Enhancement Design of Multi-phase Transformer for Cascaded H-Bridge Motor Driver

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Abstract: - The growth of using medium-voltage drivers (MVDs) to control medium-voltage motors has led to more complicated designs to cover the market demand. Multi-phase transformers (MPT) are one of the most preferred components for AC-DC-AC converters. MPT in MVD systems has essential functions: harmonic filtering between the grid and rectifier, Isolation between the grid and rectifier, converting voltage to suitable voltage for the rectifier, and preventing block common-mode voltages, which could cause failure in motor winding insulation. MPTs are critical to motor drivers because of their pure sine wave, low THD, grid isolation from the motor, efficacy, and cost-effectiveness. This work addresses the configuration, winding turn ratios, selection factors, and calculations of power, weight, and design procedure for shifting transformers. The proposal design is confirmed by simulation results, which support the experimental studies validated by different load levels. The result determines the inductance value for cost-effectiveness, low-harmonics, and power factor improvement. This work provides an experimental method to specify the IPT inductance value, which improves the power rating and reduces the THD. Mathematical specification, an experimental method, was applied to calculate the optimal value of the IPT inductance. The simulation and experimental results analysis were studied and verified. The optimal value of inductance obtained by the simulation result is 25mH; at this value, the THD equals 4.6%.

Key-Words: - Medium Voltage Driver, topology; Phase-Shift Transformers; multi winding transformers; multi winding transformers; eighteen pulse rectifiers; 18-phase Shift Autotransformer (PSAT).

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1 Introduction

Energy quality in the industry has become critical in the last few years, especially after the rebound in using AC-DC-AC converters. Using rectifier switches like Thyristors or diodes provides power to DC links in the system, [1], [2]. However, the main problems of this utilization are harmonics in current, distortions in voltage, ripples in DC links, and low quality of power, [3], [4]. Solving those problems and covering the standards of power quality plays a big part in power electronic converter research, like reducing output harmonics and ripples, getting higher quality factors, improving the rateability of MVD, and developing the MVD combinations and configurations, [5]. Several pieces of literature on MPT with rectifiers focused on reducing total size, lowering costs, and increasing power ratings, [6], [7]. Controlling induction motors with the phase driver depends on transformer design, [8]. The [9] described a common-mode voltage method DC motor (BLDCM) application. The [10] presented an optimal design for a multi-phase transformer, [11]. This work addresses phase-shifting transformer primary connections, types, and designs. The phase-shifting transformer has multiple secondary windings that connect with rectifiers, [12], [13]. Optimally, [14], [15] the harmonic grid cancellation is made by the primary winding side, and the secondary winding side makes the rectifier and inverter harmonic cancellation. A practical formula to determine the optimum value for MPT to obtain maximum power rating and minimum line current harmonics, [16]. The DC link voltage, power rating, and Line current harmonics were proposed, [17].

The suggested design simulation and experimental have been validated under different conditions.

2 MPT Selection Factors

MVD transformers are generally the dry type with copper winding transformers because of the total space requirements, [18]. The copper terminal must be plated with tin or silver. The primary terminal preferred to be at the top of the transformer body with incoming isolators. Secondary terminals must be detailed in the mechanical specifications. Secondary terminals are front or back-accessible, [19], [20]. All connection Terminals must be large enough to provide the minimum current density of 2.5 A/mm^2 in Aluminum and 3 A/mm^2 in copper. Terminals must be accessible and easily configured with the required voltage isolation clearance. Electrical connections must have visible markings after connection points. Wye primary has +/- 5% taps standard. Phase tolerance and voltage tolerance of secondary provide 3% or less THD in current, [21].

Phase tolerance of +/- 0.50 degrees max, voltage tolerance +/- 1% shall not be exceeded. The pulse rectifier bridge is connected to each phase in secondary windings. The rectifier bridges are connected to obtain the required DC bus voltage, [22]. The rectifier load is selected as capacitive to reduce the harmonic. The inverter topology should be defined. The system designer must specify power rating, Primary Voltage, and frequency.

Temperature indication sensors at coil insulation tubes must be located at the hot spot of the transformer, [23]. They will be on the opposite side of the transformer from the input and output terminals. Transformer manufacturers must provide test data with verified average winding temperature and hot spot. Cooling fans mounted on the top of the back side of the enclosure pull air into the door vents from the front and up through the enclosure through the transformer, [24]. The airspeed is approximately 1.25 m/Sec for 2400 kVA and 2.5 m/Sec for 2650 kVA to 5250 kVA. Service Conditions the life expectancy of the transformer will be designed for a minimum of 20 years of operating continuous duty.

Transformer losses include excitation losses and load loss. Efficiency is to be calculated at 50%, 75%, and 100% load. 98% minimum efficiency at 100% load is required. Each transformer temperature rises, and rating is a crucial verification in the MVD product to ensure a 20-year life minimum, [25]. The transformer's duty cycle is 100% for 9 minutes, with the overload of 150% for 1 minute continuously. Environment conditions like Altitude are 1000m standard, operating temperature is between (-20 -40) °C, Humidity is 95% max, and Standard Sound Pressure Level (SPL) must not exceed 75 dB at rated load, [26]. The nameplate must be in front of the transformer installed in the drive, [27].

3 MPT with Rectifier Mathematical Theory

The eighteen MPT with rectifier (18-MPT-R) is widely utilized in conversions like high DC voltage transmission lines, UPS and VSD, and medium voltage motor drives since it covers the standard harmonic limitation with cost-effectiveness, [28]. 18-MPT-R has a 20^o degree of phase shifting, obtained by connecting the transformer star winding with three identical star special windings per phase. After that, three identical star special windings connect with the input side of the rectifiers' where the output side is connected with two interphase transformers (IPT), as shown in Figure 1.

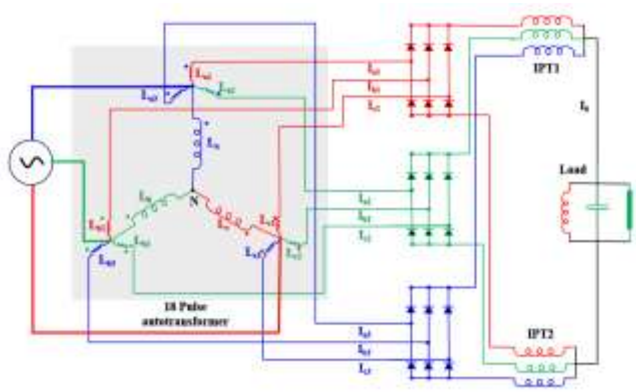

Fig. 1: 18 pulse star connected autotransformer

Assuming the primary side of 18-MPT-R is L_a, L_b, and L_c which is connected with grid voltages Va, Vb, and Vc voltages. The star special identical winding L_{a1}, L_{a2}, and L_{an} are connected to the rectifier sets and have voltages V_{a1}, V_{a2}, and V_{a3}, which are calculated using equation (1). The N_2 is the turn ratio of star special identical winding, which is obtained from equation (2), [29].

$$V_{a1} = V_{a2} = V_{a3} = \frac{\sin 20^{\circ}}{\sin 100^{\circ}} V_a = 0.35 V_a \quad (1)$$

$$N_2 = \frac{V_a}{V_{a1}} = \frac{V_a}{0.35 V_a} = 2.85 \quad (2)$$

The voltages V_{aN}, V_{bN} and V_{cN} were calculated using equation (3) according to the imaginary neutral point N. The N_1 is the turn ratio of the primary winding, which is obtained from equation (4), [30].

$$V_{aN} = V_{a2} = V_{a3} = V_a - \frac{\sin 60^{\circ}}{\sin 100^{\circ}} V_a = 0.12V_a \quad (3)$$

$$N_1 = \frac{V_a}{V_{aN}} = \frac{V_a}{0.12V_a} = 8.29 \quad (4)$$

The transformer voltage output is 88% of the grid voltage input. Obtained from equation (4).

$$V_0 = \frac{6}{2\pi} \int_0^{2\pi} (\sqrt{2}\sqrt{2}\ 0.88V_a \sin(\omega t)) = 2.06V_a \quad (5)$$

The interphase transformer is utilized in a high-power converter system. IPT removes the differences between voltages and cancellation of circulating current. IPT is connected in parallel with rectifier outputs and serial with load. The IPT current and voltage were calculated using equations (6) and (7), [30].

$$i_s = i_{1s} + i_{2s} + i_{3s} \quad (6)$$

$$V_s = V_{1s} = V_{2s} = V_{3s} = L_P \frac{di_1}{dt} - \frac{1}{N} L_P \frac{di_s}{dt} \quad (7)$$

The MATLAB/Simulink simulation model is shown in Figure 2.

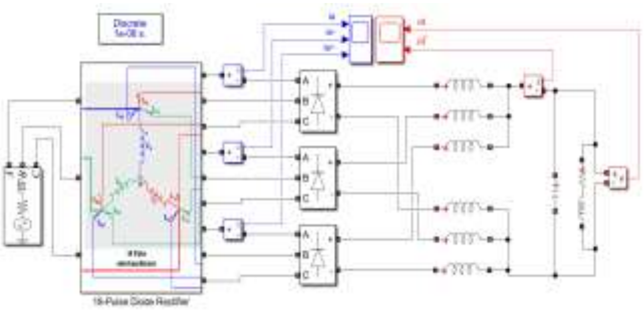

Fig. 2: MATLAB model of 18-PT-R with rectifier.

4 18-PT-R with Rectifier Simulation and Experimental Results

An infinite inductance value of the rectifier is known to produce the highest power rating and minimum THD since the infinite value is inapplicable. This study provides the optimal value for IPT, which produces maximum power rating and minimum harmonics. Before determining the optimal inductance value for IPT, it is vital to calculate the correct parameters. Assuming the voltage reference value is given in equation (8).

$$V_{reference} = V_{a1} = V_{a2} = V_{a3} = V_{b1} = V_{b2} = V_{b3} = V_{c1} = V_{c2} = V_{c3} \quad (8)$$

Assuming the P0 is the standard power value. The Preference is the power reference value, which is obtained from equation (9).

$$P_{reference} = \frac{P_0}{9} \quad (9)$$

Assuming the f_0 is the grid frequency value. The $f_{reference}$ is the frequency reference value, which is obtained from equation (10).

$$f_{reference} = f_0 \quad (10)$$

Assuming The $Z_{reference}$ is the impedance reference value and the $I_{reference}$ is the current reference value, which is obtained from equations (11) and (12).

$$I_{reference} = \frac{P_{reference}}{V_{reference}} \quad (11)$$

$$Z_{reference} = \frac{V_{reference}^{\ 2}}{P_{reference}} \quad (12)$$

Assuming the $Z_{IPT\text{-}N}$ is the standard impedance reference value, the $L_{IPT\text{-}N}$ is the standard inductance reference value and the L_{IPT} is the actual inductance reference value, which is obtained from equations (13), (14) and (15).

$$Z_{IPT-N} = \frac{Z_{IPT}}{Z_{reference}} = \frac{2\pi f_{reference} * L_{IPT}}{V_{reference}/I_{reference}} = 2\pi \frac{I_{reference} * f_{reference}}{V_{reference}} = 2\pi L_{IPT-N} \quad (13)$$

$$L_{IPT-N} = L_{IPT} \frac{f_{reference} * I_{reference}}{V_{reference}} \quad (14)$$

$$L_{IPT} = L_{IPT-N} \frac{V_{reference}}{f_{reference} * I_{reference}} \quad (15)$$

The simulation of 18-PT with the rectifier is valid for different inductance values using MATLAB. As a result, if the inductance value is equal to 2mH, the THD will be 9.5%. Also, if the inductance value equals 18mH, the THD will be 4.9%. The optimal value of inductance obtained by the simulation result is 25mH; at this value, the THD equals to 4.6%. At the same time, any value up to 25mH had a higher THD. If the inductance value equals 28mH, the THD will be 4.75%. As a result, the experimental value of inductance can be obtained from equation (15). The output current and voltage results of MATLAB/Simulink simulations are shown in Figure 3.

Figure 3 shows the output harmonics of the current decrease, and its waveform is almost a sinusoidal wave. Nevertheless, after a specific value (25 mH), increasing does not help to decrease the

THD and only increases the cost and size of the system. The 18-PT with rectifier simulation values P_0=25kW, V_a=220V, and f_s=50Hz. It is shown that if the value of inductance increases, the THD will be decreased.

However, there is a limitation to this increment. The actual application of 18-PT is shown in Figure 4.

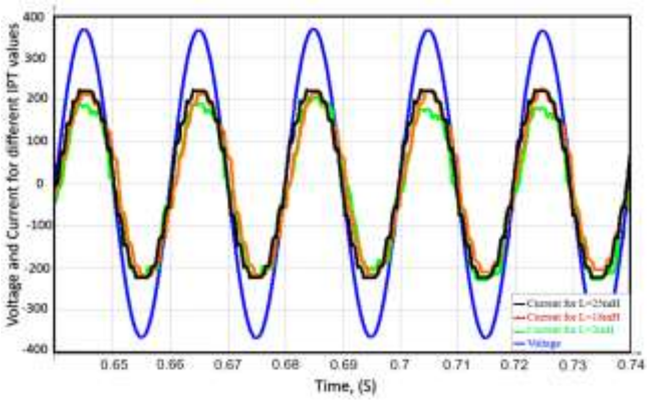

Fig. 3: The simulation results of 18-PT with the rectifier

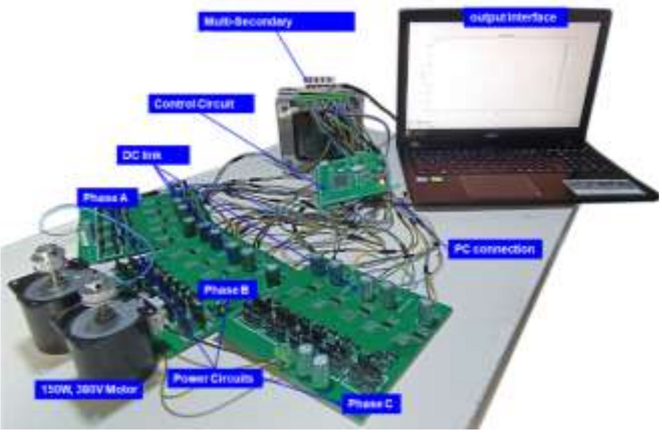

Fig. 4: The application of setup18-PT with CHB-MD

Figure 5 shows the core losses by watts per meter cube. The 18-pulse transformer was designed at 25 kW, 380 V, three-phase, and 50Hz, as shown in previous work. Figure 6. Shows the output current and voltage for 18mH inductance values. The THD value is 5.5%. Figure 7. Shows the output current and voltage for 25mH inductance values. The THD values is 4.95%.

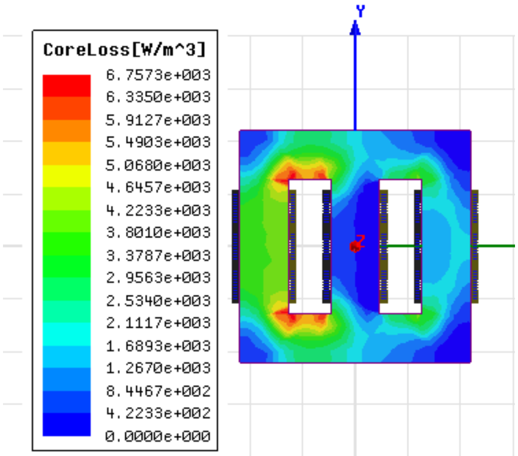

Fig. 5: 18-PT core loss (watts per meter cube)

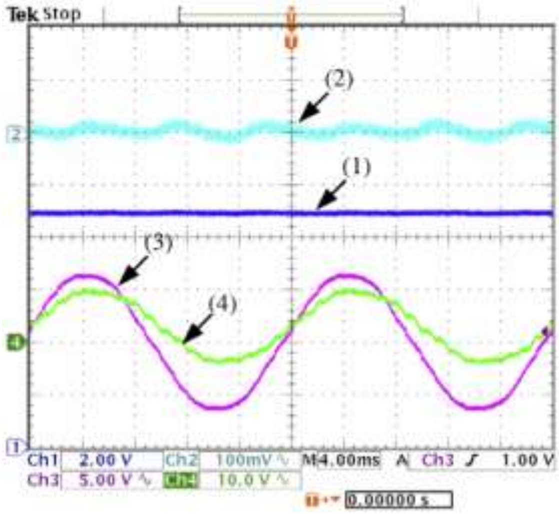

Fig. 6: Output current and voltage for 18mH and 25mH inductance values

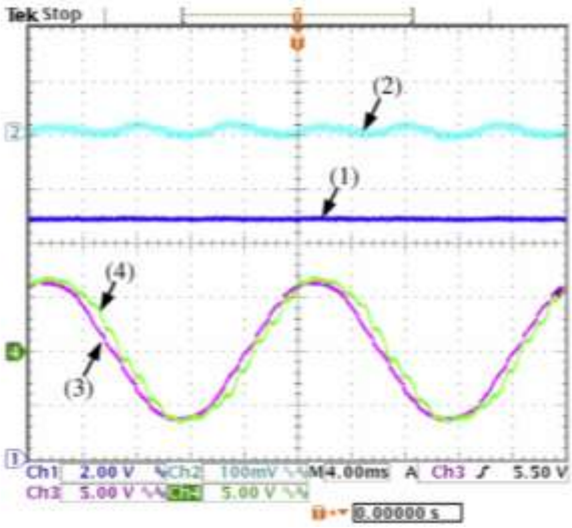

Fig. 7: Output current and voltage for 18mH and 25mH inductance values

5 Conclusion

This work presents a technical overview of the transformer design procedure, the connection of transformer winding, and the transformer design equations of 18-pulse systems. The main configurations for 18-pulse rectifiers are used in the phase-shifting transformers. The structure of the transformers is discussed. The relationship between the required phase-shifting angle and transformer turns ratio is tabulated to assist the transformer design. The principle of harmonic current cancellation by the phase-shifting transformers is also demonstrated. The main functions of phase-shifting transformers in MVD systems are harmonic filtering, isolation, and block common-mode voltages. The configuration, winding turn ratios, and grid harmonic filtering are addressed. The THD of multi-pulse phase shifting transformers can decrease by increasing the number of pulses, it will cost more than using filters. This work provides an experimental method to specify IPT inductance value which improves the power rating and reduces the THD. Mathematical specification, an experimental method, was applied to calculate the optimal value of the IPT inductance. The simulation and experimental results analysis were studied and verified. The obtained results verified the optimal values of IPT inductance equal to 25mH. This study provides the optimal value for IPT, which produces maximum power rating and minimum harmonics.

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It is an optional section where the authors may write a short text on what should be acknowledged regarding their manuscript.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflict of Interest

The authors have no conflicts of interest to declare.