Research article

Investigating the input power quality of multi-pulse AC-DC power converter fed induction motor drives

Nazmul Islam Nahin, Mahdee Nafis, Shuvra Prokash Biswas *, Md. Kamal Hosain, Pranta Das, Safa Haq

Electronics & Telecommunication Engineering, Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh

A R T I C L E   I N F O

Keywords:
Multi-pulse
AC-DC power converter
Induction motor drive
Supply current
Total harmonic distortion

A B S T R A C T

Optimization of supply current total harmonic distortion (THD) of multi-pulse AC-DC power converter fed induction motor drive (IMD) is always a challenging issue. Higher amount of supply current THD degrades the input power quality of IMD. The supply current THD should be controlled in such a way so that it adheres the power quality standard of IEEE-519. With the increase of the pulse number of multi-pulse AC-DC converter, supply current THD increases. In this work, an investigation has been carried out on 6-pulse, 12-pulse, 18-pulse, and 24-pulse AC-DC power converters based IMD. A thorough analysis of input current profile, THD, dynamic responses including stator current, speed, torque profile of the induction motor are highlighted in this work with the various load perturbation conditions. This work will provide a message to the industrial community about the proper selection of AC-DC power converter for IMD application considering power quality and circuit configuration issues. All the investigating works are conducted in MATLAB/Simulink platform.

1. Introduction

In the recent years, AC-DC converters are extensively used in numerous applications such as variable frequency induction motor drives (VFIMD), high voltage DC transmission (HVDC), renewable energy conversion, control systems, aerospace, and in daily electrical appliances. They usually require DC power for operation, though some applications including AC drives require DC power at transitional phases. These AC-DC converters are usually known as the rectifier which are fed by three phase AC supply having 33 kV or 11 kV followed by a step down transformer for medium power applications [1]. However, these AC-DC converters suffer from poor input power quality, increased total harmonic distortion (THD), low input power factor, and increased DC voltage ripple. To remove these limitations, various methods have been devised in [2, 3, 4, 5]. Generally, filters are used to remove harmonics which can be categorized into active or passive. These filters are not economical, increase losses and circuit complexity. As a result, for improving the input power quality and reducing harmonics, multi pulse rectifiers (MPR) have obtained popularity due to their remarkable efficiency, high robustness and simple configuration. Moreover, multi-pulse rectifiers do not require any LC filters which remove the possibility of LC resonances and the common mode voltage produced by rectifiers are eliminated by the employment of phase shifting transformer. MPR utilizes the phase shifted transformer to lessen the harmonics at the input side and allows multiple rectifiers to operate in series or separately. In general, the pulse number determines the limiting capability of harmonics of MPR [6].

MPRs are designed for AC-DC conversion at a mature level with low THD at the ac main and reduced ripple dc output with unidirectional and bidirectional power flow for feeding loads varying from kilowatts to megawatts. Multi-pulse rectifiers consist of a set of six pulse rectifiers along with a phase-shifting transformer. MPRs are categorized according to the number of pulses and its output rectifier connection which can be either series, separated or parallel [7]. Apart from that, they can also be classified based on connections such as extended delta and double star [8], [9], zigzag [10, 11, 12], reduced rating autotransformers and T-connections [13, 14, 15]. Phase shifting transformer is utilized to design the MPR which includes splitting the supply into a number of outputs, each of which is phase-shifted to the others at a suitable angle to reduce harmonics. Phase shifting transformers are employed to mitigate the current harmonics and withstand the overheating occurs due to harmonic injection [16]. Detailed winding turns design

* Corresponding author.
E-mail address: spbiswas@ete.ruet.ac.bd (S. Prokash Biswas).

https://doi.org/10.1016/j.heliyon.2022.e11733
Received 1 March 2022; Received in revised form 11 June 2022; Accepted 10 November 2022

2405-8440/© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
and analysis of phase shifted multi-pulse rectifier is discussed in [17, 18, 19]. Different configurations of MPRs are now studied to meet the criteria for proper applications by maintaining the input power quality.

The most common type of MPR is 6-pulse rectifier which is used in low power applications due to its simplicity and less circuit complexity. However, at full load condition, it’s input power quality degrades massively and total harmonic distortion can be surpassed up to 100% with no harmonic filter. On the other hand, the 12-pulse rectifier is the most common among MPRs. Two 6-pulse diode bridge rectifiers combined with a multi-phase transformer construct a 12-pulse rectifier. Due to series connection of two 6-pulse rectifiers, the DC current ripple is quite low. The 12-pulse rectifier can impressively remove (6n ± 1) harmonics in the input line current but harmonics (12n ± 1) (where n is an integer) remain in the system. The 11th and 13th are the dominant harmonics [20]. Due to their low cost and reduced size, they are extensively used in numerous fields such as variable frequency drive (VFD), DC drives, electrolytation and electric aircraft [21], [22]. Low input current THD and reduced dc voltage ripple are the feature of 18-pulse converter which makes it distinct from the other converters. 18-pulse converter is constructed by connecting three 6-pulse rectifiers in series. One of the advantages of this converter is; it bypasses the input voltage harmonics and interphase components. It can effectively reduce dominant harmonics except for the 17th and 19th harmonics [23]. The 24 pulse converters are utilized in high power situations where the usage of numerous devices is allowed. It eliminates the majority of the dominant harmonics and provides input-side ac current that is almost sinusoidal and ripple-free dc output voltage [24]. As the number of pulse increases for the multi-pulse rectifier, the performance of the system also increases so as the system complexity.

Although the increasing of pulse number reduces harmonics at a certain limit, different strategies have also been established to reduce THD. Researchers have conducted various studies and devised numerous strategies so that the amount of THD in the input AC line current of AC-DC power converter can be reduced to a suitable range. Pulse width modulation (PWM) is one of the taken strategies to reduce THD. The PWM method uses constant amplitude pulses with variable duty cycles for each period. To adjust inverter output voltage and reduce harmonic content, the width of these pulses is controlled [25]. The PWM technique used in voltage source inverter (VSI) has a great impact on the performance parameters of IMD such as output voltage THD of an inverter, stator current THD, and motor torque ripple. These are the main performance parameters of IMD which greatly depend upon inverter switching technique [26]. The most notable PWM are sinusoidal PWM (SPWM) and conventional space vector PWM (CSVPWM). When compared to SPWM, CSVPWM and third harmonic injection PWM (THIPWM) result in higher line side voltage for the same DC bus voltage. Furthermore, for a given line voltage, CSVPWM and THIPWM produce less THD in motor currents and inverter output voltage than SPWM [27, 28, 29, 30]. Similarly, some advanced PWM strategies are also gained popularity due to their capability of reducing THD and losses such as third harmonic sixty-degree pulse width modulation (THSD-PWM), sixty-degree PWM (SDPWM) and third harmonic trapezoidal PWM (THTRPWM) which are discussed in [31, 32, 33]. In addition, the hybrid PWM strategies, which are produced by merging CSVPWM and advanced bus clamping PWM (ABCPWM), have received attention due to their superiority in terms of increased efficiency, reduced switching losses, and minimized torque ripple over existing strategies [34]. Several torque ripple reduction approaches for AC-DC converter fed IMD have been discussed in [35], [36]. For low speed operation, torque ripple reduction of three level inverter fed IMD is found in [37]. PWM techniques have also gained popularity for reducing torque ripple. A new PWM method along with a novel rotor speed independent transformation can be found in [38]. Harmonics are mainly generated due to the constant on and off switching and connection of non-linear loads in the power system. In [39] improvement of THD performance on the grid side using a robust controller is studied. A comparative study control method for wind based energy system at grid side for reducing THD is given in [40]. However, the THD reduction at the inverter side focuses on the new controlling methods and different topologies. A brief review on multilevel inverter topologies is discussed here [41]. An efficient method of reducing of THD in cascaded H-bridge MLI can be presented in [42]. In [43], solar fed asymmetric MLI with reduced is presented. A cascaded MLI in a standalone PV system was suggested in [44], to reduce THD and produce high-quality power. The main contributions of the paper are summarized as follows:

- Topologies such as 6-pulse, 12-pulse, 18-pulse, and 24-pulse system.
- To observe the line current and its harmonics profile for various configurations of the IMD.
- To observe the impact of different modulation techniques on the power quality parameters of IMD in terms of THD of supply voltage/current, distortion factor, power factor and dc-link voltage.
- To observe the dynamic response of IMD for 6-pulse, 12-pulse, 18-pulse, and 24-pulse converter systems in terms of stator current, speed and torque.
- To provide a clear comparative analysis among 6-pulse, 12-pulse, 18-pulse, and 24-pulse converter based IMD in terms of various power quality parameters and modulation techniques so that one can choose proper IMD configuration for specific application based on the study.

The performance of the IMD by utilizing 6-pulse, 12-pulse, 18-pulse, and 24-pulse converter systems has been investigated in detail in the study so that the industrial community can receive a clear message in the case of selecting proper configuration of IMD for specific industrial application.

2. Structure of induction motor drives

The multi-pulse rectifiers classified based on pulse number are discussed in this section. The topologies are elaborated in such a way that one can choose the right configuration for a specific application.

2.1. DC-link voltage estimation

In this work, a 2-level VSI is used to feed power to an induction motor. The voltage of the DC-link capacitor (\(V_{dc}\)) is found in [25]. The rectified voltage across the DC-link capacitor is given in (1),

\[
V_{dc} = \frac{V_{L-L}}{0.612a(L-1)} = \frac{420}{0.612 \times 1 \times 1} = 686.27
\]  

(1)

where, \(V_{L-L}\), \(a\) and \(L\) are the line-to-line voltage, modulation index, and inverter level respectively.

2.2. Transformer configuration

The elimination of lower order harmonics in multi-pulse rectifiers is achieved by proper arrangement of transformer winding. The harmonics generated in a system by multi-pulse rectifier can be found in (2),

\[
H = np \pm 1
\]  

(2)

where, \(H\) is the harmonics generated by a rectifier, \(n = 1, 2, 3, \ldots\), and \(p\) is the pulse number. To eliminate these harmonics, the generalized phase-shifting angle is given in (3),

\[
\text{Phase shifting angle} \, \delta = \frac{360°}{\text{No. of pulses}}
\]  

(3)

For 12-pulse rectifier, \(\delta = 360°/12 = 30°\). Using Y-Y and Y-\(\Delta\) configuration of transformer, this phase shift is easily obtained. For 18-pulse
rectifier, $\delta = 360^\circ/18 = 20^\circ$. A phase-shifting transformer with a $20^\circ$ phase difference between any two adjacent secondary windings can be used to achieve this. For the top, middle, and bottom secondary windings, the values of angle are $20^\circ$, $0^\circ$, and $-20^\circ$ respectively. For 24-pulse rectifier, $\delta = 360^\circ/24 = 15^\circ$. Zigzag transformer is used for providing $15^\circ$ phase-shifting angle as $Y-\Delta$ configuration is not suitable for $\pm 15^\circ$, $0^\circ$, $+15^\circ$ and $30^\circ$ are the corresponding phase shifted angles for the four secondary transformers winding from each to each.

### 2.3. Description of the structure

![Fig. 1. 6-pulse AC-DC converter fed IMD.](image)

![Fig. 2. 12-pulse AC-DC converter fed IMD.](image)

Table 1. Mathematical representation of various PWM methods.

| PWM strategy | Expression |
|--------------|------------|
| SPWM [26]   | $I_1 = A \sin (\omega t + \phi)$ |
| THSDPWM [26] | $X_r = I_s$ (when $I_s > 0.76A$) $= -0.76A$ (when $I_s < -0.76A$) $I_s = X_t = B$ |
| CSPWM [26]   | $I_1 = \frac{1}{\omega} \{ [A \sin (\omega t + \phi)] + \frac{1}{2} \{ \max (I_{d1}, I_{d2}, I_{d3}) + \min (I_{d1}, I_{d2}, I_{d3}) \} \}$ |

### 3. Various PWM techniques

SPWM, THPWM, THSDPWM, and CSVPWM are the most often used modulation techniques [26].

The modulating signals of SPWM, THSDPWM, and CSVPWM are shown in Fig. 5(a), 5(b), and 5(c), respectively. In PWM, a triangular carrier with a specific frequency is compared with the modulating signals and corresponding gate pulses are produced for bipolar insulated gate transistors (IGBTs), which drives the AC-DC converter fed IMD. The reference signal is maintained at 50 Hz for each modulation technique and a 10 kHz triangle signal is being utilized as the carrier signal to produce the gate pulses. Table 1 depicts the mathematical expression for three PWM methods.

Table 2 shows the comparison of different power quality parameters of AC-DC converter fed IMD for various PWM techniques. For 6-pulse converter, the THD of input current is 27.11% for SPWM whereas the
4. Performance analysis of induction motor drives

The multi-pulse rectifier removes most of the deadly odd harmonics from the input current by utilizing the phase shifting transformers which ensures the better performance of IMD.

4.1. Supply current profile

Fig. 6(a), 6(b), 6(c), and 6(d) depict the waveforms of supply current for 6-pulse, 12-pulse, 18-pulse, and 24-pulse AC-DC converter-fed IMDs. Accordingly, the harmonic spectrum of line current of 6-pulse, 12-pulse, 18-pulse, and 24-pulse converter-based IMDs are shown in Fig. 7(a), 7(b), 7(c), and 7(d), respectively. The THD of supply current of 6-pulse is depicted in Fig. 7(a) which is found as 27.11%. The odd harmonics including the 3rd and 5th order harmonics remain in the system which degrades the performance of induction motor. The THD of 12-pulse converter is found as 8.36% which is shown in 7(b). Though, the dominant odd harmonics are removed, the 11th and 13th order harmonics are retained. However, the supply current THD of 12-pulse converter doesn’t meet the IEEE-519 standard requirement.

As a result, in order to use this converter in industry, additional procedures are required. Similarly, the 18-pulse converter eliminates the majority of fundamental harmonics, hence lowering the supply current THD to 4.23% which is shown in Fig. 7(c). However, the 17th and 19th order harmonics are the remaining and they are the dominating harmonics in an 18-pulse converter.
Table 2. Comparison of different power quality parameters of various converters for three types of PWM techniques.

| Pulse number of converters | PWM technique | THD of $V_s$ (%) | THD of $I_s$ (%) | DF | PF | $V_{dc}$ (V) |
|---------------------------|---------------|------------------|-----------------|----|----|-------------|
| 6-pulse                   | SPWM          | 5.21             | 27.11           | 0.984 | 0.9654 | 471.9       |
|                           | THSPWM        | 5.69             | 27.45           | 0.987 | 0.9661 | 453.2       |
|                           | CSPWM         | 5.82             | 28.02           | 0.991 | 0.9678 | 437.8       |
| 12-pulse                  | SPWM          | 3.11             | 7.37            | 0.9821 | 0.9766 | 532.8       |
|                           | THSPWM        | 3.78             | 6.41            | 0.9863 | 0.9679 | 519.3       |
|                           | CSPWM         | 3.52             | 6.32            | 0.9905 | 0.9782 | 511.1       |
| 18-pulse                  | SPWM          | 2.97             | 4.23            | 0.9871 | 0.9546 | 561.4       |
|                           | THSPWM        | 2.87             | 4.99            | 0.9887 | 0.9678 | 549.4       |
|                           | CSPWM         | 2.98             | 5.12            | 0.9956 | 0.9799 | 536.7       |
| 24-pulse                  | SPWM          | 2.59             | 3.21            | 0.9815 | 0.9998 | 577.8       |
|                           | THSPWM        | 2.60             | 3.30            | 0.9827 | 0.9997 | 569.1       |
|                           | CSPWM         | 2.72             | 3.46            | 0.9968 | 0.9995 | 567.3       |

Likewise, the 24-pulse converter offers 2.99% THD by taking advantage of four phase shifting transformers which is presented in Fig. 7(d).

4.2. Dynamic response of IMDS

Fig. 8-11 illustrate the dynamic performance of induction motor at different load disturbance for four multi-pulse converters. The dynamic features of the IMDS can be classified into three categories. They are as follows: (i) stator current change, (ii) change of speed, and (iii) change of load. At $t = 0.35$ s and $t = 0.7$ s, 70% and 90% of rated torques are applied. The dynamic response of IMD for 6-pulse converter is depicted.
mitigation capability of different multi-pulse converters in term of load variation is presented in Table 4. The load variation has a significant impact on the line current THD. If the load increases, it draws more current from the AC mains, hence lowering the THD.

When the load increases gradually, the input current magnitude also increases which in turn reduces the THD, as depicted in Table 4. A magnitude of input current of 32.57A is recorded for the 12-pulse converter with a THD of 8.21% at 50% load. However, THD decreases slightly when the load increases, but it still falls short to IEEE-519 requirements. Similarly, for 18-pulse and 24-pulse converters, the input current is found as 11.2A and 7.56A with the corresponding THD of 5.21% and 3.21% at 50% load, as shown in Table 4. Thus, it can be concluded that the input current THD of 18-pulse and 24-pulse converter comply with the IEEE-519 standard whereas the 6-pulse and 12-pulse converter do not comply with it.

6. Conclusion

In this work, an analytical survey on multi-pulse AC-DC converter based IMD has been carried by highlighting the input power quality profile. Apart from input current analysis, the dynamic responses of 6-pulse, 12-pulse, 18-pulse, and 24-pulse converters are also incorporated in the work. With the increase of the pulse number of multi-pulse AC-DC converter, the THD of the input current is decreased significantly. On the contrary, the transformer size and complexity of the AC-DC power converter is increased for higher pulse converter. Different load variation effects have also been studied while calculating input current and it's THD. The input current THDs for 6-pulse and 12-pulse converters are recorded as 27.11% and 8.36%, respectively which do not comply IEEE-519 standard. Whereas the input current THDs of 4.23% and 2.99% are recorded for 18-pulse and 24-pulse system which follow IEEE-519 standard. From this survey, one can easily understand the ins and out of input power quality profile of IMD for various structures of multi-pulse AC-DC converter.

5. Comparison and discussion

Performance parameters of IMD in terms of load variation for different multi-pulse converters are summarized in Table 3. To calculate power quality parameters such as THD of AC mains, distortion factor (DF), and power factor (PF), two types of load are considered which are full load and light load. The line current THD offered by 6-pulse and 12-pulse converters at full load are 27.11% and 7.37% respectively which doesn’t meet the standard IEEE-519 criteria. On the contrary, 18-pulse and 24-pulse converters provide line current THD of 4.23% and 3.21% at full load.

The THD in AC mains is lowest for 24-pulse converter. Thus it is decided that, with the increasing of pulse numbers, the power quality indicators are also increased. Lower order harmonics are extremely detrimental to the IMD as it degrades the performance. The harmonics

---

**Fig. 9.** Dynamic response of 12-pulse AC-DC converter fed IMD.

**Fig. 10.** Dynamic response of 18-pulse AC-DC converter fed IMD.

**Fig. 11.** Dynamic response of 24-pulse AC-DC converter fed IMD.
Md. Kamal Hosain: Performed the experiments; Wrote the paper.
Pranta Das; Safa Haq: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Funding statement
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement
Data will be made available on request.

Declaration of interests statement
The authors declare no conflict of interest.

Additional information
No additional information is available for this paper.

Appendix A
The Motor specifications: Three-phase squirrel-cage induction motor, 7.2 hp (5.4 kW), three phase four pole, Y connected, 415 V, 50 Hz.

Line filter: \( R_s = 2.5 \, \Omega, \quad L_s = 2 \, mH \)

DC link filter: \( L_q = 2 \, mF, \quad C_q = 3200 \, mF \)

Inverter filter: \( L_m = 2 \, mH, \quad C_m = 3.3 \, mF \)

References
[1] P. Kant, B. Singh, Multiwinding transformer fed CHB inverter with on-line switching angle calculation based SHE technique for vector controlled induction motor drive, IEEE Trans. Ind. Appl. 56 (3) (May/June 2020) 2807–2815.
[2] S.P. Biswas, M.S. Anower, M.R.I. Sheikh, M.R. Islam, K.M. Muttaqi, Investigation of the impact of different PWM techniques on rectifier-inverter fed induction motor drive, in: Proc. Australasian Universities Power Eng. Conf. (AUPEC), Hobart, Australia, 29 Nov.–2 Dec. 2020, pp. 1–6.
[3] H. Liu, N.N. Gulak, R.A. Lukaszewski, G.L. Skiabinski, Mitigation of current harmonics for multipulse diode front-end rectifier systems, IEEE Trans. Ind. Appl. 43 (3) (May–Jun. 2007) 787–797.
[4] B. Singh, S. Gauria, B.N. Singh, A. Chandra, A. Al-Haddad, Multipulse AC-DC converters for improving power quality: a review, IEEE Trans. Power Electron. 23 (1) (Jan. 2008) 260–281.
[5] S.P. Biswas, S. Haq, M.R. Islam, M.K. Hosain, R.N. Shaw, Advanced level shifted carrier based bus-clamping PWM technique for a 54-pulse AC to DC converter fed MLI based induction motor drive, in: Proc. IEEE 6th Int. Conf. on Computing, Communication and Automation (ICCCA), Arad, Romania, 17–19 Dec. 2021, pp. 587–592.
[6] S.P. Biswas, M. Shamin Anower, S. Haq, M.R. Islam, M. Ashib Rahman, K.M. Muttaqi, A new level shifted carrier based PWM technique for a 5-level multilevel inverter used in induction motor drives, in: Proc. IEEE Ind. Appl. Society Annual Meeting (IAS), Vancouver, BC, Canada, 10–14 Oct. 2021, pp. 1–6.
[7] B. Wu, High-Power Converters and AC Drives, IEEE Press, Wiley-Interscience, Piscataway, NJ, 2006.
[8] R. Fuentes, J. Quezada, I. Saavedra, Harmonic losses at measured current and rated voltage in 12 pulses high current controlled transformer-rectifiers, in: Proc. IEEE 9th Int. Conf. Harmonics Quality Power, vol. 3, Oct. 1–4, 2000, pp. 1065–1072.
[9] R. Fuentes, L. Fernicen, Harmonics mitigation in high current multipulse controlled transformer rectifiers, in: Proc. 10th IEEE Int. Conf. Harmonics Quality Power, vol. 1, 2002, pp. 189–195.
[10] D.A. Paice, Simplified Wye-connected 3-phase to 9-phase auto-transformer, U.S. Patent 6528951, Feb. 25, 2003.
[11] E.J. Charn, The ANSI-49 rectifier with phase shift, IEEE Trans. Ind. Appl. 1A-20 (3) (May/Jun. 1984) 615–624.
[12] G. Paulillo, C.A.M. Guimaraes, J. Policarpo, G. Abreu, R.A. Oliveira, T-ADZ-a novel converter transformer, in: Proc. IEEE ICHQP, 2000, pp. 715–719.
[13] M. El-Kabel, G. Olivier, G.E. Apr, C. Guimaraes, Transformateurs de conversion cinqu et sept phases, in: Proc. IEEE-CCGF95, 2005, pp. 708–711.
[14] C. Guimaraes, G. Olivier, G.E. Apr, High current ac/dc power converters using T-connected transformers, in: IEEE Can. Conf. ECE’95, 1995, pp. 704–707.
[15] G.N. Vorolomee, S.A. Evdokimov, N.I. Scuvor, B.V. Malozønov, Optimum multi-pulse rectifiers based on the scheme of Charles Scott, in: Proc. 7th Int. Conf. APEIE, 2004, pp. 189–190.
[16] J. Wen, H. Qin, S. Wang, B. Zhou, Basic connections and strategies of isolated phase-shifting transformers for multipulse rectifiers: a review, in: Proc. Asia-Pacific Symposium on Electromagnetic Compatibility, Singapore, 12 July 2012, pp. 105–108.
[17] A.D. Gaonkar, R.G. Rane, S.R. Wagh, N.M. Singh, Multi-winding phase-shifting transformer for 36-pulse rectifier: winding turns design and analysis, in: Proc. North American Power Symposium (NAPS), Denver, CO, USA, Nov. 21, 2016, pp. 1–6.
[18] H.S. Krishnamoorthy, P.N. Enjeti, J.J. Sandoval, Solid-state transformer for grid interface of high-power multipulse rectifiers, IEEE Trans. Ind. Appl. 54 (5) (Sept.–Oct. 2018) 5504–5511.
[19] J. Verboomen, D. Van Hertem, P.H. Schaevamen, W.L. Kling, R. Belmans, Phase shifting transformers: principles and applications, in: Proc. International Conference on Future Power Systems, Amsterdam, Netherlands, March 6, 2016, pp. 1–6.
[20] J. Wang, A. Chen, X. Yao, Q. Guan, Q. Chen, Input current step-doubleing for autotransformer based 12-pulse rectifier using two auxiliary diodes, IEEE Trans. Ind. Electron. 69 (8) (Aug. 2022) 7607–7617.
[21] S.M. Nadweh, G. Hayek, B. Atieth, Power quality improvement in variable speed drive systems VSDS with 12-pulse rectifier topology for industrial applications, Majlesi J. Mechatron. Syst. 8 (2) (2019) 1–6.
[22] S. Choi, P.N. Enjeti, H.H. Lee, L.J. Pietel, A new active inphase reactor for 12-pulse rectifiers provides clean power utility interface, IEEE Trans. Ind. Appl. 32 (6) (Nov./Dec. 1996) 1304–1311.
[23] W. Slezynski, A. Cichowiski, P. Mysial, Suppression of supply current harmonics of 18-pulse diode rectifier by series active power filter with lc coupling, Energies 22 (13) (2020) 6060.
[24] B.S. Lee, P.N. Enjeti, L.J. Pietel, A new 24-pulse diode rectifier system for AC motor drives provides clean power utility interface with low kVA components, in: Proc. IEEE IAS’96, 1996, pp. 1024–1031.
[25] H.M. Kojabadi, A comparative analysis of different pulse width modulation methods for low cost induction motor drives, Energy Convers. Manag. 52 (1) (Jan. 2011) 136–146.
[26] G. Carrasco, C.A. Silva, Space vector PWM method for five-phase two-level VSI with minimum harmonic injection in the overmodulation region, IEEE Trans. Ind. Electron. 60 (5) (May 2012) 2042–2053.
[27] A.C. Binojkumar, B. Saritha, G. Narayanan, Experimental comparison of conventional and bus-clamping PWM methods based on electrical and acoustic noise spectra of induction motor drives, IEEE Trans. Ind. Appl. 52 (5) (June 2016) 4061–4073.
[28] N. Okononou, J. Holtz, Closed-loop control of medium-voltage drives operated with synchronous optimal pulswidth modulation, IEEE Trans. Ind. Appl. 44 (1) (Jan. 2008) 115–123.
[29] J. Holtz, Pulsewidth modulation for electronic power conversion, Proc. IEEE 82 (8) (Aug. 1994) 1194–1214.
[30] N.I. Nahin, S.P. Biswas, R. Islam, A modified SVPWM strategy to improve the performance of variable frequency induction motor drive, in: Proc. Conf. on Electrical and Electronics Eng., Springer, Singapore, 8–9 Jan. 2022, pp. 481–493.
[31] B. Nandhini, A. Sivaprakasam, A review of various control strategies based on space vector pulse width modulation for the voltage source inverter, IETE J. Res. (2020) 1–15.
[32] M.R. Islam, A.M. Mahfuz-Ur-Rahman, M.M. Islam, Y.G. Guo, J.G. Zhu, Modular medium-voltage grid-connected converter with improved switching techniques for solar photovoltaic systems, IEEE Trans. Ind. Electron. 64 (11) (Jan. 2021) 8887–8896.
[33] F. Meng, X. Xu, L. Guo, A simple harmonic reduction method in multipulse rectifier using passive devices, IEEE Trans. Ind. Inform. 13 (July 2017) 2680–2692.
[34] K. Basu, J.S. Prasad, G. Narayanan, H.K. Krishnamurthy, R. Ayyanar, Reduction of torque ripple in induction motor drives using an advanced hybrid PWM technique, IEEE Trans. Ind. Electron. 57 (6) (Oct. 2009) 2085–2091.
[35] Y. Zhang, H. Yang, Torque ripple reduction of model predictive torque control of induction motor drives, in: Proc. IEEE Energy Conv. Cong. and Exp., Denver, CO, USA, 15–19 September 2013, pp. 1176–1183.
[36] C. Zhu, Z. Zeng, L. Zhao, Comprehensive analysis and reduction of torque ripples in three-phase four-switch inverter-fed PMSM drives using space vector pulse-width modulation, IEEE Trans. Power Electron. 32 (7) (Sep. 2016) 5411–5424.
[37] P. Naganathan, S. Srinivas, Direct torque control techniques of three-level H-bridge inverter fed induction motor for torque ripple reduction at low speed operations, IEEE Trans. Ind. Electron. 10 (67) (Nov. 2019) 8262–8270.
[38] N.K. Bajiuri, A.K. Jain, Torque ripple reduction in double-inverter fed wound rotor induction machine drives using PWM techniques, IEEE Trans. Ind. Electron. 66 (6) (June 2019) 4250–4261.
[39] K. Elyasalaoui, M. Ouassaïd, M. Cherkaoui, Improvement of THD performance of a robust controller for grid-side energy conversion system based on LCL filter without RC sensor, Int. J. Electr. Power Energy Syst. 121 (Oct. 2020) 106143.
[40] M.S. Esahi, S. Vaez-Zadeh, A. Jabbarnejad, A comparative study of control methods for grid side converters in PMSG-based wind energy conversion systems, in: Proc. IEEE 29th International Symposium on Industrial Electronics (ISIE), Delft, Netherlands, 17–19 June 2020, pp. 979–984.
[41] A. Balal, S. Dinkhah, F. Shahabi, M. Herrera, Y.L. Chuang, A review on multilevel inverter topologies, Emerg. Sci. J. 1 (6) (2022) 185–200.
[42] S. Maurya, D. Mishra, K. Singh, A.K. Mishra, Y. Pandey, An efficient technique to reduce total harmonics distortion in cascaded H-bridge multilevel inverter, in: Proc IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT), Coimbatore, India, Feb. 20–22, 2019, pp. 1–5.
[43] D. Shunmugham Vanaja, A.A. Stonier, A novel PV fed asymmetric multilevel inverter with reduced THD for a grid-connected system, Int. Trans. Electr. Energy Syst. 4 (30) (2020) e12267.
[44] V. Bhargava, S.K. Sinha, M. Dave, A methodology for 11-level AC output voltage generation for stand-alone/grid tied solar PV applications, in: Proc. Recent Developments in Control, Automation & Power Engineering (RDCAPE), Noida, India, 26–27 Oct. 2017, pp. 471–476.