

Modified approach for harmonic reduction in three-phase to seven-phase using transformer winding connections

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ABSTRACT

Three phase supply is available in the generating station or grid, were as seven phase supply is required for many industrial applications such as, aerospace, railway and automobile applications. There are different methods in which we can convert 3 to 7 phase using 24-Pulse Converter, Carrier Based PWM Technique, multilevel converter and Multiphase Transformer. The above said methods which are more complicated to design for higher ratings or a pure sine wave will not be obtained or harmonics will be more. For Multiphase power transmission system multiphase transformers are needed. In the multiphase power transmission and multiphase rectifier systems, the number of phase can be designed and developed in multiples of three. Therefore, the variable speed multiphase drive system considered in the literature are mostly of five, seven, nine, eleven, twelve, and fifteen phase. So, there is a need to design and develop special transformer which converts from 3 to 7 phase for different arrangement of input and output. Thus, with the proposed technique, a pure seven-phase sine-wave of fixed voltage/current and frequency is obtained, which can be used for RL load and motor testing purposes. Complete design and simulation of the proposed solution is presented. Analytical calculation and simulation results for RL load is presented in the paper. This model can be simulated by using Orcad simulation software and "SimPowerSystem" block sets of MATLAB/SIMULINK software.

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1. INTRODUCTION

Multi-phase (more than three-phase) systems have received much attention of researchers in recent times due to their inherent advantages when compared with the conventional three-phase counterpart. The applicability of multi-phase systems is investigated in electric power generation [1-2], transmission [3-4] and utilization [5-7]. The research on six-phase transmission system was initiated due to rising cost of right of way for transmission corridors, environmental issues and various stringent licensing laws. Six-phase transmission lines can provide the same power capacity with a lower phase to phase voltage and smaller, more compact towers as compared to a standard double circuit three-phase line. The geometry of the six-phase compact towers may also aid in the reduction of magnetic fields and thus electromagnetic interference issues as well [3].

The research on multi-phase generators have started recently [1-2]. Multi-phase systems are mostly the subject of interest in variable speed motor drive applications. Research on multiphase drive is mostly focused on five-phase and six-phase systems with the objective of developing highly reliable and efficient

drive system. The research results on multi-phase drives are summarized in [7-8]. It is to be noted that the multi-phase motors are invariably supplied by power electronic converters since variable speed applications are sought. Thus the emphasis of the research on multi-phase electric drive is limited to the modelling and control of the power electronic converters such as inverters and matrix converters [7-17]. Initially, only two-level converters were used [6], and later on multi-level multi-phase converters is investigated [18]. Ward and Harer [19] proposed multiphase motor drives, but the research on it was slow in its release.

The research on multiphase drive systems has been significantly developed since the beginning of this century due to advancement in semi conductor devices and digital signal processors technologies. Detailed reviews on state-of-the-art multiphase drive research are available in [15]-[18] and [20]. It is to be emphasized here that ac/dc/ac converters generally supply the multiphase motors. Thus, the focus of the current research on multiphase electric drives is limited to the modeling and controlling of the power converters [21]-[26], [27], [28], [29]-[31]. Little effort is being made to develop static transformation system to change the phase number from three-to-n-phase (where $n > 3$ and odd). An exception is [32], where a new type of transformer is presented, which is three-to-five-phase system. In [33] and [34], the authors presented an interesting solution for three-to-five-phase conversion. At the end of [33], the authors briefly mention the seven-phase system; however, no study or analysis was done on three-to-seven-phase transformer.

Accordingly, this paper is based on the same principle as that of [32]. The analysis and design, however, are completely different. In our approach, in contrast to the system of [32], the phase angle between two consecutive phases is not an integer number. Multiphase, especially 6- and 12-phase, systems are found to produce less amplitude of ripples with higher frequency in ac dc rectifier system [35]. Thus, 6- and 12-phase transformers are designed to feed a multi-pulse rectifier system and the technology is matured. Recently, 24- and 36-phase transformer systems were proposed for supplying a multi-pulse rectifier system [36-39].

The reason of adopting a 6-, 12-, or 24-phase system is that these numbers are multiples of three and designing such system is simple and straightforward. However, increasing the number of phases certainly affects the complexity of the system. No such design is available for odd number of phases, such as 7, 11, etc., as far as is known to the authors. The usual practice for analysis is to test the designed motor for a number of operating conditions with pure sinusoidal supply [40]. Normally, no-load test, blocked rotor, and load tests are performed on a motor to determine its parameters. Although supply used for multiphase motor drives obtained from multi phase inverters could have more current ripples, there are control methods available to lower the current distortion below 1%, based on application and requirement [25].

The machine parameters obtained using a PWM inverter may not provide the correct value. Thus, a pure sinusoidal supply system is required to feed the motor for better analysis. Accordingly, this paper proposes a special transformer connection scheme to obtain a balanced three-to-seven-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 seven-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:

- a. Input star, output star.
- b. Input star, output heptagon.
- c. Input delta, output star.
- d. Input delta, output heptagon.

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. The heptagon output connection may be derived following a similar approach. Thus, only star output connection is discussed in the following section and other connections are omitted.

2. WINDING ARRANGEMENT SEVEN-PHASE STAR OUTPUT

Three separate iron cores are designed with each of them carrying one primary and four secondary coils, except in one core where five secondary coils are wound. Six terminals of primaries are connected in an appropriate manner resulting in star and/or delta connections, and the 26 terminals of secondary are connected in a different fashion resulting in a star or heptagon output. The connection scheme of secondary windings to obtain star output is illustrated in Figures. 1 and 2 and the corresponding phasor diagram is illustrated in Figure 3. The construction of output phases with requisite phase angles of $360/7 = 51.43^\circ$ 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 Figure 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 1. The input phases are designated with letters “X,” “Y,” and “Z” and the output are designated with letters “a,” “b,” “c,” “d,” “e,” “f,” and “g.” The mathematical basis for this 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 “b,” (Vb taken as unity)

$$V_x \left[\cos\left(\frac{2\pi}{7}\right) + j \sin\left(\frac{2\pi}{7}\right) \right] - V_z \left[\cos\left(\frac{\pi}{21}\right) - j \sin\left(\frac{\pi}{21}\right) \right] = 1 \tag{1}$$

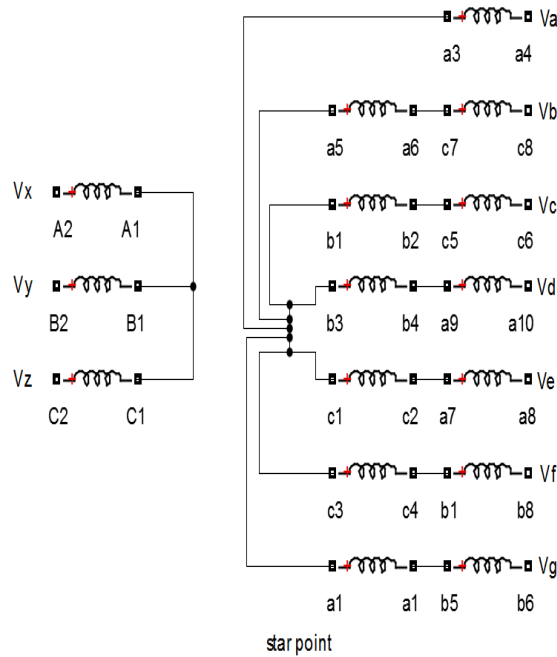


Figure 1. Proposed transformer winding connection (star)

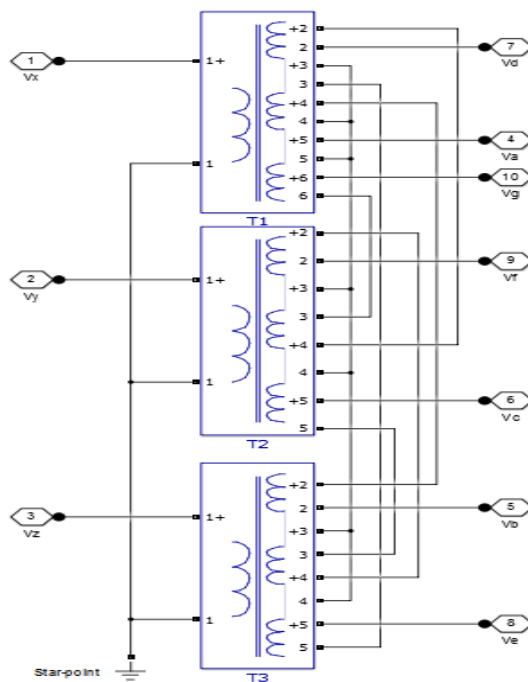


Figure 2. Proposed transformer winding arrangements (star-star)

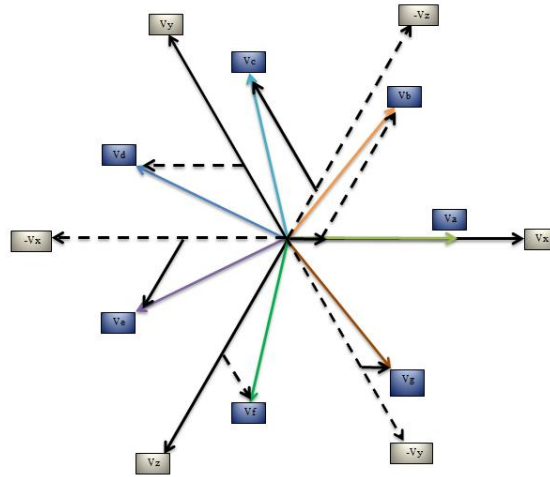


Figure 3. Phasor diagram of the proposed transformer connection (star-star)

Table 1. Turn Ratio Secondary Turns (N₂) to Primary (A₁ A₂) Turns (N₁)

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	0.1721	b1b2	0.7854	c1c2	0.5010
a3a4	1.0000	b3b4	0.5010	c3c4	0.7854
a5a6	0.1721	b5b6	0.9028	c5c6	0.3404
a7a8	0.6505	b7b8	0.3404	c7c8	0.9028

Equating real and imaginary parts and solving for V_x and V_z we get:

$$|V_x| = \left| \frac{\sin(\pi/21)}{\sin(\pi/3)} \right| = 0.1721 \tag{2}$$

$$|V_z| = \left| -\frac{\sin(2\pi/7)}{\sin(\pi/3)} \right| = 0.9028 \tag{3}$$

The (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 “a” output is generated from only one coil namely “a3a4” in contrast to other phases which utilizes two coils. Thus, the voltage rating of “a3a4” coil should be kept to that of rated phase voltage to obtain balanced and equal voltages.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \frac{1}{\sin(\frac{\pi}{3})} * \begin{bmatrix} \sin(\frac{\pi}{3}) & 0 & 0 \\ \sin(\frac{\pi}{21}) & 0 & -\sin(\frac{2\pi}{7}) \\ 0 & \sin(\frac{5\pi}{21}) & -\sin(\frac{2\pi}{21}) \\ -\sin(\frac{4\pi}{21}) & \sin(\frac{\pi}{7}) & 0 \\ -\sin(\frac{4\pi}{21}) & 0 & \sin(\frac{\pi}{7}) \\ 0 & -\sin(\frac{2\pi}{21}) & \sin(\frac{5\pi}{21}) \\ \sin(\frac{\pi}{21}) & -\sin(\frac{2\pi}{7}) & 0 \end{bmatrix} * \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \tag{4}$$

Where the three-phase voltages (line-to-neutral) are defined as:

$$V_j = V_{\max} \sin\left(\omega t - n \frac{\pi}{3}\right) \tag{5}$$

$$j = x, y, z, n = 0, 2, 4$$

$$V_k = V_{\max} \sin\left(\omega t - n \frac{\pi}{7}\right), \rightarrow k = a, b, c, d, e, f, g \tag{6}$$

$$\text{and } \rightarrow n = 0, 2, 4, 6, 8, 10, 12$$

Using (1c), a seven-phase output can be created from a three-phase input supply. A general expression for an “n” phase system is derived and shown in (6). Since a transformer works as a two-port network, the reverse connection is also possible, i.e., if a seven-phase supply is given at the input the output can be three phase. This is especially important if electric power is generated using a seven-phase alternator and the supply to the grid is given as three phase. To obtain three-phase outputs from a seven-phase input supply, following relations hold good.

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \frac{1}{\sin\left(\frac{2\pi}{7}\right)} * \begin{bmatrix} \sin\left(\frac{2\pi}{7}\right) & 0 & 0 \\ 0 & \sin\left(\frac{4\pi}{7}\right) & 0 \\ 0 & \sin\left(\frac{2\pi}{7}\right) & 0 \\ 0 & 0 & \sin\left(\frac{2\pi}{7}\right) \\ 0 & 0 & \sin\left(\frac{4\pi}{7}\right) \\ 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} \tag{7}$$

3. WINDING ARRANGEMENT SEVEN-PHASE DELTA OUTPUT

Three separate iron cores are designed with each of them carrying one primary and four secondary coils, except in one core where five secondary coils are wound. Six terminals of primaries are connected in an appropriate manner resulting in delta connections, and the 26 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 Figure 4.

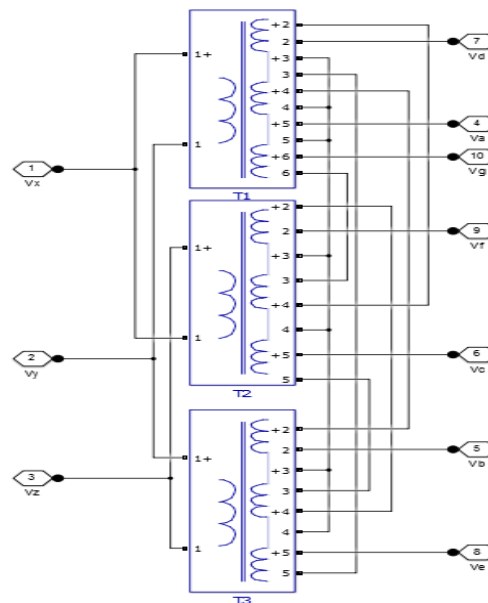


Figure 4. Proposed transformer winding arrangements (delta-star)

The corresponding phasor diagram is illustrated in Figure 5. The construction of output phases with requisite phase angles of $360/7=51.43^\circ$ between each phase is obtained using appropriate turn ratios.

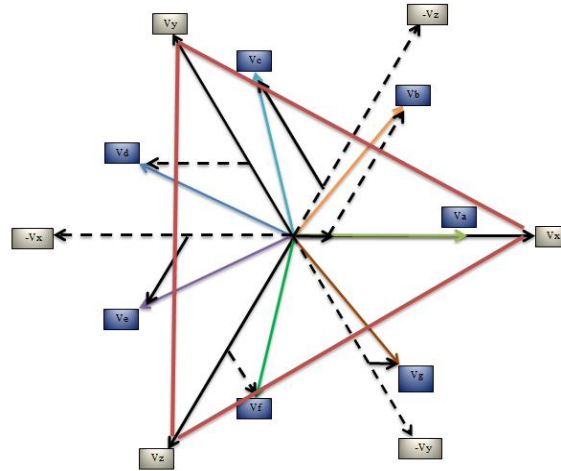


Figure 5. Phasor diagram of the proposed transformer connection (delta-star)

4. WINDING ARRANGEMENT SEVEN-PHASE HEPTAGON OUTPUT

The construction of output phases with requisite phase angles of $360/8=45^\circ$ between each phase is obtained using appropriate turn ratios. Three separate iron cores are designed with each of them carrying one primary and four secondary coils, except in one core where five secondary coils are wound. Six terminals of primaries are connected in an appropriate manner resulting in delta or star connections, and the 28 terminals of secondaries are connected in a heptagon output. Figure 6 show proposed transformer winding arrangements (star- heptagon). Table 2 show turn ratio secondary turns (N_2) to primary ($A_1 A_2$) turns (N_1) star-heptagon and delta-heptagon [41].

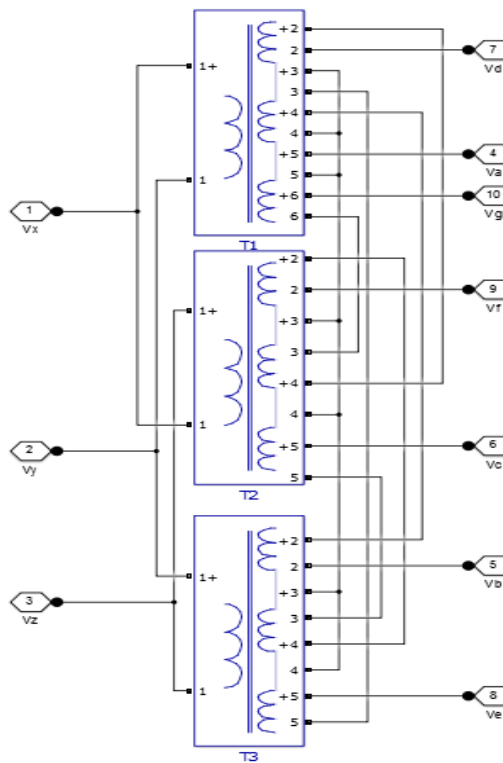


Figure 6. Proposed transformer winding arrangements (star- heptagon)

Table 2. Turn Ratio Secondary Turns (N_2) to Primary ($A_1 A_2$) Turns (N_1) Star-Heptagon and Delta Heptagon [41]

Name of the winding	Turns ratio N_2/N_1	Name of the winding	Turns ratio N_2/N_1	Name of the winding	Turns ratio N_2/N_1
a1a2	1.0000	b1b2	0.5773	c1c2	0.8165
a3a4	0.2988	b3b4	0.8165	c3c4	0.5773
a5a6	0.2988	b5b6	0.5773	c5c6	0.8165
a7a8	1.0000				
a9a10	0.2988	b7b8	0.8165	c7c8	0.5773
a11a12	0.2988				

5. SIMULATION RESULTS

The designed transformer is at first simulated using “SimPowerSystem” block sets of the MATLAB/Simulink software. The inbuilt transformer blocks are used to simulate the conceptual design. The appropriate turn ratios are set in the dialog box and the simulation is run. Turn ratios are shown in Tables 1 and 2. The resulting input and output voltage waveforms are illustrated in Figure 7. It is seen that the output is a balanced seven-phase supply for a balanced three-phase input.

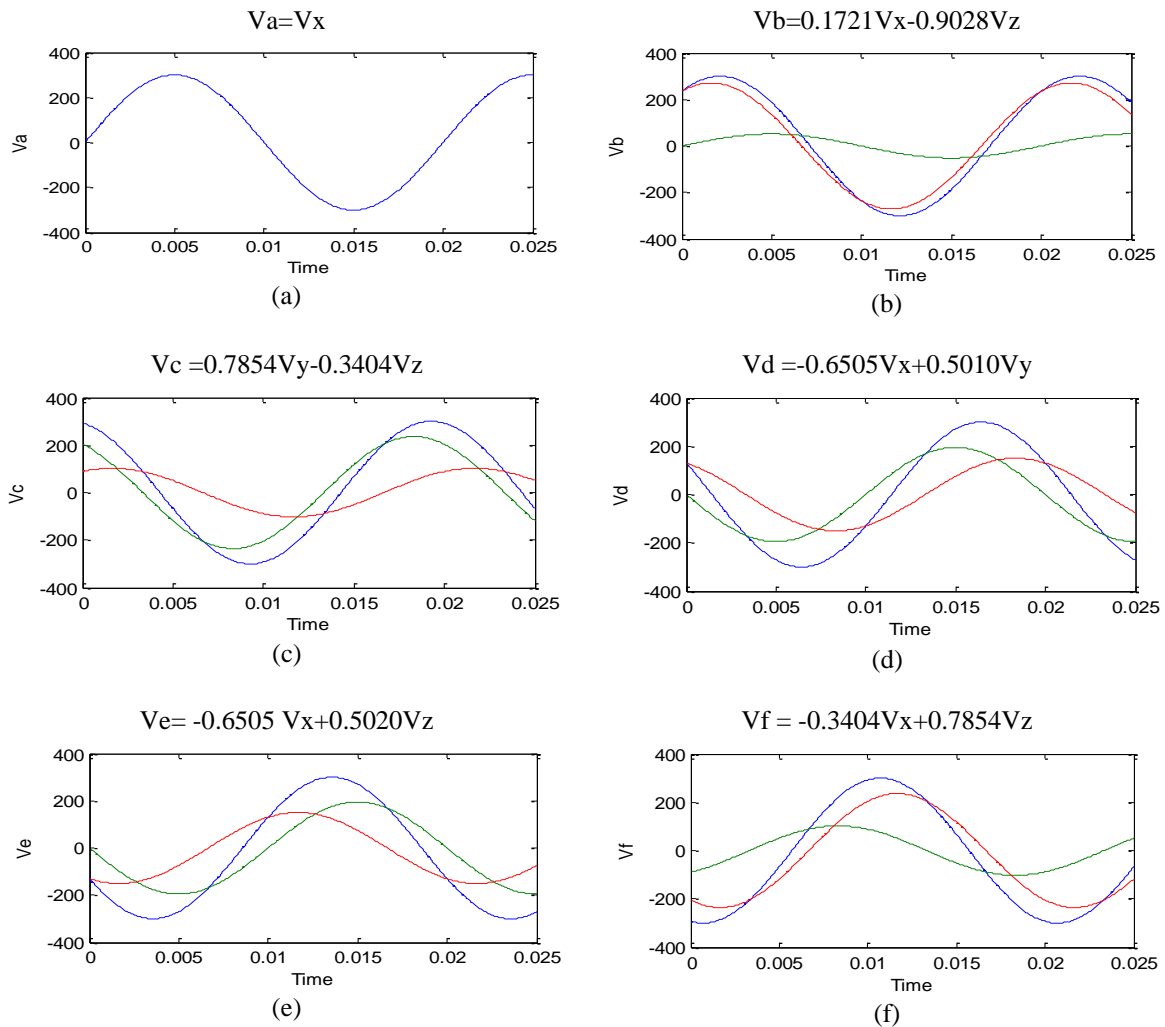


Figure 7. (a) V_a output voltage and inputs V_x , (b) V_b output voltage and inputs V_x and $-V_z$, (c) V_c output voltage and inputs V_y and $-V_z$, (d) V_d output voltage and inputs $-V_x$ and V_y , (e) V_e output voltage and inputs $-V_x$ and V_z , (f) V_f output voltage and inputs $-V_x$ and V_z ,

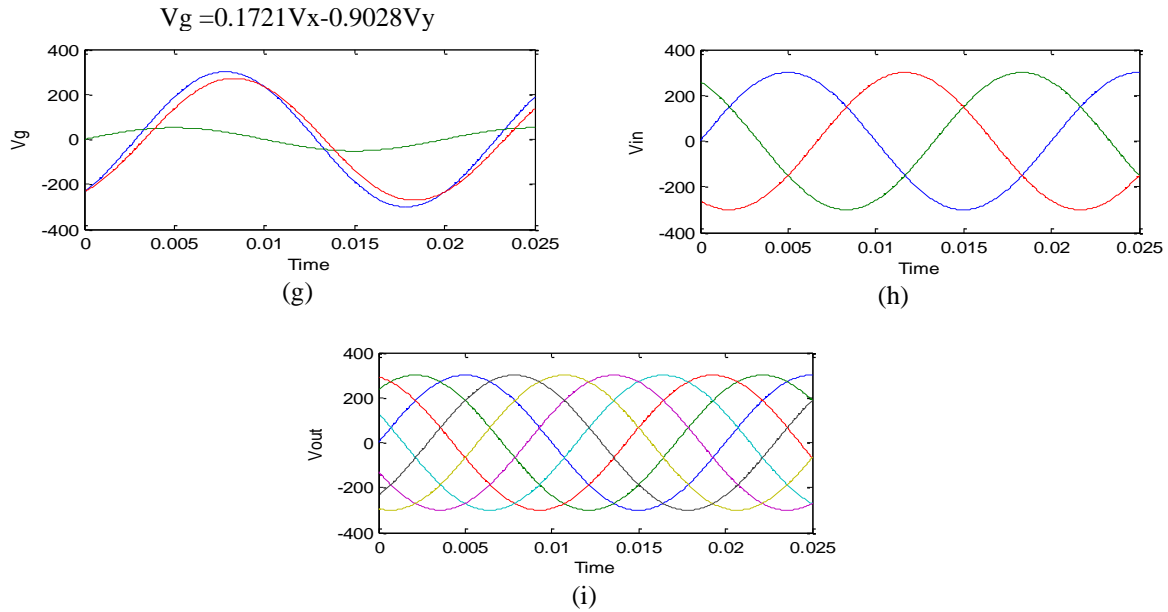


Figure 7. (g) V_g output voltage and inputs V_x and $-V_y$, (h) input voltage V_x and V_y and V_z , (i) The output voltage $V_a, V_b, V_c, V_d, V_e, V_f$ and V_g

The output will be unbalanced if the input is unbalanced. The unbalancing study is out of the scope of this paper and will be dealt separately and reported in the future. Individual output phases are also shown along with their respective input voltages. The phase V_a is not shown because $V_a = V_x$, i.e., the input and the output phases are same. Figure 7 shows the reconstruction of seven-phase output waveform from a three-phase input waveform. The three-phase output from a seven-phase input supply can also be obtained in similar fashion.

6. FFT ANALYSIS

Fourier analysis is the process of representing a function in terms of sinusoidal components. It is widely employed in many areas of engineering, science, and applied mathematics. It provides information as to what frequency components represent a function. The FFT analysis gives the THD of the system to that of a fundamental value. Rate of harmonic generation in Star-Star mode very high and the rate of the harmonic in novel connection delta-star reaches to zero. Figure 8a and 8b is THD measured at the position shown.

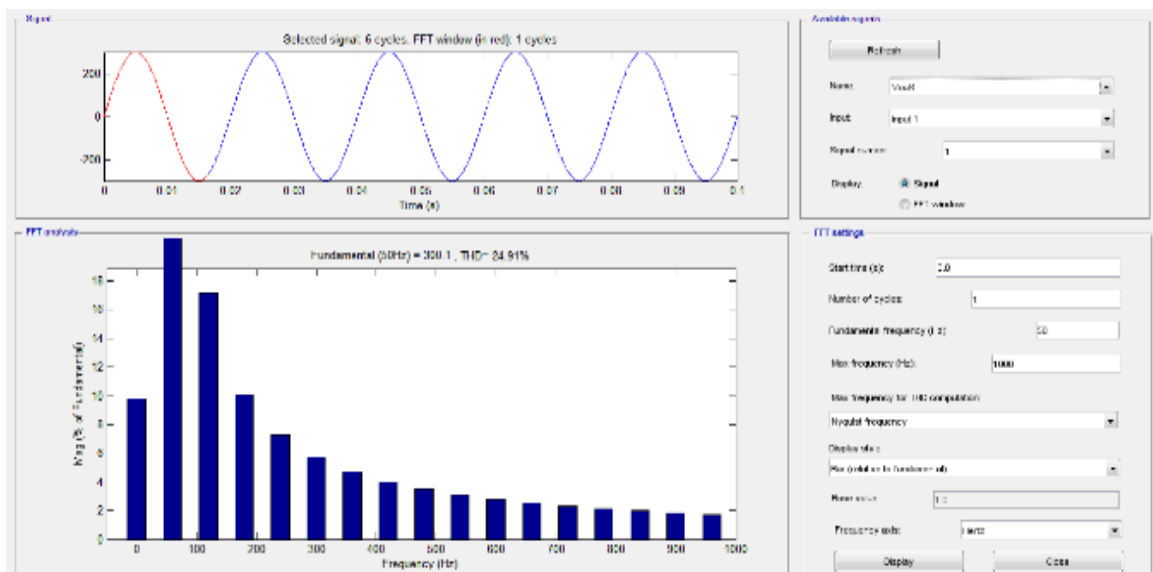


Figure 8a. The output voltage fundamental harmonics in the star-stars

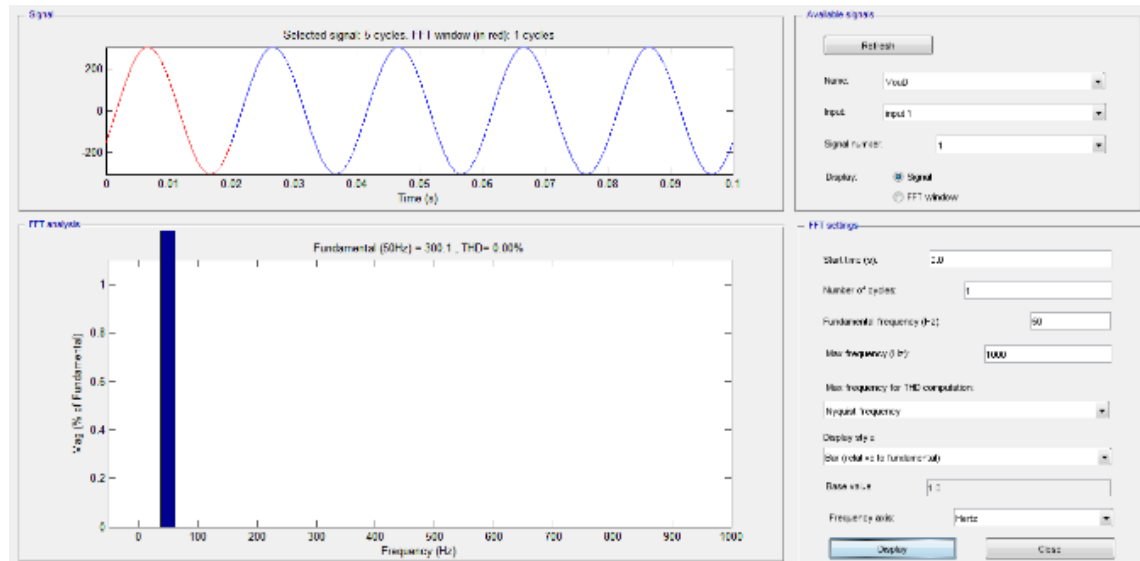


Figure 8b. The output voltage fundamental harmonics in the delta –stars

7. CONCLUSION

This paper gives a new method to convert 3 phase to 7 phase using special transformer connection. The winding arrangement and the vector diagram, along with the turn ratios, are given in the table. The successful implementation of the proposed connection scheme is elaborated upon using simulation of matlab software using simpower system blocks. The proposed connection scheme can be used in drives and other multiphase applications. By using the same method we can also get the heptagon output.

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