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A Novel Theory of Three Phases to Eleven Phases

Mr. B.Somashekar[1]
Asst.Prof., Electrical and Electronics
Dr. T. Thimmaiah Institute of Technology
KGF, India
Soma0103@yahoo.co.in

Mr. David Livingston.D[2]
Asst.Prof.,Electrical and Electronics
Dr. T.Thimmaiah Institute of Technology
KGF, India
Doss.david@gmail.com

***Abstract*—**More than three-phase electric power is called multiphase .multiphase electric drive system is very important in research in the last decade. Multiphase power transmission system is also investigated in the literature survey, because multiphase transformers are needed at the input of rectifiers. In the multiphase power transmission and multiphase rectifier systems, the number of phases investigated is a multiple of three.
However, the variable speed multiphase drive system are mostly of five, seven, nine, eleven, twelve, and fifteen phases. Multiphase is supplied from power electronic devices (converters). This paper proposes technique to obtain Eleven-phase output from three-phase supply system using novel transformer with special connections. Thus, with the special transformer, a pure eleven phase sine-wave voltage/current is obtained, which can be used for load testing purposes. Complete design of the proposed solution is presented. Analytical analysis is presented in the paper.

Keywords— *converting transformer, multiphase drive systems, multiphase system, multiphase transmission, three-to-eleven*

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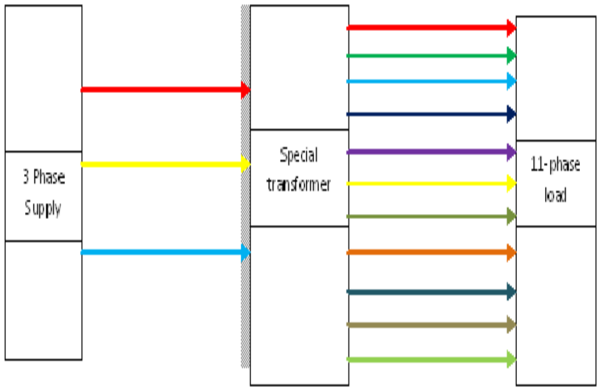
I. INTRODUCTION

The advantages of N number of phase systems compared to three phase systems have much interest in research .The multiphase systems is used in electric power generation, transmission and utilization. The research on six phase transmission systems was initiated due to rising cost of transmission towers, environmental issues, and various IE rules and laws. Six-phase transmission lines can provide the same power capacity with a lower line voltage and smaller towers as compared to a standard double circuit three-phase line.

Block diagram



By using the static transformation system to increase the phase number from three-to-*n*-phase (where $n > 3$ and odd). A new type of transformer is presented, which is three phase-to-Eleven-phase system. Accordingly, this paper is based on the same principle as that of three phases to five phases.

The analysis and design, however, are completely different. In 6 and 12 phase, systems are found to produce less amplitude of ripples with higher frequency in ac–dc rectifier system. This paper proposes a special transformer connection scheme to obtain a balanced three-to-Eleven-phase supply with sinusoidal waveforms. The expected application areas of the proposed transformer are the electric power transmission system, power electronic converters (ac–dc and ac–ac), and the multiphase electric drive system. The fixed three-phase voltage and fixed frequency available in grid power supply can be transformed to fixed voltage and fixed frequency Eleven-phase output supply. Furthermore, the output magnitude may be made variable by inserting a three-phase autotransformer at the input side. In this paper, the input and output supply can be arranged in the following manners:

1) Input star, output star.
2) Input star, output hendegon
3) Input delta, output star.
4) Input delta, output hendegon

Since input is a three-phase system the windings are connected in usual manner. The output/secondary side star connection is discussed in the following sections.

II. WINDING ARRANGEMENT FOR ELEVEN-PHASE STAR OUTPUT

Three separate iron cores are designed with each of them carrying one primary and seven secondary coils, are wound. Six terminals of primaries are connected in an appropriate manner resulting in star connections, and the 42 terminals of secondaries are connected in a different fashion resulting in a star output. The connection scheme of secondary windings to obtain star output is illustrated in Figs. 1 and 2 and the corresponding phasor diagram is illustrated in Fig. 3.

The construction of output phases with requisite phase angles of 360/11 = 32.72^o between each phase is obtained using appropriate turn ratios and the governing phasor equation is illustrated in (1c). The turn ratios are different in each phase as shown in Fig. 1. The choice of turn ratio is the key in creating the requisite phase displacement in the output phases. The turn ratios between different phases are given in Table I.

The input phases are designated with letters "X," "Y," and "Z" and the output are designated with numbers 1,2,3,4,5,6,7,8,9,10 and 11. The mathematical equation for this type of connection is the basic addition of real and imaginary parts of the vectors. For example, the solution for (1a) gives the turn ratio of phase "2," (V2 *taken* as unity)

$$V_x\ [\cos\ (2\pi/11)\ +j\ \sin\ (2\pi/11)]-V_z\ [\cos\ (1.66\pi/11)\ -j\ \sin\ (1.66\pi/11)] =1 \qquad \text{-----------1a}$$

Equating real and imaginary parts and solving for *Vx* and *Vz* , we get

$$|Vx| = \sin (1.66\pi/11)/\sin (\pi/3) = 0.52715$$
$$|Vz| =-\sin (2\pi/11)/\sin (\pi/3)= 0.6242 \qquad \text{-------1b}$$

Equation (1c) is the result of solutions of equations like (1a) for other phases.

Therefore, by simply summing the voltages of two different coils, one output phase is created. It is important to note that the phase "*1*" output is generated from only one coil namely "*a*3*a*4"in contrast to other phases which utilizes two coils. Thus, the voltage rating of "*a*3*a*4" coil should be kept to that of rated phase voltage to obtain balanced and equal voltages

$$\left|\begin{array}{l} V1 \\ V2 \\ V3 \\ V4 \\ V5 \\ V6 \\ V7 \\ V8 \\ V9 \\ V10 \\ V11 \end{array}\right| = 1/\mathrm{Sin}(\pi/3) \left|\begin{array}{lll} \mathrm{Sin}(\pi/3) & 0 & 0 \\ \mathrm{Sin}(1.66\pi/11) & 0 & -\mathrm{Sin}(2\pi/11) \\ 0 & \mathrm{Sin}(5.4544) & -\mathrm{Sin}(54.54) \\ 0 & \mathrm{Sin}(38.1816) & -\sin(21.82) \\ -\mathrm{Sin}(10.90) & \mathrm{Sin}(49.1072) & 0 \\ -\mathrm{Sin}(43.6272) & \mathrm{Sin}(16.38) & 0 \\ -\mathrm{Sin}(43.654) & 0 & \mathrm{Sin}(16.34) \\ -\mathrm{Sin}(10.93) & 0 & \mathrm{Sin}(49.0672) \\ 0 & -\mathrm{Sin}(21.79) & \mathrm{Sin}(38.2172) \\ 0 & -\mathrm{Sin}(54.5172) & \mathrm{Sin}(5.49) \\ 0 & -\mathrm{Sin}(32.72) & \mathrm{Sin}(27.23) \end{array}\right|$$

---Eq:1c

$V1=V_{max}\sin(\omega t)$
$V2= V_{max}\sin(\omega t+2\pi/11)$
$V3= V_{max}\sin(\omega t+4\pi/11)$
$V4= V_{max}\sin(\omega t+6\pi/11)$
$V5= V_{max}\sin(\omega t+8\pi/11)$
$V6= V_{max}\sin(\omega t+10\pi/11)$
$V7= V_{max}\sin(\omega t-10\pi/11)$
$V8= V_{max}\sin(\omega t-8\pi/11)$
$V9= V_{max}\sin(\omega t-6\pi/11)$
$V10= V_{max}\sin(\omega t-4\pi/11)$
$V11= V_{max}\sin(\omega t-2\pi/11)$

$Vx= V_{max}\sin(\omega t)$
$Vy= V_{max}\sin(\omega t+2\pi/3)$
$Vz= V_{max}\sin(\omega t-2\pi/3)$

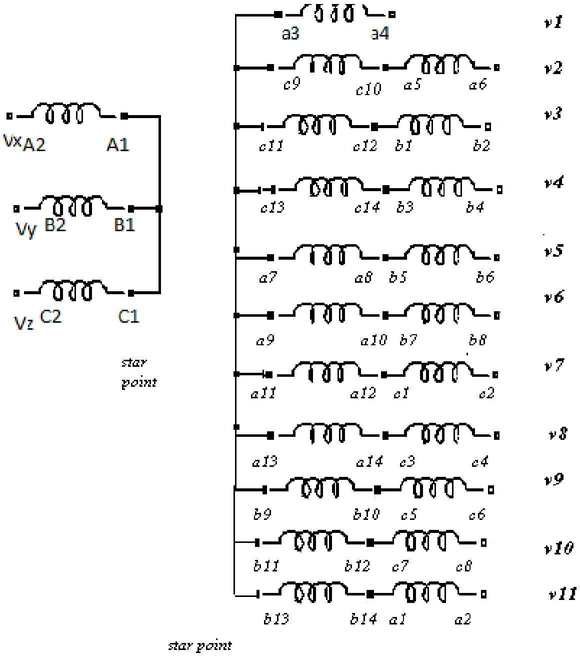


Fig. I. Proposed transformer winding connection (star).

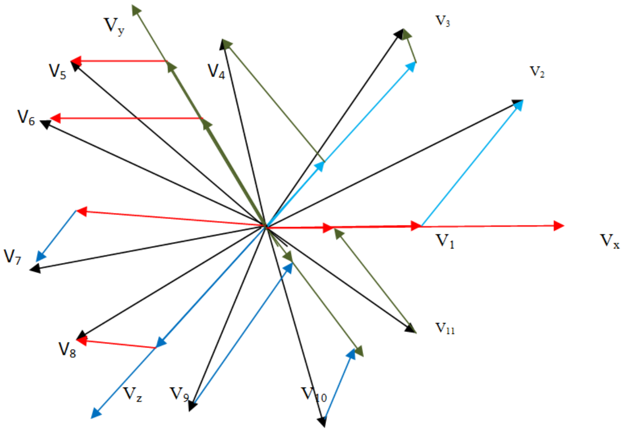


Fig II: Phasor diagram of the proposed transformer connection (star-star).

The mathematical equation for all the voltages are ,

V_1=Vx
V_2=0.52715Vx-0.6242Vz
V_3=0.1097Vy-0.9405Vz
V_4=0.7137Vy-0.4291Vz
V_5=0.8728Vy-0.2183Vx
V_6=0.3256Vy-0.7967Vx
V_7=0.3249Vz-0.7971Vx
V_8=0.87235-0.2189Vx
V_9=0.7143Vz-0.4286Vy
V_{10}=0.110Vz-0.9402Vy
V_{11}=0.5283Vx-0.6241Vy

From the above equation we get the no of turns required for the allthe winding on the secoundary side of multi winding transformer which is been tabulated in the table 1.

TABLE I TURN RATIO SECONDARY TURNS (N_2) TO PRIMARY TURNS (N_1)

Name of the winding	Turns ratio N2/N1	Name of the winding	Turns ratio N2/N1	Name of the winding	Turns ratio N2/N1
a1a2	0.5283	b1b2	0.1097	c1c2	0.3249
a3a4	1.00	b3b4	0.7137	c3c4	0.87235
a5a6	0.52715	b5b6	0.8728	c5c6	0.7143
a7a8	-0.2183	b7b8	0.3256	c7c8	0.110
a9a10	-0.7967	b9b10	-0.4286	c9c10	-0.6242
a11a12	-0.7971	b11b12	-0.9402	c11c12	-0.9405
a13a14	-0.2189	b13b14	-0.6241	c13c14	-0.4291

Where the three-phase voltages (line-to-neutral) are defined as
Vj = Vmax sin (ωt + nπ/3)

j = x, y, z, and n = 0, 2, 4, respectively, (2)

Vk = Vmax sin (ωt + nπ/11),
k = 1,2,3,4,5,6,7,8,9,10,11 and n = 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20 respectively. (3)
Using (1c), a eleven -phase output can be created from a three phase input supply.

A transformer is a two-port network; the reverse connection is also possible, i.e., if a eleven-phase supply is given at the input the output can be three phase. It is very important if the power generated is eleven phase it has to be converted to 3 phase which has to be connected to the grid.

To obtain three-phase outputs from a Eleven-phase input supply, following relation is used,

$$\begin{vmatrix} Vx \\ Vy \\ Vz \end{vmatrix} = 1/\mathrm{Sin}(2\pi/11) \begin{vmatrix} \sin(2\pi/11) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sin(-21.82) & \sin(109) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sin(-10.93) & \sin(98.14) & 0 & 0 \end{vmatrix} \begin{vmatrix} V1 \\ V2 \\ V3 \\ V4 \\ V5 \\ V6 \\ V7 \\ V8 \\ V9 \\ V10 \\ V11 \end{vmatrix}$$

A general expression for an "*n*" phase system is derived and shown in (4)
$Vr = [(-1)aVx \sin(\theta) + (-1)bVy \sin(\varphi) + (-1)cVz \sin(\gamma)]$ (4)
Where r=phase no 1,2,3……………n;

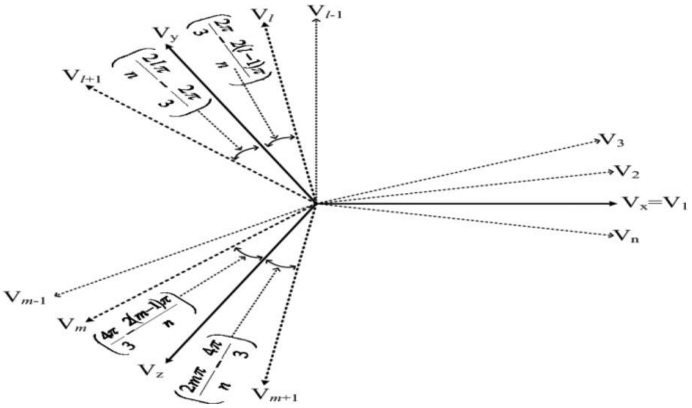


Fig IV. General Phasor diagram for three-phase system from "*n*" phase system.

From the above fig we can derive an expression for a general case as shown ,
Let us assume $V_x = V_1$; and n = number of phases in the system.
V_x, V_y, V_1, V_2, V_3. . . V_l, . . . V_m . . . are phases. Then

V_y =1/sin (2π/n) [sin (2lπ/n-2π/3) V_l+sin (2π/3-2(l-1)π/n)V $_{l+1}$]

Where l = 4 And (2lπ/n)>(2π/3)>(2(l-1)π/n) and n=11

Vy=1/sin(2π/11) [sin (2x4π/11-2π/3) V_4+sin (2π/3-2(4-1)π/11)V $_{4+1}$]
Vy=1/sin(32.72)(sin(10.90)+sin(54.54)V5

And it lies between 130>120>98.18

V_z=1/sin (2π/n) [sin (2mπ/n-2π/3) Vm + sin(2π/3-2(m-1)π/n)V m+1]

Where (2mπ/n)> (2π/3)> (2(m-1) π/n) and m>1
N=11
M=8

V_z=1/sin (2π/11) [sin (2x8π/11-2π/3) V8 + sin(2π/3-2(7)π/11)V 9]
Vz=1/sin(32.72)[sin(141.81)V8+sin(-109.09)V9]

And it lies between 261.81>120>229.09

III. LOAD SHARING OF SECONDARY WINDINGS

S_1 is the averageper phase output power and $V_1 * I_1 = S_1$, where $V1$ and $I1$ are input phase voltage and current, respectively, and $S1$ is average per phase input Volt ampere (VA).Also, let $V_2 * I_2 = S_2$, where V_2 and I_2 are output phase voltage and current, respectively, and S_2 is per phase output VA. After neglecting the losses, we have: 3 S_1 = 11 S_2 . For transformer A: VA of winding $a1a2$

$S_{a_1a_2} = 3S_1/11\sin(\pi/3)$ [sin (27.23).cos (32.72)] where (2π/11) is the angle between input V_x and output V_{11} in which winding a_1a_2 is connected and sin (π/11)/sin (π/3) is the turns ration of secondary winding a1a2 to primary winding A_1A_2.

The VA relationship for transformer A is shown as follows.

$$\left|\begin{array}{c} S_{a1a2} \\ S_{a3a4} \\ S_{a5a6} \\ S_{a7a8} \\ S_{a9a10} \\ S_{a11a12} \\ S_{a13a14} \end{array}\right| = 3S1/11\sin(60) \left|\begin{array}{ll} \sin(27.23) & \cos(32.72) \\ \sin(60) & \\ \sin(27.27) & \cos(32.72) \\ -\sin(10.90) & \cos(228.96) \\ -\sin(43.62) & \cos(196.24) \\ -\sin(43.62) & \cos(163.6) \\ -\sin(10.93) & \cos(130.94) \end{array}\right| \left|\begin{array}{c} V_{11} \\ V_1 \\ V_2 \\ V_5 \\ V_6 \\ V_7 \\ V_8 \end{array}\right|$$

Negative signs indicate opposite polarity of connection for that particular winding .The sum of VA of all secondary windings of transformer A is equal to 1.010*S_1

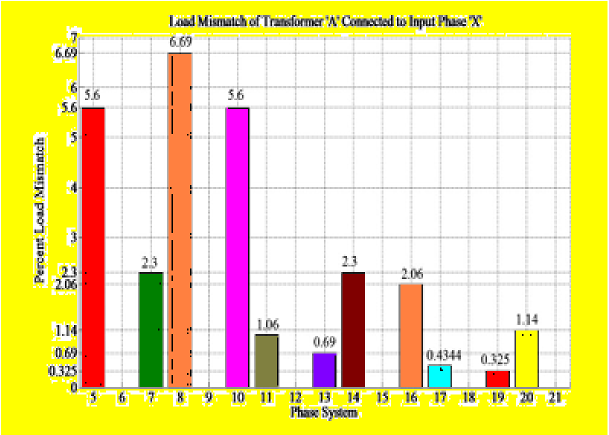
Similarly, the VA relationships for transformers B and C are

$$\left|\begin{array}{c} S_{b1b2} \\ S_{b3b4} \\ S_{b5b6} \\ S_{b7b8} \\ S_{b9b10} \\ S_{b11b12} \\ S_{b13b14} \end{array}\right| = 3S1/11\sin(60) \left|\begin{array}{ll} \sin(5.4544) & \cos(54.5472) \\ \sin(38.1816) & \cos(21.82) \\ \sin(49.1072) & \cos(10.90) \\ \sin(16.38) & \cos(43.6272) \\ -\sin(21.77) & \cos(141.77) \\ -\sin(54.4972) & \cos(174.49) \\ -\sin(32.7272) & \cos(-152.7272) \end{array}\right| \left|\begin{array}{c} V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_9 \\ V_{10} \\ V_{11} \end{array}\right|$$

The sum of VA of all secondary windings of transformer B is equal to 0.994* S_1,

$$\left|\begin{array}{c} S_{c1c2} \\ S_{c3c4} \\ S_{c5c6} \\ S_{c7c8} \\ S_{c9c10} \\ S_{c11c12} \\ S_{c13c14} \end{array}\right| = 3S1/11\sin(60) \left|\begin{array}{ll} \sin(16.34) & \cos(43.6572) \\ \sin(49.06) & \cos(10.93) \\ \sin(38.21) & \cos(21.77) \\ \sin(5.49) & \cos(54.4972) \\ -\sin(32.72) & \cos(-152.72) \\ -\sin(65.44) & \cos(174.5472) \\ -\sin(21.82) & \cos(141.82) \end{array}\right| \left|\begin{array}{c} V_7 \\ V_8 \\ V_9 \\ V_{10} \\ V_2 \\ V_3 \\ V_4 \end{array}\right|$$

The sum of VA of all secondary windings of transformer C is equal to 1.0245*S1.
The sum of VA of all three transformers
= 1.010 * S_1 + 0.994 * S_1 + 1.0245 * S_1 = 3.028*S_1.
From the analysis all the three transformers does not share equal load.
The load mismatch in Transformer "A," which is connected to input phase "X," is shown in Fig



IV. VOLT AMPERE CALCULATION

FOR PHASE 1:

$V_1 = V_{a3a4}\cos(0)$ if $V_{a3a4} = Vx$

V_1=cos (0) Vx

Now per phase of VA S2=V_{a3a4}= V_1I_1

$V_1I_1=V_xI_a=V_aI_a=S_2$=3S1/11

$V_1=V_{a3a4}=3S_1/11$

For phase 2:

$V_2=V_{a5a6}$cos(32.72)+V_{C9C10}cos(-152.72)

Now per phase of VA S2=V_{a5a6}+V_{c9C10}

V_{a5a6}=Sin(27.27)cos(32.72)/sin(60).3S1/11

V_{c9c10}=-sin(32.72).cos(-152.72)/sin(60).3S1/11

$V_2=V_{a5a6}.3S_1/11 + V_{c9c10.}3S_1/11$

For phase 3:

$V_3=V_{b1b2}$cos(54.5472)+V_{c11c12}cos(174.5472)

Now per phase of VA S2=V_{b1b2}+V_{c11c12}

V_{b1b2}=Sin(5.4544)cos(54.5472)/sin(60).3S1/11

V_{c11c12}=-sin(65.44).cos(174.5477)/sin(60).3S1/11

$V_2=V_{b1b2}.3S_1/11 + V_{c11c12.}3S_1/11$

FOR PHASE 4:

$V_4=V_{b3B4}$cos(21.82)+V_{c13C14}cos(141.82)

Now per phase of VA S2=V_{b3b4}+V_{c13c14}

V_{b3b4}=Sin(38.1816)cos(21.82)/sin(60).3S1/11

V_{c13c14}=-sin(21.82).cos(141.82)/sin(60).3S1/11

V_2= V_{b3b4}.3S_1/11 + $V_{c13c14.}$3S_1/11

FOR PHASE 5:

$V_5=V_{a7a8}$cos(228.96)+V_{b5b6}cos(10.90)

Now per phase of VA S2= V_{a7a8}+ V_{b5b6}

V_{a7a8}=-Sin(10.90)cos(228.96)/sin(60).3S1/11

V_{b5b6}=+sin(49.1072).cos(10.90)/sin(60).3S1/11

V_2= V_{a7a8}.3S_1/11 + $V_{b5b6.}$3S_1/11

FOR PHASE 6:

$V_6=V_{a9a10}$cos(196.24)+V_{b7b8}cos(43.62)

Now per phase of VA S2= V_{a7a8}+ V_{b7b8}

V_{a9a10}=-Sin(43.62)cos(196.24)/sin(60).3S1/11

V_{b7b8}=+sin(16.38).cos(43.6272)/sin(60).3S1/11

V_2= V_{a9a10}3S_1/11 + V_{b7b8}3S_1/11

FOR PHASE 7:

$V_7=V_{a11a13}$cos(163.64)+V_{c1c2}cos(43.6572)

Now per phase of VA S2= V_{a11a13}+ V_{c1c2}

V_{a11a13}=-Sin(43.62)cos(163.64)/sin(60).3S1/11

V_{c1c2}=+sin(16.34).cos(43.6572)/sin(60).3S1/11

V_2= V_{a11a13}3S_1/11 + V_{c1c2}3S_1/11

FOR PHASE 8:

$V_8=V_{a1314}$cos(130.94)+V_{c3c4}cos(10.93)

Now per phase of VA S2= V_{a1314}+ V_{c3c4}

V_{a1314}=-Sin(10.93)cos(130.94)/sin(60).3S1/11

V_{c3c4}=+sin(49.06).cos(10.93)/sin(60).3S1/11

V_2= V_{a1314}3S_1/11 + V_{c3c4}3S_1/11

FOR PHASE 9:

$V_9=V_{b9b10}$cos(141.77)+V_{c6c5}cos(21.77)

Now per phase of VA S2= V_{b9b10}+ V_{c6c5}

V_{b9b10}=-Sin(43.62)cos(163.64)/sin(60).3S1/11

V_{c6c5}=+sin(16.34).cos(43.6572)/sin(60).3S1/11

V_2= V_{b9b10}3S_1/11 + V_{c6c5}3S_1/11

FOR PHASE 10:

$V_{10}=V_{b11b12}$cos(174.49)+V_{c9c10}cos(-152.72)

Now per phase of VA S2= V_{b11b12}+ V_{c6c5}

V_{b11b12}=-Sin(54.49)cos(174.49)/sin(60).3S1/11

V_{c9c10}=+sin(32.72).cos(-152.72)/sin(60).3S1/11

$\mathbf{V_2}= V_{b11b12}\mathbf{3S_1/11} + V_{c9c10}\mathbf{3S_1/11}$

FOR PHASE 11:

$V_{11}=V_{a1a2}\cos(32.72)+V_{b13b14}\cos(-152.72)$

Now per phase of VA S2= $V_{b11b12}+ V_{c6c5}$

V_{a1a2}=-Sin(54.49)cos(174.49)/sin(60).3S1/11

V_{b13b14}=+sin(32.72).cos(-152.72)/sin(60).3S1/11

$\mathbf{V_2}= V_{a1a2}\mathbf{3S_1/11} + V_{b13b14}\mathbf{3S_1/11}$

V. CONCLUSION

This paper proposes a new transformer connection scheme to transform the three-phase grid power to an eleven-phase output supply. The connection scheme and the phasor diagram, along with the turn ratios, are illustrated. This connection scheme can be simulated using matlab simulink and tested using the motor load.

It is expected that the proposed connection scheme can be used in drives and other multiphase applications, e.g., ac–ac and dc–ac power conversion systems.

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SOMASHEKAR. B received B.E degree (Electrical & Electronics Engineering) in Golden Valley Institute of Technology, K.G.F in 1998 under Bangalore University and M. Tech (VLSI & Embedded Systems) from VTU in 2010.

I am currently working as a Asst.Prof in the Department of Electrical Engineering, Dr.TTIT, KGF. My research areas are Power Systems, VLSI and Power Electronics.

DAVID LIVINGSTON.D received B.E degree from **(**Electrical & Electronics Engineering) in Dr.Thimmaiah institute of Technology, KGF in 2008 under VTU, Belgaum and M.Tech (Power Electronics) from KEC, Chittor under JNTUA in 2014.

He is currently working as Asst.Prof. in Dr.TTIT, KGF. His research areas include Power Electronics, Digital signal processing.