DOUBLE ZIGZAG-CONNECTED AUTOTRANSFORMER-BASED 24-PULSE AC-DC CONVERTER FOR POWER QUALITY IMPROVEMENT

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ABSTRACT*-This paper presents the design and analysis of a double zigzag-connected autotransformer based 24-phase ac-dc converter which supplies direct torque controlled induction motor drives (DTCIMD's) in order to have better power quality conditions at the point of common coupling. The proposed converter output voltage is accomplished via four paralleled six-pulse ac-dc converters each of them consisting of 3-phase diode bridge rectifier. An autotransformer is designed to supply the rectifiers. The design procedure of magnetics is in a way such that makes it suitable for retrofit applications where a six-pulse diode bridge rectifier is being utilized. The aforementioned structure improves power quality criteria at ac mains and makes them consistent with the IEEE-519 standard requirements for varying loads. Furthermore, near unity power factor is obtained for a wide range of DTCIMD operation. A comparison is made between 6-pulse and proposed converters from view point of power quality indices. Results show that input current total harmonic distortion (THD) is less than 5% for the proposed topology at variable loads.*

Index Terms—24-pulse AC–DC converter, double zigzag-connected autotransformer, power quality, direct torque controlled induction motor drive (DTCIMD).

I. INTRODUCTION

Recent advances in solid state conversion technology has led to the proliferation of variable frequency induction motor drives (VFIMD's) that are used in several applications such as air conditioning, blowers, fans, pumps for waste water treatment plants, textile mills, rolling mills etc [1]. The most practical technique in VFIMD's is vector-controlled strategy in that it offers better performance rather than the other control techniques. Vector-controlled technique is implemented in voltage source inverter which is mostly fed from six-pulse diode bridge rectifier, Insulated gate bipolar transistors (IGBT's) are employed as the VSI switches. The most important drawback of the six-pulse diode-bridge rectifier is its poor power factor injection of current harmonics into ac mains.

The circulation of current harmonics into the source impedance yields in harmonic polluted voltages at the point of common coupling (PCC) and consequently resulting in undesired supply voltage conditions for costumers in the vicinity. The value of current harmonic components which are injected into the grid by nonlinear loads such as DTCIMD's should be confined within the standard limitations. The most prominent standards in this field are IEEE standard 519 [2] and the International Electrotechnical Commission (IEC) 61000-3-2 [3].

According to considerable growth of Static Power Converters (SPC's) that are the major sources of harmonic distortion and as a result their power quality problems, researchers have focused their

attention on harmonic eliminating solutions. For DTCIMD's one effective solution is to employ multipulse AC-DC converters. Different techniques have been proposed for harmonic mitigation in the literature [4-26]. Although, in the conditions of light load or small source impedance, line current total harmonic distortion (THD) will be more than 5% for up to 24-pulse converters[7-14]. For mitigating the total harmonic distortion (THD) problems observed in the input currents 30, 36 and 40-pulse converters are reported in [14-25], But this topologies are high cost (cost is nearly doubled), increased complexity, and higher dc-link voltage due to boost operation. A Zigzag-Connected Autotransformer-Based 24-pulse AC-DC converter is reported in [26] which has THD variation of 4.67% to 6.38% from full-load to light-load (20% of full-load), but even with this configuration, the THD of ac mains current at light load is 6.38%, which is also not within IEEE Standard 519 limits. In this paper, a 24-pulse ac-dc converter is proposed employing a novel zigzag autotransformer as shown in Fig. 1. The proposed design method will be suitable even when the transformer output voltages vary while keeping its 24-pulse operation. In the proposed structure, four 3-leg diode-bridge rectifiers are paralleled via four interphase transformers and fed from an autotransformer. Hence, a 24-pulse output voltage is obtained. Detailed design tips of the IPT and totally the whole structure of 24-pulse ac-dc converter are described in this paper and the proposed converter is modeled and simulated in

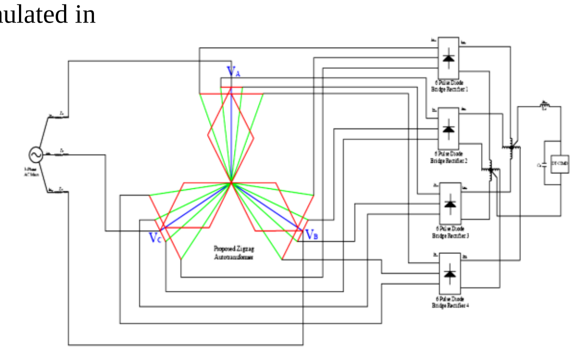

Fig. 1 Zigzag-autotransformer configuration for 24-pulse ac–dc conversion

MATLAB to study its behavior and specifically to analyze the power quality indices at ac mains. Furthermore, a 24-pulse ac-dc converter consisting of a zigzag autotransformer, four six-pulse diode bridge rectifiers paralleled through four IPTs, and with a DTCIMD load Fig. 1. Simulation results of six-pulse and proposed 24-pulse ac-dc converters feeding a DTCIMD load

are scheduled and various quality criteria such as THD of ac mains current, power factor, displacement factor, distortion factor, and THD of the supply voltage at PCC are compared.

II. PROPOSED 24-PULSE AC-DC CONVERTER

In order to implement a 24-pulse ac-dc converter through paralleling four bridge rectifiers, i.e. four 6-pulse rectifiers, four sets of 3-phase voltages with a phase difference of 120

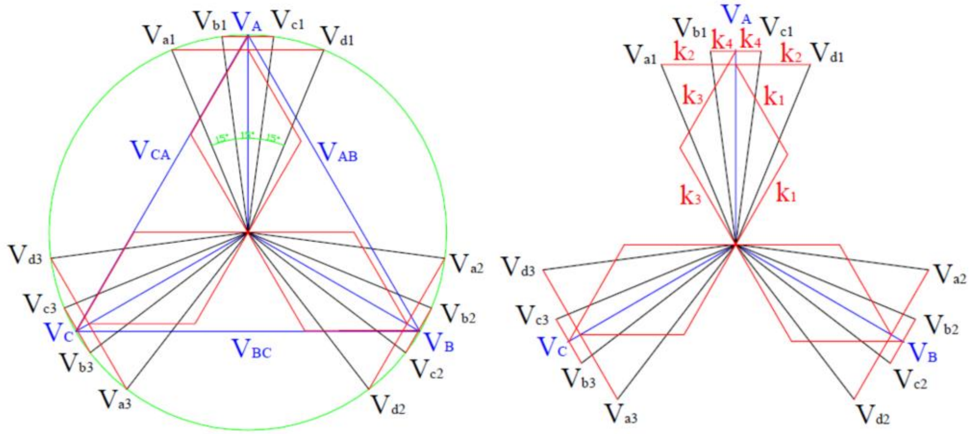

Fig.2 Zigzag connection of proposed autotransformer for 24-pulse converter and its phasor representation.

degrees between the voltages of each group and 15 degrees between the same voltages of the four groups are required. Accordingly, each bridge rectifier consists of 3 common-anode and 3 common-cathode diodes (four 3-leg rectifiers). Autotransformer connections and its phasor diagram which shows the angular displacement of voltages are illustrated in Fig. 2.

Design of the Proposed Autotransformer for 24-Pulse AC–DC

A. Converter

The aforementioned four voltage sets are called as (V_{a1}, V_{a2}, V_{a3}) and (V_{b1}, V_{b2}, V_{b3}) and (V_{c1}, V_{c2}, V_{c3}) and (V_{d1}, V_{d2}, V_{d3}) that are fed to rectifiers I and II, respectively. The same voltages of the four groups, i.e. V_{ai}, V_{bi}, V_{ci} and V_{di}, are phase displaced of 15 degrees. V_{a1}, V_{b1}, V_{c1} and V_{d1} has a phase shift of +22.5, +7.5, -7.5 and -22.5 degrees from the input voltage of phase A, respectively.

According to phasor diagram, the 3-phase voltages are made from ac main phase and line voltages with fractions of the primary winding turns which are expressed with the following relationships. Consider three-phase voltages of primary windings as follows:

$$V_A = V_s\angle 0^\circ,\ V_B = V_s\angle -120^\circ,\ V_C = V_s\angle 120^\circ. \quad (1)$$

Where four voltage sets voltages are:

$$\begin{aligned}
&V_{a1} = V_s\angle +22.5^\circ, V_{a2} = V_s\angle -97.5^\circ, V_{a3} = V_s\angle -217.5^\circ\\
&V_{b1} = V_s\angle +7.5^\circ, V_{b2} = V_s\angle -112.5^\circ, V_{b3} = V_s\angle -232.5^\circ\\
&V_{c1} = V_s\angle -7.5^\circ, V_{c2} = V_s\angle -127.5^\circ, V_{c3} = V_s\angle -247.5^\circ\\
&V_{d1} = V_s\angle -22.5^\circ, V_{d2} = V_s\angle -142.5^\circ, V_{d3} = V_s\angle -262.5^\circ
\end{aligned} \quad (2)$$

Input voltages for converter I are:

$$\begin{aligned}
&V_{a1} = K_1(V_{AB} - V_{CA}) - K_2V_{BC}\\
&V_{a2} = K_1(V_{BC} - V_{AB}) - K_2V_{CA}\\
&V_{a3} = K_1(V_{CA} - V_{BC}) - K_2V_{AB}
\end{aligned} \quad (3)$$

Input voltages for converter II are:

$$\begin{aligned}
&V_{b1} = K_3(V_{AB} - V_{CA}) - K_4V_{BC}\\
&V_{b2} = K_3(V_{BC} - V_{AB}) - K_4V_{CA}\\
&V_{b3} = K_3(V_{CA} - V_{BC}) - K_4V_{AB}
\end{aligned} \quad (4)$$

Input voltages for converter III are:

$$\begin{aligned}
&V_{c1} = K_3(V_{AB} - V_{CA}) + K_4V_{BC}\\
&V_{c2} = K_3(V_{BC} - V_{AB}) + K_4V_{CA}\\
&V_{c3} = K_3(V_{CA} - V_{BC}) + K_4V_{AB}
\end{aligned} \quad (5)$$

Input voltages for converter IV are:

$$\begin{aligned}
&V_{d1} = K_1(V_{AB} - V_{CA}) + K_2V_{BC}\\
&V_{d2} = K_1(V_{BC} - V_{AB}) + K_2V_{CA}\\
&V_{d3} = K_1(V_{CA} - V_{BC}) + K_2V_{AB}
\end{aligned} \quad (6)$$

$$V_{AB} = \sqrt{3}V_A\angle 30^\circ, V_{BC} = \sqrt{3}V_B\angle 30^\circ, V_{CA} = \sqrt{3}V_C\angle 30^\circ. \quad (7)$$

Constants K_1-K_4 are calculated using (2)-(7) to obtain the required windings turn numbers to have the desired phase shift for the four voltage sets:

$$K_1 = 0.3079, K_2 = 0.2209, K_3 = 0.3304, K_4 = 0.0753 \quad (8)$$

B. Design of Autotransformer for Retrofit Applications

The value of output voltage in multipulse rectifiers boosts relative to the output voltage of a six-pulse converter making the multipulse rectifier inappropriate for retrofit applications. For instance, with the autotransformer arrangement of the proposed 24-pulse converter, the rectified output voltage is 5% higher than that of six-pulse rectifier.

For retrofit applications, the above design procedure is modified so that the dc-link voltage becomes equal to that of six-pulse rectifier. This will be accomplished via modifications in the tapping positions on the windings as shown in Fig. 3. It should be noted that with this approach, the desired phase shift is still unchanged. Similar to section II part A, the following equations can be derived as:

$$|V_S| = 0.95|V_A| \quad (8)$$

Accordingly, the values of constants K1-K4 are changed for retrofit applications as:

$$K_1 = 0.2919, K_2 = 0.2094, K_3 = 0.3132, K_4 = 0.0714 \quad (9)$$

The values of K_1-K_4 establish the essential turn numbers of the autotransformer windings to have the required output voltages and phase shifts. To ensure the independent operation of the rectifier groups, interphase transformers (IPTs), which are relatively small in size, are connected at the output of the rectifier bridges. With this arrangement, the rectifier diodes conduct for 120 per cycle. [8]

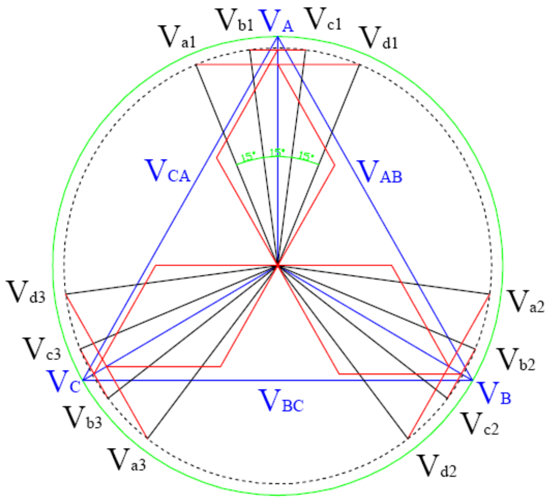

Fig.3 Phasor diagram of voltages in the proposed autotransformer connection alongwith modifications for retrofit arrangement.

The kilovoltampere rating of the autotransformer is calculated as [4]:

$$kVA = 0.5\sum V_{winding} I_{winding} \tag{10}$$

Where, $V_{winding}$ is the voltage across each autotransformer winding and $I_{winding}$ indicates the full load current of the winding. The apparent power rating of the interphase transformer is also calculated in a same way.

III. MATLAB-BASED SIMULATIONS

The implemented ac-dc converter with DTCIMD in MATLAB software using SIMULINK and power system block set (PSB) toolboxes. In this model, a three-phase 460 V and 60 Hz network is utilized as the supply for the 24-pulse converter. The designed autotransformer is modeled via three multi-winding transformers. Multi-winding transformer block is also used to IPT.

At the converter output, a series inductance (L) and a parallel capacitor (C) as the dc link are connected to IGBT-based Voltage Source Inverter (VSI). VSI drives a squirrel cage induction motor employing direct torque control strategy. The simulated motor is 50 hp (37.3 kW), 4-pole, and Y-connected. Detailed data of motor are listed in Appendix. Matlab block diagram of 24-pulse ac–dc converter system simulation, as shown in Fig. 4. Simulation results are depicted in Figs. 5-12. Power quality parameters are also listed in Table 1 for 6-pulse and 24-pulse ac-dc converters.

IV. RESULTS AND DISCUSSION

Fig. 5 depicts four groups of 3-phase voltage waveforms with a phase shift of 15 degrees between the same voltages of each group.

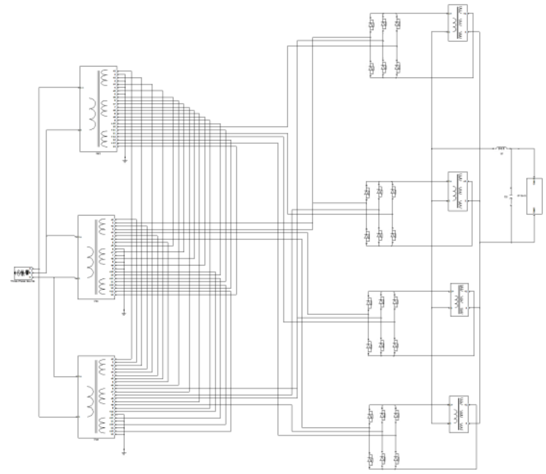

Fig. 4 Matlab block diagram of 24-pulse ac–dc converter system simulation.

The 24-pulse converter output voltage (shown in Fig. 6) is almost smooth and free of ripples and its average value is 607.1 volts which is approximately equal to the DC link voltage of a six-pulse rectifier (607.9 volts). This makes the 24-pulse converter suitable for retrofit applications.

Input current waveforms and its harmonic spectrum of the 6-pulseand 24-pulse converters extracted and shown in Figs. 7-10, respectively to check their consistency with the limitations of the IEEE standard 519. These harmonic spectra are obtained when induction motor operates under light load (20% of full load) and full load conditions. Obviously, for 6-pulse converter, fifth and seventh order harmonics are dominant.

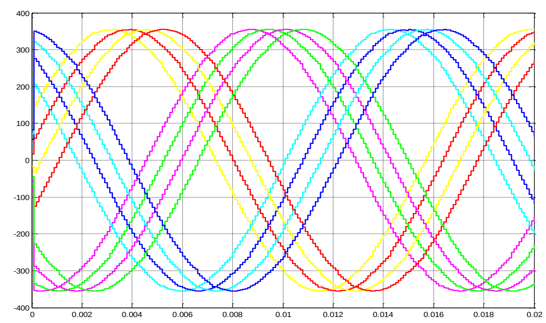

Fig. 5 proposed autotransformer output voltage.

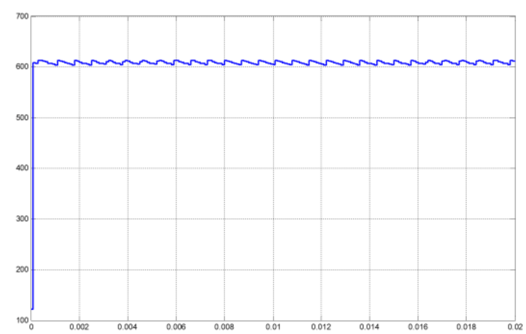

Fig. 6 24-pulse ac–dc converter output voltage.

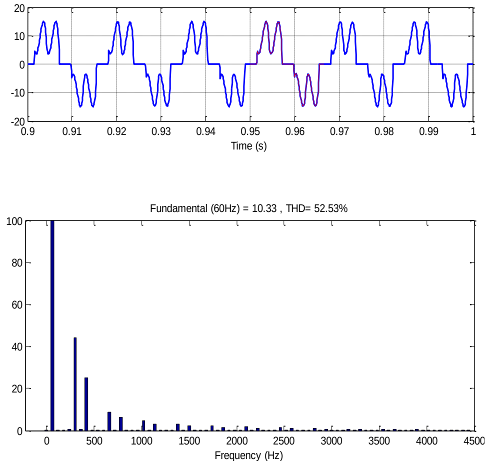

Fig. 7 Input current waveform of six-pulse ac–dc converter at light load and its harmonic spectrum.

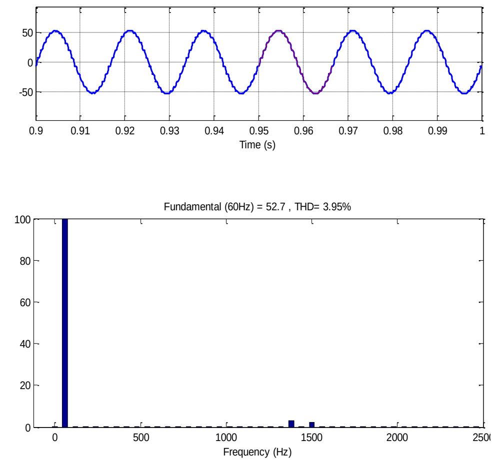

Fig. 10 Input current waveform of 24-pulse ac–dc converter at full load and its harmonic spectrum.

Hence, input current THD of this converter will be relatively a large amount and is equal to 28.53% and 52.52% for full load and light load conditions that are not within the standard margins. On the other hand, as shown in Figs. 9-10, 24-pulse converter has an acceptable current THD (5.85% for light load and 3.95% for full load conditions). In this configuration, low order harmonics up to 21st are eliminated in the supply current.

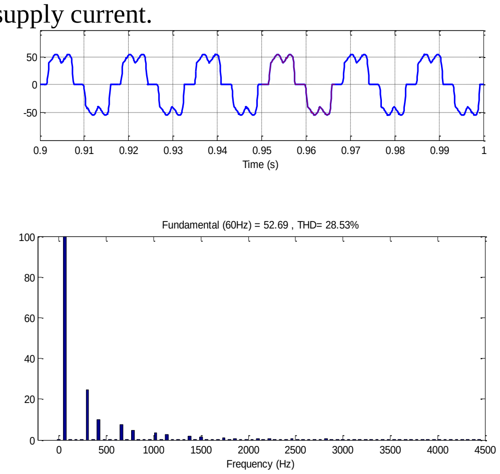

Fig. 8 Input current waveform of six-pulse ac–dc converter at full load and its harmonic spectrum.

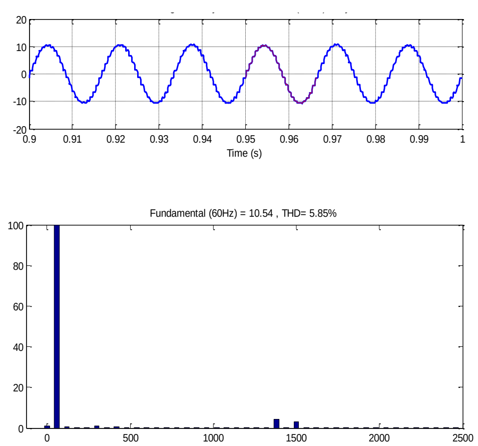

Fig. 9 Input current waveform of 24-pulse ac–dc converter at light load and its harmonic spectrum.

In general, the largely improved performance of the 24-pulse converter makes the power quality indices such as THD of supply current and voltage (THDi and THDv), displacement power factor (DPF), distortion factor (DF), and power factor (PF) satisfactory for different loading conditions. The aforementioned criteria are listed in Table 1 for the three types of converters.

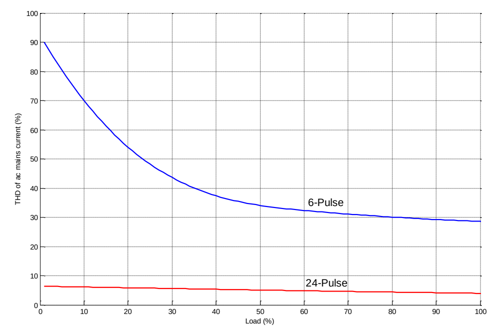

Fig 11 Variation of THD with load on DTCIMD in 6-pulse and 24-pulse ac-dc converter.

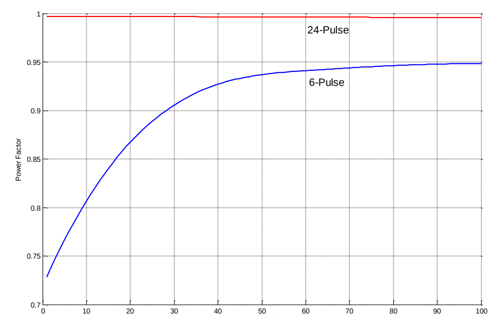

Fig. 12 Variation of power factor with load on DTCIMD in 6-pulse and 24-pulse ac-dc converter.

Input current THD and power factor variations are also shown in Figs. 11 and 12 respectively, for 6-pulse, and 24-pulse ac-dc converters. Results show that the input current corresponding to the proposed configuration has an almost unity power factor. Furthermore, in the worst case (light loads) the current THD has reached below 5% for the proposed topology.

Table 1 Comparison Of Simulated Power Quality Parameters of The Dtcimd Fed From Different Ac–Dc Converters.

Topology	% THD of V_{ac}	AC Mains Current I_{SA} (A)		% THD of I_{SA}, at		Distortion Factor, DF		Displacement Factor, DPF		Power Factor, PF		DC Voltage (V)	
		Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load
6-pulse	5.64	10.33	52.69	52.53	28.53	0.885	0.959	0.985	0.988	0.873	0.948	616.6	607.6
24-pulse	2.16	10.54	52.7	5.85	3.95	0.998	0.998	0.998	0.996	0.996	0.995	611.9	607.1

Different power quality indices of the proposed topology under different loading conditions are shown in Table 2. Results show that even under load variations, the 24-pulse converter has an improved performance and the current THD is always less than 5% for all loading conditions.

Table 2 Comparison of power quality indices of proposed 24-pulse ac-dc converter

Load (%)	THD (%)		CF of I_S	DF	DPF	TPF	RF (%)
	I_S	V_S					
20	5.85	1.03	1.412	0.9982	0.9984	0.9967	0.002
40	5.32	1.59	1.412	0.9985	0.9981	0.9965	0.006
60	4.82	2.15	1.413	0.9986	0.9975	0.9962	0.006
80	4.37	2.49	1.413	0.9987	0.9971	0.9959	0.003
100	3.95	2.87	1.413	0.9988	0.9966	0.9954	0.006

V. CONCLUSIONS

A novel zigzag-connected autotransformer was designed and modeled to make a 24-pulse ac-dc converter with DTCIMD load. Afterwards, the proposed design procedure was modified for retrofit applications. Simulation results prove that, for the proposed topology, input current distortion factor is in a good agreement with IEEE 519 requirements. Current THD is less than 5% for varying loads. It was also observed that the input power factor is close to unity resulting in reduced input current for DTCIMD load. In summary, the proposed 24-pulse ac–dc converter can easily replace the existing 6-pulse converter without much alteration in the existing system layout and equipment.

APPENDIX

Motor and Controller Specifications

Three-phase squirrel cage induction motor—50 hp (37.3 kW), three phase, four pole, Y-connected, 460 V, 60 Hz.

Rs = 0.0148 Ω; Rr = 0.0092 Ω; Xls = 1.14Ω; Xlr = 1.14 Ω, XLm = 3.94 Ω, J = 3.1 Kg · m2 .

Controller parameters: PI controller Kp = 300; Ki = 2000.

DC link parameters: Ld = 2 mH; Cd = 3200 μF.

Source impedance: Zs = j0.1884 Ω (=3%).

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