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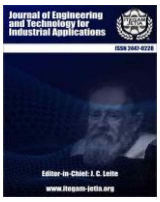

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CAUSES, EFFECTS, AND PRACTICAL METHODS OF HARMONIC REDUCTION IN IRANIAN CEMENT FACTORIES WITH A FOCUS ON PLANT DEVELOPMENT

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ABSTRACT

Cement factories in Iran are considered among the oldest industries. Due to favorable domestic and international markets, these plants have pursued development, whether willingly or unwillingly. Development involves improving the existing structure to enhance efficiency and adding production lines parallel to the old ones. In this situation, the presence of very large nonlinear loads in these industries, which are mostly formed by high-power variable-speed electric drives, has always caused serious problems due to harmonic distortions imposed on the factory and distribution lines. These effects should be considered in various sections when developing and designing new electrical systems. Despite various studies on this subject, none has presented a comprehensive approach specifically for this industry. This article delves into a thoroughly practical and empirical examination of the causes and consequences stemming from harmonics, alongside the constraints posed by standards. It also scrutinizes implementable techniques for solving harmonic-related problems and mitigating their effects with a focus on the development outlook of cement factories.

I. INTRODUCTION

Cement factories in Iran are considered among the oldest and largest industries. Due to the presence of large DC and AC motors and the necessity of controlling them, high-power AC and DC drives are used in various divisions such as mills, induced draft fans (known as ID fans), crushers, separators, and rotary kilns. The input voltage levels of the drives are typically in MV (6.3 KV) and LV (400 V, 690 V, and 800 V) levels. Most of Iran's cement factories operate within these voltage ranges and other voltage levels rarely observed. Motors and large drives in Iran's cement industries are often DC, but in development departments and modern factories, only AC motors and drives are utilized. Figure 1 illustrates a single-line diagram (SLD) of the development section of one of the major cement producers in Iran. The presence of large AC motors and drives in this factory signifies high energy consumption within this industry and as a result a large volume of harmonics with high amplitudes. Generally, the energy consumption of the cement industry accounts for nearly 5% of the total global industrial energy consumption [1], and the advantage of controlling harmonics caused by variable speed drives (a major source of nonlinear loads in the cement industry), besides its impact on the protection and lifespan enhancement of electrical equipment, can result in a reduction in losses, thereby decreasing global energy consumption, as well as return on investment in a cement plant [2].

So far, various studies, measurements and practical investigations have been carried out in the field of harmonics, methods of reducing them and improving power quality specifically for the cement industry [2-8]. However, these studies have been few and do not offer a comprehensive perspective to the reader for decision-making in electrical designs aimed at cement plant development. This paper attempts to not only present the causes, effects, measurement techniques, and practical comparison of control and reduction methods for harmonics in the cement industry but also provide a succinct review of relevant standards. Such insights can significantly assist electrical engineers in the design of electrical systems and the development of cement plants.

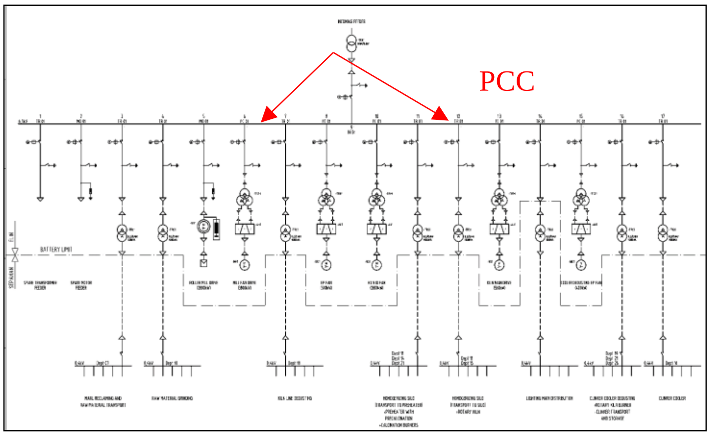


Figure 1: Single-line diagram of development section of modern cement plant in Iran.
Source: Authors, (2024).

From the point of view of the utility power system, only the amount of distortions in the input medium voltage (MV) levels holds significance, whereas in industrial plants, distortions at low voltage (LV) levels are crucial [5]; But in a cement factory, due to the existence of a dedicated substation and the use of both voltage levels, the values of harmonics in both sides of the grid and the plant are important. Therefore, the approach of this manuscript is to provide appropriate solutions while considering this aspect.

II. HARMONICS AND THEIR GENERATION CAUSES IN CEMENT INDUSTRIES

In accordance with IEEE 519-1992, harmonic is defined as a sinusoidal component of a periodic waveform or quantity (such as voltage or current), possessing a frequency that is a whole-number multiple of the fundamental frequency (50 or 60 Hz) [9]. Harmonics arise from all nonlinear sources within a cement plant. A source is considered nonlinear if its impedance varies with the applied voltage at any moment of time. Due to this impedance variation, the current drawn by the nonlinear load is also nonlinear [10]. Essentially, when a non-linear load is connected to a sinusoidal voltage source, the waveform becomes non-sinusoidal. Power electronic converters (AC/AC, AC/DC, DC/AC, DC/DC) and transformers are considered as sources of non-linear loads. Non-linear loads present in a cement plant include variable speed drives (variable frequency), uninterruptible power supplies (UPS), generators, power and distribution transformers, lighting systems (including LED or gas discharge lamps), computers, programmable logic controllers (PLCs), static var compensators (SVCs), and some laboratory equipment equipped with switching power supplies or rectifiers; nonetheless, the most influential nonlinear load in cement industries are large variable speed drives. They are the most important sources of harmonics and inter-harmonic distortions in cement industries [6]; although, one should not overlook the effects of arc furnaces that exist in a few cement factories in Iran. Table 1, inspired by the SLD of Figure 1, illustrates the power of large AC variable speed drives of the development segment of the sample factory, which can be relatively generalized for other cement plants in Iran.

Table 1: Large AC variable speed drives in a modern cement plant sample in Iran.

Equipment	Power
Mill fan drive	3800 kW
Kiln ID fan	2800 kW
Roller mill drive	2800 kW
Kiln main drive	560 kW
EP fan	500 kW
Cooler Dedusting EP fan	400 kW

Source: Authors, (2024).

The mentioned drives draw large non-linear or so-called non-sinusoidal currents from the grid and distort the power supply voltage waveform at the point of common coupling (PCC). Typically, the PCC is defined as the closest point to the user in the power system, so that the operator (system owner) can provide services to other subscribers from that point. For industrial users, the PCC is often considered at the high-voltage (HV) side of the transformer, while for commercial users, it is situated at the LV side of the transformer [9]. From the point of view of a cement plant with a dedicated substation, this point is considered to be on the MV side of the distribution transformers, i.e. the 6.3 kV side of the SLD in Figure 1 (where all the distribution transformers are connected). Figure 2 shows the equivalent circuit of a factory distribution system with non-linear load connection. The voltage in PCC is displayed as V_{PCC} and is calculated by subtracting the source voltage from the source impedance voltage drop (LS) caused by the passage of the nonlinear current i_{ac} as follows

$$V_{PCC} = (V_s - V_L) = \left\{ V_S - L_s \frac{d(i_{ac})}{dt} \right\} \quad (1)$$

By reason of the nonlinear nature of the current flow i_{ac} through the LS impedance, distortions in V_{PCC} will be observed. To mathematically express the non-linearity of current and voltage at the PCC, Fourier analysis is employed. Accordingly, the waveforms of complex alternating voltage and current can be expressed as the sum of an infinite number of sinusoidal oscillatory functions with different frequencies and amplitudes, which are integer multiples of the fundamental frequency.

Equations (2) and (3) represent symmetrical AC current and voltage without DC component at PCC point respectively, where i_{ac1} and V_{PCC1} are the fundamental frequency components (50 or 60 Hz), and i_{ach} and V_{PCCh} are components at the h_{th} harmonic frequency [10]. Figure 3 illustrates the practical measurement of root mean square (rms) values of voltages and currents containing harmonics at the PCC of a cement factory.

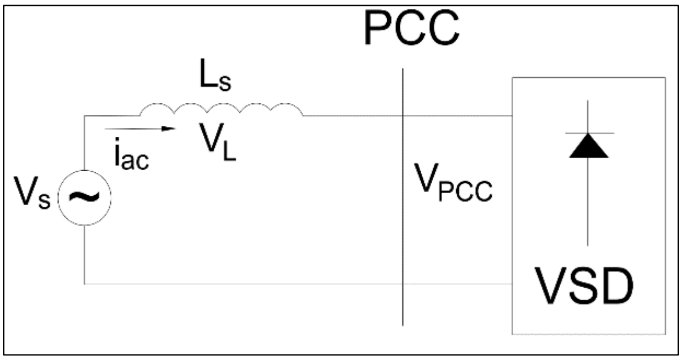


Figure 2: Equivalent circuit of the distribution system and PCC location.
Source: Authors, (2024).

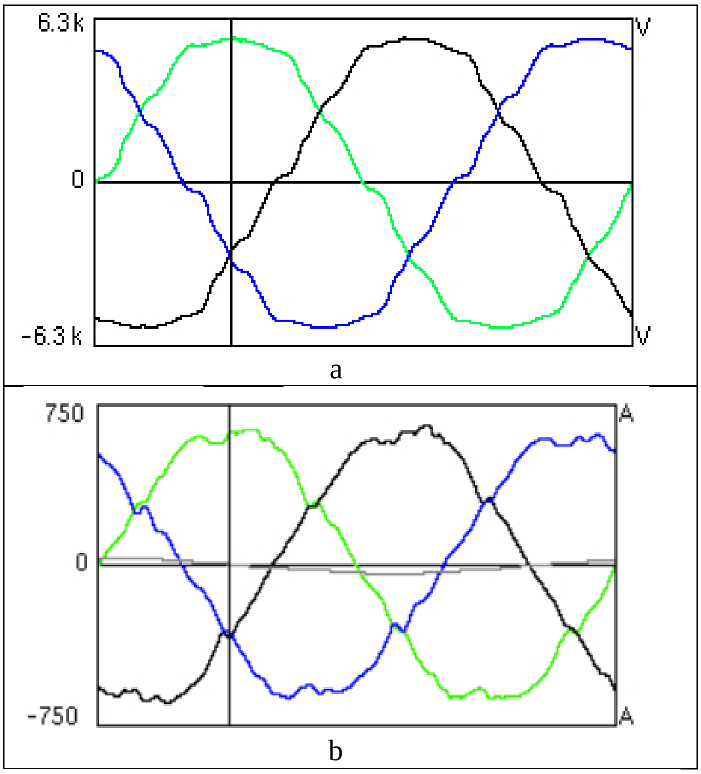


Figure 3: Measured rms voltage (a) and current (b) containing harmonics at the PCC of a cement factory.
Source: Authors, (2024).

$$i_{ac}(t) = i_{ac1}(t) + \sum_{h=2}^{\infty} i_{ach}(t) \quad (2)$$

$$V_{PCC}(t) = V_{PCC1}(t) + \sum_{h=2}^{\infty} V_{PCCh}(t) \quad (3)$$

The characteristic harmonics of electrical drives (or all power electronic converters) in steady-state are obtained from equation (4) [10],[11] and the amplitude of harmonic currents for an ideal square wave from equation (5) [11], where h represents the harmonic order, P is the number of pulses per cycle, n is any integer, I_h is the harmonic current of the h_{th} order, and I_1 is the fundamental current.

$$h = nP \pm 1 \quad (4)$$

$$I_h = \frac{I_1}{h} \quad (5)$$

Based on equations (4) and (5), for prevalent electrical drives in cement plants, whether with DC or AC motors, the characteristic or dominant harmonics and the percentage of harmonic currents, are as follows:

- Predominant harmonics in 6-pulse drives: 5, 7, 11, 13, 17, 19, 23, 25, ...
- Predominant harmonics in 12-pulse drives: 11, 13, 23, 25, 35, 37, ...
- Predominant harmonics in 18-pulse drives (currently not common in Iranian cement plants): 17, 19, 35, 37, ...
- The magnitude of harmonic currents for the 5th, 7th, 11th, 13th, 17th, orders are, in turn, 20%, 14.3%, 11.1%, 7.7%, 5.8%, ...

The amount of distortion in voltage and current waveforms at the PCC are determined by the Total Harmonic Distortion (THD) index and calculated by equations (6) and (7) respectively.

$$\%THD_{Vpcc} = \frac{\sqrt{\sum_{h=2}^{\infty} V_{pcch}^{2}}}{V_1} \times 100 \quad (6)$$

$$\%THD_{I} = \frac{\sqrt{\sum_{h=2}^{\infty} I_{h}^{2}}}{I_1} \times 100 \quad (7)$$

IEEE 519-2014 introduces an additional metric, known as Total Demand Distortion (TDD), to assess the overall impact of distortion on the current waveform at the PCC. TDD is a percentage of the maximum demand current at the PCC and is computed using equation (8):

$$\%TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_{h}^{2}}}{I_L} \times 100 \quad (8)$$

In the above equation, I_h represents the magnitude of individual harmonic components (rms amps), h denotes the harmonic order, and I_L stands for the maximum demand load current (rms value) at the PCC, typically defined as the sum of load currents associated with maximum demand during each of the twelve previous months divided by 12. TDD can also be represented as a measured %THD_I per unit of load current [10]; however, TDD is utilized at the PCC instead of THD_I.

Normally, harmonics up to the 50th order (in typical industrial applications, which Iran's cement factories also follow, up to the 25th order [10]) are used to measure THD_{Vpcc}, THD_I and TDD. Harmonic components beyond the 50th order are measured only if necessary (for sensitive applications) [9]. Additionally, IEEE 519-2014 introduces the following relationships under the headings of very short time and short time harmonic measurements. These measurements were not present in previous IEEE standards. Very short time harmonic values are evaluated over a 3-second interval by aggregating 15 consecutive sections and 12 (or 10) cycles for 60 (or 50) Hz power systems, and are calculated using equation (9). In practice, the duration of this measurement is 24 hours. Short time harmonic values are also assessed for a specific frequency component over a 10-minute interval based on summing up 200 consecutive very short-time values by equation (10). Practically, the duration of this measurement is one week.

$$F_{n,vs} = \sqrt[2]{\frac{1}{15}\sum_{i=1}^{15} F_{n.i}^{2}} \quad (9)$$

$$F_{n,sh} = \sqrt[2]{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),i}^{2}} \quad (10)$$

In equations (9) and (10), F represents the rms values of voltage or current, n denotes the harmonic order, i is a simple counter, and the subscripts vs and sh correspond to "very short" and "short", respectively.

The recommended values and limits for voltage and current distortion are outlined in Section IV. It's noteworthy that in cement plants without arc furnaces (similar to the majority of cement plants in Iran), odd harmonics are predominantly present, and in most cases, even harmonics can be disregarded. odd harmonics are often dominant and even harmonics can be ignored in most cases.

III. HARMONIC EFFECTS ON CEMENT PLANT DEVELOPMENT

The penetration of new equipment such as mills, fans, crushers, rotary kilns, etc., into the development divisions of a cement factory significantly alters harmonic conditions. An empirical recommendation suggests conducting harmonic studies in the current state of the factory prior to the design of development sections; Because changes in new harmonic conditions can lead to damage to old equipment, reduce power factor, increase maintenance costs, and energy consumption [3], [8], [10], [12]. The effects of harmonics in cement factories vary depending on the type of electrical equipment and the sensitivities of different departments. Usually, the problems caused by harmonics are not obvious at first glance and operators only observe secondary effects such as sudden production line interruptions, transformer overheating, and electronic equipment malfunctions. In many cases, attempts are made to solve the problem (such as increasing transformer capacity, increasing cable size, and so on) regardless of the root cause of these issues (i.e., harmonics). However, it should be noted that even if there are no apparent problems in the existing factory, it is uncertain how close it is to a critical situation [8]. Minor developments or optimizations in cement factory production lines (such as using power factor compensators, changing DC drives to modern AC drives, etc.) will reveal these effects. It should be noted that all protective relays, capacitor banks, reactors, cables, transformers, and switches are not designed and sized for the effects caused by harmonics. It should be acknowledged that none of the protective relays, capacitor banks, reactors, cables, transformers, and switches are designed and sized to mitigate the effects caused by harmonics.

The addition of new equipment means an increase in non-linear current drawn from the AC source. These harmonic currents pass through all impedances between the load and the source, causing voltage drops for each harmonic frequency. The total voltage distortion, resulting from the vector summation of all individual voltage drops, is substantially influenced by the impedance between the source and the load. The significant effects of harmonics in cement factories are briefly discussed below. The significant impacts of harmonics in cement factories are succinctly addressed herein. It is noteworthy that other effects have been neglected owing to fewer problems in this type of plants.

III.1 POWER QUALITY

The first tangible effect can be considered as the reduction in power quality. Harmonics cause distortion in the waveform and a decrease in the power factor. While initially, the power factor may appear to be determined solely by reactive power, theinfluence of harmonics on reducing the power factor cannot be disregarded. While power factor may initially be perceived solely as reactive power dependence, the effects resulting from harmonics cannot be overlooked in power factor reduction. Reference [13] expresses equation (11) as the relationship between THD_I and power factor. Consequently, an increase in harmonics results in a decrease in power factor. In this equation, $\cos\phi_1 = P_1 / S_1$, P_1 and S_1 respectively refer to active and reactive power at the fundamental frequency.

$$PF \approx \frac{\cos\phi_1}{\sqrt{1+THD_I^{\,2}}} \tag{11}$$

It is worth mentioning that power factor correction capacitors in the cement factory power grid are also affected by harmonics and may be subject to overloading and premature failure. This is because the capacitive reactance is inversely proportional to the frequency, thus acting as a harmonic current consumer.

III.2 TRANSFORMERS

Harmonics induce heightened flux dispersion and iron losses within transformers, attributed to amplified eddy and hysteresis currents. These effects culminate in elevated thermal dissipation and insulation stress on winding conductors, ultimately diminishing the transformer's operational longevity. Harmonics also intensifies the vibration of the core laminations and result in the production of additional acoustic noise. Moreover, due to the increase in the rms current values, copper losses in the transformer (RI^2) are also elevated [3],[10],[14].

III.3 ELECTRICAL MOTORS

Electrical motors employed within cement factories, whether DC or AC, will be affected by harmonics, necessitating meticulous attention during their design or procurement processes [15], as harmonics manifest in the outputs of converters and directly impact motors. Analogous to transformers, their adverse effects include losses from eddy and hysteresis currents. These effects lead to increased heat losses, winding insulation stress, lubrication degradation of bearings, and diminished motor longevity. For every 10 degrees temperature increase above the rated temperature of the motor, the insulation life of the motor may decrease by 50% [10]. Another effect is the generation of bearing currents, which, if left unaddressed, significantly reduce bearing lifespan. Practical solutions to prevent them include employing insulated bearings, insulated couplings, and installing shaft grounding brushes [16]. Figure 4 demonstrates an example of the use of shaft grounding brushes installed on the shaft of a large motor to ground bearing currents. Harmonics can lead to an increase in torque ripple (one of the factors causing vibration and audible noise) and torsional oscillations of the motor’s shaft (especially AC motors). Furthermore, under harmonic conditions,

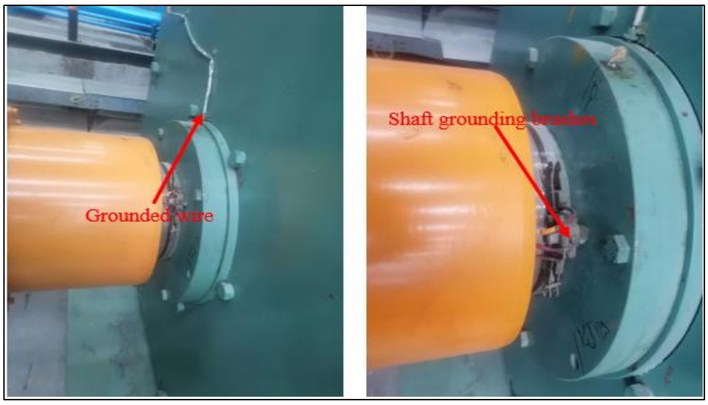


Figure 4: The installed grounding brushes on the shaft of a 1000 MW DC motor in a cement factory.
Source: Authors, (2024).

serious damage to the shaft and mechanical structure of the motor may occur due to the frequency matching of oscillations with the natural mechanical frequency of the shaft.

III.4 GENERATORS

The use of emergency power generators in cement factories is inevitable due to the critical nature of uninterrupted power supply. Generators typically exhibit an impedance three to four times higher than that of distribution transformers, rendering them more susceptible to the effects of harmonics. Similar to transformers and electrical motors, harmonics contribute to increased generator temperature by amplifying iron and copper losses, as well as inducing torque fluctuations and torsional vibrations [10].

Another significant concern is the potential for generators to trip unexpectedly under harmonic conditions due to protection system interventions. Generators are equipped with voltage and frequency controllers, and excessive voltage distortion caused by nonlinear loads can disrupt these settings. Specifically, the generator controller monitors the zero-crossing points of the phase to determine the frequency of the AC line. Voltage distortion introduces a "fuzzy" characteristic to the voltage waveform at these zero crossings, leading to imprecise and unreliable frequency calculations. The controller actively responds to fluctuations in the line frequency, striving to stabilize it towards the desired target frequency (typically 50 or 60 Hz). In extreme cases, the generator may experience surges or oscillations in its effort to reach the target frequency, ultimately necessitating disconnection from the grid [17].

Design engineers involved in cement plant development must consider the derated range of generators under harmonic conditions. Alternatively, they should request generators with specified tolerance levels to harmonic distortions from manufacturers.

III.5 CABLES

Cable resistance (especially AC resistance) is subject to skin effects and proximity. Both of these effects depend on the frequency, spacing between cables, the size, and cable structure. Consequently, notable increases in RI^2 losses may occur in harmonic conditions [10,18]. In the development of cement factory plants, neglecting to address harmonic control or not considering the derated range for cable size during the design phases may lead to excessive conductor heating and insulation damage under nominal loads.

It's important to note that in a four-wire power system (comprising three phases and a neutral), three-phase currents return to the grid via the neutral cable. Under linear balanced load conditions, neutral cable current is zero. Whereas, in harmonic conditions, even if the three-phase system is balanced, currents caused by odd harmonics combine, resulting in additional neutral cable current (up to 172% of phase current). For clarity, Figure 5 depicts practical measurements of three-phase currents and neutral wire for lighting of LED lamps in the development hall of a cement factory.

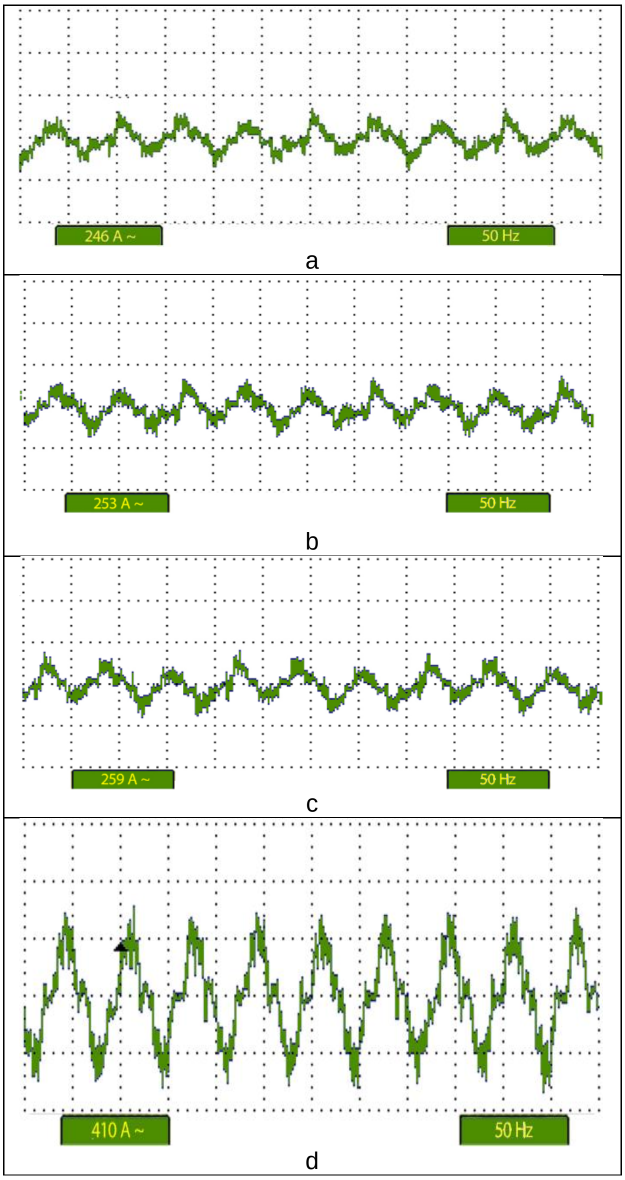


Figure 5: Three-phase four-wire system currents under harmonic conditions: (a) Phase A current (b) Phase B current (c) Phase C current (d) Neutral wire current.
Source: Authors, (2024).

III.6 CIRCUIT BREAKERS AND FUSES

As previously discussed, in the presence of nonlinear loads, the rms current value increases. Therefore, if the trip level of circuit breakers remains unchanged, premature and unwarranted trips may occur. On the other hand, the circuit breakers are designed to interrupt current at the zero crossing point of phase currents, and under harmonic conditions, false zero crossings may occur due to waveform distortion and high rates of di/dt at this point, leading to premature tripping of circuit breakers without any actual fault occurrence [10],[18]. To overcome this issue, some manufacturers suggest a derated range of circuit breaker or the utilization of electronic control circuits for precise detection of the zero crossing point.

In the case of fuses, the rise in rms current diminishes their current carrying capacity and introduces changes in both their time-current characteristic and melting time [18]. Additionally, under harmonic conditions, proximity effects cause non-uniform current distribution in fuse elements, ultimately leading to thermal stresses [10].

III.7 PROTECTION RELAYS AND MEASUREMENT EQUIPMENT

Harmonics may lead to errors and incorrect operation of some protection relays (especially traditional relays) [18],[19]. Despite efforts in today's relay structures to ensure proper performance even under the most challenging harmonic conditions, various reports indicate the vulnerability of relays to harmonic effects [20-22]. Henceforth, in the development of cement factories and the alteration of harmonic conditions, these effects should be taken into account in the selection or adjustment of protective relays to prevent future damages.

Common measurement equipment is typically designed to read sinusoidal quantities at the fundamental frequency. Non-linear currents and voltages induce errors in measurement circuits that cause wrong readings [10]. For instance, electromechanical kilowatt-hour meters may overestimate consumption under harmonic conditions [18],[23], while analog power factor meters may indicate lower power factor values [18].

III.8 RESONANCE

One of the undesirable effects of harmonics that can occur with the development of an industrial plant (increasing inductive and capacitive loads) is the phenomenon of resonance. This effect becomes more obvious especially with the installation of capacitor banks or SVCs for power factor correction. Resonance leads to higher levels of harmonic voltage and current distortions [9], resulting in damage to capacitor banks, cable overvoltage incidents, occurrences of corona discharge, increased inrush currents in transformers, and prolonged decay rates (especially during simultaneous switching of capacitors and transformers), as well as heightened duty of switching equipment [18]. Practically, to mitigate or eliminate resonance, series reactors are commonly employed with loads, functioning as low-pass filters to attenuate higher harmonic components. It is crucial to note that even the addition of a small capacitor to a large power system can create resonance. Equation (12) can be used to estimate the harmonic order of the parallel resonant frequency during the installation of capacitor banks [24].

$$h_R = \sqrt{\frac{MVA_{SC}}{MVAR_{CAP}}} \tag{12}$$

In equation (12),

$$MVA_{SC} = \frac{S_T}{U_{CC}} \tag{13}$$

Where MVA_{SC} denotes the short-circuit power of the transformer at the desired bus in terms of MVA, and $MVAR_{CAP}$ represents the reactive power of the capacitor bank in terms of MVAR. S_T indicates the power of the MV/LV transformer (or the sum of several parallel MV/LV transformers) in terms of MVA, while UCC expresses the short-circuit voltage of the MV/LV transformer as a percentage. Figure 6 illustrates the resonance effect in a power system with a six-pulse drive and power factor correction capacitor in a simple simulation conducted using MATLAB.

IV. CONTROL STANDARDS AND PRACTICAL METHODS FOR HARMONIC MEASUREMENT

Various international standards have been introduced for the measurement, control, and limitation of harmonics, which are categorized and listed in references [25-28]. Based on these references and the current common guidelines in Iran's cement industries, the relevant standards can be divided into two sections: measurement standards and limits on harmonic ranges at the PCC. In general, IEC 61000-4-7 can be considered the most suitable standard for THD and TDD measurements in an industrial plant because this document provides a detailed examination of harmonic measurement methods and has been endorsed by other common standards. In most standards, THD is used to express voltage distortion and TDD for current distortion. Industrial plants must consistently be responsible to controlling harmonic currents and take steps to reduce harmonics within the permissible range at the PCC. Figure 7 shows a practical connection example of a portable power analyzer model DW-6095 for harmonic measurement at the PCC.

Regarding the permissible ranges of THD and TDD, international standards IEEE 519 and EN50160, as well as the national standard [29], are recognized as the preferred references in Iranian industrial plants, irrespective of their different revisions. However, in plants with dedicated high-voltage lines or dedicated power plants, only two mentioned international standards are considered for setting limits on harmonic ranges. Nevertheless, there is no difference between the Iranian national standard and IEEE 519 in terms of the permissible range of THD_{Vpcc}. In a comparative analysis between EN 50160 and IEEE 519, it can be said that EN 50160 focuses on a wider spectrum of parameters related to power quality besides harmonics, while IEEE 519 specifically and precisely addresses only harmonics and their limitations for acceptable levels in power systems. Investigations indicate that IEEE 519 is currently accepted as the best reference for permissible levels of harmonics in cement plants in Iran and is also endorsed by power distribution companies. This standard was initially introduced in 1981 and has been continually updated due to the increasing nonlinear loads, experiences gained, and the various conditions arising in power systems. Tables 2 and 3 from IEEE 519-2022 respectively show the limits of THD and TDD at the PCC. It is important to clarify that Table 2 exclusively presents voltage distortion limits at the PCC for Iranian cement plants, (that is, LV and MV voltage levels), and the information pertaining to voltage levels other than LV and MV is omitted from the table.

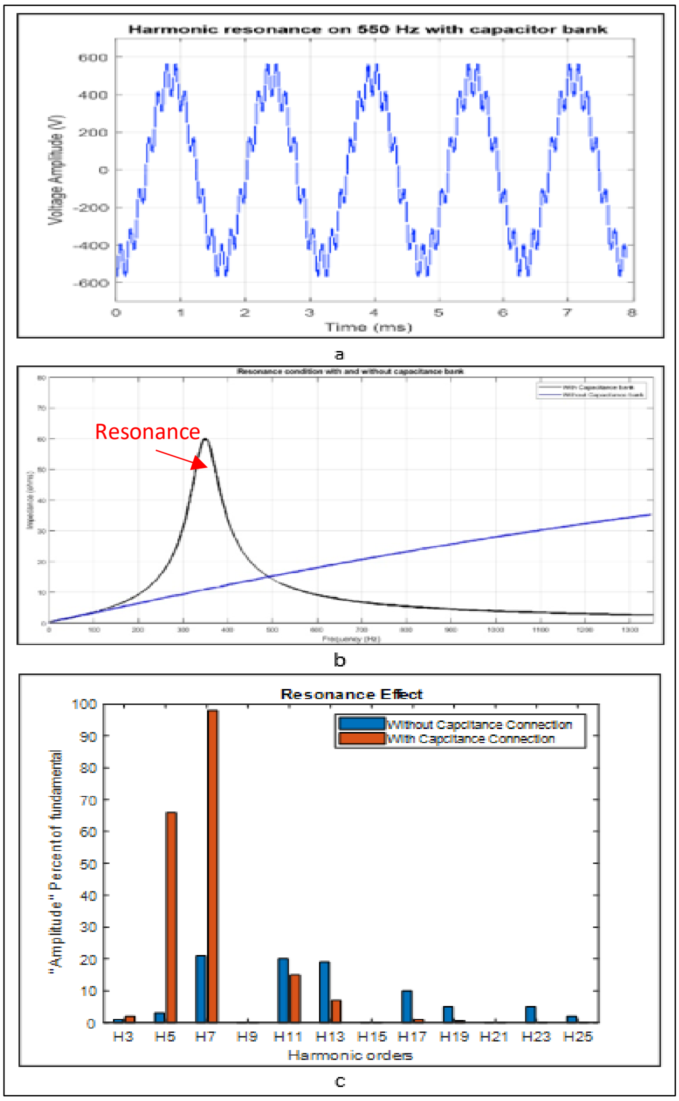


Figure 6: Resonance conditions and harmonic voltage amplification: (a) Resonance example at 550 Hz and harmonic voltage enhancement (b) Impedance profile of the network before and after the addition of the capacitor bank (c) Comparison of voltage harmonic distortion levels before and after the addition of the capacitor bank.
Source: Authors, (2024).

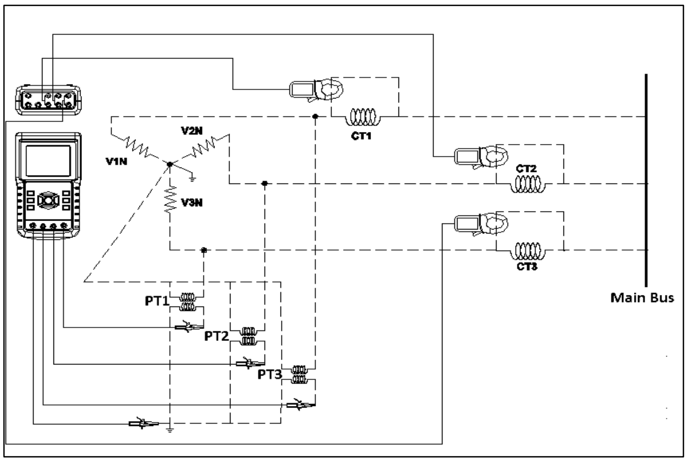


Figure 7: An example of the practical connection method of a portable power analyzer for measuring harmonics.
Source: 3 Phase power analyzer-Model DW-6095-Operation manual, (2010).

By comparing Tables 2 and 3, it can be said that voltage distortion limitations are absolutely and clearly stated in the standard, while current distortion limitations are contingent upon the electrical source impedance and harmonic suppression capability. According to Table 3, as I_{SC} increases relative to I_L, the likelihood of the circuit being impacted by harmonic presence decreases; in other words, According to Table 3, as ISC increases relative to IL, the probability of the circuit being impacted by harmonic presence decreases; in other words, while a strong grid can effectively reduce current harmonics with minimal impact on voltage, a weak grid may encounter greater voltage fluctuations in its efforts to suppress harmonics. In extremely weak grids, both voltage and current distortions may have similar magnitudes. Thus, it could be contended that current emission requirements must be stricter in weaker grids.

A notable aspect of existing standards is their focus solely on low frequencies (up to the 50th harmonic) and very high frequencies (above 150 kHz). Modern active harmonic mitigation devices, such as Active Power Filters (APFs) and Active Front End (AFE) drives (introduced in Section V), generate harmonic frequencies through switching operations. These frequencies typically range between 2 kHz to 150 kHz, a spectrum not currently addressed by existing standards. This gap enables manufacturers to employ less effective and cost-efficient LCL passive filters [30].

Table 2: Voltage distortion limits.

Bus voltage V at PCC	**Individual harmonic (%)**	**Total harmonic distortion THD (%)**
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0

Source:[31].

V. PRACTICAL STRATEGIES FOR HARMONIC MITIGATION OR ELIMINATION

Various methods for mitigating or eliminating harmonics have been scrutinized and analyzed in the literature [10], [26], [31], [32], [33], [34], [35]. Based on these references, methods for reducing harmonics can be broadly categorized into three main groups. The first category includes effective and optimal design methods for harmonic-generating equipment (such as electrical drives, motors, and transformers). When developing cement plants, proactive measures should be taken to mitigate this issue prior to equipment procurement. Considering the return on investment, it is advisable to acquire production lines that inherently produce much lower levels of harmonics. The second category comprises power management techniques and power system resilience (such as active power management, current distribution improvement, proper management and distribution of nonlinear and linear loads, appropriate sizing of motors and transformers, and techniques for enhancing power network stability). This aspect should be incorporated into the power system design phase of cement plant projects. The third category relates to additional methods (such as adding active and passive filters, isolated transformers, and reactors). These types of methods are implemented after a detailed study of harmonic sources and analysis of injected harmonics into the network.

In general, it is preferable for harmonics to be limited at their sources unless conditions make it technically and economically infeasible. The selection of optimal methods or their combination for harmonic reduction depends on the characteristics and structure of each plant's power system, and requires a precise evaluation of the electrical system, financial budget, and operational environment. Herein, the most common practical techniques currently employed in Iran's cement industries are examined in more detail and ultimately compared from both technical and economic standpoints with a view to plant development.

Table 3: Current distortion limits for systems with rated voltages from 120 V through 69 kV.

I_{SC}/I_L	**Harmonic limits** ^{a,b} $2 \leq h < 11$	**Harmonic limits** ^{a,b} $11 \leq h < 17$	**Harmonic limits** ^{a,b} $17 \leq h < 23$	**Harmonic limits** ^{a,b} $23 \leq h < 35$	**Harmonic limits** ^{a,b} $35 \leq h \leq 50$	**TDD Required**
< 20 ^{c}	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

[a] For $h \leq 6$, even harmonics are limited to 50% of the harmonic limits shown in the table.

[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed

[c] Power generation facilities are limited to these values of current distortion, regardless of actual I_{SC}/I_L unless covered by other standards with applicable scope.

Where:

I_{SC} = maximum short-circuit current at PCC

I_L= maximum demand load current (fundamental frequency component) at PCC under normal load operating conditions

Source:[31].

V.1 UTILIZATION OF LARGE AC OR DC CHOKES (REACTORS)

It is one of the most common methods of reducing harmonics in industrial factories and is known as an effective, simple and inexpensive way to reduce harmonics of electrical drives [10],[26],[36],[37]. In AC drives, chokes can be implemented in three configurations: on the AC line side (commonly known as AC chokes, which is a very popular method), in the DC link circuit (known as DC chokes, which are integrated within the drive itself), or both (especially in very large drives where the short-circuit capacity of a dedicated source is relatively low compared to the drive's apparent power). The choice of configuration depends on the drive's design and the power system [10],[36]. Figure 8 illustrates the configurations of AC and DC chokes in electrical drives [36]. There are varying approaches on the comparative effectiveness of AC versus DC chokes in reducing harmonic currents [38],[39]. However, it is generally accepted that using chokes not only limits harmonic currents but also reduces harmonic voltage distortion and protects the drive against voltage disturbances and imbalances (such as surges, spikes, and transients) [10],[11],[26],[36],[38],[39]. For better understanding, Figure 9 shows the effects of chokes on reducing current ripple [40],[41].

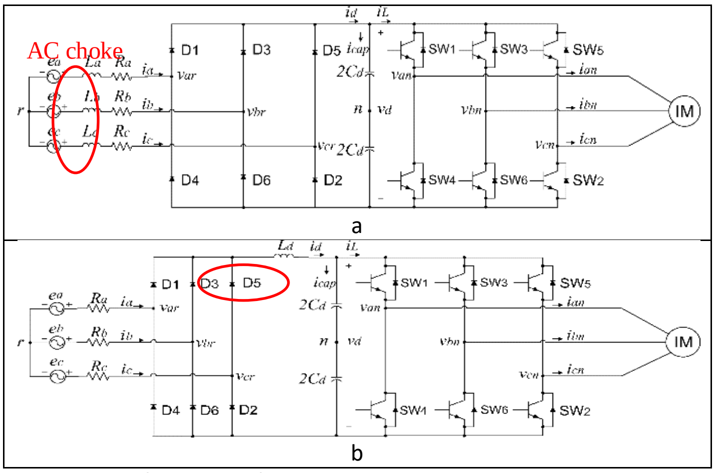


Figure 8: Configuration of utilizing DC and AC chokes: (a) Reactors La, Lb, and Lc on the AC line side of the induction motor drive (b) Reactor Ld in the DC link of the induction motor drive.
Source: [36].

From a practical standpoint, in most cases, chokes alone are insufficient for effective harmonic reduction. They need to be used in combination with other harmonic mitigation techniques to achieve optimal results [10],[38]. Typically, chokes are available in standard impedance ranges (such as 2%, 3%, 5%, and 7.5%) [10] and are only necessary for 6-pulse drives [38]. A drawback of using chokes is the voltage drop they cause [10],[38],[39], which can lead to under-voltage faults and negatively affect drive performance under unstable input voltage conditions.

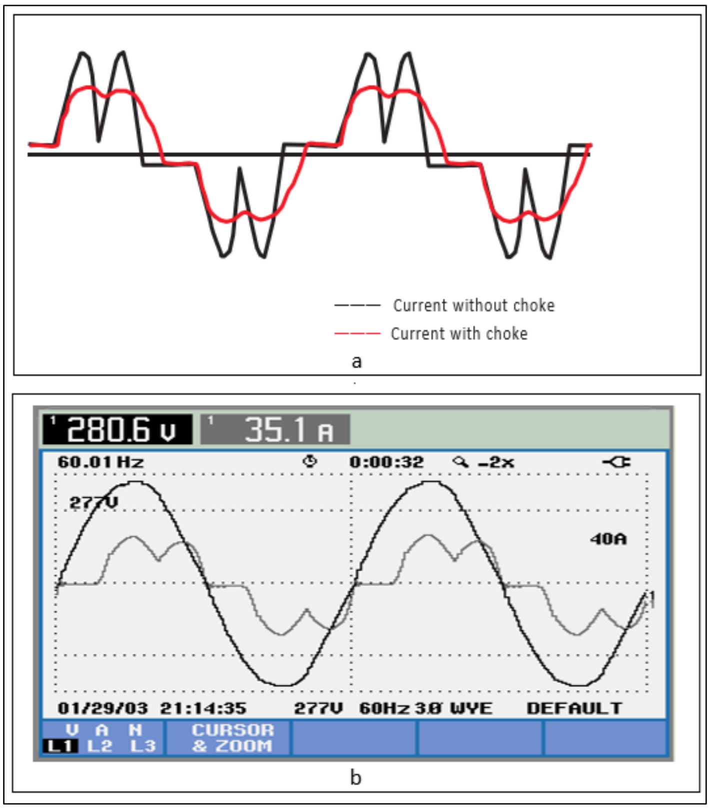


Figure 9: Effects of utilizing chokes: (a) Schematic waveforms showing the effect of a choke on the input current to a six-pulse drive (b) Practical results of using an AC choke with 3% impedance for a 480-volt, 30-horsepower motor at full load.
Source: (a) [40], (b) [41].

V.2 ISOLATION TRANSFORMERS

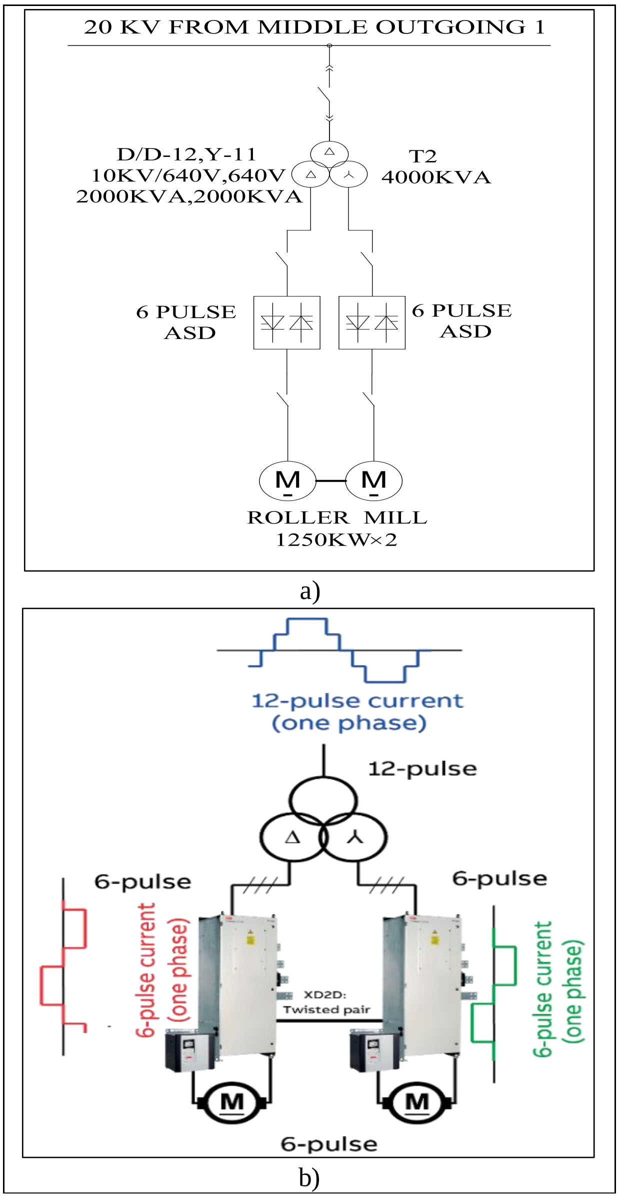
The use of isolation transformers is common in many cement factory structures in Iran and is considered an appropriate solution for reducing harmonics. Similar to chokes, they utilize their reactance to reduce harmonics. Additionally, due to their conventional delta-star configuration, they help mitigate triple harmonics [42]. However, the reason for using them is not solely limited to harmonic reduction. They do not perform significantly better than simple chokes and have higher costs [10],[26],[42]. Their advantages include the ability to step up or step down voltage levels, establishing a neutral ground reference for nuisance ground faults [10],[42], and eliminating certain common-mode frequency disturbances [26],[42]. This harmonic reduction method can be considered the best solution when using AC and DC drives that have SCRs in the rectifier bridge structure [10], as it not only reduces harmonics but also facilitates voltage level changes and protective measures.

The size (or capacity) and impedance of transformers play crucial roles in reducing voltage harmonics. In simpler terms, on the low-voltage side, larger transformer sizes or lower impedance result in a more pronounced reduction in voltage harmonics [40]. It's imperative, particularly in the development or procurement of cement production lines, to adhere to IEEE C57.110-2018 standards when manufacturing, ordering, or utilizing transformers.

V.3 QUASI 12-PULSE ELECTRICAL DRIVES

Quasi 12-pulse drives incorporate phase-shifting transformers in their structure. These transformers are employed in various configurations and vector groupings to mitigate harmonics in different industries [26]. However, it has been observed that most cement factories in Iran use two transformers with configurations of delta (primary)-delta (secondary) and delta (primary)-star (secondary), each supplying equal nonlinear loads (6-pulse variable speed drives with equal loads). Typically, instead of using two transformers, a single transformer with two separate secondary windings, as shown in Figure 10, is used. Each secondary winding supplies an electrical drive for a motor. with both motors having equal power and being mechanically coupled. These motors have equal power and are mechanically coupled to each other. This type of structure creates a quasi-12-pulse converter configuration, offering nearly the same advantages as a true 12-pulse electrical drive, significantly reducing the 5th and 7th harmonics and overall total harmonic distortion (THD) [10],[43],[44],[45]. In this configuration, the predominant harmonics are the 11th and 13th, while the amplitudes of other harmonics, such as the 17th, 19th, and higher orders, are effectively minimized [45].

The advantages of this arrangement include not only providing the required voltage for the drives via the transformer but also leveraging cost-effective 6-pulse drives, achieving a notable reduction in total harmonic distortion, and attaining lower inertia by using two series-connected motors instead of a single larger motor. Additionally, if one drive or motor fails, the production process can continue at reduced power. The disadvantages include the predominant 11th and 13th harmonics and the potential complete system shutdown in the event of any failure in the primary winding of the transformer.



a)

b)

Figure 10: Quasi-12-pulse drive configuration: (a) A section of the single-line diagram of a sample cement plant in Iran equipped with a quasi-12-pulse drive, (b) Implementation of the quasi-12-pulse structure using two ABB DCS880 drives.
Source: (a) Authors, (2024), (b) [45].

V.4 PASSIVE HARMONIC FILTERS

Passive harmonic filters are a highly practical and widely used method for reducing harmonics in the power systems of cement plants [3],[8],[46],[47]. After series chokes, they are considered the simplest and most cost-effective technique for reducing THD [26]. Passive harmonic filters, also known as harmonic trap filters [10], can be categorized into series and shunt types. Among these, the shunt type is more commonly used to create a low-impedance path for specific harmonics [48]. In the single-line diagram shown in Figure 1, an example of a shunt connection of a passive harmonic filter to a roller mill drive can be seen. These filters are composed of passive elements such as inductors, capacitors, and often resistors (for damping) [8],[10],[48] and are available in various topologies. Figure 11 depicts different topologies of shunt passive filters, which can be used either in combination or individually, depending on the power system of the cement plant and the load characteristics [49]. Observations indicate that in Iranian cement plants, typically at low voltage levels (800V, 690V, and 400V), one or more single-tuned filters are used, and at medium voltage levels (mostly 6.3kV and rarely 33kV, 20kV, and 11kV), sometimes other topologies are used in combination. Nevertheless, the application of single-tuned filter topologies in the cement industry is much more common due to their simple structure, lower cost, and effective performance. It is recommended to place passive filters near the harmonic source, as by reducing harmonics at the source, in addition to eliminating the need for oversizing electrical equipment, losses can be minimized, voltage distortions can be effectively reduced, and the filter can be sized for a specific load [48]. Figure 12 shows an example of connecting a double-branch filter to a nonlinear load in a cement plant to eliminate the 5th and 7th harmonics. As detailed in the accompanying SLD, each passive filter is designed and tuned for a specific harmonic frequency that needs to be reduced or eliminated.

From a practical standpoint, passive harmonic filters are predominantly used to eliminate or control lower-order predominant harmonics, especially the 5th, 7th, 11th, and 13th harmonics. They perform poorly for harmonics above the 13th order and are rarely used for higher-order harmonics [10]. Their operating principle is based on the resonance phenomenon (due to changes in filter components as a result of frequency variations) to create minimal impedance for a specific harmonic (or in some cases, with a combined structure for a specific frequency band [48]) [8],[10],[48],[50]. The resonance frequency or tuning frequency for a single-tuned filter is calculated using equation (14) [10],[33],[50],[51]. In this equation, L is the inductance of the filter in henries, and C is the capacitance of the filter in farads. At this frequency, the filter provides low impedance for the harmonic frequency f_r and high impedance for other harmonics [50,51].

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{14}$$

In practice, due to the risk of filter resonance with the power system frequency, the tuning frequency of the filter is set slightly below the harmonic frequency [11],[48],[49],[50]. For example, a 5th harmonic filter is tuned to the 4.7th harmonic [11],[50].

Besides harmonic reduction, improving power quality through reactive power compensation is another advantage of these filters [8],[48],[50],[51]. However, it should also be noted that these filters can absorb harmonics from other sources [10], and to prevent filter resonance with the power system and ensure their effective performance, thorough studies of load, power quality, and network impedance during their design are essential [52].

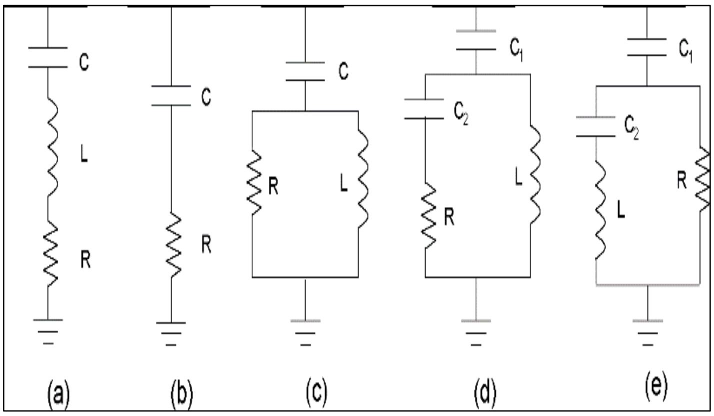


Figure 11: Types of passive shunt filter topologies: (a) single tuned, (b) first order, (c) second order, (d) third order, (e) C-type. Source: [49].

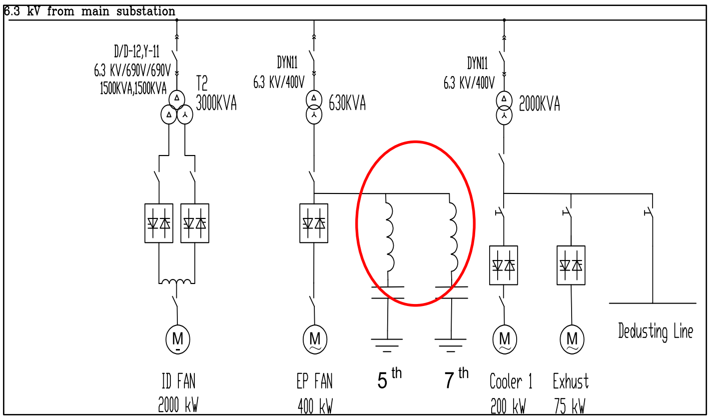


Figure 12: Part of the single-line diagram of a cement plant and the connection of a double-branch passive filter to the nonlinear load.
Source: Authors, (2024).

V.5 HIGH PULSE CONVERTERS

From an industrial perspective, electric drives with 12-pulse, 18-pulse, 24-pulse, 30-pulse, 36-pulse, 42-pulse, and 48-pulse converters [53] are recognized as high-pulse converters. Among these, 30-pulse and 42-pulse converters are rarely produced due to the special requirements for transformers. Normally, only 12-pulse, 18-pulse, 24-pulse, and 36-pulse converters can be found in various industries with different structures, the most common topologies of which are shown in Figure 13 [53],[54].

According to equations (4) and (5), as the number of pulses of power converters increases, the amplitude of harmonic currents and ultimately the THD decreases. Invariably, increasing the number of converter pulses not only mitigates harmonic distortion in the AC input current, but also delivers a smoother and higher average DC output level [10]. Since it is not feasible to find all common high-pulse drives in one factory with completely similar supply and loading conditions for practical investigation, simulation methods have been used here to analyze the harmonic injection of various converters. Figures 14 and 15 respectively compare the input current of phase a and the level of harmonic currents of various common high-pulse converters with configurations shown in Figure 13 under ohmic full load conditions (THD_I equals TDD). As observed, increasing the number of pulses significantly affects reducing THD_I. Despite this, based on field studies and as shown in the SLDs of Figures 1 and 12, only 12-pulse drives are prevalent in the cement industry in Iran, and other high-pulse converters are not used. This can be attributed to the considerably higher cost of high-pulse converters and their more intricate circuits (which consequently render them more susceptible to disturbances and failures) [8], as well as the necessity for large and specialized transformers to achieve phase shifting [10],[53]. Different configurations of industrial 12-pulse DC and AC drives (known as True 12-pulse) currently deployed in numerous cement factories can be found in [45], [55].

As evident from Figure 15, the advantage of 12-pulse converters lies in their ability to mitigate not only the 5th and 7th harmonics but also higher-order frequency components, where the 11th and 13th emerge as predominant [10],[38],[43],[45],[54]. While this technique diminishes the amplitude of harmonics, it does not entirely eradicate them [10]. Among the drawbacks of 12-pulse drives compared to prevalent industrial six-pulse drives are the more intricate converter architecture, higher price [10],[40], and decreased overall drive efficiency due to voltage drop caused by the phase-shifting transformer [10].

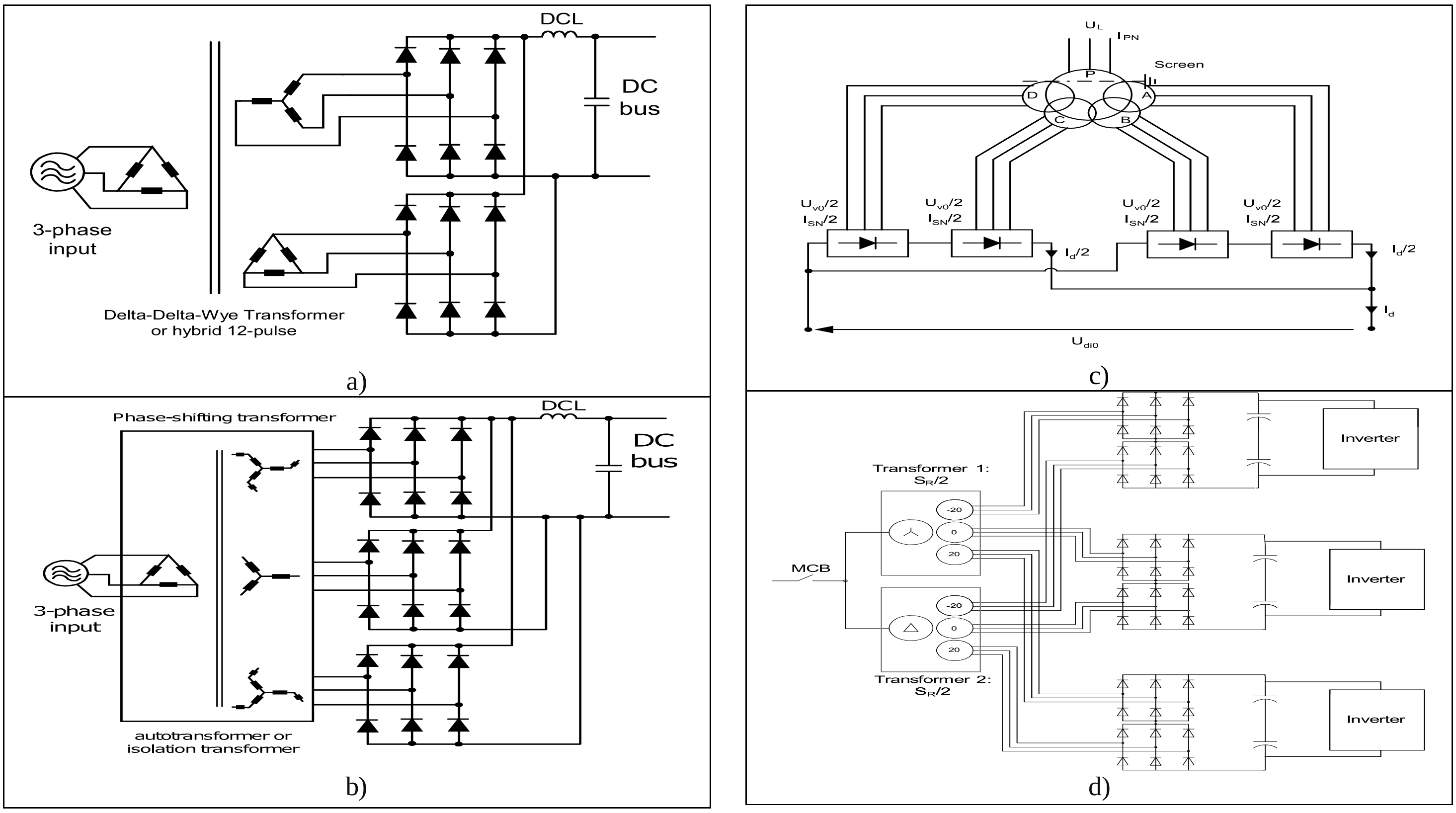


Figure 13: Some common configuration of high pulse industrial drives: a) 12-pulse converter b) 18-pulse converter c) 24-pulse converter d) 36-pulse converter.
Source: (a) , (b) [54],(c), (d) [53].

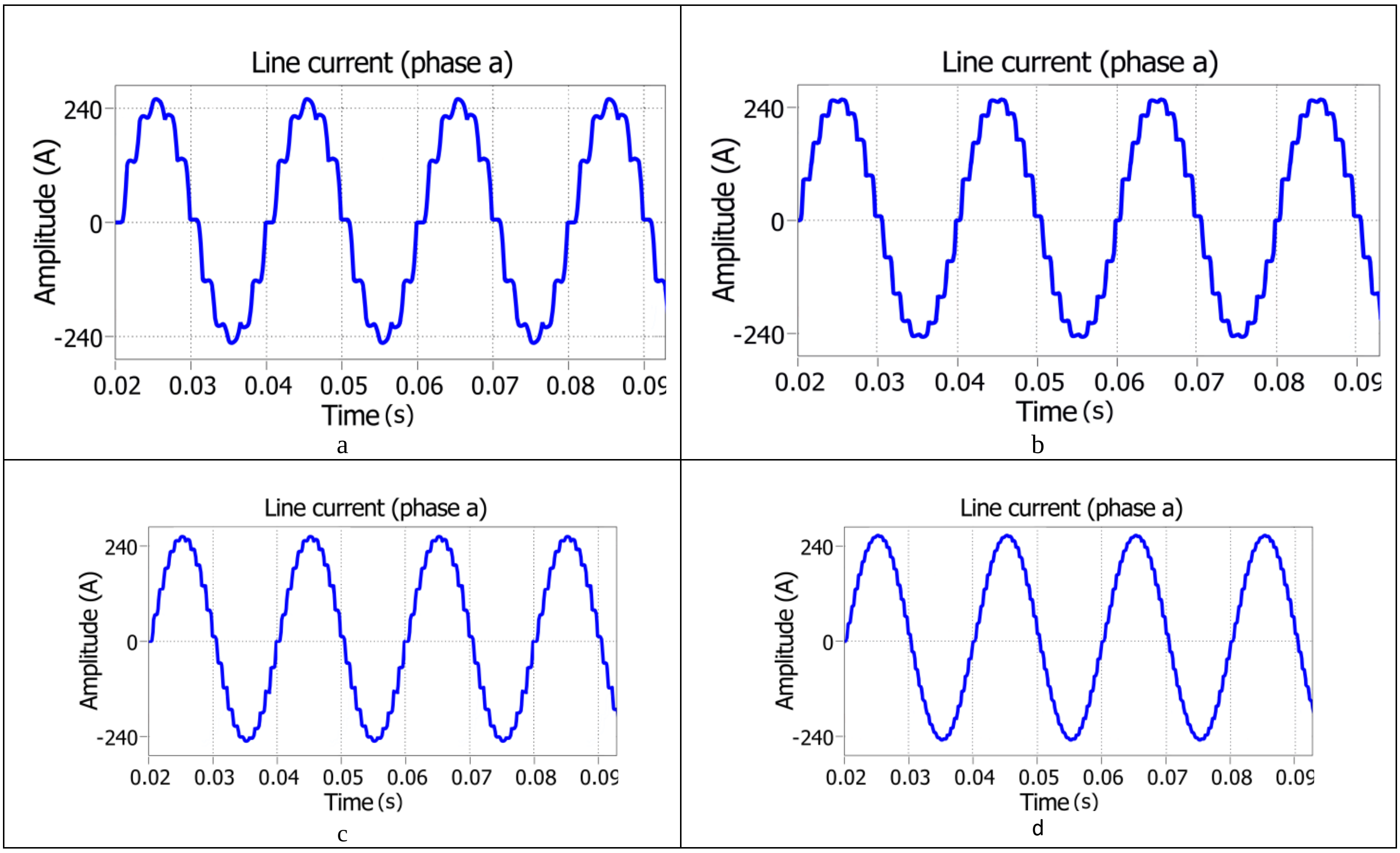


Figure 14: Comparison of the input current of phase a from various high pulse converters with diode rectifier and ohmic load: (a) 12-pulse converter (b) 18-pulse converter powered by a three-phase to nine-phase autotransformer (c) 24-pulse converter (d) 36-pulse converter.
Source: Authors, (2024).

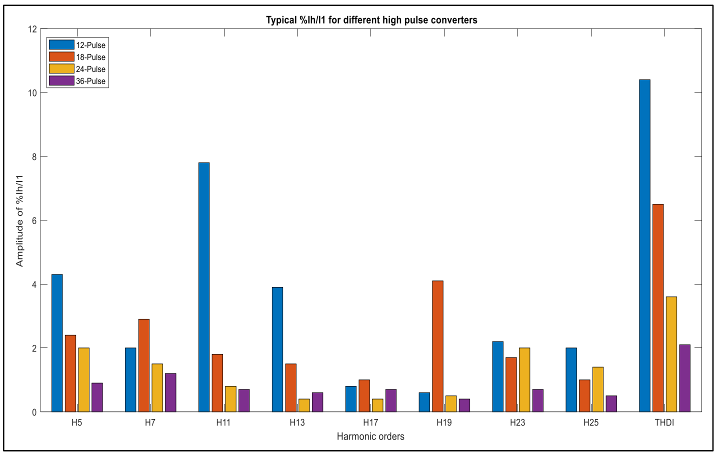


Figure 15: Comparison of the harmonic orders of the input current of high pulse converters with diode rectifier and ohmic load: (blue) 12-pulse converter (THDI=10.4%), (red) 18-pulse converter powered by a three-phase to nine-phase autotransformer (THDI=6.5%), (orange) 24-pulse converter (THDI=3.6%), (purple) 36-pulse converter (THDI=2.1%).
Source: Authors, (2024).

V.6 ACTIVE HARMONIC FILTERS

Although active harmonic filters (AHFs) have gained traction in diverse industries for their effective reduction of harmonics and compensation of reactive power [7],[10], they are not commonly used in the cement industry due to their significantly high cost [8]. However, their deployment in the cement industry is recommended due to the return on investment and their proper effectiveness [2],[7],[47]. AHFs can be classified into four categories: series, shunt, a combination of both, and hybrid (a combination of active and passive filters) [31],[33], among which the shunt configuration is much more prevalent [10],[30],[33]. The operating principle of a shunt AHF involves monitoring and measuring the distortions of nonlinear load currents by filtering the main current and subsequently injecting equal but opposite harmonic currents in real-time to eliminate harmonics [10],[28],[32],[43]. In fact, the voltage distortion caused by harmonic currents passing through the system impedance can be corrected by injecting a nonlinear current with the opposite polarity. This process can restore the voltage to its sinusoidal state [31]. Figure 16 depicts its operating principles [52].

AHFs are capable of removing harmonics up to the 50th order [26],[43], achieving a total harmonic distortion of current (THDI) lower than 5% [7],[26],[28],[43],[47], and improving the power factor close to unity [25],[28]. Compared to passive harmonic filters, AHFs offer several advantages: they do not resonate with the power network [10],[28],[33], are insensitive to changes in source and load impedance [10],[28], are not limited to specific frequencies, and operate over a wide frequency range [8],[34]. Additionally, AHFs do not require detailed harmonic studies of the power system [52], especially in self-tuning models. Nevertheless, investigations suggest that these types of filters currently do not have a place in Iranian cement factories. This could be attributed to the complex control systems of AHFs, which lead to very high costs and increased maintenance expenses [8],[10],[25],[33], relatively high levels of electromagnetic interference (EMI) [30], and possibly the leniency of regional power companies in Iran, especially at dedicated 63 kV substations.

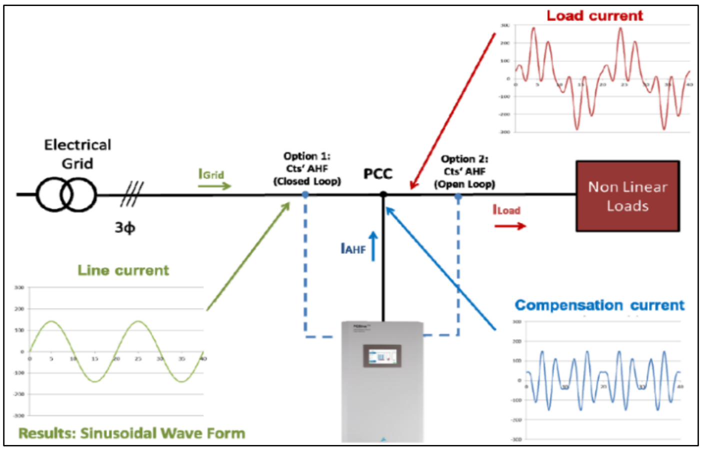


Figure 16: Principles of active shunt filter operation.
Source: [52].

V.7 LOW HARMONIC DRIVES

Some manufacturers of industrial electric drives have introduced and marketed a variety of low harmonic electric drives to meet IEEE 519 requirements. These types of drives are generally active front end (AFE) [5],[10],[30],[56],[57], and in some cases, drives with an integrated active filter [58]. Figures 17 and 18 show examples of the configuration of this type of industrial drives. As observed in Figure 17, unlike the common six-pulse industrial drives, the AFE drive utilizes a fully controlled IGBT bridge instead of a diode bridge rectifier at the input of the drive. This IGBT bridge allows the drive to draw a more sinusoidal current from the grid, significantly reducing low-order harmonics (below 50th) [10], [30], [56], [57]. Therefore, these drives are also referred to as drives with a sinusoidal input rectifier [10]. It should be acknowledged that the switching losses of the IGBTs in the input unit of the AFE drive reduce its efficiency compared to the traditional six-pulse drive. However, when considering the overall system losses, including those caused by harmonic reduction filters, the total losses of AFEs are the same or less [56]. In addition to significant reduction in harmonic distortions (even below the limits specified in IEEE 519), the advantages of AFE drives include inherent four-quadrant operation, regenerative capability (returning energy to the grid in braking mode), high dynamic response, reactive current control capability, unity power factor operation, elimination of the need for external filters and special transformers, and voltage drop elimination at motor terminals (usually caused by commutation or voltage disturbances in the source) [5],[10],[40],[56],[57]. While the features of AFE drives compared to commonly used six-pulse VSDs can result in some capital return due to a reduction in cable size by approximately 10%, distribution transformer capacity by 20%, generator capacity by 50%, and energy storage [59], their economic justification is currently lacking due to nearly 2.5 times production costs [40], especially in conditions where significant regenerative or braking modes are absent. Therefore, their utilization in cement factories is not widespread [8], and their application is mostly found in downhill conveyor belts in very large cement production complexes [60]. Other disadvantages of industrial AFE drives include the inherent generation of harmonics higher than 50th and relatively high levels of EMI in the range of 2 to 150 kHz [10,30], which must be carefully considered when using them in various industries.

In industrial drives with an integrated active filter, an AHF as shown in Figure 18 is employed to mitigate harmonics. As previously discussed regarding AHFs, despite their presence, the drive can draw a much more sinusoidal current with a unity power factor from the grid [58]. The disadvantages of this type of drive are similar to those of AHFs, but in terms of cost, depending on the technology used, it may be somewhat cheaper than modern AFE drives.

Field studies and investigations indicate the lack of utilization of low harmonic industrial drives in Iranian cement factories due to their very high cost. It is obvious that currently replacing existing six-pulse drives in a cement factory, whether in operation or nearing the end of their life cycle, with an AFE drive is not ideal and cost-effective. However, with the growth of production and technology, it is expected that in the not-too-distant future, advanced AFE drives will replace six-pulse drives and even 12-pulse or quasi-12-pulse drives in modern cement factories.

Table 4, derived from the analysis of data recorded in four Iranian cement factories with almost similar characteristics, compares the types of practical methods available for harmonic reduction in terms of THD_I level and total cost (including all necessary components such as transformers, additional cables, etc.) for a 500 kW EP fan at the PCC (primary side of transformers). Considering the absence of completely identical conditions in the studied factories, all values in the mentioned table are relative. This information can assist engineers in selecting harmonic reduction techniques for development or control in current conditions in cement factories and even other industrial complexes. An interesting conclusion that can be drawn from Table (4) is the comparison between 12-pulse and quasi-12-pulse converters. It is observed that a quasi-12-pulse converter may have economic advantages and superior THD_I reduction compared to the conventional structure of 12-pulse converters in the cement industry.

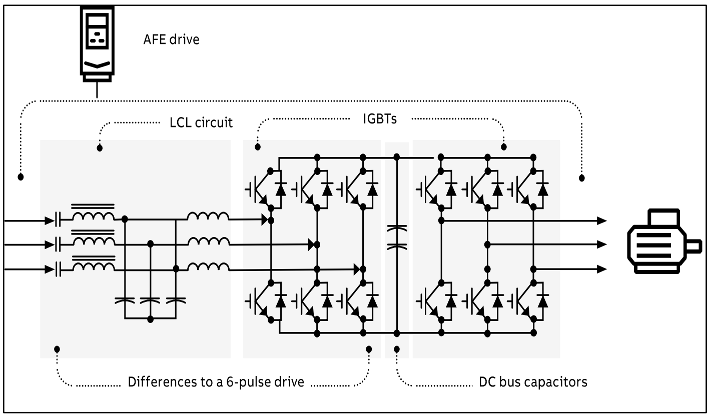


Figure 17: A simplified hardware configuration of an AFE drive.
Source: [56].

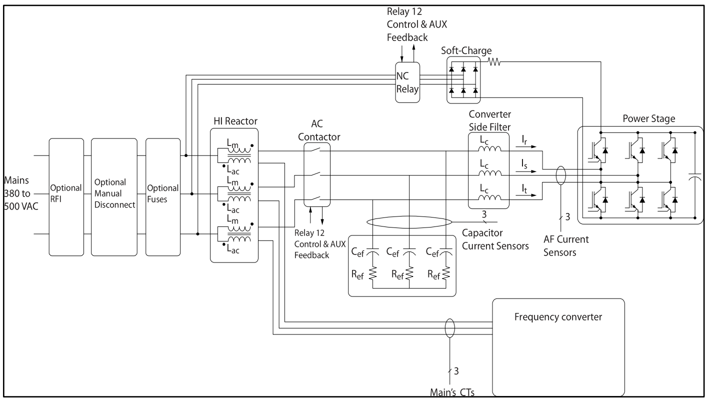


Figure 18: Basic topology of a low harmonic drive with integrated active filter.
Source: [58].

Table 4: Technical and economic comparison of harmonic reduction strategies at full load.

	Current harmonic orders ($\%I_h/I_1$)								THD_I	Cost
	5th	**7th**	**11th**	**13th**	**17th**	**19th**	**23th**	**25th**		
6-pulse without choke	84%	63%	20%	11%	8.9%	7.2%	5.6%	2.8%	**108.24%**	100%
6-pulse with 3% AC choke	41.6%	16%	7.8%	6.1%	5%	3.9%	2.5%	2.5%	**46.23%**	104%
6-pulse with 5% AC choke	33.4%	10.2%	5%	3.2%	2.9%	2%	1.6%	1.2%	**35.65%**	106%
6-pulse with passive harmonic filter	2.7%	3%	2.5%	2.3%	1.4%	1%	0.5%	0.4%	**5.58%**	183%
Quasi 12-pulse	3.5%	1.5%	6.7%	3.4%	0.3%	0.3%	1.5%	1.3%	**8.66%**	188%
12-Pulse with Dd-Dy transformer	4.8%	2.7%	9.3%	5.3%	1%	0.8%	3.5%	2.6%	**12.86%**	194%

Source: Authors, (2024).

VI. CONCLUSIONS

Cement factories in Iran are recognized as significant sources of harmonics due to the presence of very large nonlinear loads. Therefore, it is necessary to conduct fundamental studies on the causes, effects, and methods of harmonic reduction in this industry. Controlling and reducing harmonics are considered important and mandatory both from the perspective of distribution network standards and the lifespan of electrical equipment. However, major problems caused by harmonics typically become apparent during the development of such factories. This is because the addition of new equipment in the development divisions or even optimization of the existing production line can significantly alter the harmonic conditions.

Based on comprehensive studies and investigations regarding the causes and effects of harmonics, it is strongly recommended that power quality studies be conducted for the current conditions before designing the development divisions, and that the harmonic effects be considered when procuring new equipment. Various standards recommend measuring harmonics up to the 50th order at the PCC but in cement factories, this is typically done up to the 25th order. The PCC in a cement factory can be at the LV (Low Voltage) level or, given the presence of dedicated high-voltage substations, at the MV (Medium Voltage) level. Most standards use THD to express voltage distortion and TDD to express current distortion.

In general, it is better to limit harmonics at their sources unless it is technically and economically unfeasible. The cost issue is an important factor in selecting harmonic reduction techniques; currently, Iranian cement factories only use AC chokes, passive harmonic filters, and quasi-12-pulse and 12-pulse drives. Field research results indicate that a quasi-12-pulse converter can somewhat outperform the conventional 12-pulse converter in the cement industry both economically and in terms of harmonic reduction. Although many new techniques, such as active filters or low-harmonic drives, are considered suitable methods, they currently have no place in the Iranian cement industry due to their very high costs. Nonetheless, it is expected that advanced AFE drives will replace six-pulse and even 12-pulse or quasi-12-pulse drives in modern cement factories in the future.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Author One, Author Two and Author Three.
Methodology: Author One and Author Two.
Investigation: Author One and Author Two.
Discussion of results: Author One, Author Two and Author Three.
Writing – Original Draft: Author One.
Writing – Review and Editing: Author One and Author Two.
Resources: Author Two.
Supervision: Author Two and Author Three.
Approval of the final text: Author One, Author Two and Author Three.

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