 6 to Fig. 9, it is evident that the transformer gives a balanced output for a balanced input and with any unbalancing at the supply side the same appears at the output side also.

VII. EXPERIMENTAL VERIFICATION FOR 3-PHASE TO 5-PHASE TRANSFORMATION WITH RESPECTIVE VUF

A prototype of chosen transformer scheme has been developed in the lab as shown in Fig. 10 and output of the 3-to-5 Phase transformer has been analysed for various input conditions.

Fig. 10: Setup of the three- to-five phase transformer developed in lab.

The 3-to-5 Phase transformer has been analysed for various input voltages and the readings so obtained are produced below:

A. Output voltage of 3-Phase To 5-Phase Transformer with Balanced Supply:

TABLE I: OUTPUT WITH BALANCED THREE-PHASE INPUT.

S. No.	**Primary Side Volt**	**Secondary Side Voltages**				
	R=Y=B	**A**	**B**	**C**	**D**	**E**
1	10	10	11	10	11	11
2	20	20	23	20	25	23
3	40	40	50	38	52	46
4	50	50	57	50	59	55
5	70	70	79	70	82	77
6	100	101	115	99	119	110
7	125	126	138	126	141	134
8	150	151	161	151	165	160
9	180	181	193	182	196	190
10	200	201	210	204	213	210

B. Output voltage of 3-Phase To 5-Phase Transformer with unbalanced Supply:

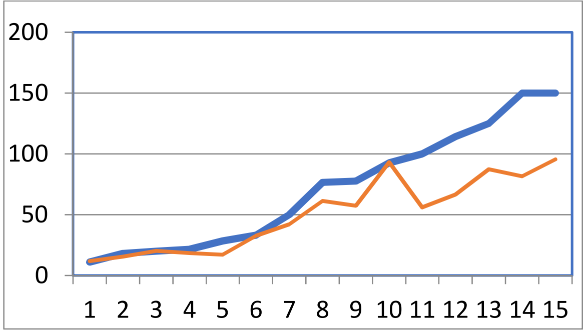

Fig. 11: Comparision between the three phase VUF and five Phase VUF taken at different readings.

The graph shown in Fig. 11 gives the comparison between the three phase VUF and five phase VUF at different readings. The orange line (thin-line) signifies five phase VUF and blue line (thick-line) signifies three phase VUF. From the above graph it is concluded that amount of VUF is less in a five-phase system as compared to the value of VUF of the three-phase side at different supply volatges.

TABLE II: UNBALANCED THREE-PHASE INPUT AND VUF.

S. No.	**Primary Side Voltages (Volt)**			
	R	**Y**	**B**	**VUF %**
1	10	5	2	76.67
2	15	2	3	125
3	2	10	15	77.77
4	20	20	1	92.67
5	30	5	30	100
6	10	20	30	50
7	20	30	40	33.33
8	50	70	90	28.57
9	100	80	120	20
10	120	150	100	21.6
11	150	120	170	18.14
12	200	180	160	11.11
13	0	5	2	114.4
14	15	0	3	150
15	2	10	0	150

TABLE III: OUTPUT VOLTAGES WITH UNBALANCED THREE-PHASE INPUT AND VUF.

Secondary Side Voltages (Volt)					
A	**B**	**C**	**D**	**E**	**VUF %**
2	6	3	8	7	61.53
3	10	1	12	6	87.5
14	7	13	4	9	57.44
1	15	13	23	23	93.33
3	34	15	25	10	56.10
30	20	29	13	20	42.22
40	31	40	23	30	32.80
90	78	91	67	78	17.07
120	123	100	100	84	20.3
100	110	125	135	144	18.5
172	180	147	156	133	15.6
162	188	162	202	188	11.9
2	1	5	2	5	66.6
3	12	2	12	4	81.8
1	1	7	5	9	95.6

VIII. RESULT AND CONCLUSION

In this paper three to five phase transformer has been analysed under various operating voltages at the supply side with unbalance condition. As discussed in Section VII, it has been found that Voltage Unbalance Factor (VUF) at five phase side is less than the value of VUF at three phase side under various operating condition. Hence it may be concluded that five-phase scheme is less disastrous to the system under unbalance condition when compared to three-phase counterpart. Determination of symmetrical component, calculation of active and reactive power in a five-phase system is discussed in detail. A complete symmetrical analysis of five-phase system is presented in the paper. Further, sequence circuit of three-to-five phase transformers is developed to model various operating conditions.

REFERENCES

[1] J.E. Parton, "A general theory of phase transformation," *Proceedings IEE –Part IV: Institution Monographs* 99 (2), (1952) 12–23. DOI: 10.1049/pi-4.1952.0002

[2] A. Iqbal, S. M. Ahmed, and H. Abu-Rub, "Space vector PWM technique for a three-to-five-phase matrix converter," *IEEE Trans. Industrial Application* Volume 48, no. 2, pp. 697–707, 2012.

[3] E. Levi, "Multiphase electric machines for variable-speed applications," *IEEE Trans. Ind. Electron*., vol. 55, no. 5, pp. 1893–1909, 2008.

[4] He, X.; Guo, A.; Peng, X.; Zhou, Y.; Shi, Z.; Shu, Z. A "Traction Three-Phase to Single-Phase Cascade Converter Substation in an Advanced Traction Power Supply System,". *Energies* 2015, 8, 9915-9929. doi: 10.3390/en8099915

[5] Chandramohan, K.; Padmanaban, S.; Kalyanasundaram, R.; Bhaskar, M.S.; Mihet-Popa, L. "Grid Synchronization of a Seven-Phase Wind Electric Generator Using *d-q* PLL,". *Energies* 2017, *10*, 926. doi: 10.3390/en10070926

[6] Enas Mohammad, Fatima Khan, Hadeel Bassel, Atif Iqbal & Ahmed Riyaz, "Comparative analysis of three-phase to five-phase transformer connections", *Australian Journal of Electrical and Electronics Engineering*, Vol. 14, Nos. 1-2, pp. 20-29, DOI: 10.1080/1448837X.2018.1437678

[7] Tabrez, M., Sadhu, P.K., Iqbal, A. *et al.* Analysis of a three-phase to seven-phase transformer under unbalanced input. *Microsyst Technol* **26,** 2507–2516 (2020). https://doi.org/10.1007/s00542-020-04791-z

[8] Hazrat Ali, M., Chakma, U., Howlader, D. *et al.* Studies on performance parameters of a practical transformer for various utilizations. *Microsyst Technol* **26,** 1661–1670 (2020). https://doi.org/10.1007/s00542-019-04711-w

[9] A. S. Abdel-Khalik, Z. Shafik, A. Elserougi, S. Ahmed and A. Massoud, "A static three-phase to five-phase transformer based on Scott connection," *Electric Power Syst. Res.,* vol. 110, pp. 84–93, 2014.

[10] A. Iqbal, S. Moinuddin, M. R. Khan, S. M. Ahmed, and H. Abu-Rub, "A novel three-phase to five-phase transformation using a special transformer connection," *IEEE Trans. Power Deliv.,* vol. 25, no. 3, pp. 1637–1644, 2010

[11] W. C. Yang, et al., "Application of SIMULINK to Analyze the Unbalanced Operation Characteristics of a Three Phase Transformer with Non-Identical Winding Impedances," *International Conference on Artificial Intelligence and Industrial Engineering* (AIIE 2015)

[12] Mohammed K. Edan, "Effect of Unbalance Voltage on the Operation and Performance of a Three Phase Distribution Transformers," *Journal of Babylon University, Engineering Sciences*, No.5, Vol.21, 2013.

[13] Kouzou Abdellah, Saifullah Payami, Atif Iqbal and Haitham Abu-Rub, "Performance Analysis of a Five Phase Induction Motor under Unbalanced Voltage Supply," *10th International Multi-Conference on Systems, Signals & Devices* (SSD), Hammamet, Tunisia, March 18-21, 2013.

[14] P. Pillay and M. Manage, "Definitions of Voltage Unbalance," *IEEE power Engineering Review*, May 2001, pp. 50–51.

[15] James E. Brittain, "Scanning the Past: Charles L. G. Fortescue and Method of Symmetrical Components," *Proceedings of IEEE*, Vol. 86(5), pp. 1020-1021, May 1998.

[16] J. L. Kirtley Jr, "Introduction to Power Systems: Class Notes, Introduction to Symmetrical Components," *Massachusetts Institute of Technology Department of Electrical Engineering and Computer Science* 6.061