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Comparison of Three Autotransformer Based 24-Pulse AC-DC Converters Incorporated DC Ripple Reinjection Technique Feeding VCIMD and DTCIMD Loads

***Abstract.** In this paper, the comparison of star, polygon and zigzag connected autotransformer based 24-pulse AC-DC converters has been presented. They are12-pulse rectifiers incorporated pulse doubling DC ripple re-injection technique supplying VCIMD or DTCIMD load. Simulation results indicate that lower capacitances result in more deterioration in power quality indices at ac mains. In this case, VCIMD has a bitter impact than DTCIMD. Also, using polygon and star connection autotransformers result in lower voltage and current distortions respectively.*

***Streszczenie.** Przedstawiono porównanie 24-pulsowego przekształtnika AC-DC z autotransformatorem połączonym w gwiazdę, zygzak lub wielokąt. Obciążeniem jest silnik indukcyjny w konfiguracji VCIMD i DTCIMD. Symulacje pokazały, że otrzymuje się bardzo małe zakłócenie jakości napięcia. (**Porównanie trzech przekształtników 24-pulsowych z autotransformatorem o różnym połączeniu**)*

Keywords: Autotransformer Based Multipulse Converters, DC Ripple Reinjection Technique, VCIMD & DTCIMD, Impact of DC Link Capacitance.
Słowa kluczowe: przekształtnik wielopulsowy, .autotransformator.

Introduction

Nowadays, electrical machines are the preferred prime mover of many applications. Among them, squirrel cage induction motors are the rugged, reliable, maintenance free, and economic ones. Today with the development of semiconductor knowledge, these motors are controlled in variable frequency mode. The use of these variable frequency induction motor drives (VFIMDs) as solid-state converters has been vastly grown in various applications, i.e. heating, lighting, pumps, fans, blowers, and etc. [1].

Their power supply is usually a 6-pulse diode bridge rectifier which injects harmonic currents into ac mains, resulting in equipment overheating and low rectification efficiency [1]. The growing use of them has reached to a point that became a serious problem due to their harmonic distortions. Thus an IEEE Standard 519 [2] was reissued in 1992 providing limitations for current and voltage distortions.

The two mostly used VFIMD techniques are Vector control and direct torque control [3]. The direct torque control drive technique is an easy to deploy, reliable and low cost technique compared to the other one. But vector control drive technique is capable of controlling the induction motor similar to a dc motor having independent signals for flux and torque control resulting in a smoother operation and better performance of it.

To diminish the injected harmonics, active and passive waveshaping techniques has been used. These techniques have their design complexity, higher losses, overall cost and some unwanted side effects.

Multipulse methods yet have been proven to be rugged, reliable and cost-effective solution to diminish these distortions. The main idea is to use multiple converter bridges in a manner that they draw currents with a phase variance which results in cancellation of certain harmonics in AC mains. Thus sets of 3 phase voltages are needed which can be produced using transformers and autotransformers [4].

Although they do not isolate the input and output, and outputs from each other, autotransformers have proven to be better choices. Use of them result in lower cost, volume, and magnetic ratings as they transfer only a small portion of the total kVA of the load [4].

It has been proven that with higher number of pulses, there is more improvement in power quality indices. But this usually result in larger magnetics, higher number of bridges therefore higher cost of the drive [4].

DC ripple reinjection technique has been introduced in [5], [6] for pulse multiplication and harmonic current reduction. With this technique similar performance of higher numbers of pulses is achieved with reduction in magnetics, volume and overall cost of the drive. Such configuration has also been reported in [7-9].

The zigzag connection of autotransformer has been introduced in [7] for a 36-pulse AC-DC converter using controlled rectifier bridges. But star and polygon connected autotransformer based 24-pulse AC-DC converters introduced in [8] and [9] respectively are comprised of incorporation of DC ripple reinjection technique in a 12-pulse AC-DC converter for pulse doubling.

Therefore, to have a better comparison, the zigzag connection of autotransformer has been used for a 24-pulse AC-DC converter incorporating DC ripple reinjection technique in a 12-pulse AC-DC converter for pulse doubling like [8] and [9].

In [7] the proposed converter feeds an R-L load, in [8] and [9] it feeds VCIMD load. In this paper for investigating the power quality at AC mains of each converter topology and to compare their simulation results, both type of VFIMDS loads: VCIMD and DTCIMD have been used.

In [7-9] the DC link capacitance was 2200 μF which prevents any load disturbances from occurring at AC mains. In this case the there will be no differences in power quality indices using different kind of VFIMD loads. Thus to investigate more, the simulations have been done with different capacitances: 200 and 800 2200 μF to measure the disturbance each load creates at AC mains in form of power quality indices. The 2200 μF capacitance has been chosen to have a better comparison with the results achieved in [7-9]. The induction motor used is also a 20-hp motor to have the same criteria as that of [8, 9].

Rectifiers have been simulated using Matlab software. The simulation results show that using the 24-pulse AC-DC converters, power-quality indices will be achieved complying with IEEE Standard 519. Moreover, the load on the VCIMD and DTCIMD has been varied to study its effect on the power quality indices. The results have been tabulated for comparing different power-quality indices in the operation range.

Total harmonic distortion (THD) and total demand distortion (TDD) of voltage and current, crest factor (CF) of current, total power factor (TPF), displacement power factor (DPF), distortion factor (DF) at the point of common coupling (PCC) is presented for the 6, 12 and 24-pulse AC–DC converters in case of feeding the VCMD or DTCIMD load with different DC link capacitances.

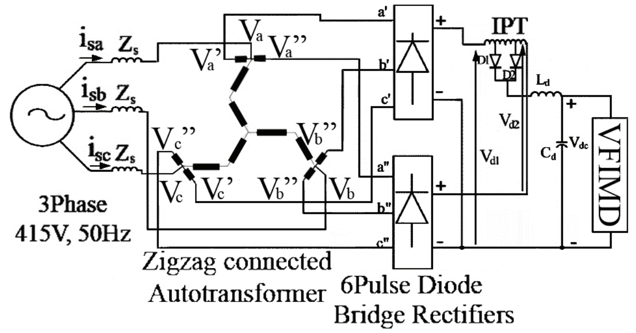

Fig.1. zigzag connected autotransformer based 24-pulse AC-DC converter with VFIMD load

12-Pulse AC–DC Converters

As mentioned in [4, 8, 9] for achieving 12-pulse rectification, the autotransformer is designed to produce two sets of 3phase voltages with +15° and -15° phase variances with respect to the supply voltages are needed.

Fig. 1 shows the schematic diagram of the zigzag connected autotransformer for producing the foretold voltages in the 24-pulse rectifier circuit. The design of this autotransformer is presented in [7]. The connection diagram and design of the star and polygon connections of the autotransformers and the schematic circuit diagram of their rectifiers are introduced in [8] and [9] respectively.

It must be denoted that the mentioned star and polygon connections do have the flexibility to adjust the input per output voltage ratio. It makes it possible to adjust the resulting DC link voltage amplitude to make the scheme suitable for retrofit applications where presently a 6-pulse diode bridge rectifier is used. But the mentioned zigzag connection does not have this flexibility, resulting in higher DC link voltage amplitude than that of a 6-pulse diode bridge rectifier. It makes the scheme using this connection of autotransformer unsuitable for retrofit applications.

Design of Autotransformers for Retrofit Applications

To have a realistic approach in simulation of the circuit of AC-DC converters, the circuit loses has been considered in simulations. The loses like the voltage drop over semiconductor devices, winding's leakage inductances and resistances, and also the capacitor leakage current and R-C snubber's current.

Thus the Vo/Vi ratio of the autotransformer must be calculated to overcome these loses resulting in the same DC link voltage amplitude as that of a 6-pulase diode bridge rectifier.

Furthermore winding's leakage inductances will change the phase shift of the output voltages of the Autotransformer, reducing the 30 degree phase variance needed for 12-pulse rectifications. Thus the design parameters of the autotransformer must be recalculated to change the phase shifts to achieve the required phase variance.

The required V_o/V_i ratio and phase shift for each autotransformer connection along with its winding parameters are discussed in simulation section.

DC Ripple Reinjection Technique

The DC ripple reinjection technique has been characterized in [5] and its pulse doubling state is presented in [6]. Using higher number of pulses will result in better power quality indices but with higher overall cost. In this paper, the power rating of the load (15kW) is so that the power quality indices complying with IEEE standard 519 will be achieved at AC mains with 24-pulse rectification. Thus it is more economic to use this number of pulses for the application as higher number of pulses will have higher overall cost of the drive.

Therefore in this paper, 24-pulse rectification has been achieved using pulse doubling state of this technique to double the number of pulses of 12-pulse AC-DC converters as done in [8, 9].

The pulse doubling state of the DC ripple reinjection technique uses only two diodes which are connected to each tap of an interphase transformer (IPT). Thus the IPT design must be changed in order to have two taps. Using diodes there will be no need to use extra control systems thus the pulse doubling will depend on the position of IPT taps. This results in its easy implantation and lower overall cost of the drive [6-9].

Vector controlled and Direct Torque Controlled Induction Motor Drives (VCIMD & DTCIMD)

Vector control drive technique is capable of controlling the induction motor similar to a dc motor having independent signals for flux and torque control. This results in reliable, smooth operation and good performance of the drive [3]. The design and simulation block diagram used - for VCIMD - in this paper is presented in [7-9].

Also to achieve acceptable performance with low cost of the drive, simplicity to implement, the induction motor drive is done using direct torque control technique [3]. The design and simulation block diagram used - for DTCIMD - in this paper is presented in [10].

MATLAB Based Simulation

Simulation of the AC-DC converters has been done using SimPowerSystem blockset (PSB) toolboxes in simulink environment of MATLAB software.

Simulation of the Autotransformers for 12-pulse rectification

The autotransformers have been designed using tree single phase shell type 8B. E-I core [11] core and been simulated using mutual inductance block.

The e.m.f. per turn of the mentioned core must be calculated to find the number of turns each winding should have [12]:

$$V_{winding} = T*E_f = T*4.44*f*B_m*A_i \quad (1)$$

where Ef is e.m.f. per turn of the core (V), f is the frequency of supply (Hz), Bm is the maximum value of the flux density in the core (Tesla), Ai is the net cross sectional area of the core (m2), T is the number of winding turns (Turns) and Vwinding is the voltage across each winding (V).

- Zigzag connected autotransformer:

The core thickness used is 84 mm. This connection of autotransformer does not have the flexibility of changing its voltage gain. Thus this connection topology makes the entire scheme not suitable for retrofit applications. But as mentioned before, to produce the required 30° phase variance the phase shift must be 15.15°.

Using equation (1) and 15.15° phase shift, number of winding turns will be calculated as follows:

$N_1 = N_2$ (winding ratio k_2) = 94 Turns

$N_3 = N_4$ (winding ratio k_1) = 44 Turns

- Star connected autotransformer:

The core thickness used is 99 mm. It has been realized from simulations that, 1.035 voltage gain and 15.25° phase shift will be needed. Using equation (1), V_o/V_i = 1.035 and 15.25^o phase shift, number of winding turns will be calculated as follows:

N_1 (winding ratio 1-k_1) = 22 + (2/3) Turns

N_2 (winding ratio k_1) = 120 + (1/3) Turns

N_3 = N_4 (winding ratio k_2) = 45 Turns

- Polygon connected autotransformer:

The core thickness used is 99 mm. A voltage gain of 1.027 and a phase shift of 15.22^o will be needed. Using equation (1), V_o/V_i = 1.027 and 15.22^o phase shift, number of winding turns will be calculated as follows:

N_1 = N_3 (winding ratio k_2) = 1.5 Turns

N_2 (winding ratio N-2k_2) = 207 Turns

N_4 = N_5 (winding ratio k_1) = 38 Turns

Simulation of the IPT for 12-pulse rectifications

The interphase transformer has been designed using a single phase shell type 33No. E-I core [11] with 40 mm thickness. To prevent the transformer from saturation due to being used on the DC side of the rectifier, an air gap of 0.1 mm has been considered between the connecting points of E and I laminations of its core. It has been simulated using multi-winding transformer as it has 2 identical windings. Using equation (1) the number of winding turns will be calculated as: N_1 = N_2 = 46 Turns

Simulation of the Autotransformers for 24-pulse rectifications

The core used for the autotransformer of 24-pulse AC-DC converters is an 8No. E-I core [11].

- Zigzag connected autotransformer:

The design and simulation parameters are as mentioned earlier for 12-pulse rectifications. It is due to lack of flexibility to changing voltage gain ratio of the connection topology of the autotransformer.

- Star connected autotransformer:

The core thickness used is 89 mm. A voltage gain of 1.017 and a phase shift of 15.2o will be needed. Using equation (1), V_o/V_i = 1.017 and 15.2^o phase shift, number of winding turns will be calculated as follows:

N_1 (winding ratio 1-k_1) = 27.5 Turns

N_2 (winding ratio k_1) = 131.5 Turns

N_3 = N_4 (winding ratio k_2) = 49 Turns

- Polygon connected autotransformer:

The core thickness used is 85 mm. A voltage gain of 0.998 and a phase shift of 15.1^o will be needed.

Using equation (1), V_o/V_i = 0.998 and 15.1^o phase shift, number of winding turns will be calculated as follows:

N_1 = N_3 (winding ratio k_2) = 7 Turns

N_2 (winding ratio N-2k_2) = 249 Turns

N_4 = N_5 (winding ratio k_1) = 40 Turns

Simulation of the IPT for 24-pulse rectifications

The interphase transformer has been designed using a single phase shell type 33No. E-I core [11] with 17 mm thickness. It has been simulated using mutual inductance block. To prevent the transformer from saturation due to being used on the DC side of the rectifier, an air gap of 0.1 mm has been considered between the connecting points of E and I laminations of its core. Using equation (1) and K = 0.2457 (the DC ripple reinjection technique tap position ratio [6]), the number of winding turns will be calculated as follows:

N_1 = N_3 (winding ratio 0.5-K) = 17 Turns

N_2 (winding ratio 2K) = 33 Turns

Simulation of the ZSBT for 24-pulse rectifications

The zero sequence block transformer has been designed using a single phase shell type 3No. E-I core [11] with 30 mm thickness. It has been simulated using multi-winding transformer block as it has 4 identical windings. To prevent the transformer from saturation due to being used on the DC side of the rectifier, an air gap of 0.1 mm has been considered between the connecting points of E and I laminations of its core. Using equation (1), the number of winding turns will be calculated as follows:

N_1 = N_2 = N_3 = N_4 = 53 Turns

Compared to 12-pulse AC-DC converters, 24-pulse AC-DC converters have less ripple amplitude in the output DC voltage, resulting in higher average of DC voltage amplitude. Therefore 24-pulse rectification needs lower voltage gain than 12-pulse rectification as being seen from the needed voltage gain ratios in this section. Furthermore for 24-pulse AC-DC converters, less phase shift would be needed to achieve the required 30^o phase variance (needed for 12 pulse rectification) than 12-pulse AC-DC converters.

Results and Discussion

The simulation results of the conventional 6-pulse, 12 and 24-pulse AC-DC converters consisted of autotransformers with zigzag, star or polygon connection are shown in table1. These results are tabulated in case of using 2200, 800 and 200 μF DC link capacitances and load variations from light load (20%) to full load (100%) on induction motor in 20% steps. These results show that the THD of AC mains current of 6-pulse diode bridge rectifier in operational range is so high which do not comply with IEEE standard 519. Thus indicating that improving the power quality of AC mains at PCC is essential.

This table shows that using 12-pulse AC-DC converters, lower AC mains current THDs are achieved than the 6-pulse AC-DC converters in case of feeding both VFIMDs and even with different DC link capacitances. Furthermore the TPF have also been improved.

Using 24-pulse AC-DC converters there will be even more improvements in current and voltage THDs using both VFIMDs and different DC link capacitances. Furthermore the TPF is almost unity in the wide range of the drive operation.

THD index measures the ratio of the harmonic current to its own main component. Thus it is not a good index in case of comparing the measure of distorted currents in different systems. To do so, the amplitude of distorted currents of different systems must be measured to one common reference current. Therefore TDD is the right power quality index suitable to do the task. The reference value assumed for TDD of AC mains current and voltage are the highest current value 31.95 (A) and the lowest voltage value 232 (V) derived from the simulations.

As shown in table 1, the power quality indices achieved in for the simulations of 24-pulse AC-DC converters comply with the IEEE standard 519 for SCR>20 in case of using 2200 and 800 μF DC link capacitances.

The current TDD of AC-DC converters in case of feeding VCIMD or DTCIMD with 2200, 800 and 200 μF DC link capacitances are shown in fig. 2. These curves show that reducing the load will result in decrease of current TDD.

It can be realized from table 1 that using polygon connection, there will be more reduction in the voltage distortions than star connection. This is due to the use of line voltage amplitude on the windings of the polygon connected autotransformer which is √3 times the phase voltage to produce the output voltages. The star connected autotransformer uses the phase voltage on its windings for this purpose.

Table 1. Power Quality Indices Derived from Simulation Results of AC-DC converters in case of 2200, 800 and 200 µF DC link capacitances, feeding VCIMD or DTCIMD under load variation (Z: AC-DC converter using zigzag connected autotransformer, S: AC-DC converter using Star connected autotransformer, P: AC-DC converter using Polygon connected autotransformer)

			VCIMD											DTCIMD										
DC link capacitance	Pulse #	Load (%)	V_S (V)	THD V_S (%)	TDD V_S (%)	I_S (A)	THD I_S (%)	TDD I_S (%)	Crest Factor of I_S	Distortion Factor (DF)	Displacement Power Factor (DPF)	Total Power Factor (TPF)	DC link Voltage (V)	V_S (V)	THD V_S (%)	I_S (A)	THD I_S (%)	TDD I_S (%)	Crest Factor of I_S	Distortion Factor (DF)	Displacement Power Factor (DPF)	Total Power Factor (TPF)	Total Power Factor (TPF)	DC link Voltage (V)
2200 µF	6	20	238.8	3.89	4.00	7.10	66.07	14.69	1.178	0.8322	0.9771	0.8131	557.2	238.8	3.84	3.95	7.206	65.56	14.78	1.184	0.8358	0.9772	0.8167	557.1
		100	236.8	7.78	7.94	25.04	32.40	25.39	1.345	0.9477	0.9826	0.9312	546.2	236.8	7.54	7.69	25.16	32.39	25.50	1.345	0.9475	0.9820	0.9304	546.1
	12 Z	20	237.4	2.74	2.80	6.770	10.36	2.19	1.403	0.9917	0.8836	0.8769	571.7	237.4	2.79	2.85	6.821	10.31	2.18	1.406	0.9936	0.8855	0.8799	571.6
		100	234.6	7.13	7.20	24.66	8.32	6.45	1.409	0.9939	0.9731	0.9671	557.4	234.6	7.10	7.17	24.81	8.32	6.45	1.409	0.9939	0.9732	0.9672	557.3
	12 S	20	236.6	3.42	3.49	7.77	31.96	7.77	1.343	0.9489	0.8214	0.7794	596.0	236.6	3.27	3.33	7.816	30.25	7.40	1.352	0.9555	0.8239	0.7872	597.0
		100	232.4	6.75	6.76	25.67	8.05	6.47	1.409	0.9939	0.9508	0.9451	547.2	232.0	6.14	6.14	26.24	7.97	6.54	1.410	0.9947	0.9378	0.9328	547.1
	12 P	20	236.6	3.29	3.35	7.746	30.29	7.34	1.348	0.9523	0.8164	0.7774	590.9	236.6	3.31	3.37	7.819	29.81	7.29	1.354	0.9565	0.8176	0.7820	590.1
		100	232.4	6.71	6.72	25.68	7.98	6.41	1.409	0.9944	0.9443	0.9390	547.6	232.3	6.59	6.59	25.85	7.97	6.45	1.410	0.9945	0.9444	0.9392	547.4
	24 Z	20	237.4	1.98	2.02	6.721	9.89	2.08	1.406	0.9936	0.8948	0.8891	586.6	237.4	1.99	2.03	6.790	9.87	2.09	1.406	0.9940	0.8965	0.8911	586.4
		100	234.2	4.35	4.39	24.61	4.03	3.10	1.413	0.9982	0.9725	0.9708	567.9	234.2	4.36	4.40	24.78	4.05	3.14	1.413	0.9982	0.9728	0.9710	567.8
	24 S	20	237.3	1.90	1.95	6.747	10.02	2.10	1.403	0.9924	0.8889	0.8820	572.4	237.3	1.91	1.95	6.806	9.95	2.11	1.405	0.9933	0.8901	0.8841	572.2
		100	233.8	4.26	4.29	24.89	4.43	3.44	1.413	0.9980	0.9719	0.9700	548.3	233.8	4.26	4.29	25.08	4.42	3.47	1.413	0.9981	0.9720	0.9702	548.1
	24 P	20	238.4	1.26	1.29	5.346	12.63	2.11	1.403	0.9917	0.8544	0.8474	568.4	238.3	1.40	1.44	6.714	10.99	2.31	1.404	0.9930	0.8931	0.8869	565.7
		100	236.4	3.29	3.35	23.12	5.56	4.02	1.412	0.9979	0.9715	0.9694	549.3	236.4	3.28	3.34	24.61	5.53	4.23	1.412	0.9979	0.9731	0.9710	548.4
800 µF	6	20	238.8	3.91	4.02	7.237	69.82	15.81	1.155	0.8154	0.9741	0.7943	557.2	238.8	3.98	4.09	7.381	69.60	16.08	1.163	0.8212	0.9745	0.8002	557.2
		100	236.7	7.88	8.04	25.08	33.40	26.22	1.341	0.9448	0.9823	0.9281	546.2	236.8	7.68	7.84	25.35	33.73	26.76	1.341	0.9448	0.9808	0.9267	546.2
	12 Z	20	237.4	2.74	2.80	6.770	10.36	2.19	1.403	0.9917	0.8836	0.8769	571.7	237.4	2.73	2.79	6.821	10.31	2.20	1.407	0.9943	0.8843	0.8793	571.6
		100	234.6	7.13	7.20	24.66	8.32	6.45	1.409	0.9939	0.9731	0.9671	557.4	234.6	6.64	6.71	24.90	7.68	5.98	1.410	0.9946	0.9688	0.9636	557.8
	12 S	20	236.6	3.42	3.49	7.77	31.96	7.77	1.343	0.9489	0.8214	0.7794	596.0	236.8	3.32	3.39	7.827	30.70	7.52	1.352	0.9551	0.8236	0.7865	597.0
		100	232.4	6.75	6.76	25.67	8.05	6.47	1.409	0.9939	0.9508	0.9451	547.2	232.3	6.12	6.13	26.29	7.97	6.56	1.410	0.9949	0.9363	0.9315	546.9
	12 P	20	236.8	3.39	3.46	7.725	30.74	7.46	1.352	0.9549	0.8158	0.7790	590.9	236.7	3.37	3.44	7.829	30.28	7.42	1.355	0.9560	0.8170	0.7811	590.0
		100	233.0	6.57	6.60	25.69	7.98	6.41	1.410	0.9945	0.9445	0.9393	547.6	232.0	6.65	6.68	25.87	7.96	6.44	1.410	0.9943	0.9452	0.9398	547.6
	24 Z	20	237.4	1.99	2.03	6.697	9.98	2.09	1.407	0.9946	0.8940	0.8892	586.6	237.4	2.00	2.04	6.786	9.97	2.11	1.407	0.9948	0.8957	0.8911	586.4
		100	234.2	4.35	4.39	24.59	4.05	3.12	1.413	0.9982	0.9724	0.9707	567.9	234.1	4.36	4.40	24.79	4.04	3.13	1.413	0.9982	0.9724	0.9706	567.7
	24 S	20	237.4	1.90	1.94	6.731	9.96	2.98	1.407	0.9946	0.8868	0.8831	572.3	237.4	1.92	1.96	6.801	9.91	2.08	1.406	0.9942	0.8898	0.8847	572.2
		100	233.8	4.26	4.29	24.89	4.43	3.44	1.413	0.9980	0.9719	0.9700	548.3	234.1	4.26	4.30	25.11	4.42	3.44	1.413	0.9981	0.9727	0.9708	548.1
	24 P	20	238.4	1.28	1.31	5.366	12.98	2.72	1.402	0.9916	0.8543	0.8471	568.4	238.3	1.40	1.44	6.710	11.26	2.36	1.405	0.9935	0.8927	0.8870	565.7
		100	236.6	3.23	3.29	23.07	5.58	4.30	1.412	0.9980	0.9719	0.9700	549.3	236.5	3.42	3.48	24.71	5.52	4.27	1.412	0.9979	0.9728	0.9707	548.3
200 µF	6	20	238.8	4.48	4.61	7.764	83.36	20.25	1.090	0.7692	0.9793	0.7533	562.7	238.8	4.58	3.95	7.853	82.76	20.34	1.090	0.7689	0.9771	0.7514	562.9
		100	236.2	15.12	15.39	31.95	83.15	83.15	1.122	0.7830	0.9690	0.7587	550.8	236.7	9.24	7.69	27.33	45.71	39.10	1.261	0.8853	0.9754	0.8636	546.7
	12 Z	20	237.4	2.74	2.80	6.770	10.36	2.19	1.403	0.9917	0.8836	0.8769	571.7	237.4	2.69	2.75	6.816	10.69	2.28	1.407	0.9941	0.8859	0.8807	571.7
		100	234.6	7.13	7.20	24.66	8.32	6.45	1.409	0.9939	0.9731	0.9671	557.4	234.5	6.53	6.60	25.45	12.50	9.95	1.384	0.9750	0.9718	0.9475	557.5
	12 S	20	236.8	3.70	3.77	7.852	35.08	8.62	1.336	0.9438	0.8186	0.7726	596.1	236.8	3.52	3.34	7.897	33.08	8.17	1.343	0.9484	0.8214	0.7790	597.1
		100	234.1	13.54	13.66	29.50	65.43	60.41	1.265	0.8864	0.9456	0.8381	546.9	232.6	6.43	6.15	26.51	13.70	11.37	1.394	0.9829	0.9383	0.9222	547.0
	12 P	20	237.4	2.68	10.73	7.755	10.73	2.27	1.406	0.9936	0.8848	0.8892	571.7	236.7	3.56	3.38	7.910	32.82	8.12	1.344	0.9494	0.8152	0.7739	590.0
		100	235.2	10.50	48.99	30.87	48.99	47.33	1.194	0.8328	0.9516	0.7925	561.2	233.0	6.68	6.62	25.95	12.11	9.83	1.402	0.9888	0.9463	0.9357	547.0
	24 Z	20	237.4	2.03	2.08	6.727	11.23	2.36	1.405	0.9931	0.8929	0.8867	586.5	237.4	2.04	2.03	6.814	10.97	2.34	1.405	0.9932	0.8962	0.8901	586.4
		100	236.8	12.56	12.82	31.22	61.92	59.89	1.127	0.7837	0.9761	0.7650	579.3	234.1	5.55	4.40	25.31	20.50	16.24	1.399	0.9875	0.9705	0.9584	567.4
	24 S	20	237.4	1.93	1.97	6.744	10.61	2.24	1.406	0.9936	0.8890	0.8834	572.3	237.4	1.91	1.95	6.788	10.34	2.19	1.406	0.9942	0.8906	0.8855	572.2
		100	234.3	10.76	10.86	26.99	52.17	44.07	1.299	0.9127	0.9636	0.8795	552.2	233.2	4.58	4.30	25.08	4.42	3.46	1.413	0.9981	0.9720	0.9702	548.1
	24 P	20	238.4	1.30	1.33	5.386	13.91	2.34	1.400	0.9900	0.8559	0.8474	568.3	238.3	1.40	1.44	6.711	11.04	2.32	1.406	0.9938	0.8930	0.8875	565.6
		100	237.0	2.49	2.54	27.38	7.28	6.24	1.187	0.8346	0.9553	0.7973	559.6	236.6	3.40	3.34	25.66	12.50	10.04	1.384	0.9973	0.9734	0.9513	546.5

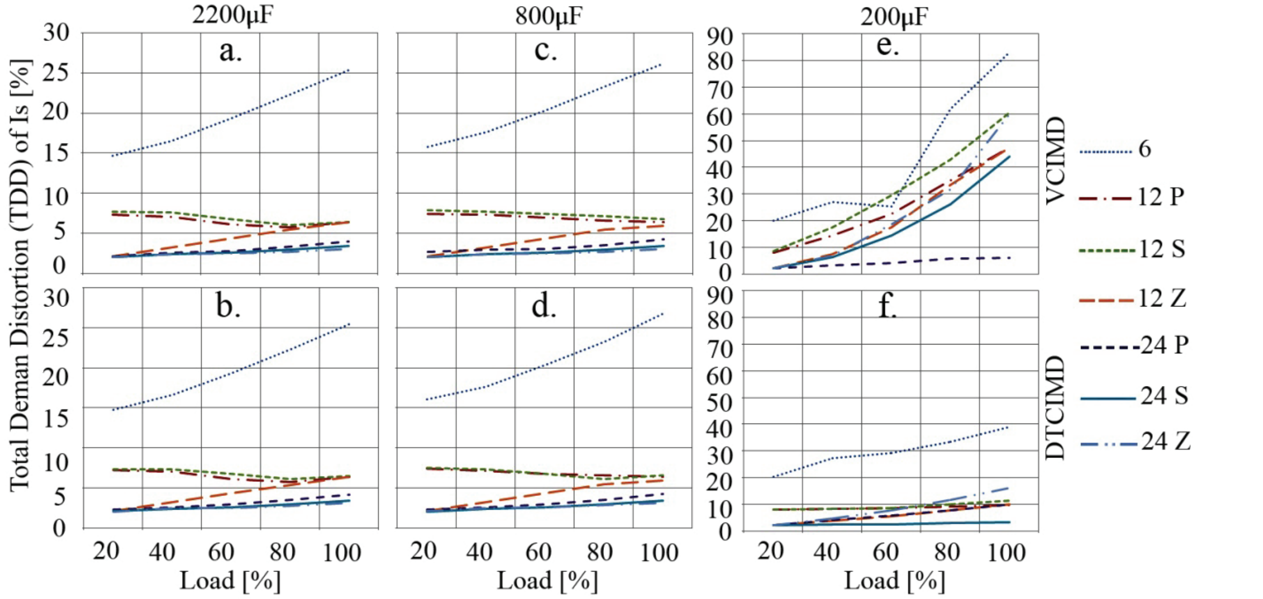

Fig. 2. Variation of Total Demand Distortion (TDD) of supply current with load perturbation on the induction motor fed from 6, 12, and 24-pulse autotransformer based AC-DC converters in case of feeding each of the two VFIMDs and different DC link capacitances: 2200µF: a. VCIMD, b. DTCIMD, 800µF: c. VCIMD, d. DTCIMD, 200µF: e. VCIMD, f. DTCIM

This is unlike the current distortions which will be lesser using star connection than polygon connection. This is due to the use of line current amplitude in the windings of star connected autotransformer to produce the output currents which is √3 times the phase current for creating the output currents. The polygon connected autotransformer uses the phase current in its windings for this purpose.

It can be seen from the figures that reducing the DC link capacitance, the distortions created by the drive systems will affect the AC mains deteriorating the power quality indices. It is also being seen that in this case using VCIMD will result in injection of more disturbances to PCC than DTCIMD. In the case of using VCIMD, using polygon connection in 24-pulse AC-DC converter and zigzag connection in 12-pulse AC-DC converter will result in more reduction in the disturbances created by the drive system than the other connections of the autotransformer.

In the case of using DTCIMD, this is possible using star connection in 24-pulse AC-DC converter and zigzag connection of the autotransformer in 12-pulse AC-DC converter.

Fig. 2 also shows that the TDD curves of the 24-pulse AC-DC converters are below the TDD curves of the other converters. It is as mentioned before that the distortion created by the 24-pulse rectification is less than 6 and 12-pulse rectifications.

Table 2 shows the ratings of magnetic circuits used for each AC-DC converter and the ratio percentage compared to power rating of the load. It shows that rating of the magnetic circuits of the 24-pulse AC-DC converter using zigzag connected autotransformer is 3.966 kVA only 26.44 percent of the load. It is the lowest magnetic rating due to the characteristic of zigzag connection in cancelation of ZSBT. It means lower overall cost and volume of the drive system compared to other AC-DC converters making it a more economical scheme.

Table 2. Ratings of magnetic circuits needed for AC-DC converters feeding 15 kW load

Pulse #	Autotransformer (kVA)	IPT (kVA)	ZSBT (kVA)	Ratio of magnetic ratings to Load (%)
12 Z	3×1.25	0.544	-	28.26
12 S	3×1.92	2×0.513	-	45.24
12 P	3×1.58	2×0.513	-	38.44
24 Z	3×1.25	0.217	-	26.44
24 S	3×1.93	0.220	1.03	46.93
24 P	3×1.26	0.209	0.97	33.06

Conclusions

The 6, 12 and 24-pulse AC-DC converters have been simulated in case of feeding VCIMD or DTCIMD loads and three DC link capacitances. It has been realized that where there is the need of less distortions in current, the star connection is the choice. Also where there is the need for less distortion in voltage, the polygon connection is the choice.

The Zigzag connected autotransformer blocks the zero sequence currents, resulting in cancelation of ZSBT in 24-pulse rectifications incorporated DC ripple reinjection technique. It also results in the use of only one IPT in 12-pulse rectifications. This had resulted in less ratings of the magnetic circuit, making the converters a more compact and cost effective scheme.

With a large DC link capacitor (2200 & 800 μF), there will be no differences in power quality indices in case of using VCIMD and DTCIMD loads. The differences of using these two VFIMDs have been detected using 200 μF DC link capacitor. In this case, the VCIMD will result in more distortions in PCC than DTCIMD. Polygon connection of the autotransformer can be used for 24-pulse rectifications to reduce the distortions caused by VCIMD. For 12-pulse rectifications the zigzag connection of the autotransformer can be used.

Appendix

Induction Motor: 3-phase squirrel cage 20hp (15 kW),
4-pole, Y-connected, 400 V, 50 Hz
R_s = 0.2147 Ω, R_r = 0.2205 Ω, L_s = L_r = 0.991mH
L_m = 64.19 mh, J = 0.102 kg.m2, F = 0.009541 N.m.s
PI controller: KP = 50, K_I = 0.003
DC-link parameters: L_{dc} = 1 mH, C_{dc} = 200, 800, 2200 μF.
3-phase supply: S = 300 kVA, V = 415 V, X/R = 7

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