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Harmonic Distortion Analysis in Thyristor Rectifier System in Aluminum Smelting Industry and Its Mitigation Strategy Based on IEEE STD 519

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Abstract : *Thyristor-based rectifiers in the aluminum smelting industry produce harmonics that can degrade power quality and affect the reliability of the electrical system. This study aims to analyze the harmonic characteristics of 6-pulse and 12-pulse rectifiers, examine their relationship with the IEEE Std 519-2022 criteria, and evaluate mitigation strategies. The study uses a literature study method with a descriptive quantitative analysis approach. The population and sample of the study are not defined in the form of respondents, but rather in the form of scientific literature and technical publications relevant to rectifier harmonics, power quality standards, and harmonic mitigation. The research instrument is in the form of literature documentation, while the analysis is carried out through the identification of harmonic orders using the equation (h = kp \pm 1), wave reconstruction based on Fourier series, Total Harmonic Distortion (THD) estimation, and conceptual comparison with the Total Demand Distortion (TDD) criteria. The analysis results show that the theoretical current THD of the 6-pulse rectifier reaches 31.1%, while the 12-pulse configuration reduces it to 15.3%. Mitigation strategies studied include increasing the number of pulses, passive harmonic filters, and shunt active power filters. Conclusion: THD reduction can be achieved through the selection of rectifier configurations and the application of filters, but compliance with IEEE Std 519-2022 must be verified through TDD measurements and the Isc/IL ratio at the common connection point.*

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Introduction

The aluminum smelting industry uses an electrolysis process (the Hall-Héroult process) that requires a very large direct current (DC) supply, generally reaching hundreds of kiloamperes at a relatively low DC voltage per cell, because each electrolysis pot operates at a voltage of around 3.9-4.5 volts and is arranged in series in hundreds of units to form a potline. To meet these current requirements, large-capacity diode- or thyristor-based rectifiers or rectiformers are used to convert the AC supply from the grid into DC.

The nature of the rectifier as a non-linear load causes the current it draws from the AC network to no longer be a pure sinusoidal current, but instead contains frequency components that are multiples of the fundamental frequency, called harmonics. This phenomenon causes distortion of the current and voltage waves at the common connection point (PCC), which can impact transformer overheating, reduced equipment life, disruption to the protection system, resonance with the capacitor bank, and even electromagnetic interference to surrounding control and instrumentation equipment.

Most of the available literature discusses rectifier harmonic characteristics (e.g., Rice, 1986; Matin, 2013) or mitigation techniques (e.g., Thakkar et al., 2015; Al-Mahari et al., 2018) in a relatively isolated manner, and is generally oriented towards specific software-based numerical simulations. Studies that explicitly link analytical calculations of characteristic harmonic orders, their quantitative validation through Fourier series waveform reconstruction, and their correlation with actual IEEE Std 519 evaluation criteria (THD versus TDD and Isc/IL ratio) in the context of the aluminum smelting industry are still relatively limited. This article aims to fill this gap and to emphasize the limitations of interpreting theoretical THD results against actual IEEE Std 519 compliance criteria.

As a group that studies DC rectifier systems in electrolysis-based industries, a deep understanding of harmonic characteristics and mitigation strategies is important to master, both as a scientific foundation for prospective operators and planners of industrial electrical systems and to ensure compliance with applicable power quality standards. This article aims to: (1) analyze the sources and characteristics of harmonics generated by thyristor rectifiers in various pulse configurations, (2) examine the relationship between the harmonic distortion (THD) levels of the analysis results and the current distortion limit (TDD) criteria in IEEE Std 519, and (3) examine harmonic mitigation strategies commonly applied in the aluminum smelting industry along with their technical-economic considerations.

Literature review

Working Principle of Rectifier in Aluminum Smelting Industry

Rectifiers used in aluminum power lines are generally rectifiers, which are a combination of a rectifier transformer and a three-phase diode- or thyristor-based rectifier bridge. Several rectifier units are operated in parallel to achieve the required total power line current. The basic configuration commonly used is a six-pulse bridge, while to suppress harmonic distortion on the AC side, many modern installations use a 12-pulse configuration obtained by connecting two 6-pulse bridges through a transformer with a 30° phase shift, or even 18-pulse and 24-pulse configurations for more stringent power quality requirements.

Harmonic Phenomena in Rectifier Systems

In an ideal p-pulse rectifier, the characteristic harmonic orders that arise on the AC side follow the equation $h = kp \pm 1$, where k is a positive integer (1, 2, 3, ...) and p is the number of rectifier pulses. For a 6-pulse rectifier, the dominant harmonic orders are the 5th, 7th, 11th, 13th, and so on, while a 12-pulse rectifier eliminates the 5th and 7th orders so that the dominant harmonics shift to the 11th, 13th, 23rd, and 25th orders.

Based on Matin's (2013) analysis, an ideal 6-pulse rectifier produces a total harmonic distortion (THD) of 31.1% of the AC side current, while a 12-pulse configuration can reduce the THD to 15.3%. Both values represent a high level of spectral distortion of the fundamental components, but they do not directly indicate compliance with IEEE Std 519, as the standard evaluates current limits using Total Demand Distortion (TDD) normalized to the maximum load current, not THD normalized to the instantaneous fundamental current. A study by Rice (1986) also confirmed that harmonics generated by

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variable speed drives and power rectifiers significantly impact surrounding power system components, ranging from overheating of transformers to interference with protective equipment.

Power Quality Standards Related to Harmonics

IEEE Std 519 is the most commonly used reference for establishing acceptable harmonic distortion limits in power systems. This standard defines individual harmonic distortion limits as well as total demand distortion (TDD) for current, and THD for voltage, at the point of common connection (PCC). TDD is defined as:

$$TDD = [\sqrt{(\Sigma\ Ih^2 \text{ for } h = 2 \text{ to } 50)}] / IL \times 100\%$$

where Ih is the rms value of the hth-order harmonic current and IL is the maximum load current (average of the last 12 months' peak demand) at the PCC — not the instantaneous fundamental current as in the THD definition. This difference in the normalization basis is why TDD values are generally smaller than THD at full load conditions, and is the reason why THD cannot be directly compared with the TDD limits in Table 2 without actual maximum load current data. The current TDD limit itself is not a single value, but depends on the ratio of the system short-circuit current to the maximum load current (Isc/IL) at that PCC: the higher the Isc/IL ratio (the more "tough" the system is to the load), the looser the permissible current distortion limits, as summarized in Table 2. In addition to IEEE 519, the IEC 61000-4-7 standard is also commonly referred to as a general guideline for harmonic and interharmonic measurement techniques in power systems.

Table 1. Current Distortion Limits (TDD) according to IEEE Std 519-2022 for 120 V-69 kV Systems, as a Function of Isc/IL Ratio

ISC/IL	h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h ≤ 50	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 - 50	7.0	3.5	2.5	1.0	0.5	8.0
50 - 100	10.0	4.5	4.0	1.5	0.7	12.0
100 - 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Notes:*Values are in percent of IL (maximum load current) and apply to odd harmonic limits as well as TDD, which are unchanged between IEEE Std 519-2014 and IEEE Std 519-2022 editions. For even harmonics, IEEE Std 519-2022 edition limits only the 2nd, 4th, and 6th orders to 50% of the nearest odd order limit in the same group, unlike the 2014 edition which limited all even harmonics to 25% of the odd harmonic limit. Isc = maximum short-circuit current at PCC; IL = maximum load current at PCC. Adapted from IEEE Std 519-2022 (replaces IEEE Std 519-2014 since August 2022).*

As an illustration of the application of Table 2, in an aluminum smelting installation with a very large rectifier load, the Isc/IL ratio at the PCC has the potential to be in a relatively low range if the source short-circuit capacity at the connection point is not much greater than the rectifier load current — as observed in the case study of Wiestner et al. (2010) who reported the variation of THD with the network short-circuit capacity in a large-capacity smelter. However, the actual Isc/IL ratio value is highly dependent on the network configuration, source short-circuit capacity, and transformer impedance at each installation, so it cannot be generalized without specific field data. This uncertainty makes a multi-level harmonic mitigation strategy (a combination of increased pulse count and filtering) a practical necessity, rather than just an additional option, in large-capacity rectifier installations that potentially fall into the low Isc/IL category.

The Impact of Harmonics on Industrial Electrical Systems

1. Overheating in transformers due to eddy current losses and increased hysteresis at high frequencies, so that the transformer capacity needs to be reduced (derating).
2. Increased current in the neutral conductor due to the accumulation of triplen harmonics (3rd, 9th, and multiples thereof) in a three-phase, four-wire system.

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3. The risk of resonance between the reactance of the capacitor bank (for power factor improvement) and the reactance of the system at a certain harmonic order, which can increase the harmonic current and voltage.
4. Disturbances in the operation of protection equipment and instrumentation, including measuring instrument reading errors and relay mal-operation.
5. Electromagnetic interference (EMI) to control equipment, data communications, and instrumentation systems around the rectifier area.

METHOD

This study uses a literature review approach combined with descriptive quantitative analysis. Literature searches were conducted in the IEEE Xplore, ScienceDirect, Springer, and Google Scholar databases using a combination of keywords "aluminum smelter harmonic rectifier", "12-pulse rectifier harmonic", "IEEE 519 rectifier compliance", and "harmonic mitigation aluminum smelter", limited to English-language publications without year restrictions considering that some standard references (e.g., Rice, 1986) are classic and still relevant. Inclusion criteria included publications discussing the characteristics of rectifier harmonics, case studies of the aluminum smelting industry/similar heavy industries, or harmonic mitigation techniques (multi-pulse, PHF, SAPF); publications that did not contain data or technical discussions relevant to these three topics were excluded from the study. The analysis stages were as follows:

1. Identify rectifier configurations commonly used in the aluminum smelting industry (6-pulse, 12-pulse, and advanced multi-pulse configurations).
2. Calculate/estimate the characteristic harmonic order using the equation $h = kp \pm 1$ for each configuration.
3. Reconstructing the ideal AC current waveform and its harmonic spectrum using the Fourier series of p-pulse rectifier to quantitatively visualize and validate the THD calculation results.
4. Compare the theoretical THD estimates of each configuration against the IEEE Std 519 recommended limits.
5. Review published case studies in the aluminum smelting industry (including ALBA, DUBAL, and ABB technical references) to understand the application of mitigation strategies in the field.
6. Summarizes relevant harmonic mitigation strategies for application to industrial rectifier operations.

It should be noted that the quantitative data used in this article is sourced from published scientific literature, not from confidential operational data belonging to a particular company, so that the results of the study are general in nature and can be applied as an initial reference before conducting field measurements using a power quality analyzer according to IEC 61000-4-7.

Results and Discussion

Harmonic Sources in Thyristor Rectifiers

The main source of harmonics in thyristor rectifiers is the non-linear switching process where the thyristor conducts and blocks current alternately during each AC waveform cycle. The firing angle used to regulate the output DC voltage also affects the waveform of the AC current drawn from the network, so that the larger the firing angle (to reduce the DC voltage), the greater the harmonic distortion and the decrease in the AC power factor.

Estimation of Harmonic Order and THD in Various Configurations

The following table summarizes the characteristic harmonic orders and theoretical current THD estimates for several rectifier configurations commonly used in the aluminum smelting industry, based on the equation $h = kp \pm 1$ and data from Matin (2013):

Table 2. Comparison of Characteristic Harmonic Order and Theoretical THD in Various Rectifier Configurations

Rectifier Configuration	Harmonic Order Characteristics	Theoretical THD (Current)	Distortion Level Indication*

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6-pulse (diode/thyristor)	h = 6k ± 1 (5, 7, 11, 13, ...)	± 31.1%	High; potentially exceeds TDD limits in most Isc/IL categories
12-pulse (dual bridge, phase shift transformer)	h = 12k ± 1 (11, 13, 23, 25, ...)	± 15.3%	Medium; TDD verification and Isc/IL ratio are still required
18/24-pulse + active/passive filter	h = 18k ± 1 / 24k ± 1 (higher order)	< 5%	Low; potentially compliant, definitive compliance needs to be verified at PCC

Notes:*This column shows an indication of the distortion level based on theoretical THD, not a definitive compliance assessment. The THD values are calculated based on an ideal rectifier configuration according to Matin (2013) and normalized to the fundamental current, while the official IEEE Std 519 limits in Table 2 use TDD normalized to the maximum load current (IL); actual field values may vary depending on system impedance conditions and load profile.*

From the table above, it can be seen that increasing the number of pulses significantly reduces the THD of the AC side current. However, even in the 12-pulse configuration, the theoretical THD of 15.3% still indicates a high level of spectral distortion compared to the tightest TDD limit in Table 2 (5.0% for the Isc/IL < 20 category), so the application of additional filters or a further increase in the number of pulses (18 or 24 pulses) is still necessary in large capacity installations.

To clarify the distortion characteristics quantitatively, the network side AC current waveform reconstruction is carried out based on the ideal Fourier series of a p-pulse rectifier (referring to Mohan et al., 2003). For a 6-pulse rectifier, the AC side current is expressed as:

$$i(t) = (2\sqrt{3}\, Id/\pi) [\cos(\omega t) - (1/5)\cos(5\omega t) + (1/7)\cos(7\omega t) - (1/11)\cos(11\omega t) + (1/13)\cos(13\omega t) - ...]$$

whereas for a 12-pulse rectifier, the 5th and 7th harmonic components cancel each other out due to the sum of two 6-pulse bridges that are 30° out of phase, so the equation becomes:

$$i(t) = (4\sqrt{3}\, Id/\pi) [\cos(\omega t) - (1/11)\cos(11\omega t) + (1/13)\cos(13\omega t) - (1/23)\cos(23\omega t) + (1/25)\cos(25\omega t) - ...]$$

where Id is the DC current (assumed constant/flat) and ω is the fundamental angular frequency. The reconstruction in this study numerically sums the fundamental component and all characteristic harmonics in both equations up to the 199th order, with alternating signs as per the equation above. Figure 1 shows the results of the wave reconstruction for the 6-pulse and 12-pulse configurations, while Figure 2 shows their amplitude spectra.

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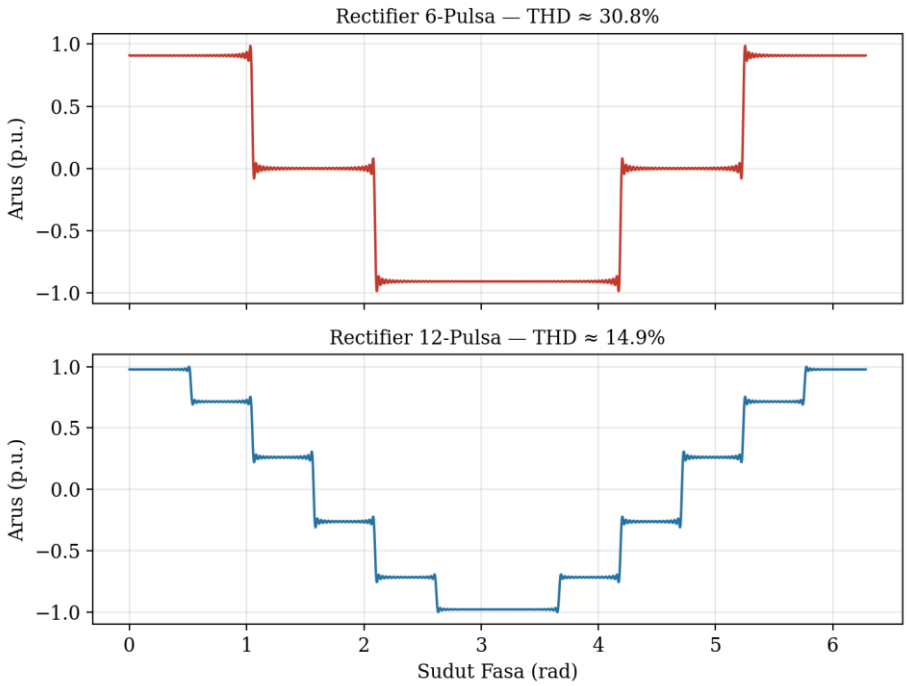


Figure 1. Reconstruction of the grid-side AC current waveforms for 6-pulse and 12-pulse rectifiers (Fourier series, ideal conditions, constant DC load). The author's calculations and visualizations are not quoted from any reference.

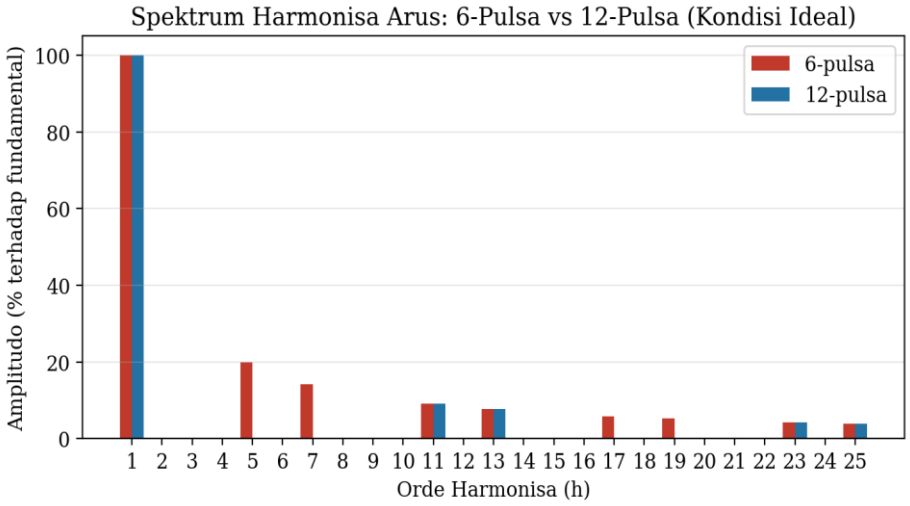


Figure 2. Current harmonic spectrum resulting from Fourier series reconstruction: 6-pulse vs. 12-pulse rectifier (ideal conditions). The author's calculations and visualizations are not quoted from any reference.

The waveforms in Figure 1 show a quasi-square wave pattern typical of a 6-pulse rectifier with a conduction width of 120° per half cycle, while in the 12-pulse configuration the waveform approaches a stepped sinusoidal shape due to the summation of two 6-pulse bridges that are phase shifted by 30°. The reconstructed THD (≈30.8% for 6-pulse and ≈14.9% for 12-pulse) is consistent with the theoretical values in Table 1, with a small difference due to the limitation of the summed harmonic orders (up to the 199th order) compared to the infinite series. In Figure 2, it is clear that the 12-pulse configuration eliminates the dominant 5th and 7th order harmonics in the 6-pulse configuration, leaving the 11th and

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13th order harmonics as the next dominant components — in line with the equation h = 12k ± 1 in Table 1.

Case Study in the Aluminum Smelting Industry

Several published case studies demonstrate the practical application of harmonic mitigation strategies in the aluminum smelting industry. Thakkar et al. (2015) examined a comprehensive harmonic mitigation approach to the power grid of an aluminum smelting industry, including a combination of passive filters and rectifier configuration adjustments. Wiestner et al. (2010) from ABB reported power quality measurements at a large-capacity smelter with medium- and high-voltage (220 kV) compensation systems, showing that THD varied with the short-circuit capacity of the network at the connection point.

Meanwhile, Al-Mahari et al. (2018) proposed a new potline rectifier scheme with hybrid active filter capabilities that has been proven by simulation to provide better harmonic attenuation than conventional passive filter schemes, as applied to several large smelters such as Aluminium Bahrain (ALBA). Badrzadeh et al. (2011) also published a passive harmonic filter design procedure for grid-connected aluminum smelting installations, including harmonic penetration studies under various operating scenarios (including N-1 and N-2 generation conditions and outages of one of the filters or rectifier transformers) to ensure filter reliability under contingency conditions. These findings are relevant as a reference for the aluminum smelting industry in Indonesia in designing and evaluating harmonic mitigation systems in operating rectifier installations. Table 3 summarizes the main characteristics of each of these case studies.

Table 3. Summary of Published Case Studies of Harmonic Mitigation in the Aluminum Smelting Industry

Studies	Focus/Object	Mitigation Approach	Key Findings
Wiestner et al. (2010)	220 kV smelter, medium-high voltage compensation	Field measurement & compensation system	THD varies with the short-circuit capacity of the network at the connection point.
Thakkar et al. (2015)	Aluminum smelting industry power grid (general)	Combination of passive filter & rectifier configuration settings	A comprehensive mitigation approach reduces distortion at multiple points in the network.
Al-Mahari et al. (2018)	Rectiformer potline, ALBA case study	Hybrid active filter (hybrid SAPF)	Harmonic attenuation is better than conventional passive filter schemes (simulation)
Badrzadeh et al. (2011)	Grid-connected aluminum smelter	Passive filter design & multi-scenario harmonic penetration study	Filter remains reliable under contingency conditions (N-1/N-2, filter/transformer outage)

Notes:*The summary is qualitative based on the descriptions in the source publication; detailed quantitative data (measured THD/TDD values, filter capacities) are not all publicly published by the original source and are therefore not reproduced here.*

Harmonious Mitigation Strategy

In general, harmonic filters are installed in shunt (parallel) on the common connection point (PCC) busbar between the rectifier and the network, as illustrated in Figure 3. This position allows the filter to absorb the harmonic currents generated by the rectifier before they spread to the wider network side.

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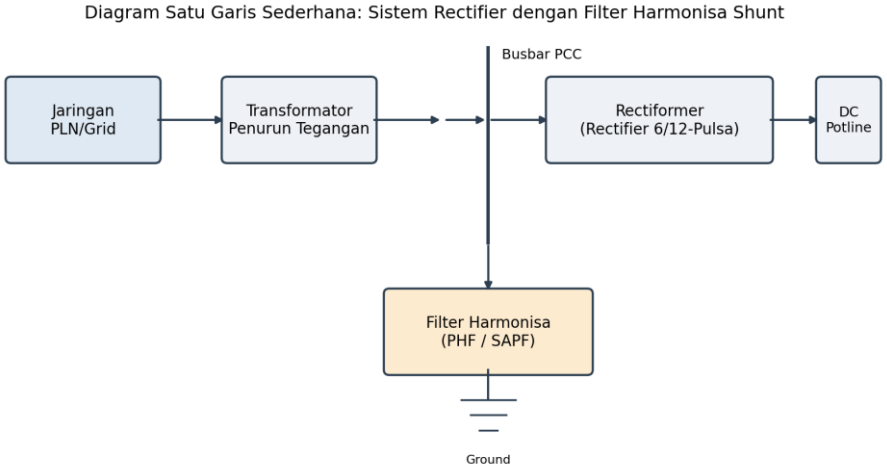


Figure 3. Simple one-line diagram of a rectifier system with a harmonic filter installed in shunt on the PCC busbar. The conceptual diagram is prepared by the author for illustrative purposes and is not a diagram of a specific existing system.

1. Multi-Pulse Rectification

This strategy is implemented by connecting several rectifier bridges through a transformer with a specific phase shift (e.g., 30° for 12-pulse, 20° for 18-pulse), so that some harmonic orders cancel each other out (cancellation) on the primary side of the transformer. This method is passive, reliable, and does not require additional power electronic components, but further increasing the number of pulses requires additional transformers and installation space, which increases investment costs.

2. Passive Harmonic Filter (PHF)

A PHF consists of a series of inductors and capacitors tuned to absorb harmonic currents of a specific order, typically installed on the medium-voltage side near the rectifier. The advantages of a PHF are its relatively low cost and simple construction, but its performance is highly dependent on system impedance conditions and is at risk of resonance if the network configuration changes. A case study by Park et al. (2021) on a steel mill electrical system with a large capacity non-linear load confirms that similar considerations apply widely to other heavy industrial installations: the need to account for overvoltage risks under light load conditions, the potential for parallel resonance with step-down transformers, and the need to consider K-factors and harmonic peak voltages in the selection of reactor and filter capacitor components.

3. Shunt Active Power Filter (SAPF) and Hybrid Scheme

SAPF uses a power electronic converter to inject real-time compensation currents that are out of phase with the measured harmonic components, thus adapting to dynamic changes in the load conditions of the power line. Hybrid schemes combining PHF with SAPF, as reviewed by Al-Mahari et al. (2018) and Rajesh & Nirmalkumar (2016), have been shown to provide better harmonic compensation than passive filters alone, albeit with higher investment costs and control complexity.

4. Economic Considerations (CAPEX vs Performance)

The choice of harmonic mitigation strategy in practice is not only determined by technical performance, but also by considerations of initial investment costs (CAPEX) and operational costs. Increasing the number of pulses through a phase-shifting transformer generally requires significant investment costs for additional transformers and installation space, but is relatively low in terms of operational costs due to its passive nature and minimal maintenance. PHF offers a much lower investment cost than SAPF, but its performance is less adaptive to load changes and risks resonance if the network configuration changes. In contrast, SAPF is technically superior because it is able to respond to dynamic load conditions in real time, but requires a much higher initial investment due to the complexity of its power electronics components and control system. With these considerations, a hybrid

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scheme that combines PHF as the main support with a smaller capacity SAPF as dynamic compensation can be an attractive alternative, because it has the potential to reduce CAPEX compared to a full SAPF while still maintaining some of its adaptive advantages. However, determining the most economical strategy cannot be generalized simply, because it depends on the rectifier capacity, the actual harmonic spectrum, system power, space requirements, investment and maintenance costs, and the power quality targets to be achieved. the final selection should be based on a technical-economic study of actual system conditions.

Implications for Industrial Electrical Operators

For operators handling DC rectifier systems in the aluminum smelting industry, harmonic distortion monitoring can be integrated into the rectifier monitoring HMI system along with existing current stability parameters and thyristor protection alarms. Periodic monitoring using a power quality analyzer, accompanied by recording THD trends over time, can be part of a predictive maintenance program to detect early indications of harmonic resonance and degradation of installed filter performance.

LC Filter Circuit Principles and Practical Design Considerations

One form of passive harmonic filter implementation commonly used in industry is a series LC filter installed in shunt (parallel) to the busbar. This filter is composed of an inductor (reactor) and a capacitor connected in series, with the impedance at the nth harmonic frequency expressed as $Zn = R + j(n\omega L - 1/(n\omega C))$, where the inductive reactance $XL = \omega L = 2\pi fL$ and the capacitive reactance $XC = 1/(\omega C) = 1/(2\pi fC)$. In series resonance conditions, XL is equal to XC so that the filter impedance approaches its resistance value only ($Zn \approx R$). This condition causes most of the harmonic currents at that frequency to be attracted to flow through the low-impedance filter branch, so that the proportion of harmonic currents spreading to the main network is significantly reduced. The filter resonance frequency is calculated using the equation $fr = 1/(2\pi\sqrt{(LC)})$, and the values of L and C are chosen so that the resonance frequency approaches the target harmonic order to be damped, generally the 5th and 7th orders in a system with a 6-pulse rectifier.

In addition to harmonic attenuation, this type of LC filter also provides capacitive reactive power compensation at the fundamental frequency, thereby simultaneously improving the system power factor. In practice, filters can be arranged in several topologies, for example a single reactor serving several parallel capacitor groups, or separate reactors for each filter branch. The choice of this topology affects the effective inductive-capacitive impedance ratio at the measurement point, thereby shifting the actual resonance point of the system. In topologies with a common reactor, all capacitor branches connected to the reactor generally need to be operated simultaneously, because disconnecting one branch can significantly shift the filter resonance point and potentially reduce the effectiveness of the designed harmonic attenuation.

One of the side effects that needs to be taken into account in the design of LC filters is the voltage rise on the capacitor elements due to the presence of series inductive reactance, which can increase the capacitor's operating voltage beyond the nominal system voltage. Therefore, capacitors used in LC filters are generally selected with a voltage rating that has a certain margin above the nominal operating voltage, and the capacitor's working voltage needs to be monitored periodically to remain within the insulation tolerance limits permitted by the manufacturer.

From a maintenance perspective, capacitor components in LC filters require regular inspection for signs of leaks, physical deformation such as casing swelling, and re-measurement of capacitance values to detect dielectric degradation over time. Reactor components require inspection of the condition of the protective coating and cooling ventilation ducts, considering that losses in the reactor generate heat that needs to be dissipated adequately to prevent overheating. From an occupational safety perspective, the energy stored in the capacitors remains even after the power supply has been disconnected, so common practice requires a certain waiting time (discharge time) before personnel are allowed access to the filter area, in line with Lock-Out Tag-Out (LOTO) procedures and zero energy verification before any maintenance work is carried out.

Conclusion

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Thyristor rectifiers in the aluminum smelting industry are a significant source of harmonics due to their nonlinear nature. A 6-pulse configuration produces a theoretical current THD of approximately 31.1%, while a 12-pulse configuration reduces it to approximately 15.3%; both values indicate a high level of spectral distortion and indicate the need for harmonic mitigation, but definitive compliance evaluation with IEEE Std 519 requires Total Demand Distortion (TDD) data normalized to the maximum load current and determination of the Isc/IL ratio category at the point of common connection (PCC) from field measurements—not just theoretical THD values. Three relevant mitigation strategies are increasing the number of pulses through a phase-shifting transformer, installing a passive harmonic filter tuned to the characteristic harmonic order, and implementing a shunt active power filter for dynamic compensation under varying load conditions, with the strategy selection needing to consider load capacity, network short-circuit strength, and investment and operational costs. Field measurements using a power quality analyzer according to IEC 61000-4-7, followed by TDD calculations and Isc/IL category mapping according to IEEE Std 519, remain necessary steps to definitively ensure compliance status in operating rectifier installations.

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