International Journal of Latest Engineering and Management Research (IJLEMR)
ISSN: 2455-4847
www.ijlemr.com || REETA-2K16 ǁ PP. 568-573

A SPECIAL TRANSFORMER CONNECTION FOR THREE-PHASE TO FIVE-PHASE TRANSFORMATION

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ABSTRACT : The first five-phase induction motor drive system was proposed in the late 1970s for adjustable speed drive applications. Since then, a considerable research effort has been in place to develop commercially feasible multiphase drive Systems .Multiphase (more than three phase) systems are the focus of research recently due to their inherent advantages compared to their three-phase counterparts. The multiphase motors are invariably supplied by ac/dc/ac converters. A five-phase induction motor under a loaded condition is used to prove the viability of the transformation system. It is expected that the proposed connection scheme can be used in drives applications and may also be further explored to be utilized in multiphase power transmission systems.

I. INTRODUCTION

Multiphase (more than three phase) systems are the focus of research recently due to their inherent advantages compared to their three-phase counterparts. The applicability of multiphase systems is explored in electric power generation [2]–[8], transmission [9]–[15], and utilization [16]–[33]. The research on six-phase transmission system was initiated due to the 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 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 as well [12]. The research on multiphase generators has started recently and only a few references are available [2]–[8]. The present work on multiphase generation has investigated asymmetrical six-phase (two sets of stator windings with 30 phase displacement) induction generator configuration as the solution for use in renewable energy generation. As far as multiphase motor drives are concerned, the first proposal was given by Ward and Harrer way back in 1969 [1] and since then, the research was slow and steady until the end of the last century. The research on multiphase drive systems has gained momentum by the start of this century due to availability of cheap reliable semiconductor devices and digital signal processors. Detailed reviews on the state of the art in multiphase drive research are available in [18]–[22]. It is to be emphasized here that the multiphase motors are invariably supplied by ac/dc/ac converters. Thus, the focus of the research on the multiphase electric drive is limited to the modeling and control of the supply systems (i.e., the inverters [23]–[33]). Little effort is made to develop any static transformation system to change the phase number from three to -phase (where 3 and odd). The scenario has now changed with this paper, proposing a novel phase transformation system which converts an available three-phase supply to an output five-phase supply.

Multiphase, especially a 6-phase and 12-phase system is found to produce less ripple with a higher frequency of ripple in an ac–dc rectifier system. Thus, 6- and 12-phase transformers are designed to feed a multi-pulse rectifier system and the technology has matured. Recently, a 24-phase and 36-phase transformer system have been proposed for supplying a multi-pulse rectifier system [34]–[37]. The reason of choice for a 6-, 12-, or 24-phase system is that these numbers are multiples of three and designing this type of system is simple and straightforward. However, increasing the number of phases certainly enhances the complexity of the system. None of these designs are available for an odd number of phases, such as 5, 7, 11, etc., as far as the authors know.

The usual practice is to test the designed motor for a number of operating conditions with a pure sinusoidal supply to ascertain the desired performance of the motor [38]. Normally, a no-load test, blocked rotor, and load tests are performed on a motor to determine its parameters. Although the supply used for a multiphase motor drive obtained from a multiphase inverter could have more current ripple, there are control methods available to lower the current distortion even below 1%, based on application and requirement. Hence, the machine parameters obtained by using the pulse width-modulated (PWM) supply may not provide the precise true value. Thus, a pure sinusoidal supply system available from the utility grid is required to feed the motor. This paper proposes a special transformer connection scheme to obtain a balanced five-phase supply with the input as balanced three phases. The block diagram of the proposed system is shown in Fig. The fixed voltage and fixed frequency available grid supply can be transformed to the fixed voltage and fixed frequency five-phase output supply. The output, however, may be made variable by inserting the autotransformer at the input side.

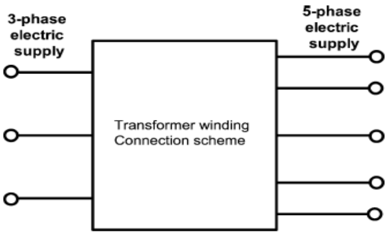


Fig. Block representation of the proposed system

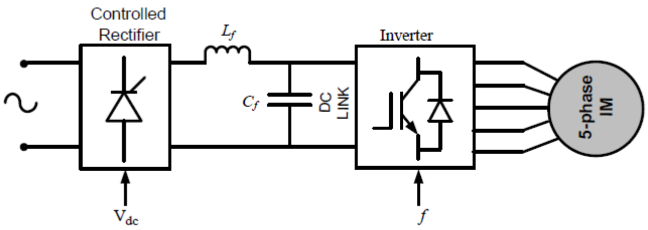
The input and output supply can be arranged in the following manner:
1) input star, output star;
2) input star, output polygon;
3) input delta, output star;
4) input delta, output polygon.
Since input is a three-phase system, the windings are connected in a usual fashion. The output/secondary side connection is discussed in the following subsections.

II. FIVE-PHASE SYSTEM

Variable speed electric drives predominately utilise three-phase machines. However, since the variable speed ac drives require a power electronic converter for their supply (in vast majority of cases an inverter with a dc link), the number of machine phases is essentially not limited. This has led to an increase in the interest in multi-phase ac drive applications, since multi-phase machines offer some inherent advantages over their three-phase counterpart. Interesting research results have been published over the years on multi-phase drives and detailed review is available in Singh (2002), Jones and Levi (2002), Bojoi et al. (2006), Levi et al. (2007), Levi (2008a) and Levi (2008b). Major advantages of using a multi-phase machine instead of a three-phase machine are higher torque density, greater efficiency, reduced torque pulsations, greater fault tolerance, and reduction in the required rating per inverter leg (and therefore simpler and more reliable power conditioning equipment).

FIVE-PHASE DRIVE STRUCTURE

A simple open-loop five-phase drive structure is elaborated in Figure. The dc link voltage is adjusted from the controlled rectifier by varying the conduction angles of the thyristors. The frequency of the fundamental output is controlled from the IGBT based voltage source inverter. The inverter is operating in the quasi square wave mode instead of more complex PWM mode. Thus the overall control scheme is similar to a three-phase drive system. Since the inverter is operating in square wave mode the analogue circuit based controller is much simpler and cheaper compared to more sophisticated digital signal processor based control schemes. This type of solution is very cheap and convenient for use in coarse applications such as water pumping. These types of applications do not require fast dynamic response of drive systems and thus the need of high performance control schemes do not arise. The power quality of the remote locations in developing countries such as Indian subcontinents are not adequate for reliable and durable operation of sensitive microprocessors/microcontrollers/digital signal processors based controllers. It is thus intended to develop cheap and robust controller based on simple, and reliable analogue circuit components for such locations. The subsequent section describes the implantation issues of control of a five-phase voltage source inverter. The motivation behind choosing this structure lies in the fault tolerant nature of a five-phase drive system (Apsley et al., 2006).



FIVE-PHASE DRIVE

The predominant harmonics in a five-phase machine are 9th and 11th, with 9th being backward rotating and 11th being forward rotating both leading to 10th harmonic torques, Iqbal et al. (2008).

The tenth harmonic pulsating torque for 180° conduction mode is obtained as;

$$(T_{e10})_{180^\circ} = \frac{5}{2}P[\psi_{m1}(I_{r11} - I_{r9})Sin(10\omega t) + I_{r1}(\psi_{m11} + \psi_{m9})Cos(10\omega t)]$$

The tenth harmonic pulsating torque for 144° conduction mode is obtained as;

$$(T_{e10})_{144^\circ} = \frac{5}{2}P[\psi_{m1}(I_{r11} - I_{r9})Sin(10\omega t) + I_{r1}(\psi_{m11} + \psi_{m9})Cos(10\omega t)]$$

An expression is derived for the tenth harmonic pulsating torque in terms of fundamental voltage and equivalent circuit parameter and is obtained as;

$$(T_{e10})_{180^\circ} = \frac{5}{2}\left(\frac{PZ}{\omega_s X_{eq}}\right)\left(\frac{2V_{Dc}}{\pi}\right)^2 Sin(\omega t)[Sin(10\omega t + \alpha)]$$

$$(T_{e10})_{144^\circ} = \frac{-5}{2}\left(\frac{PZ}{\omega_s X_{eq}}\right)\left(\frac{2V_{Dc}}{\pi}\right)^2 Cos^2\left(\frac{\pi}{10}\right) Sin(\omega t)[Sin(10\omega t + \alpha)]$$

where

$$Z = \sqrt{A^2 + B^2}, A = ZCos(\alpha), B = ZSin(\alpha), \alpha = Tan^{-1}\frac{B}{A},$$

$$A = \left(\frac{1}{(11)^2}Sin(11\omega_s t) - \frac{1}{(9)^2}Sin(9\omega_s t)\right)$$

$$B = \frac{1}{2}\left(\frac{1}{(11)^2}Sin(11\omega_s t) + \frac{1}{(9)^2}Sin(9\omega_s t)\right)$$

Thus the ratio of pulsating torques for a typical motor in two conduction modes is obtained as;

$$\frac{|(T_{e10})_{144^\circ}|}{|(T_{e10})_{180^\circ}|} = Cos^2\left(\frac{\pi}{10}\right) = 0.9045084972$$

$$\frac{(Te_6)_{180^\circ}}{(Te_{10})_{180^\circ}} = \frac{1.4x10^{-15}}{2x10^{-16}} = 7.0$$

$$\frac{(Te_6)_{180^\circ}}{(Te_{10})_{144^\circ}} = \frac{1.4x10^{-15}}{1.8x10^{-16}} = 7.78$$

The relations show, there is reduction in torque ripples in five phase motor at 144° conduction mode by 10% (approx) when compared with 180° conduction mode of five phase motor, 700% when compared with 180° conduction modes of five phase motors, and 778% when compared with 180° conduction mode of three phase motor and 144° conduction mode of five phase motor.

III. SIMULATION RESULTS

The designed transformer is at first simulated by using "simpower system" 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 Table. Standard wire gauge SWG) is shown in Table.

TABLE: DESIGN OF THE PROPOSED TRANSFORMER

Primary	Secondary	Turn Ratio (N_p/N_s)	SWG
Phase-X	a_1a_2	1	17
	a_4a_3	0.47	15
Phase-Y	b_1b_2	0.68	17
	b_4b_3	0.858	17
	b_5b_6	0.24	17
Phase-Z	c_1c_2	0.68	17
	c_4c_3	0.858	17
	c_5c_6	0.24	17

A brief design description for the turn ratio, wire gauge, and the geometry of the transformers are shown in the Appendix. The simulation model is depicted in first fig and the resulting input and output voltage waveforms are illustrated in second fig.

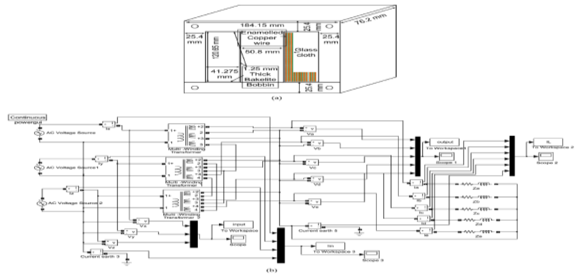


Fig. (a) Geometry of the transformer. (b) Matlab/Simulink model of the three- to five-phase transformation.

It is balanced three-phase input. Individual output phases are, also, shown along with their respective input voltages. The phase Va is not shown because Va=Vx (i.e., the input and the output phases are the same). There was no earth current flowing when both sides neutrals were earthed. The input and output currents with earth current waveforms are also shown in Fig. From this, we can say that the transformer, connected to the X input line, carries 16.77% (19.5/16.7) more current than that of the other two transformers (or two phases). Due to this efficiency, clearly seen that the output is a balanced five-phase supply for a the overall transformer set is slightly lower than the conventional three-phase transformer.

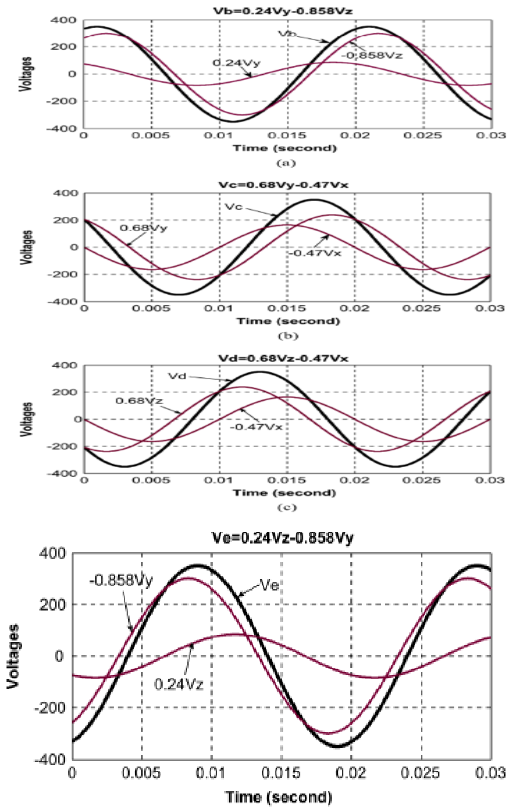


Fig. (a) Input Vy and Vz phases and output Vb phase voltage waveforms. (b) Input Vy and Vx phases and output Vc phase voltage waveforms. (c) Input Vz and Vx phases and output Vd phase voltage waveforms

IV. EXPERIMENTAL RESULTS

This section elaborates the experimental setup and the results obtained by using the designed three- to five-phase transformation system. The designed transformation system has a 1:1 input:output ratio, hence, the output voltage is equal to the input voltage. Nevertheless, this ratio can be altered to suit the step up or step down requirements. This can be achieved by simply multiplying the gain factor in the turn ratios. In the present scheme for experimental purposes, three single phase autotransformers are used to supply input phases of the transformer connections. The output voltages can be adjusted by simply varying the taps of the autotransformer. For balanced output, the input must have balanced voltages. Any unbalancing in the input is directly reflected in the output phases. The input and output voltage waveforms under no-load steady-state conditions are recorded. The input and output voltage waveforms clearly show the successful implementation of the designed transformer. Since the input-power quality is poor, the same is reflected in the output as well. The output trace shows the no-load output voltages. Only four traces are shown due to the limited capability of the oscilloscope. Further tests are conducted under load conditions on the designed transformation system by feeding a five-phase induction motor.

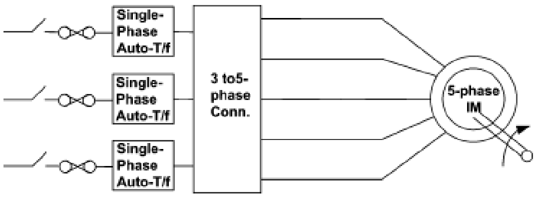


Fig. Circuit diagram for a direct-online start of the five-phase motor

Direct online starting is done for a five-phase induction motor which is loaded by using an eddy-current load system. DC current of 0.5A is applied as the eddy-current load on the five-phase induction machine. The resulting input (three-phase) waveforms and the output (five-phase) waveforms (voltages and currents) under steady state. The applied voltage to the input side is 446 V (peak to peak) , the power factor is 0.3971, and the steady-state current is seen as 7.6 A (peak-to-peak). The corresponding waveforms of the same phase “A” are equal to the input side voltage of 446 (peak-topeak), since the transformer winding has a 1:1 ratio. The power factor is now reduced in the secondary side and is equal to 0.324 and the steady-state current reduces to 3.3 A (peak-to-peak). The reduction in steady-state current is due to the increase in the number of output phases. Thus, once again, it is proved that the deigned transformation systems work satisfactorily. The transient performance of the three- to five-phase transformer is evaluated by recording the transient current when supplying the five-phase induction motor load. The maximum peak transient current is recorded as 7.04 A which is reduced to 4.32A in the steady-state condition. The settling time is recorded to be equal to 438.4 ms.

V. CONCLUSION

This paper proposes a new transformer connection scheme to transform the three-phase grid power to a five-phase output supply. The connection scheme and the phasor diagram along with the turn ratios are illustrated. The successful implementation of the proposed connection scheme is elaborated by using simulation and experimentation. A five-phase induction motor under a loaded condition is used to prove the viability of the transformation system. It is expected that the proposed connection scheme can be used in drives applications and may also be further explored to be utilized in multiphase power transmission systems.

APPENDIX

DESIGN OF THE TRANSFORMER

1)The volt per turn (E_t).

$E_t = k\sqrt{Q} = 0.7\sqrt{2} = 0.989949$ V/turn. Where k = 0.7 (assumed), Q = 2 kVA

$$\therefore Core\ area = \frac{E_t * 10000}{4.44 * f * B_m}\text{cm}^2 = \frac{0.7\sqrt{2} * 10000}{4.44 * 50 * 1.25}$$

$$= 35.67385563 \text{ cm}^2$$

where $f = 50$ Hz, $B_m = 1.25$ web/m^2.

2) Standard core size of No. 8 of E and I was used whose central limb width is 2*2.54=5.08cm =50.8mm.

3) Standard size of Bakelite bobbin for 8 no. core of 3*2.54=7.62cm=76.2 mm was taken which will give core area of 38.7096cm .

4) Turns of primary windings of all three single-phase transformers are equal and the enamelled wire gauge is 15 SWG. The VA rating of each transformer is 2000.

Wire gauge was chosen at a current density of 4 A/mm because enamelled wire was of the grade which can withstand the temperature up to 180. The winding has 15 SWG wire because it carries the sum of two currents (i.e., $I_e + I_d = \sqrt{2(1+\cos(2\pi/5))} = 1.618$ times the 5-phase rated current).

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