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An alternative proposal for HVDC transmission systems using 24-pulse AC/DC converters based on three-winding non-conventional transformers

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ABSTRACT

In order to promote savings on installed filters in traditional HVDC transmission systems, and thus provide a less polluted power quality, this paper proposes a 24-pulse controlled converter that uses two identical three-phase three-winding special transformers, as well as four thyristor-controlled 6-pulse AC/DC converters connected in series. The configuration of the two transformers, and the necessary tap calculations are presented in order to achieve the 7.5° phase lag required to obtain the 24-pulse converter system. An analysis of the performance indices (power factor and Total Harmonic Distortion – THD) of both HVDC systems (traditional 12-pulse and the proposed 24-pulse) is performed and the results show improvements in the indices when using the proposed 24-pulse system. Simulation analysis was performed using Matlab/Simulink software in order to validate the proposed 24-pulse converter for use in HVDC transmission systems, considering the operationality of the proposed system under normal and degraded operating conditions. A laboratory prototype was designed and executed based on transformers with extended delta primary windings to validate the proposed 24-pulse converter in terms of harmonic mitigation and improved power quality. The results confirm the viability and applicability of the proposed converter in HVDC transmission systems.

1. Introduction

High Voltage Direct Current (HVDC) transmission technology has long been distinguished given its performance in supplying power over long distances, interconnecting asynchronous power systems, transmitting power underground or underwater via submarine cable transmission, and its application in multi-terminal systems [1] and [2]. Most HVDC systems use Line-Commutated Converter (LCC) technology that employs 12-pulse converters for AC/DC and DC/AC conversion [3]. This is also used to reduce harmonics in 6-pulse operation [1], [4]. Harmonic filters (for 11th and 13th order harmonics) and capacitor banks are used for power factor correction and are needed to improve power quality and compensate for the reactive power consumed by the grid side converters.

1.1. Topology of the conventional 12-pulse HVDC system

HVDC transmission systems is usually carried out using 12-pulse converters. The characteristic harmonics of the supply current of these grid side converters conform to a $12k \pm 1$ ($k = 1, 2, 3, \ldots$) relationship. The first lower order characteristic harmonics are the 11th and 13th, respectively. However, harmonic filters and capacitors bank are usually installed on grid side converters, and function by compensating the reactive power consumed by the converters and by mitigating any existing harmonics. Fig. 1 shows the modern bipolar topology commonly used in HVDC transmission systems with thyristors. In this topology, converter transformers with three windings (wye/wye/delta connections) are used in the thyristor converter bridges, so that a 30° phase lag can be achieved, to power the converter bridges connected in series in the traditional 12-pulse system.

One of the advantages of this system is that it continues to function as a 12-pulse system in degraded mode, i.e. if one of the parts in the transformer failes [5]. The main disadvantage of these converters is their poor energy quality with respect to injected current harmonics, resulting in voltage distortion, and reactive power consumption. Furthermore, this system requires larger amounts of physical space for

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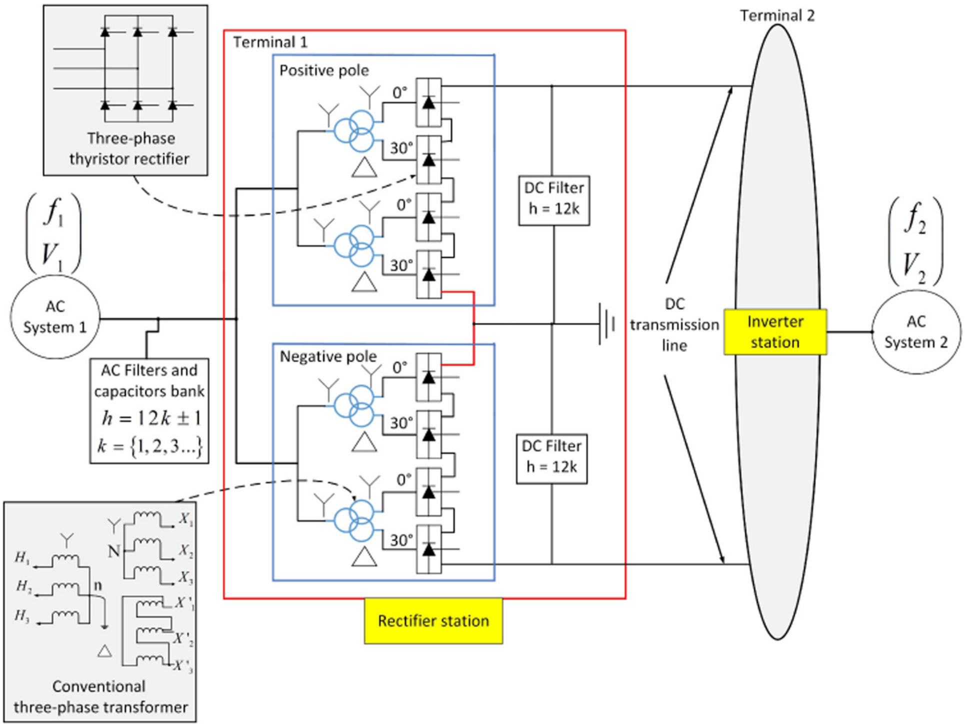


Fig. 1. Modern 12-pulse converter topology used in HVDC systems. The variables *f* and *V* related to the AC systems are the grid frequency and voltage, respectively.

installing the grid-side AC/DC filters and the DC Bus. Additionally, using filtering components can increase electrical resonance risks in AC systems [6]. Lastly, converter transformers are the most important pieces electromagnetic equipment present in HVDC systems, and harmonic currents $h = 6k \pm 1$, $k = (1, 2, 3, \ldots)$ can still penetrate these transformers, even with installed grid-side AC filters [1] and [7]. The effects caused by these harmonics on transformers are inevitable, resulting in increased losses and temperatures, vibrations, noise, higher operating costs, and negatively impacts equipment durability [8], [9] and [10]. Therefore, a new topology using a delta connected parallel filter winding was proposed by [11] to overcome this problem.

1.2. Proposed 12-pulse converter topology for use in HVDC systems [11]

The system is made up of two 6-pulse AC/DC converters and two transformers with wye/wye/delta winding connections or wye/delta/delta winding connections. There is also a tertiary winding group connected in delta that serves as a harmonic filtering winding. Compared with the conventional bipolar topology illustrated in Fig. 1, the solution proposed by [11], shown in Fig. 2, can mitigate harmonic fluxes in the transformers, and in so doing improves the power quality in the primary current, eliminating negative impacts on the transformers caused by harmonics. The method proposed by [11] efficiently eliminates the 5th, 7th, 11th, 13th, 17th, 19th, etc. harmonic currents in the primary currents of the transformer, and also eliminates undesirable impacts caused by penetrating harmonic currents in the transformers.

Although the proposed topology shown in Fig. 2 uses fewer components (two 6-pulse converters), it can suffer reliability issues and power availability problems if one of the transformer parts fails. In other words, if one of the transformers is defective, the 12-pulse system shown in Fig. 2 will function as a 6-pulse system. This is a disadvantage of the proposed system compared to the conventional 12-pulse topologies, as shown in Fig. 1. Furthermore, the additional filters may increase the cost and size of the converter system.

1.3. Standard traditional 24-pulse converter topology in HVDC systems

A standard 24-pulse system topology using a set of three-phase phase shifting transformers and four 6-pulse AC/DC converters connected in series was adopted to improve power quality, reliability, and power availability, as shown in Fig. 3. A single multi-secondary winding transformer with a 15° phase lag between secondary voltages was proposed for this specific configuration. One advantage is that this 24-pulse converter can only operate in a 12 and 18-pulse system in degraded mode [5] and therefore has proven to be more advantageous and attractive in terms of reliability than the systems shown in Figs. 1 and 2. However, in addition to using the same number of 6-pulse AC/DC converters, a reconfiguration and monitoring unit is needed to properly and automatically perform phase lag shifting, e.g. ± 20° for operation in an 18-pulse converter system.

This system can be more expensive than those shown in Figs. 1 and 2. Moreover, in practice three-phase phase shifting transformers are easy to manufacture compared to multi-secondary winding transformers [5]. Given the complexity in manufacturing multi-secondary winding transformers and the reliability issues, a new 24-pulse converter system topology has been proposed by [5], and is shown in Fig. 4, which introduces the concept of a Z/z electronic transformer. Its main function is to act as an automatic tap changer for windings in operating in degraded condition in the converter system [5].

The system architecture consists of four 6-pulse AC/DC converters connected in series, and four three-phase Z/z electronic transformers. This system can operate in degraded mode, i.e. when some components fail, as an 18, 12, and 6-pulse system, and has proven to be more reliable than the systems shown in Figs. 1–3. However, there is one disadvantages of this system, as was mentioned for the system shown in Fig. 3, in that it also requires a reconfiguration, monitoring, and command unit for the Z/z transformer to act as an automatic tap changer for transformers or rectifier bridges operating in a degraded condition, i.e. in case of component failures [5]. This system, although more reliable and efficient than the system shown in Fig. 3, is more expensive. On the other hand, the economic cost benefit viability analysis is widely considered in HVDC deployment projects. Considering reliability, cost,

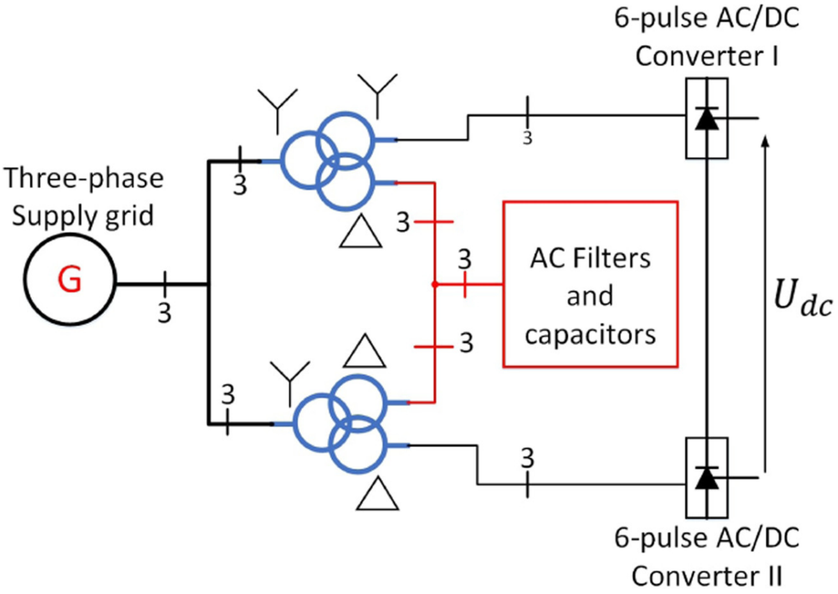


Fig. 2. Schematic of the 12-pulse converter proposed by [11].

maintenance, and physical space issues, another type of 24-pulse converter was adopted in this paper that uses two +7.5° special three-phase three-winding transformers, with zigzag or extended delta winding connections in the primary winding, and four 6-pulse AC/DC converters connected in series, for use in HVDC transmission systems.

This article is divided into the following sections. Section 2 describes the configuration of the proposed 24-pulse system and presents the wiring schematic. Section 3 presents the theoretical calculations of the taps for the two types of transformers (with zigzag and extended delta connections in the primary winding) to obtain the proposed 24-pulse system. Section 4 presents the theoretical analysis of the power factor for the two converter systems (conventional 12-pulse HVDC system and proposed 24-pulse converter system). Section 5 presents a simulation of the proposed system using Matlab/Simulink software, and the experimental results. Section 6 presents the findings and conclusions.

2. Configuration of the proposed 24-pulse converter system

This paper proposes employing a 24-pulse converter system using special three-phase three-winding transformers, shown in Fig. 5.

The secondary voltage phase lag of the supply bridge must be 15°, and the characteristic harmonics obey the generic relation $h = 24k \pm 1$ ($k = 1, 2, 3, \ldots$). Therefore, the 11th and 13th harmonics are eliminated in the conventional 12-pulse system, shown in Fig. 1, and the first characteristic harmonics in the current on the grid side are the 23rd and the 25th harmonic with reduced amplitudes, since the efficient values of the harmonic components in the order of n (neglecting the effect of commutation) obey the relation $I_n = \frac{I_1}{n}$, where I_1 is the efficient value of the fundamental component, and n is the order of the harmonic considered.

The immediate advantage of this arrangement is savings in installation costs for grid-side filters in the converter system. The connections for the special transformers in the proposed 24-pulse converter

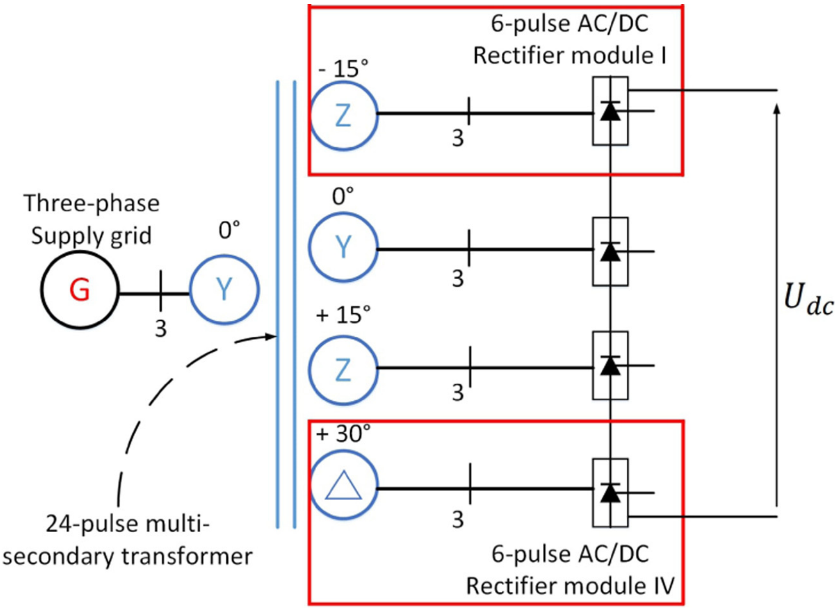


Fig. 3. Traditional 24-pulse converter used in HVDC systems.

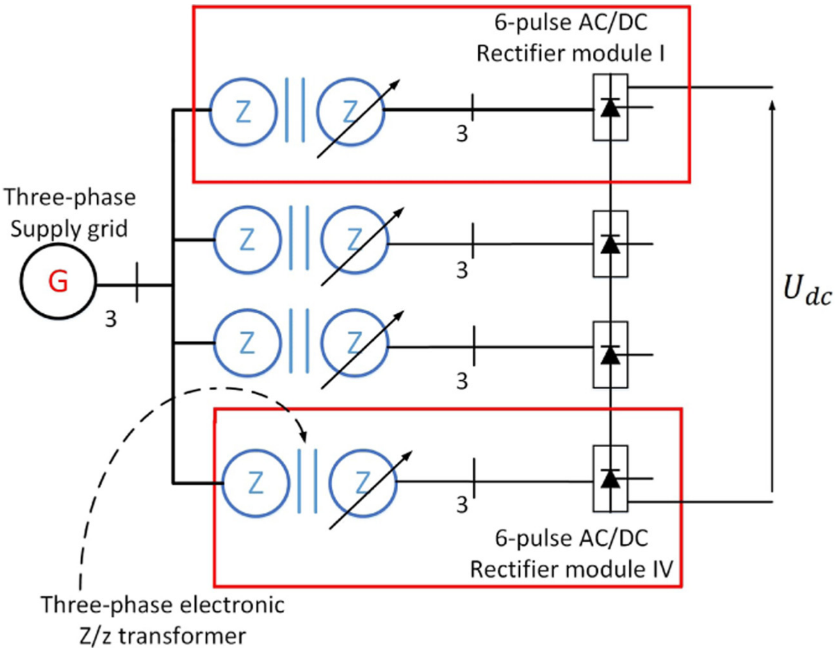


Fig. 4. 24-pulse topology proposed by [5] based on four three-phase Z/z transformers with an automatically adjustable phase lag angle.

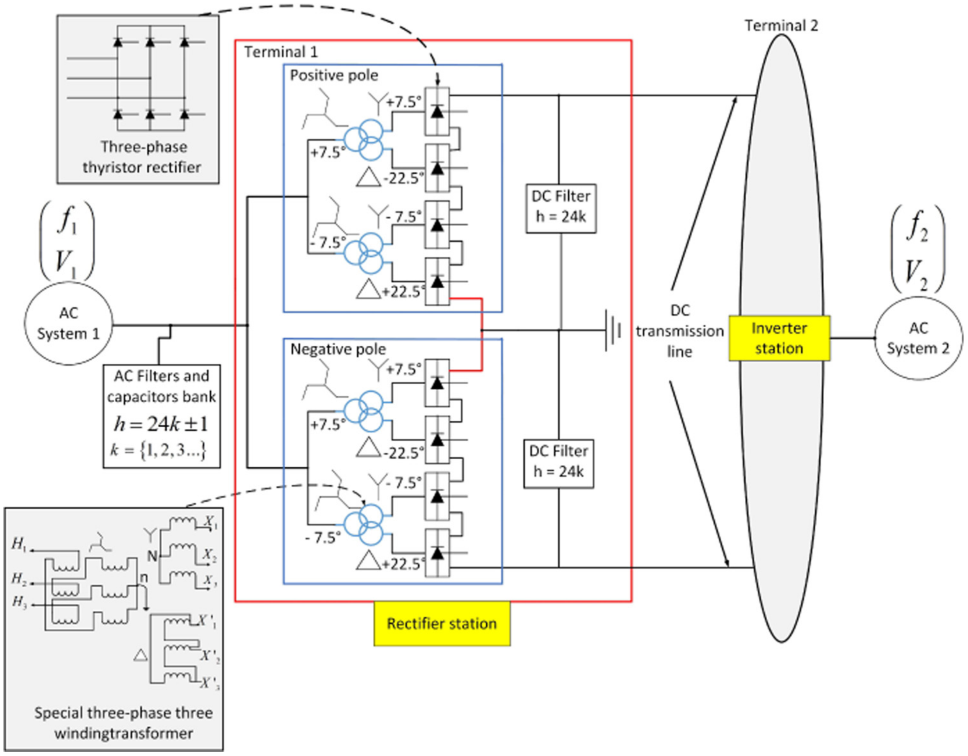


Fig. 5. Topology of the 24-pulse converter system proposed for use in HVDC systems. The variables *f* and *V* related to the AC systems are the grid frequency and voltage, respectively.

system have +7.5° zigzag or extended delta (optional) arrangements in the primary windings, 0° wye arrangements in the secondary windings, and 30° delta arrangements in the tertiary windings, supplying the 6-pulse AC/DC converters connected in series, resulting in a 12-pulse system.

An identical converter transformer unit is used to achieve a 24-pulse converter system, by simply inverting the primary power supply phase sequence for the three-winding transformer in the second unit, which will therefore have a −7.5° zigzag phase lag in the primary winding, a 0° wye phase lag in the secondary winding, and a 30° delta phase lag in the tertiary winding. This way, the required +15° phase lag is achieved to feed the four (04) converter bridges in this proposed arrangement. This is advantageous in that it results in secondary and tertiary units with conventional wye (secondary) and delta (tertiary) connections. We emphasize that, because the units are identical, this results in considerably improved ease of maintenance. The primary zigzag connection provides access to the neutral connection for grounding this connection resulting in added protection. In the case of the conventional

12-pulse system, this was achieved by grounding the primary wye connection. Design considerations for the special three-phase zigzag/ wye/delta transformer will be presented in the following sections, as well as the improvements in the power factor in the network when increasing the number of pulses of the converter system. The proposed system may have favourable applications in multi-terminal systems where power is disseminated along the line to supply communities located along the grid [12]. The proposal is also viable in cases where submarine cables are used for interconnections in populated locations with limited space for substations where passive filters are installed. Another benefit is that, in such cases, installed active filters occupy less installation space [13], and by using the 24-pulse arrangement, it reduce the power of these active filters. Lastly, the proposed 24-pulse converter system can efficiently operate as a 12-pulse system in the case of component failure.

3. Tap calculations for the phase shifting transformers

Phase shifting transformers are essential components in multi-pulse converter systems. Their main function is to create a phase lag between the primary and secondary voltages resulting in harmonic cancellation, and also to ensure proper secondary voltage, and electrical isolation between the converter system and the energy supply network [14]. As was previously mentioned in Section 2, phase shifting transformers used in the proposed 24-pulse converter system may have zigzag or delta extended connections in the primary windings. The advantage of using a zigzag connection in the primary winding is related to protective quality given the access to the neutral connection.

3.1. Tap calculations for the phase shifting transformer with zigzag connection in the primary winding

Fig. 6 shows the transformer in a zigzag connection. The different taps are determined based on the displacements θ [15]. In this Figure, (H_1, H_2, H_3) and (X_1, X_2, X_3) are the primary and secondary terminals, respectively. Also, (nc, nc') and ($c'X_1'$, cX_1) are the voltages of the first and second winding of the zigzag connection.

Applying basic trigonometry formulas to the phase diagram for triangle ncX_1, we can obtain via Eq. (1).

$$\begin{cases} \mathrm{cn} = \dfrac{\sin(\theta)}{\sin(120^\circ)} \times \mathrm{nX_1} \\ X_1c = \dfrac{\sin(60^\circ - \theta)}{\sin(120^\circ)} \times \mathrm{nX_1} \end{cases} \tag{1}$$

For 100% tap (Y/Z-30°), it results in: $\mathrm{nX_1} = \sqrt{3} \times c'n$ and $\mathrm{nX_1} = \sqrt{3} \times X_1'c'$. Finally, taps N_2 and N_3 (%), as shown in Fig. 6, are obtained from displacement angle $\theta = 7.5^\circ$ and its values are $N_2 = cn = 26.10\%$ and $N_3 = X_1c = 158.67\%$. For transformation relationship 1:1, the 100% tap corresponds to $N_2 = N_3 = 0.5773 \times N_1$. Consequently, for $\theta = 7.5^\circ$ (Y/Z-7.5°), it results in: $N_2 = 0.1506 \times N_1$ and $N_3 = 0.9160 \times N_1$.

3.2. Tap calculations for the phase shifting transformer with extended delta connection in the primary winding

Fig. 7 shows the transformer in an extended delta configuration. The different taps are determined based on the angular displacements θ. In this Figure, aX_1 and ab are the auxiliary and main coil voltages of the extended delta connection. The variables N_1, N_2 and N_3 represent the turns number related to the wye (primary)/extended delta (secondary) connections.

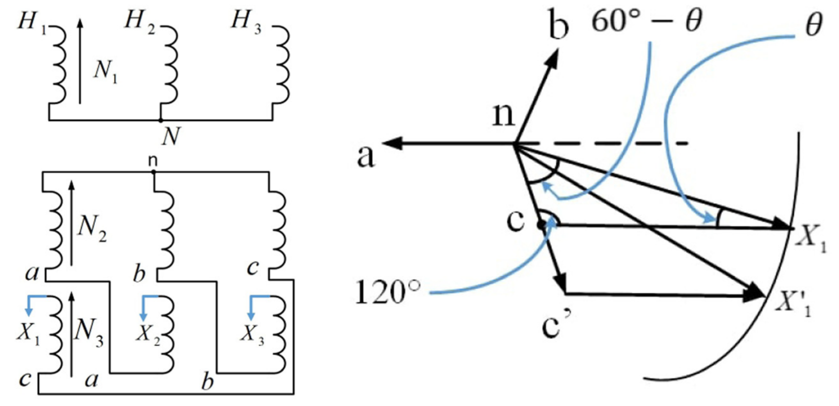
Based on Triangle aX_1X_3 and applying the Law of Sines, the trigonometric relationship can be expressed by Eq. (2).

$$\begin{cases} \mathrm{aX_1} = \dfrac{\sin(30^\circ - \theta)}{\sin(120^\circ)} \times X_1X_3 \\ \mathrm{aX_3} = \dfrac{\sin(30^\circ + \theta)}{\sin(120^\circ)} \times X_1X_3 \end{cases} \tag{2}$$

Considering Tap $X_1X_3 = 100\%$, one can obtain from Eq. (2) shown above, for angle $\theta = 7.5^\circ$: $aX_1 = 0.4419$ and $ac = aX_3 - cX_3 = aX_3 - aX_1$, i.e. $ac = 0.7029 - 0.4419 = 0.2610$. Finally, the Taps shown in Fig. 7 are deduced $N_2 = 44.19\%$ and $N_3 = 26.10\%$. For a transformation relationship of 1:1 and $\theta = 7.5^\circ$, corresponds to $N_2 = 1.7320 \times 0.4419 \times N_1 = 0.7653 \times N_1$ and $N_3 = 1.7320 \times 0.2610 \times N_1 = 0.4520 \times N_1$.

4. Theoretical power factor analysis for converters used in conventional 12-pulse and proposed 24-pulse HVDC systems

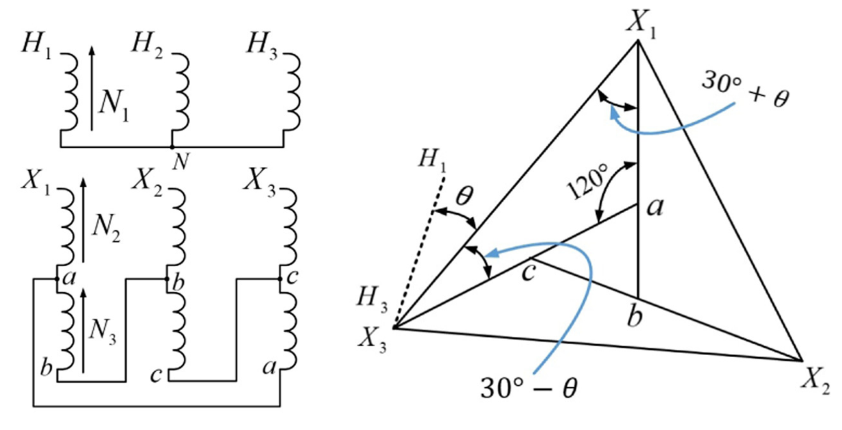
The power factor $PF(\alpha, \mu)$ is one of the most important performance indices of multi-pulse converter systems. It is calculated by considering the firing angle α, the overlap angle μ, and the number of pulses n_p of the converter. For convenience sake, we will analyse only a thyristor-controlled 6-pulse AC/DC converter in this section. Therefore, the power factor for the conventional 12-pulse converter and the new proposed 24-pulse converter for use in HVDC systems will be deduced by extrapolating the basic formulas considering only n_p. According to [16], the power factor can be expressed in Eq. (3).



(a) Transformer connection

(b) Transformer phase diagram

Fig. 6. Zigzag transformer configuration. N and n are the neutral points.



(a) Transformer connection

(b) Phase diagram

Fig. 7. Transformer in extended delta connection. *N* is the neutral point.

$$\mathrm{PF}(\alpha,\mu)=\begin{cases}\dfrac{I_1\times\cos(\alpha)}{\sqrt{(I_1)^2+\sum_n\left(\frac{I_1}{n}\right)^2}}, & \mu=0\\[2ex]\dfrac{\mathrm{HRF}_1(\mu,\alpha)\times\cos(\phi_1(\mu,\alpha))}{\sqrt{(\mathrm{HRF}_1(\mu,\alpha))^2+\sum_n\left(\frac{\mathrm{HRF}_n(\mu,\alpha)}{n}\right)^2}}, & \mu>0\end{cases}\tag{3}$$

Where variables:

$\mathrm{HRF}_n(n>1)$ – harmonic reduction factor for n (characteristic harmonic order)

HRF_1 considering the commutation effect – harmonic reduction factor for $n = 1$

ϕ_1 – fundamental current phase angle

I_1 – fundamental current component RMS value

α – thyristor firing angle

μ – overlap angle.

Variables HRF_n, HRF_1 and $\phi_1(\mu,\alpha)$ can be expressed by Eq. (4).

$$\begin{cases}\mathrm{HRF}_n(\mu,\alpha)=\dfrac{\sqrt{H^2+K^2-2\mathrm{HK}\cos(2\alpha+\mu)}}{\cos(\alpha)-\cos(\alpha+\mu)}\\[2ex]\mathrm{HRF}_1(\mu,\alpha)=\dfrac{\sqrt{H^2+K^2}}{4(\cos(\alpha)-\cos(\alpha+\mu))}\\[2ex]\phi_1(\mu,\alpha)=\tan^{-1}\left(\dfrac{2\mu+\sin(2\alpha)-\sin(2(\alpha+\mu))}{\cos(2\alpha)-\cos(2(\alpha+\mu))}\right)\end{cases}\tag{4}$$

Parameters H, K, H_1 e K_1 are auxiliary values to calculate the harmonic reduction factor $\mathrm{HRF}(\mu,\alpha)$ and can be expressed by Eq. (5).

$$\begin{cases}H=\dfrac{\sin\left((n+1)\frac{\mu}{2}\right)}{n+1}\\[2ex]K=\dfrac{\sin\left((n-1)\frac{\mu}{2}\right)}{n-1}\\[1ex]H_1=\cos(2\alpha)-\cos(2(\alpha+\mu))\\K_1=\sin(2(\alpha+\mu))-\sin(2\alpha)-2\mu\end{cases}\tag{5}$$

One can observe in Table 1 that as n_p increases, *PF* increases neglecting the commutation effect. The overlap angle μ is calculated up to 60° (1.04 radians), the maximum theoretical value for this angle.

Therefore, for a firing angle α equal to 150°, the maximum theoretical overlap angle would be 30° for switching on bridges. In practice, the overlap angle should be smaller, ensuring a minimum extinction angle for the thyristors of the converter bridges. Fig. 8 shows the variation of the power factor *PF* with the overlap angle μ for different firing angles α for the conventional 12-pulse and the proposed 24-pulse HVDC systems.

Table 1
Variation of the Power Factor with n_p, $k = (1, 2, 3\ldots)$.

Number of pulses n_p	Power Factor F_p
6-pulse ($n = 6k \pm 1$)	0.9550 × cosα
12-pulse ($n = 12k \pm 1$)	0.9901 × cosα
24-pulse ($n = 24k \pm 1$)	0.9978 × cosα
48-pulse ($n = 48k \pm 1$)	0.9996 × cosα

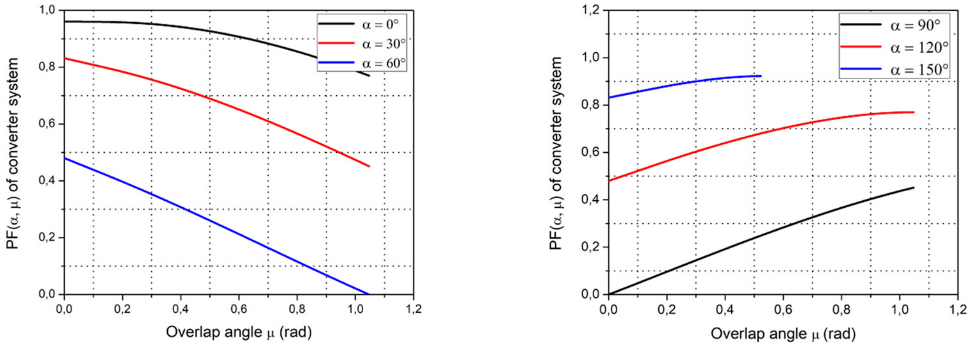
One can see in Fig. 8 that as the overlap angle μ increases, the power factor *PF* decreases to a fixed firing angle α for rectifier operation. For the converter operating as an inverter, the exact opposite effect occurs, however, the power factor *PF* increases when the firing angle α increases to a fixed overlap angle μ.

5. Simulation and experimental analysis of the proposed converter system

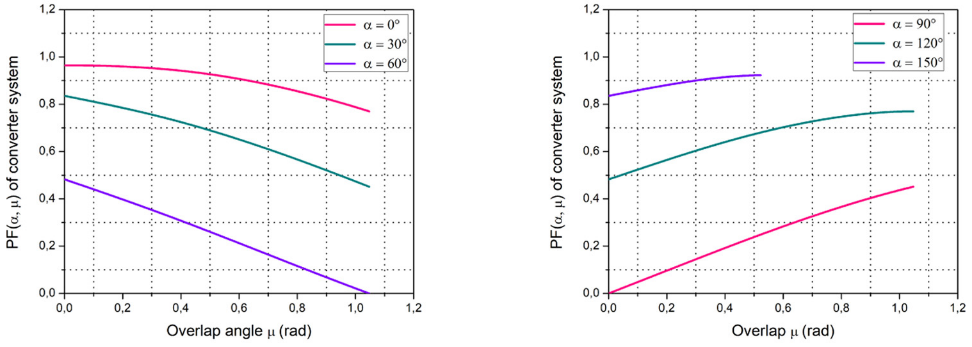
To prove and validate the efficiency of the proposed converter system, two simulation models (conventional 12-pulse and proposed 24-pulse HVDC system) were simulated in Matlab/Simulink software. The tap values for the zigzag connection in the primary windings in the transformers were calculated in Section 3, considering the transformation relationship 1:1. For the implemented prototype, the transformation relationship is 1:(180/220), i.e. 1:0.82 and the turn relationship are $N_2 = 0.1841 \times N_1$, $N_3 = 1.1195 \times N_1$ and $N_4 = 1.7320 \times N_1$. Fig. 9 shows the structure of the simulated diagram for the proposed 24-pulse converter for use in HVDC systems. Only one pole of the system shown in Fig. 5 was simulated in this paper. The transformers were modelled in Matlab/Simulink based on the single-phase transformers already available in the library of Simulink. A current source value of 4.2 A was considered for the DC load, and each thyristor 6-pulse AC/DC converter had its own synchronization and firing circuit.

Three scenarios (cases) were considered in this simulation to validate the performance of the proposed 24-pulse converter system in terms of its reliability.

- Converter operation in normal mode, i.e. no component failures.
- When Transformer II is defective or removed.
- When Transformer II is defective or removed + failure in the tertiary of transformer I.



(a) $\alpha = \{0^\circ, 30^\circ, 60^\circ\}$ (b) $\alpha = \{90^\circ, 120^\circ, 150^\circ\}$



(c) $\alpha = \{90^\circ, 120^\circ, 150^\circ\}$ (d) $\alpha = \{90^\circ, 120^\circ, 150^\circ\}$

Fig. 8. Variation of the power factor *PF* with the overlap angle μ (in radians) and for different values of the firing angle α. (a) and (b) Conventional 12-pulse HVDC system. (c) and (d) Proposed 24-pulse converter system.

The simulated didactic system is composed mainly of the three-phase three winding transformer (220/180 V/2 kVA), three-phase source ($V_{S_{\text{RMS}}} = 220$ V, phase to phase), DC bus load (current source, 4.2 A), synchronising and firing circuit blocks of firing angle $\alpha = 5^\circ$.

Fig. 10 shows the simulated waveforms of source current, DC voltage and the harmonic spectrum obtained under normal conditions from both systems (conventional 12-pulse HVDC system, and the proposed 24-pulse system).

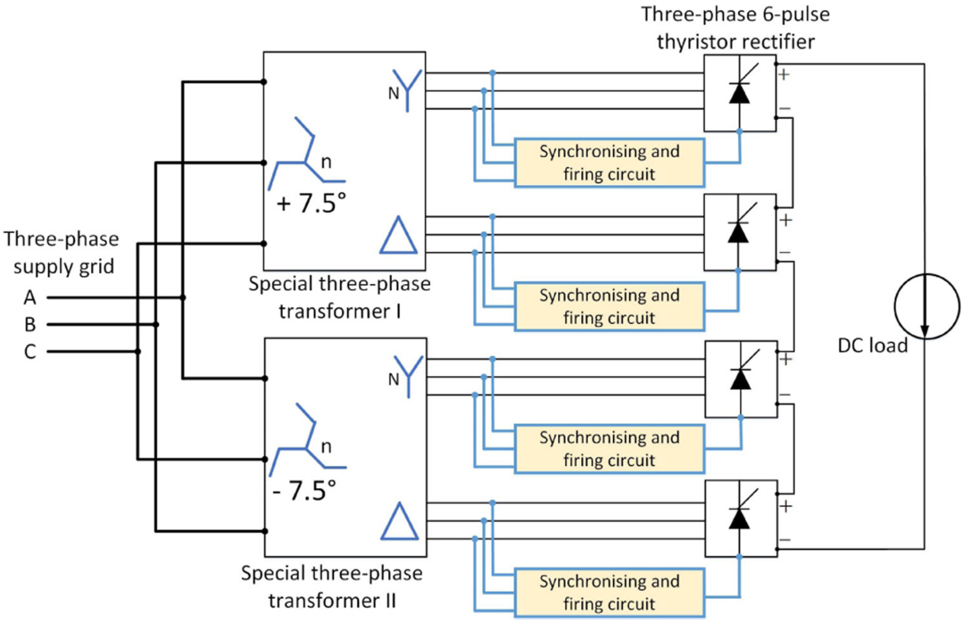
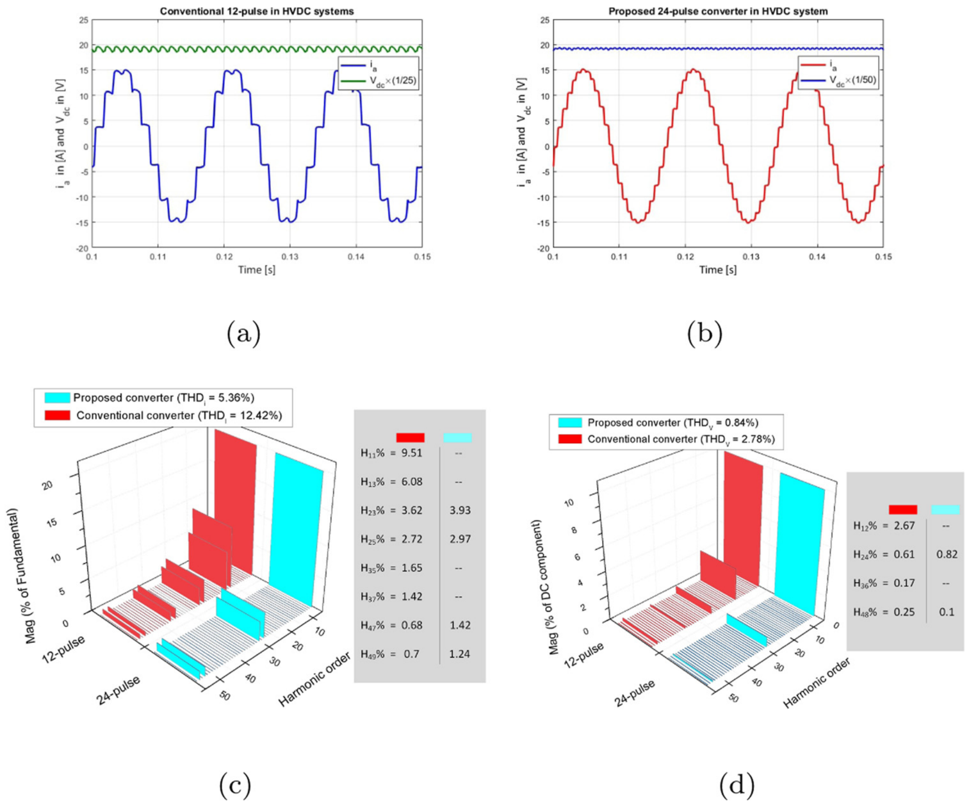


Fig. 9. Diagram of the wiring for the simulated converter. The phase sequence in the primary of transformer II is inverted to obtain the 24-pulse converter system.



(a) (b)

(c) (d)

Fig. 10. Simulated results for both systems under normal operating conditions. (a) Mains AC current and DC bus voltage of the conventional 12-pulse converter (C-12P-C). (b) Mains AC current and DC bus voltage of the proposed 24-pulse converter (P-24P-C). (c) Harmonic spectrum of the P-24P-C and C-12P-C network AC current. (d) Harmonic spectrum of the P-24P-C and C-12P-C DC bus voltage. Only 20% and 10% of the grid current and DC voltage fundamental, respectively are illustrated.

Note that the THD of the source current is equal 12.43% for the proposed 24-pulse converter and 5.35% for the conventional 12-pulse converter. The THD of the DC voltage is significantly reduced from 2.78% for the conventional system to 0.83% using the proposed system.

Furthermore, one can note that the 11th, 13th, 35th and 37th harmonics present in the harmonic spectrum of the conventional converter were totally eliminated, and that the AC current profile for the proposed 24-pulse converter more closely approximates a sine wave. The proposed converter, therefore, presented satisfactory performance when compared to the conventional 12-pulse converter. The proposed 24-pulse converter was simulated for Scenarios 2 and 3 in order to observe its performance in a degraded mode. Fig. 11 shows the waveforms of the phase A mains AC current and DC bus voltage, taking into account the three scenarios mentioned above.

One can see that transformers I and II operate normally, and that the proposed system operates as a 24-pulse converter before $t = 0.25$ s. The THD obtained from the phase A mains AC current was equal to 5.86%, thus meeting IEEE 519 requirements for this type of converter [17], and that of the DC bus voltage was 0.85%. Scenario 2 was performed during $t = 0.25$ s and $t = 0.35$ s, and the system operated as a reduced power 12-pulse converter. Note that the THD of the phase A mains AC current in this case was 13.62% (slightly higher than a conventional 12-pulse

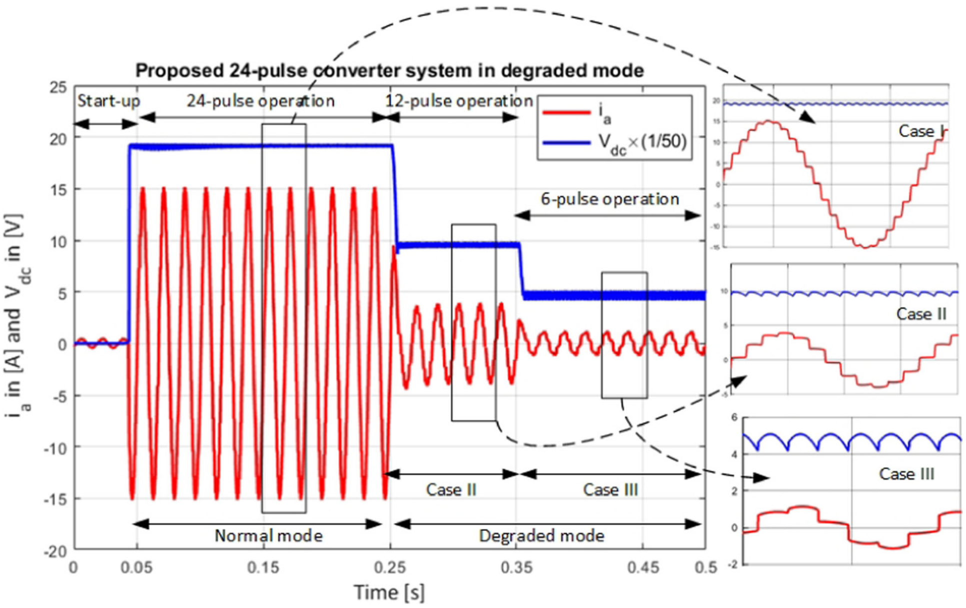
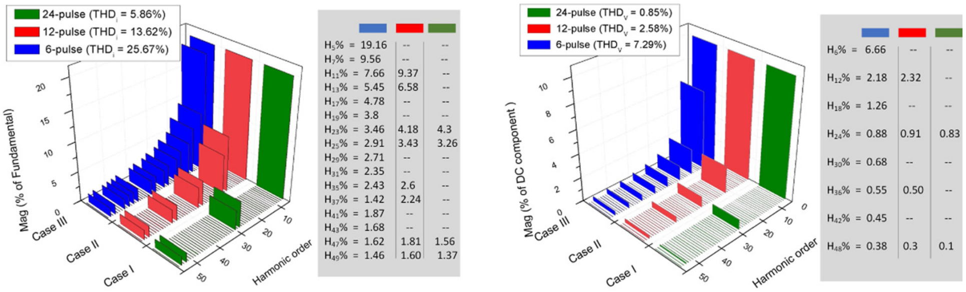


Fig. 11. Simulation results of the proposed converter in degraded mode.



	🟦	🟥	🟩
H_5% =	19.16	--	--
H_7% =	9.56	--	--
H_{11}% =	7.66	9.37	--
H_{13}% =	5.45	6.58	--
H_{17}% =	4.78	--	--
H_{19}% =	3.8	--	--
H_{23}% =	3.46	4.18	4.3
H_{25}% =	2.91	3.43	3.26
H_{29}% =	2.71	--	--
H_{31}% =	2.35	--	--
H_{35}% =	2.43	2.6	--
H_{37}% =	1.42	2.24	--
H_{41}% =	1.87	--	--
H_{43}% =	1.68	--	--
H_{47}% =	1.62	1.81	1.56
H_{49}% =	1.46	1.60	1.37

	🟦	🟥	🟩
H_6% =	6.66	--	--
H_{12}% =	2.18	2.32	--
H_{18}% =	1.26	--	--
H_{24}% =	0.88	0.91	0.83
H_{30}% =	0.68	--	--
H_{36}% =	0.55	0.50	--
H_{42}% =	0.45	--	--
H_{48}% =	0.38	0.3	0.1

(a) (b)

Fig. 12. Harmonic spectrum under various scenarios. (a) Harmonic spectrum for the Phase A mains AC current. (b) Harmonic spectrum of the DC bus voltage. Only 20% and 10% of the grid current and DC voltage fundamental, respectively are illustrated.

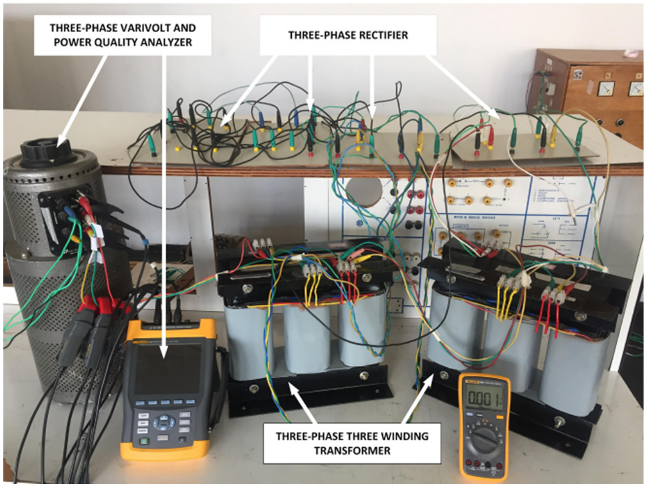


Fig. 13. Simplified laboratory prototype.

converter) and that the DC bus voltage was 2.58%.

Scenario 3 is simulated while maintaining scenario 2 active at t = 0.35 s. In this case, the system operated as a 6-pulse converter with even lower power. The THD of the phase A mains AC current was 25.67%, and the DC bus voltage was 7.29%. Fig. 12 shows the harmonic spectrum of the three scenarios. One can conclude that the proposed converter can operate as a 12 to 6-pulse converter (depending on the scenarios) in a degraded mode. This 6 and 12-pulse operation can be used only in the case of industrial rectifier applications.

6. Results by experimental validation

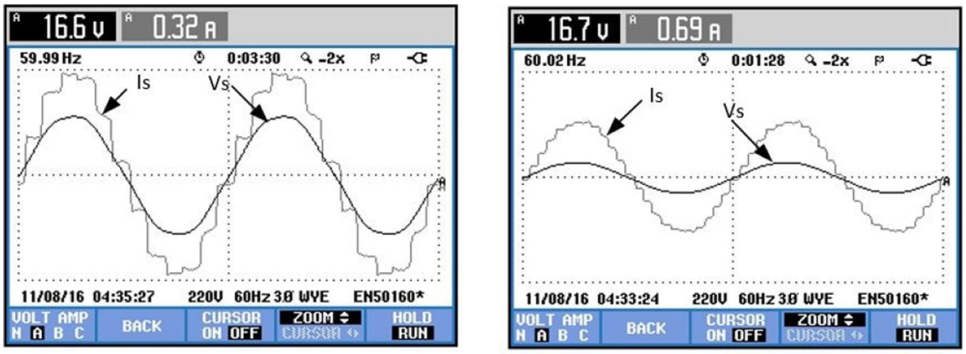
The implemented system was considered as follows to prove the viability and performance of the proposed 24-pulse converter in HVDC systems:

- The transformers used were arranged in extended delta connection in the primary winding, a wye connection in the secondary winding, and a delta connection in the tertiary winding. The taps were calculated in Section 3.
- The 6-pulse AC/DC converter bridges used were diodes, and were therefore uncontrolled, i.e. with a firing angle α equal to 0.
- The DC load was considered to be a R-L load with three 127 V/100 W bulbs in series and one inductor of value L = 114.5 mH.

Fig. 13 shows the general view of experimental setup and the main components of the 24-pulse system implemented at the research development lab.

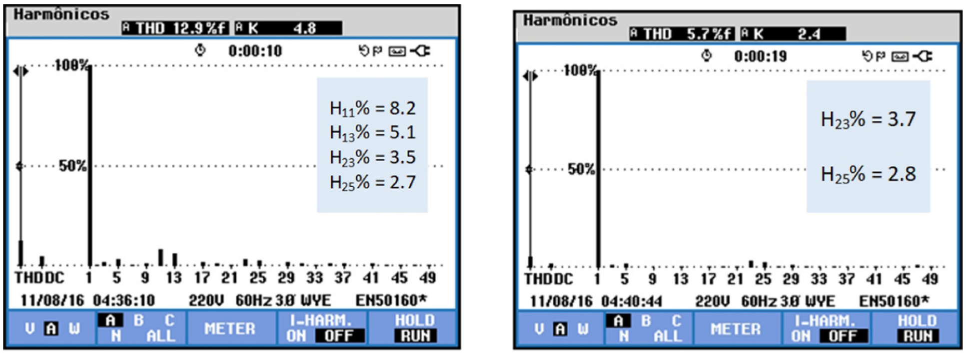
Fig. 14 shows the waveforms of the source voltage V_s and current I_s of the conventional 12-pulse converter and the proposed 24-pulse converter system. Note that the current in the proposed converter more closely approximates a sine wave compared to the conventional 12-pulse converter.

Fig. 15 shows the harmonic spectrum for both systems. One can observe that the THD value for the phase A mains current was approximately equal to 12.9% for the 12-pulse converter and 5.7% for the proposed converter. These values also meet IEEE 519 requirements [17]. One can see that the 11th, 13th, 35th, and 37th order harmonics were practically eliminated. Therefore, based on the experimental results, we can conclude that the proposed 24-pulse converter performed better than the conventional converter normally used in HVDC.



(a) (b)

Fig. 14. Current and network voltage waveforms of both systems (qualitative aspect). (a) Conventional 12-pulse converter. (b) Proposed 24-pulse converter.



(a) (b)

Fig. 15. Harmonic spectrum for both systems. (a) Conventional 12-pulse converter. (b) Proposed 24-pulse converter.

7. Conclusion

The proposed 24-pulse system that was simulated, implemented for the case of using a extended delta connection in the primary winding of the three-winding transformer, and tested, presents several advantages over the conventional system. These advantages include lower harmonic content in the AC mains current and DC bus voltage. This results in financial savings in the installation of AC and DC filters. Furthermore, less physical space is required for filter installation, as the 11th and 13th order harmonic filters are no longer required. This factor is especially relevant, as active filters are used when there is no physical space for installing filters [13], because they occupy smaller spaces. This paper sought to provide an alternative application for a 24-pulse system that resulted in an active filter with lower power. The three winding transformers employed in this paper resulted in several advantages, principally easier maintenance access because the converter units are identical, lower costs, and less required physical space. Nonetheless, the proposed 24-pulse converter system can act as a 12 to 6-pulse system in degraded mode, depending on the scenario for application only in industrial rectifiers. This paper therefore highlights an important new aspect for HVDC power system applications, as there are currently no existing studies on 24-pulse used in this way for HVDC systems in the technical literature. In some industrial systems, 18, 24 and up to 48-pulse converter arrangements are employed to mitigation harmonic distortion, and for use in AC electric motors [15]. It is noteworthy that the zigzag connection used in the primary winding of the three-winding transformers allows access to the neutral. This promotes protective features for grounding. Furthermore, the power factor of the 24-pulse system is slightly higher than that the power factor on the 12-pulse system, when considering the same firing angle α and overlap angle μ in both cases, as can be seen in the simulations presented in Fig. 8.

For future studies we recommend papering the dynamic performance and control of a complete HVDC system incorporating an inverter station that can be simulated and analysed based on a model using real HVDC transmission system parameters.

Authors'contributions

Christel Enock Ghislain: Conceptualization, Methodology, Validation, Formal analysis

Angelo José Junqueira Rezek: Conceptualization, Validation, Investigation, Supervision

François-xavier Fifatin: Writing - Original draft preparation, Writing - Review and Editing

Vinicius Zimmermann: Validation, Writing- Original draft preparation, Writing- Review and Editing, Visualization

Robson Bauwelz Gonzatti: Software

José Carlos de Oliveira: Validation

Rafael Di Lorenzo Correa: Visualization

Conflicts of interest

The authors declare no conflicts of interest.

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