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Harmonic Reduction Methods for Electrical Generation: A Review

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Abstract: This paper provides a comprehensive literature review of techniques for harmonic related power quality improvement of electrical generation systems. An increasing interest in these aspects is due to the ever more stringent power quality requirements, deriving from new grid codes and compliancy standards, aimed at limiting waveform harmonic distortion at all points of the distribution network. Although a wealth of literature is available for such techniques, it has never been compiled into a handbook incorporating all the solutions aimed at both electrical machine and power systems engineers.

1. Introduction

In the world of electrical power generation, a main point of consideration has always been to achieve adequate performance in terms of power quality. In this context, an important factor is the generation, management and reduction/compensation of spatial and time harmonics throughout the whole power system. From the first developments in the mid-1800s of electrical power generation and distribution systems, harmonic content improvement and reduction has evolved from a localised generator design problem to an internationally regulated supply characteristic that must be considered at all points of the power distribution network.

This paper is thus aimed to be a review of harmonic improvement techniques and methodologies, organised to follow and indicate the development timeline of these methods. Distribution level generation has been chosen as the focus to align with recent changes in grid topology caused by distributed and renewable generation. In this section, the paper begins by detailing the changing nature of power quality in distribution networks followed by a description of the main types of power quality issues and an overview of the key standards governing network limits. The focus then shifts to harmonic reduction procedures and methodologies. A review of harmonic reduction methods based around the design of rotating electrical generators is developed, followed by a review of modern methods applied to new generation systems, such as renewable sources.

1.1. The Changing Nature of Power Quality

With ever-increasing regulations and grid code compliance acts, the definition of power quality has today evolved to include all forms of waveform distortion [1]. This has been driven by the changing ways in which electrical power is consumed and produced. Traditionally, the main types of power system events that trigger significant power quality deterioration are

- Voltage sags – short reductions in RMS voltage usually caused by very large instantaneous increases in load [2].
- Flicker – a continuous variation in RMS voltage which would be typically observed in the light output of an incandescent bulb [2], [3].
- Phase unbalance – the mismatch of loading between the three supply phases. It is noted in [3] that domestic generation has the potential to increase the levels of imbalance.
- Harmonic distortion – the change of the voltage or current waveform relative to that of a pure sine wave by the addition of other waveforms, usually at multiples of the fundamental frequency [4].

This last aspect is quickly becoming one of the over-arching challenges related to power systems. Harmonic related issues include

- increased losses in generators, motors and transmission lines [3], [5], [6] meaning reduced efficiency and that equipment may need to be de-rated [7];
- at high frequencies, issues with communication systems and sensitive electronics can occur [5];
- overvoltage events, commonly caused by harmonic resonance, can reduce the life of insulation and damage capacitors [8].

One of the major factors contributing to the increasing presence of harmonics in power systems is that, over the last few decades, the presence of power electronic (PE) devices drawing non-linear currents [2], [3], [7] has reached unprecedented numbers. This has accelerated the authorities' efforts related to power quality standards and requirements.

This trend has continued with the recent interest in energy storage, renewables and distributed generation systems [3], [9]. These technologies are reliant on PE and as such can further impact the power system by producing harmonics and electromagnetic interference (EMI) [3].

PE systems are generally considered as the main source of harmonic degradation, although this is only true for low order harmonics when the converters are uncontrolled or incorrectly designed. In [2], it is claimed that PE converters are only one of three significant harmonic producing loads and lists 1) arcing and 2) magnetically saturated devices as the other two main sources of harmonics.

1.2. Harmonic Sources and Their Types

Harmonics have multiple sources throughout the power system. Starting with traditional generation based on rotating machines, ripples in the torque from the generator prime-mover and current from the excitation system produce time harmonics in the generator flux that vary in a non-sinusoidal mode. Additionally, the geometry of the generator and the spatial distribution of the windings result in further harmonics applied to the electrical output. The resulting harmonic content then propagates through the power system to other connected loads.

In electric generators, harmonics are classified into three groups, namely 1) forward harmonics, 2) reverse harmonics and 3) zero sequence harmonics, based on the effect they have on the torque. Forward sequence harmonics produce a positive torque, reverse sequence a negative torque and zero sequence harmonics produce no torque [10]. The effects of the forward and reverse sequence harmonics is that they can cause oscillations in the shaft resulting in vibration and potentially critical failure due to accelerated mechanical wear.

Harmonics can also be categorised by frequency where traditional harmonics exist at integer multiples of the supply frequency and inter-harmonics exist at non-integer multiples. These are produced by modern asynchronous switching converters, among other sources, and can be a major cause of flicker [11]. More recently, inter-harmonics are receiving interest from both research and regulatory bodies [12].

Table I Limits and levels imposed on odd harmonics [13]

Standard	EN 50160	IEEE 519 (up to 69kV)	IEC 61000-2-2 IEC 61000-2-12	IEC 61000-3-6
Purpose	limits	limits	compatibility levels	indicative planning levels
Voltage level	LV, MV	LV, MV	LV, MV	MV
h	Harmonic voltage as a percentage of the fundamental [%]			
3	5	3	5	4
5	6	3	6	5
7	5	3	5	4
9	1.5	3	1.5	1.2
11	3.5	3	3.5	3
13	3	3	3	2.5
15	0.5	3	0.4	0.3
17	2	3	2	1.7
19	1.5	3	1.76	1.5
21	0.5	3	0.3	0.2
23	1.5	3	1.41	1.2
25	1.5	3	1.27	1.09
$25<h<40$	-	3	$2.27x(17/h)-0.27$	$1.9x(17/h)-0.2$
THD [%]	8	5	8	6.5

1.3. Standards Regulating Harmonic Limits

Regulatory standards have been developed to mitigate harmonic and power quality issues estimated to cost businesses billions of dollars per year [7]. An early example from 1913 is the American Institute of Electrical Engineers (AIEE) requirement for a total harmonic distortion (THD) of the no-load output voltage of a generator to be no more than 10% [14]. Today standards [13], [15] go far beyond this, giving extensive coverage to the problems caused by low power quality (relative to harmonics) under different loading conditions. The standards now cover acceptable harmonic current and voltage limits for different stages of the distribution network [15]. The most commonly accepted quality factors known and used today are the overall value of THD and a suite of set limits for individual harmonics. In both cases, stricter limits are imposed for continuous events. The limits for odd harmonics, as given in [13], are detailed in Table I.

2. Harmonic Reduction by Machine Design

Knowledge of harmonics and their effects dates back to the 19th century [16]. At that time, high voltage caused by resonance issues were the main problems caused by harmonic content [17] but the effects of increased losses in transformers and motors were also known and generally understood [16]. Early generators produced voltage waveforms rich in harmonics [18], mainly due to 1) the lack of affordable waveform measurement equipment and 2) the lack of knowledge or incentive to develop methods to improve the waveform shape [14]. However, by the early 20th century, increased effort towards harmonic improvements became more common. These methodologies focused on design improvements to the main alternators with the aim of reducing no-load THD. This, linked with the AIEE harmonic limit of 10% THD (Section 1.3) and drove a marked advancement of waveform quality in the outputs of early 20th century machines [19]. In the following sections, a review of the main methodologies applied to achieve these improvements are given.

2.1. Improved Winding Configurations

Various winding configurations have been implemented onto electrical machines, aimed at improving the power quality of the output waveforms. These techniques are well consolidated and extensively dealt with in literature [20]–[24], however this section is aimed at documenting and presenting the logical passages that led to incremental enhancements in generator waveforms through relevant winding structures. It is worth mentioning that there does not exist a single, optimal winding structure for synchronous generators (SGs), rather this depends on the application. In fact, the choice of an appropriate winding layout represents a key design optimization process.

By limiting the considered case studies to three-phase, symmetrical windings embedded in the stator of classical SGs, the simplest configuration consists of a single-layer comprising 6p slots (where p is the number of pole pairs). Alternators with such winding structure were already in use by the late 1800s [25]. If a planar scheme is considered for the stator and if only one pole pair is taken into account (corresponding to 2π electrical radians), then the described winding can be illustrated as in the grid of Fig. 1a, where a distributed configuration is assumed. By using the winding function (WF) theory [20], one phase of the winding described above can be represented by the red function shown in Fig. 1c. Here, a full pitch winding is employed, meaning that the angle between the two sides of a coil (namely the winding pitch) is equal to the angle between the magnetic poles (namely the pole pitch). This solution is the optimal choice in terms of output maximization, as the highest magnitude of the fundamental component of a rectangular waveform is achieved when its trailing edge is at a distance equal to π radians from the leading edge, i.e. the case of the blue plot of Fig. 1c. One of the early winding methodologies was the introduction of concentrated windings. As shown in Fig. 1, if the winding of Fig. 1a is transformed into a concentrated configuration, then this would take the shape of a single layer with 6p slots but with the phases wound around a single stator tooth.

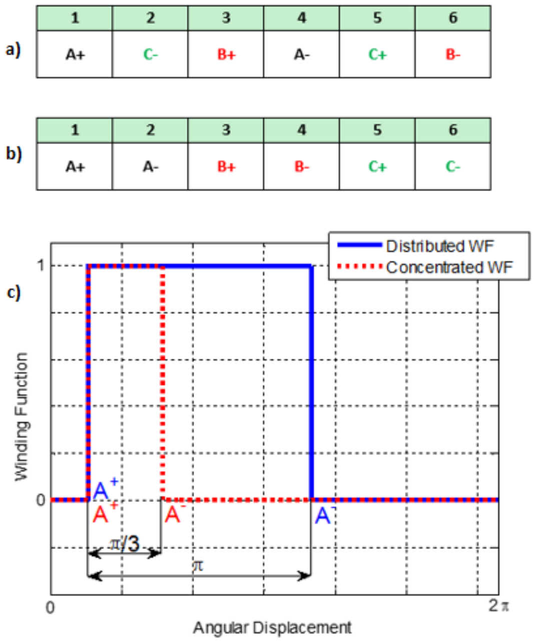


Fig. 1. *Single-layer, 1-slot-per-pole-per-phase: **a)** distributed winding planar scheme; **b)** concentrated winding planar scheme; **c)** comparison between the related winding functions*

This winding structure allows for reduction of the end winding length (a key historic benefit) as well as improvement of the slot fill factor if modern automatic winding processes are used [26]. It is clear that the concentrated winding can be highly beneficial in relatively short machines with a low number of poles [27], [28], where the end windings' length is comparable to that of the active sides of the coils. However, it is also true that the resulting WFs of each phase are modified and assume the shape of the red function of Fig. 1c, where it can be seen that the value of the fundamental is significantly reduced in comparison with the distributed winding of the same figure [21]. In the concentrated configuration described above, a short pitching is also applied to the winding, resulting in an angular distance between A+ and A- shorter than the pole pitch. In the specific case considered, a 1/3rd short pitching is obtained, allowing for attenuating specific harmonics in the induced EMF. Examples of machines employing winding of the type described above are provided in [21], [29].

Utilising a single winding layer limits the flexibility of short pitching to only the choice shown in Fig. 1. To circumvent this issue, a double layer winding can be used, where coils of different phases can be inserted into the same slot and thus an increased number of coils-per-phase can be achieved while keeping the same number of slots. Alternators built around this configuration were already present in the early 1900s [25]. This last concept is shown in Fig. 2a, where a 2/3rd short pitching is employed. It is well-known that a 2/3rd pitch winding suppresses the 3rd harmonic (and its multiples) making it suitable for four-wire systems [22], [30]. It is also clear that the WF of Fig. 2b gives a more sinusoidally-distributed output if compared with the WF shown in Fig. 1b, however at the cost of decreasing the magnitude of its fundamental component.

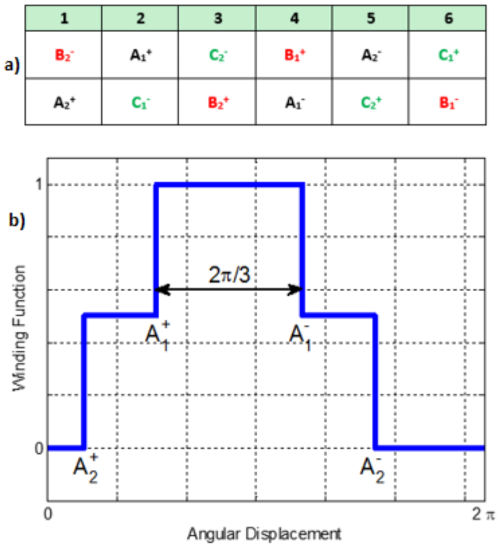
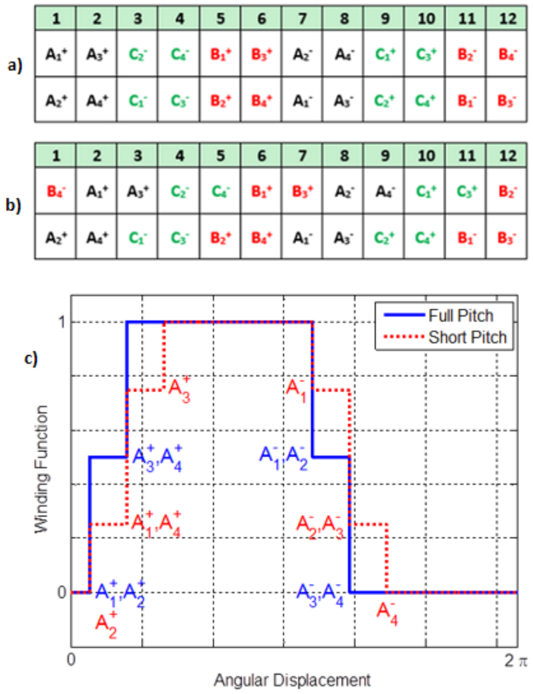


Fig. 2. *Double-layer, 2-slots-per-pole-per-phase distributed winding: **a)** planar scheme; **b)** winding function*

The winding distribution, consisting of splitting the armature coils over multiple slots (i.e. using an increased number of coils-per-phase), can be used to obtain a more sinusoidal output [7], [19], [21] and increased flexibility in terms of short pitching the windings. This concept can be observed in Fig. 3a, where 4p coils-per-phase are used with a full-pitch configuration, whereas Fig. 3b shows the same basic structure but with a 5/6th short pitching being applied to the winding. This 5/6th pitching is widely used in the field of electrical machines, as it reduces the 5th and the 7th harmonics and provides a lower THD for three-wire systems. Early literature from 1908 describes the benefits on the mechanical and manufacturing characteristics of 5/6th and other short pitched windings [23]. An example of this winding structure used in the field of SGs is given by [31]. A comparison between the WFs of these two windings can be seen in Fig. 3c, where it is again highlighted how the choice of the winding configuration is a trade-off study aimed at maximizing the output while complying with the power quality requirements. Although the winding solutions presented above represent only a portion of all the possible configurations currently used in electrical machines, they explain well how voltage waveform improvements were achieved in the history of utilization of these generators.

All the scenarios investigated above assume a homogeneous periodicity between stator (ps) and rotor (pr), meaning that an equal number of poles are used for both structures, implying that an integer number q of slots-per-pole-per-phase is employed. A further step towards the power quality improvement objective is the adoption of fractional slot windings, where ps and pr can be different, allowing for using a non-integer q [21], [32]. The relative advantages of fractional slot windings, particularly from a manufacturing and design point of view, were discussed as early as 1908 [23].

This also allows the design of the electrical machine to focus on the interaction between different stator and rotor harmonics ks and kr. However, in absolute terms, the main operation of the machine has to comply with the relationship psks = prkr. Above all, fractional slot windings present the significant benefit of increasing the degrees of freedom in the choice of the number of slots and the pitching length as well as the opportunity to remove certain harmonics [21]. However, this particular winding configuration does produce high sub-harmonics, leading to a reduction of the overall efficiency [29]. More recently, multi-phase armature windings have been investigated for attenuating specific harmonics on the output of field-wound SGs [24]. Due to their inherent drawbacks such as lower power densities, these configurations are however limited to certain niche applications where redundancy under faults conditions is highly desirable [33].



a)

1	2	3	4	5	6	7	8	9	10	11	12
A_1^+	A_3^+	C_2^-	C_4^-	B_1^+	B_3^+	A_2^-	A_4^-	C_1^+	C_3^+	B_2^-	B_4^-
A_2^+	A_4^+	C_1^-	C_3^-	B_2^+	B_4^+	A_1^-	A_3^-	C_2^+	C_4^+	B_1^-	B_3^-

b)

1	2	3	4	5	6	7	8	9	10	11	12
B_4^-	A_1^+	A_3^+	C_2^-	C_4^-	B_1^+	B_3^+	A_2^-	A_4^-	C_1^+	C_3^+	B_2^-
A_2^+	A_4^+	C_1^-	C_3^-	B_2^+	B_4^+	A_1^-	A_3^-	C_2^+	C_4^+	B_1^-	B_3^-

Fig. 3. *Double-layer, 4p slots-per-phase distributed winding: **a)** planar scheme of a full-pitched winding; **b)** planar scheme of a short-pithed winding; **c)** comparison between the related winding functions*

In non-salient machines, the field winding can be distributed into slots allowing a more sinusoidal airgap flux to be produced [21], [34]. This was identified as early as 1911 as a key advantage over salient pole machines [35]. Similarly if only two thirds of the rotor surface are slotted then the third harmonic and its multiples are cancelled [21].

Around the 1920s it was known that the connection of the windings at the terminals of a SG can cancel some harmonics. If a star connection is used then the third harmonic and its multiples are cancelled as long as the neutral is left ungrounded [36]. In a delta-connected generator the third harmonic current creates additional copper loss [36].

All the aspects discussed above, those related to the winding pitch and distribution as well as to the phase connections can be combined to produce an optimal WF which relates to the attenuation of harmonics in the machine EMF [37]. Tables of WFs for a number of example windings is given in [22].

2.2. Lamination/Core Geometry

The geometry of the machine core packs dictates the shape of the flux linkage and therefore has a significant influence on the harmonics of the generated voltage waveform. The presence of slot openings on the armature core introduces high frequency harmonics (namely tooth ripple) on the air-gap flux. This phenomenon is well described from early engineering literature from the 1900s through to modern electrical machines textbooks [7], [25]. These harmonics introduced onto the machine EMF are at fundamental frequency sidebands around the slotting frequency [7]. The amplitude of these harmonics can vary with the loading and power factor [38]. However, as these parasitic components are caused by the “slotting” effect, they can be of paramount importance in large (i.e. high voltage) SGs, where an open-slot structure is typically employed [39]. One way to reduce the inherent ripples is that of providing the stator and/or the rotor of the machine with an appropriate angular offset along the axial length. This technique is known as skewing and has been implemented in SGs since the early 1900s. For historical and manufacturing reasons it has always been implemented as an angular offset equal to one slot pitch [21], [40]. However, this non-optimal methodology leaves lee-way for significant improvements which have recently received renewed interest in the field of SGs [41], although most efforts are focused mainly on other electrical machine families [42]. The effects of skewing on the no-load phase voltage waveform of a 400kVA SG is shown as an example in Fig. 4.

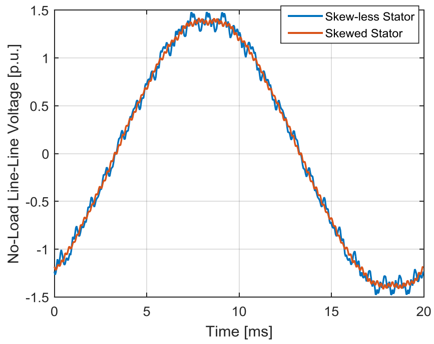


Fig. 4. *Skewing: No-load waveform improvement*

Another design aspect which can significantly affect the power quality in SGs is related to the shape of the salient poles. This technique has been implemented on early generators and was deeply investigated in a paper from 1924 [43], however it still represents a popular optimization design process, as demonstrated by more recent literature [44].

2.3. Inclusion of Damper Cage and its Optimal Design

The introduction of an induction motor (IM) style cage on the rotor of a SG was historically added to dampen torque oscillation from the prime mover [45], [46]. Transient performance in fault conditions can also be improved by the addition of a damper cage [47] and in fact on modern machines (where the prime mover is expected to produce highly smooth torque [45]) this winding is implemented mostly for guaranteeing power system stability. However, it also affects the machine behaviour under different operating conditions, including the steady state. For the sake of this study it is important to point out how the role of the damper cage also includes reducing harmonics in the air gap flux density, particularly those produced by the armature tooth ripple [45]. Several methods have been proposed in literature aiming at attenuating these parasitic effects through an optimised design of the damper cage [48]. Although, damper winding design has been traditionally performed by means of empirical and theoretical approaches [49], today modern finite-element (FE) and optimisation techniques are increasingly used to address the very complex phenomena related to the currents (and associated losses) induced in this winding and the associated harmonic distortion. In particular, the voltage THD can be improved by increasing the distance of the damping bars from the airgap (i.e. moving the bars along the radial direction) and by shifting the cage around the polar axes (i.e. moving the bars along the tangential direction) [39]. Complete and incomplete damper winding configurations have been shown to have a different impact on the voltage waveform quality, showing that complete end connections lead to higher slot ripple harmonic amplitudes [50]. However, all these designs usually come at the cost of inducing more elevated currents in the bars [51] and also the cost of modifying the generator behaviour during transients [52]. Improvement of the output voltage without compromising the bar losses can be achieved by providing the stator slots with high permeability wedges [53], as these reduce the slotting effects. This however leads to an increase of the slot leakage inductance of the machine. Recently, to counter the above challenges, a modulated damper winding (i.e. repositioning the bars) has been proposed in [31] with very positive results, which can be observed in Fig. 5. This shows the voltage waveform improvement obtained through the implementation of a modulated damper cage onto an existing 400kVA SG.

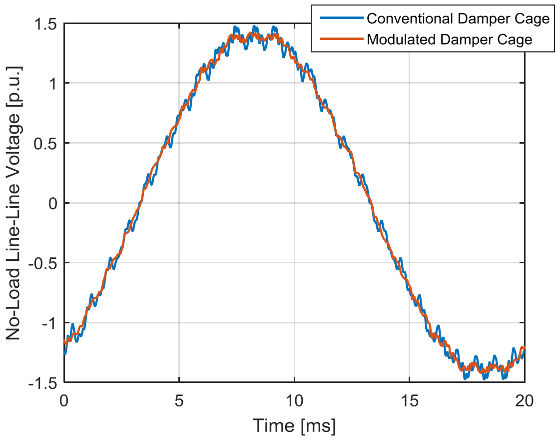


Fig. 5. *Modulating the damper cage: No-load waveform*

2.4. Final Considerations

This section has dealt with a survey of the design methods used in SGs for complying with output voltage THD requirements at the point of generation. The reviewed techniques therefore focus on the machine design choices which mostly affect the power quality of such classical machines, namely 1) the winding configuration, 2) the laminations/core geometry and 3) the damper cage design. These design methods are today enjoying a revived interest, mainly enabled by the advent of more powerful computational resources aligned with accurate FE packages that permit detailed analysis. The main challenge is that these methods are disruptive and invasive. For generator manufacturers and machine suppliers, such machine design changes represent a considerable financial and manufacturing effort that from a business perspective is not always the most cost effective investment.

Alternative methods that can address power quality at a system level are those that include passive and active compensation techniques, usually achieved by including “extra” sub-systems at the machine’s terminals, usually taking the form of power filters. The ‘retro-fit’ and flexible nature of such methodologies has resulted in their popularity in the last decades, mainly driven by the ever-increasing advancements and availability of PE. These systems primarily focus on the reduction of harmonics in the load current waveform which would otherwise result in voltage distortion at the point where the load is coupled [54].

3. Harmonic Reduction for Distributed Generation and Renewables

In early power networks harmonics typically came from the generator or saturation of magnetic components such as transformers [55], [56]. These issues were mostly overcome by the machine design methods described in Section 2. With the advent of rectifier systems and PE converters the focus of harmonic mitigation research moved to the load. However, in recent years power networks have evolved to include distributed generation (DG) and renewable energy sources (RES). This, in parallel to the push towards energy trading and the concept of smart grids, has changed the traditional layout of the grid and placed generation at all voltage levels. RES are typically coupled to the grid through PE converters and as a result has renewed interest in harmonic reduction at the point of generation.

3.1. Grid Connection of Renewables

The use of PE converters to couple RES to the grid can result in resonance and harmonic instability, particularly when used in significant number [57], [58] or if the control system is not adequately tuned [59]. A framework for determining the maximum amount of DG resources in a system while maintaining harmonic limits is given in [60]. If properly controlled and interfaced to the distribution network, DG can improve both power quality and efficiency [61].

For renewable sources, the control scheme of the grid-connected converter plays a significant role in its harmonic effect on the supply and its tolerance to externally generated harmonics [62], [63]. Recent research has looked at new control and synchronisation methods to improve harmonic performance of grid connected renewables [64], [65].

On the other hand, the existence of a PE converter on most RES allows these to also be used for harmonic mitigation and power factor control [66]. This is particularly advantageous for DG as they are typically installed close to large, harmonic producing loads [67], [68]. One system of particular note is the unified power quality conditioner (UPQC) which is a combination of shunt and series active filters with shared DC-link [69], as shown in Fig. 6. The UPQC is particularly suited to RES that can be directly connected to the DC-link, reducing inverter cost [69].

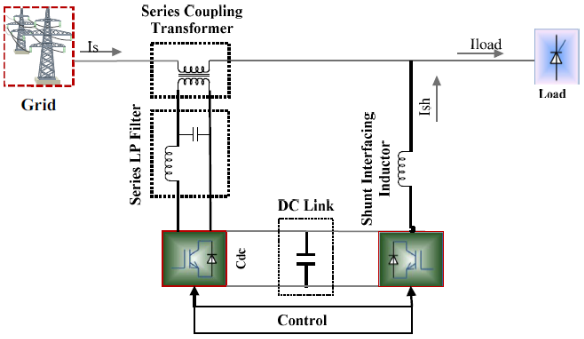


Fig. 6. *High level diagram of a UPQC* **[69]**

3.2. Harmonic Mitigation in Microgrid Applications

A recent research focus has been on smart and microgrid networks where the majority of generation comes from renewable systems. In these cases, it is typical for a high proportion of loads to be PE to maximise efficiency and performance at the cost of harmonic distortion. The design of a hybrid harmonic filter, where a passive filtering element is combined with an active filter, specific to microgrid networks has been considered in [70].

Harmonic mitigation through power sharing has been a key focus of recent research as this is key for the operation of microgrids in islanded mode [71], [72]. Harmonic loads are shared between multiple generating units in which their interfacing PE acts as an active filter system, thereby improving overall voltage quality [73].

Microgrids are in some cases designed to power their loads during loss of the main grid supply (islanded operation). When the main grid is restored the microgrid must be able to resynchronise and connect. A strategy for performing this under phase unbalance and harmonic distortion is given in [74].

3.3. Energy Storage

RES provide intermittent power which can be a key issue in areas where they make up a significant proportion of the supply capability. One option to overcome this is that of grid connected energy storage, with commercial systems now becoming available [75]. These energy storage units are able to smooth power demand as well as providing ancillary functions such as harmonic mitigation and power factor correction [76], [77]. A key feature is that they can help stabilise weak grids where there is a large proportion of RES.

3.4. Final Considerations

RES and distributed generation are the latest challenges in harmonic mitigation and the key focus of recent research. New solutions based around existing knowledge of active filter systems are able to provide useful ancillary functions using the same hardware required to interface to the grid.

Microgrid networks provide a key challenge for harmonic mitigation, particularly where intermittent RES provide a significant proportion of power. New research into power sharing and energy storage is offering solutions to these challenges.

4. Conclusions

In the work outlined above, a comprehensive review of conventional power quality improvement measures at generation level has been given. The main focus is on THD improvements, where the main techniques and methodologies implemented onto electrical machines over the last century and a half have been described in sequence. Table II highlights some of the key THD achievements of different topologies and applications. An important aspect of the above work is that, although it has been presented with all the developments shown in chronological order, it is important to note that most of the described methodologies continue to evolve and thus continue to be valid considerations for new designs.

In recent times, the main focus of research has been on the load side system, in order to correct for the presence of harmonics from non-linear devices used in PE. However, with the advent of RES and more DG, the effects of these on harmonics have become a greater research focus. This will continue in the future as a larger proportion of energy is produced by renewable sources in an effort to meet climate change targets and reduce dependence on fossil fuels.

A major associated risk of moving to multiple low power generating systems, in many cases optimised for low cost and ease of manufacture, is that of damaging connected equipment and/or destabilizing the existing supply through reduced power quality and harmonic interaction between large numbers of similar systems (as is already being seen in wind power installations [58]). Thus in the near future, concentrated efforts aimed at addressing these challenges are required.

A comprehensive review of the methods employed for mitigating harmonic distortions in electrical generation

Table II Harmonic mitigation topologies and applications

Application	**Year**	**THD**	**Topology**
Early alternators by Ganz & Co, and Siemens & Halske [16]	Late 1800s	>12%	Single layer, 1 slot-per-pole-per-phase, full-pitch, skew-less
6MVA, electric generator [17]	Early 1900s	>10% & <12%	Single layer, n slots-per-pole-per-phase, full-pitch, skew-less, delta connected
Medium to large rated SGs for power generation [35]	1950s (still produced)	>5%	Double layer, short-pitched distributed winding, skew-less
Medium to large rated SGs for standalone generation [90]	2014	~2.5%	Double layer, short-pitched distributed winding, skew-less, “shifted” damper cage
Medium to large rated SGs for standalone generation [28]	2017	~2.5%	Double layer, short-pitched winding, skew-less, modulated damper cage
Small to medium rated SGs [27], [40]	1980s (still produced)	~1.5%	Double layer, short-pitched winding, skewed stator

systems has been dealt with in this paper. In particular, the main prominent aspects considered include

Synchronous generator design with special considerations on 1) Winding configurations, 2) lamination and core geometries and 3) Damper cage design.

Distributed generation with special considerations on 1) Grid interfacing of RES, 2) Microgrid networks and 3) Energy storage systems.

In order to conclude this review paper, a summary of the machine design methods of harmonic mitigation was presented in Table II, which highlights the major applications and topologies developed from late 1800 to present day.

Even considering the extensive existing development in the context of power quality improvements, new and innovative techniques [30], [31] are continuing to be investigated and proposed. In particular [30] shows significant potential in improving the voltage THD of a 48.5kVA SG, used as vessel to prove the proposed approach. This methods allows the power density of the machine to be improved making it particularly suited for distributed generation systems which are an ever increasing component of power networks.

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