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Induction motor drive based on direct torque controlled used multi-pulse AC-DC rectifier

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Article Info	ABSTRACT
	This paper presents the direct torque-controlled induction motor drives (DTCIMDs) based on a retrofit 44-pulse rectifier (44PR). A 22-phase polygon autotransformer (PA) is designed to supply the rectifiers. The above structure improves the power quality standards in the power grid and complies with the requirements of the IEEE-519 standard for different loads. Besides, a power factor close to one is obtained for a wide range of DTCIMD performance. The results show that the total harmonic distortion (THD) of the input current under variable loads for 44PR is less than 3%.

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1. INTRODUCTION

Today, induction motor drive based on direct torque controlled (DTCIMDs) based on 6PR are used in several industrial applications [1]. The most important drawback of a 6PR used in DTCIMDs is the injection of the current harmonic into the grid. The value of current THD should be confined within the IEEE standard 519 [2] and the IEC 61000-3-2 [3]. To this end, researchers have focused on solutions to eliminate current THD such as the use of multipulse rectifiers (MPRs). These MPRs are based on phase-shifting transformers or pulse doubling circuits [4-7]. However, under low source impedance or low load, the current THD for MPRs up to 20 pulses will be more than 5% [8-14]. A 24PR based on polygon autotransformer has been reported in [15], which has a THD change from FL to LL from 4.48% to 5.65%. Another 24PR based on T autotransformer has also been reported in [16], in which current THD is more than 5% under a light load. It should be noted that some applications, such as sonar applications, require current THD less than 3%, and therefore the use of MPRs with pulses more than 24 is inevitable [17].

In order to reduce the THD of the ac main current, in [18-24] Authors have provided 20, 30, 36 and 40PRs, but these MPRs have high magnetic rating and high complexity. A 40PR based on T autotransformer has been reported in [25], which has a THD change from full load to light load from 2.55% to 3.79%. Another 40PR based on topology autotransformer has also been reported in [26], in which current THD is more than 3% under a light load. However, these topologies have high magnetic ratings and are therefore expensive.

Increasing the number of pulses reduces the current THD but with the additional complexity and cost of MPRs [27-33]. On the other hand, the use of passive or active filters can also lead to current THD reduction [34-40]. But passive filters lead to additional losses, and their efficiency is strongly influenced by frequency changes. Active filters are also very expensive and have a complex structure. Using MPRs is one of the most suitable methods for current THD reduction. In this paper, a DTCIMD based on 44PR is proposed with a novel polygon autotransformer to current THD reduction, as shown in Figure 1.
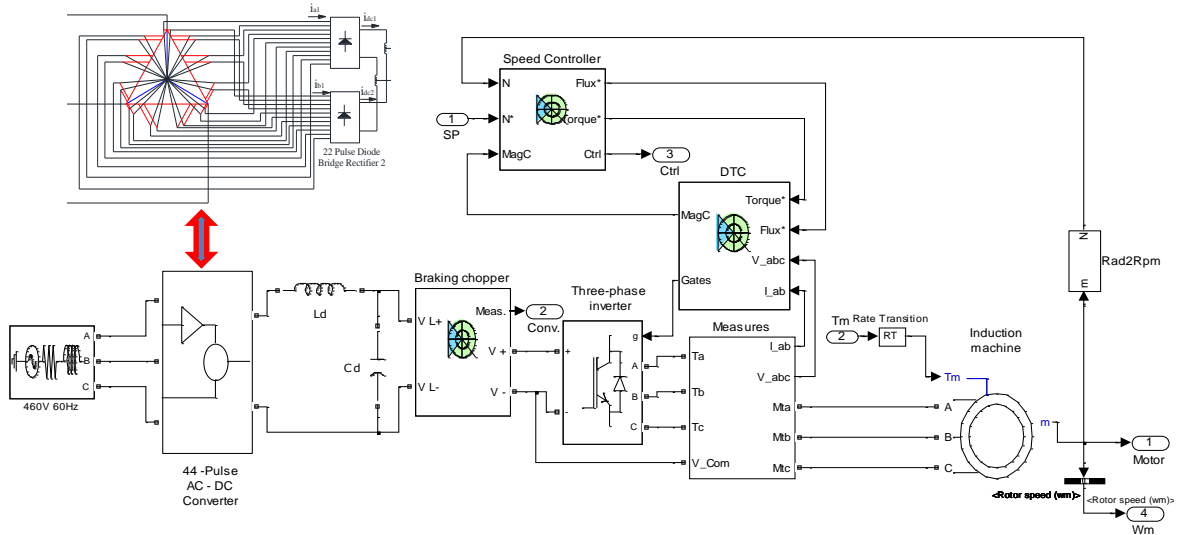

Figure 1. Proposed DTCIMD fed with 44PR

2. PROPOSED 44PR

In Figure 1, the DTCIMD fed with 44PR is presented. The proposed 44PR includes two 22PR, and an 11-phase polygon autotransformer, and two IPT. The main task of the autotransformer is to produce two series of 11-phase voltage with a phase shift of 8.18 degrees. However, the main task of the IPT in this configuration is to guarantee that the voltages of the two 11-phase autotransformer's outputs are operating independently. In Figure 2 the phasor diagram of the 11-phase autotransformer for the 28-pulse rectifier is depicted. The harmonics are eliminated with a minimum phase displacement of 8.18°. Two sets of 7 phases with the phase shift of 4.09° are generated by the 11-phase autotransformers for each bridge. The two sets of the 11-phase autotransformer output voltage are connected to the 22PR. We assume (V_{a1} to V_{a11}) and (V_{b1} to V_{b11}) for the first and second rectifiers, the three-phase voltages of primary windings and voltage of the 11 phases applied to the windings is assumed to be as follows:

$$V_A = V_s\angle 0° V_B = V_s\angle - 120°, V_C = V_s\angle 120°. \qquad (1)$$

Input voltages for two 22PRs are:

$$V_{a1} = V_s\angle + 4.09°, V_{a2} = V_s\angle - 28.637°, V_{a3} = V_s\angle - 61.364°,$$
$$V_{a4} = V_s\angle - 94.091°, V_{a5} = V_s\angle - 126.818°, V_{a6} = V_s\angle - 159.545°,$$
$$V_{a7} = V_s\angle - 192.272°, V_{a8} = V_s\angle - 224.999°, V_{a9} = V_s\angle - 257.726°, V_{a10} =$$
$$V_s\angle - 290.453°, V_{a11} = V_s\angle - 323.18°. \qquad (2)$$

$$V_{b1} = V_s\angle - 4.09°, V_{b2} = V_s\angle - 36.817°, V_{b3} = V_s\angle - 69.544°,$$
$$V_{b4} = V_s\angle - 102.271°, V_{b5} = V_s\angle - 134.998°, V_{b6} = V_s\angle - 167.725°,$$
$$V_{b7} = V_s\angle - 200.452°, V_{b8} = V_s\angle - 233.179°, V_{b9} = V_s\angle - 265.906°,$$
$$V_{b7} = V_s\angle - 298.633°, V_{b8} = V_s\angle - 331.36°. \qquad (3)$$
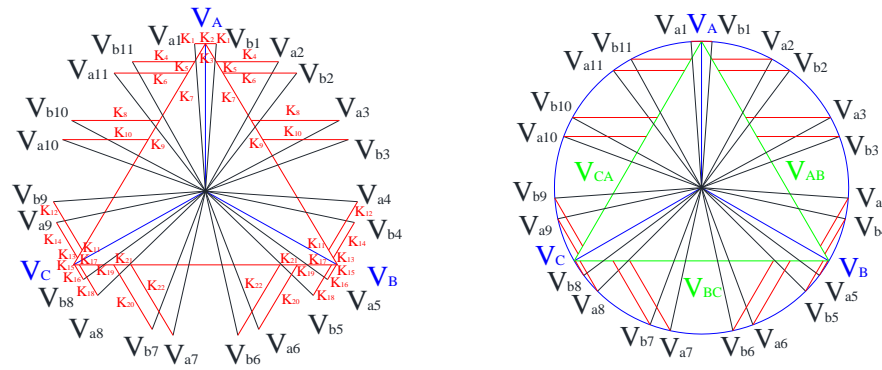
Figure 2. Phasor diagram and representation of 11-phase autotransformer for proposed 44PR

In the 44PR, the output voltage is 20% higher than the traditional rectifier with six-pulse. Therefore, to use for retrofit applications it is necessary to decline the output voltage to 20% through the recalculation of the number of winding. Accordingly, the number of turns of the 11-phase autotransformer winding for retrofit applications is modified as K_1 to K_{22} is equal to 0.11, 0.09, 0.18, 0.13, 0.22, 0.17, 0.40, 0.21, 0.47, 0.21, 0.17, 0.12, 0.14, 0.07, 0.11, 0.01, 0.13, 0.05, 0.24, 0.18, 0.29, and 0.20.

3. SIMULATION USING MATLAB/SIMULINK

The multi-winding transformer block in Simulink/Matlab software is utilized to evaluate the performance of the proposed 44PR configuration as shown in Figure 3. The three-phase input voltage' value is 460/60 Hz and the motor is 4-pole and 50 hp. Also, detailed information on DTCIMD is listed in the appendix.
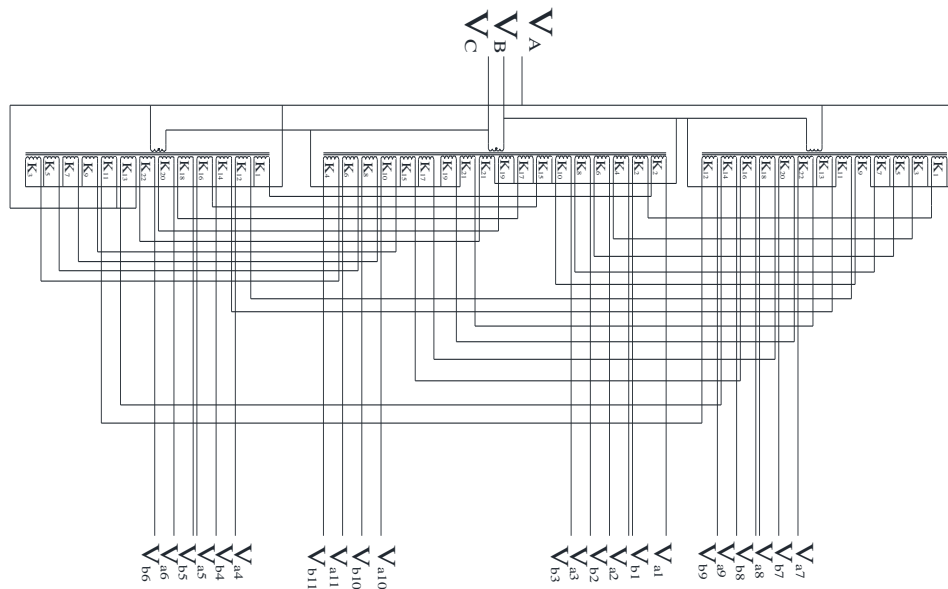

Figure 3. Simulink model of proposed 11-phase autotransformer winding

4. STUDY VALIDATION

The 44PR Simulink diagram is shown in Figure 4. The simulation results are shown in Figures 5-9. The output voltage of the 11-phase autotransformer with an 8.18° phase shift is shown in Figure 5(a). The 44PR output voltage is shown in Figure 5(b). It should be noted that this 44PR is suitable for retrofit applications. Because the average output voltage of the proposed 44PR is 609 V, and is equal to the average output voltage of a 6PR (608 V). The dynamic response of DTCIMD based on 6PR and proposed 44PR are

shown in Figures 6(a)-(b) respectively. The input current and harmonic FFT of 6PR and 44PR are shown in Figures 7-8, respectively to check their compliance with the standard limitations. Finally, the 44PR offers excellent performance in improving power quality indicators under FL and LL conditions.
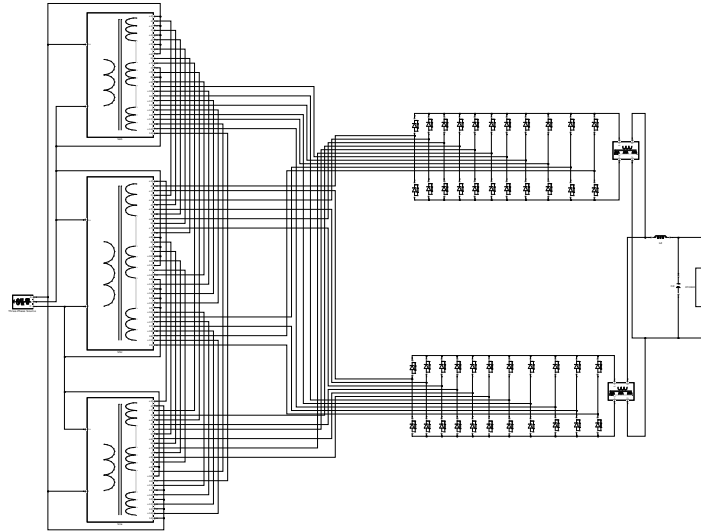
Figures 4. The Simulink 44PR block diagram
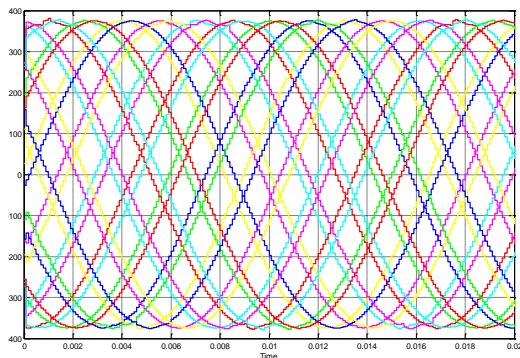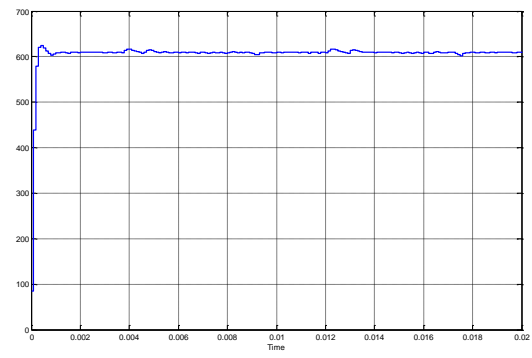
(a)   (b)

Figure 5. The output voltage of, (a) 11-phase autotransformer, (b) 44PR

(a)   (b)

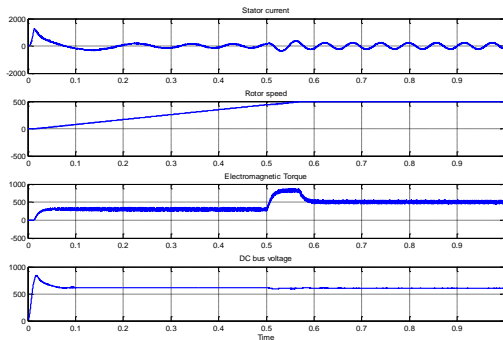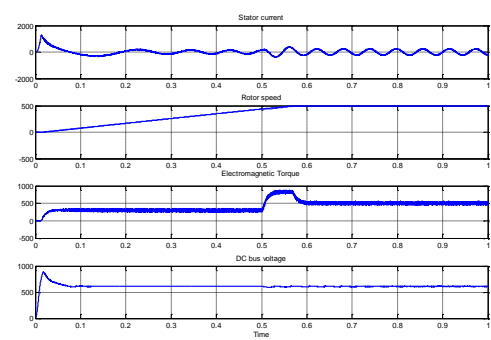Figure 6. Dynamic response of DTCIMD based on, (a) 6PR, (b) Proposed 44PR

As shown in Figure 7, the current THD of the 6PR is very high, equal to 28.53% at full load (FL) and 52.52% at light load (LL), which is outside the standard limit. As shown in Figure 8, in proposed 44PR, at FL the current THD is 1.89% and the power factor is 0.9971, and at LL, the THD current is 2.97% and the power factor is 0.9965. This confirms that the current THD proposed 44PR is always less than 3% and is suitable for sonar applications. The power quality indicators for 6PR, 40PR [25], 40PR [26], and 44PR are listed in Table 1. The 40PR based on T and polygon autotransformer for reducing current THD has been reported in [25] and [26] respectively. But in these topologies under light load conditions, the current THD is more than 3%.
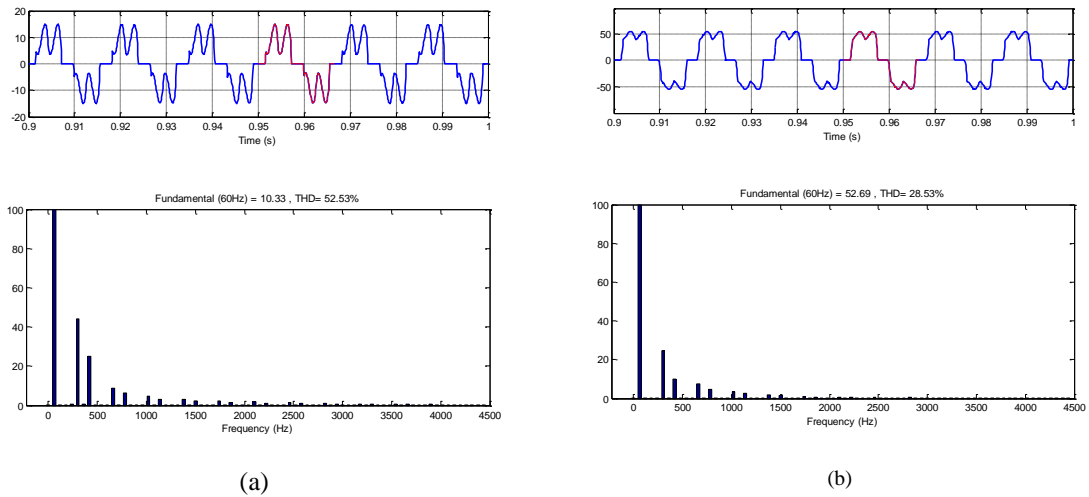

(a)   (b)

Figure 7. The input current and harmonic FFT of 6PR, (a) under light, (b) full light

(a)   (b)
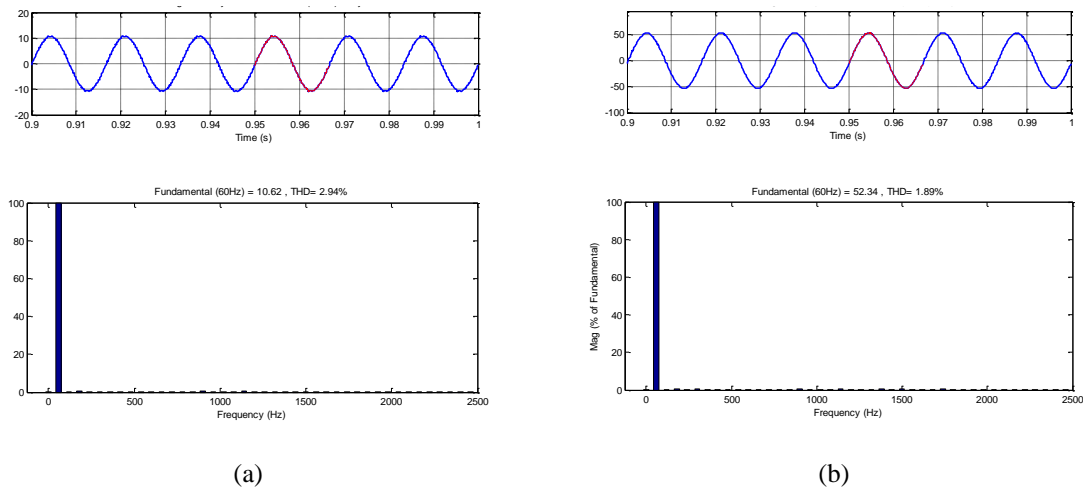
Figure 8. The input current and harmonic FFT of 44PR under (a) under light, (b) full light

Table 1. Evaluation of power quality indicators from DTCIMD fed with 6PR, 40PR [25], 40PR [26], and proposed 44PR

No	Structured	% THD of AC voltage	AC current (A)	%THD of AC current		Distortion factor		Displacement factor		Power factor		DC voltage	
				Light load	Full load	Light load	Full load	Light load	Full load	Light load	Full load	Light load	Full load
1	6PR	5.63	10.25	52.56	52.80	28.52	0.959	0.985	0.988	0.872	0.948	616.6	607.9
2	40PR [25]	2.57	10.51	52.59	3.79	2.55	0.999	0.999	0.999	0.998	0.998	610.5	607.5
3	40PR [26]	3.138	10.51	52.59	3.851	2.226	0.999	0.997	0.999	0.998	0.998	695.3	680.5
4	Proposed 44PR	1.68	10.62	53.34	2.94	1.89	0.999	0.997	0.997	0.996	0.997	613.1	609.1

Table 2 shows the effect of the load change on different power quality indicators. Also, the current THD and power factor variation for 6PR and 44PR are shown in the Figure 9. The results show that under different load conditions, the current THD is always less than 3% and the power factor is always higher than 0.99 for the proposed 44PR.

Table 2. The effect of load change on power quality indices of proposed PR

Load (%)	THD (%)		CF of Is	DF	DPF	PF	RF (%)	Vdc (V)
	Is	Vs						
20	2.94	0.72	1.413	0.9987	0.9978	0.9965	0.002	613
40	2.44	1.08	1.413	0.9994	0.9977	0.9971	0.003	612
60	2.20	1.27	1.414	0.9996	0.9976	0.9972	0.005	611
80	2.03	1.51	1.414	0.9997	0.9974	0.9971	0.002	610
100	1.89	1.68	1.414	0.9997	0.9974	0.9971	0.005	609

(a)   (b)
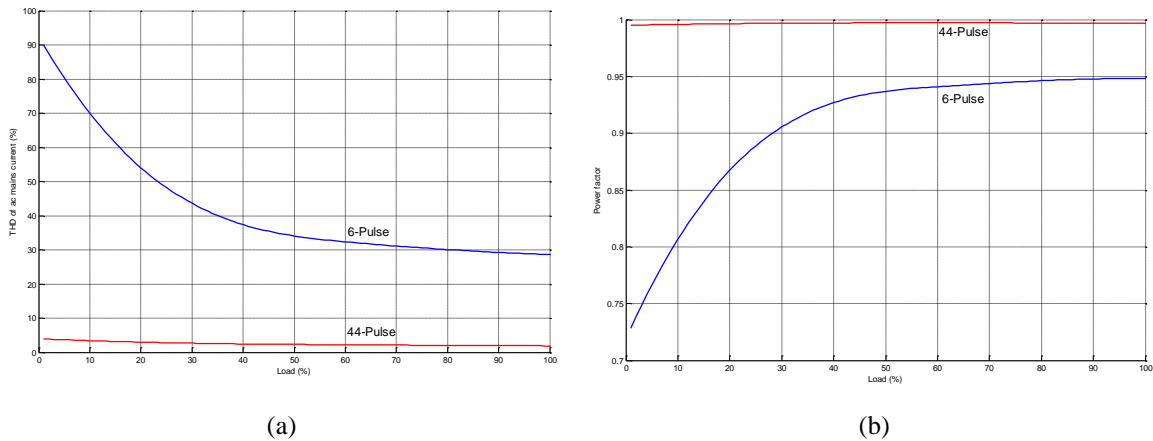
Figure 9. (a) The current THD, (b) Power factor variation for 6PR and 44PR

The kVA rating of the components in the 44PR is calculated as [4]:

$$kVA = 0.5\sum V_{winding} I_{winding} \tag{4}$$

where $V_{winding}$ and $I_{winding}$ indicate the full load voltage and current of the winding. The kVA ratings of the 11-phase autotransformer and interphase transformer (IPT) are 42.57% and 0.45% of the load rating. It should be noted that to current THD <3%, the 44PR requires 43.02% of the load rating. This rating is lower than many other MPRs. Table 3 shows a comparison of the 44PR with the 40PR [25] and the 40PR [26] in terms of the kVA rating and the price of the. The estimated price is 5 times the kVA rating of the autotransformer. The results show that the proposed 44PR costs less than 40PRs [25-26]. Also, at full load, the efficiency of the proposed 44PR is 97.8%.

Table 3. Comparison of kVA rating and cost in 40PR [24], 40PR [25], and proposed 44PR

System configuration	Magnetic ratings kVA rating of autotransformer (% of load)	ZSBT kVA rating	IPT kVA rating	Sum kVA rating	Diodes number	Estimated price ($)
40PR [24]	61.29	2.15	0.54	63.98	42	413.56
40PR [25]	53.72	2.83	0.71	57.26	42	379.96
Proposed 44PR	42.57	-	0.45	43.02	44	310.99

5. CONCLUSION

This paper presents a DTCIMD based on 44PR. The 44PR consists of an 11-phase retrofit autotransformer. The results show that the current THD at various load is less than 3% and the power factor is higher than 99%. Also, the kVA rate and the cost of the proposed 44PR are lower than similar MPRs. In

summary, reducing the input current THD, increasing the power factor along with the lower kVA rate and lower cost are the main advantages of the proposed 44PR.

APPENDIX

DTCIMD Specifications

Source impedance : Z_s = 3%.

Induction motor   : R_s = 0.0148 Ω; R_r = 0.0092 Ω; X_{ls} = 1.14Ω; X_{lr} = 1.14 Ω, X_{Lm} = 3.94 Ω, J = 3.1 Kg· m^2.

Controller   : K_i = 2000, K_p = 300.

DC link   : C_d = 3200 μF, L_d = 2 mH.

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