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Power Quality and Enhancement Techniques: Research Gaps and Current Trends

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Abstract*: The increased use of electricity-dependent devices has posed many concerns to the power industry. The devices like electric motors, printers, generators, transformers, computers, etc are widely used in today's world. The electronic devices increase the non-linear load to the power system which leads to the power quality (PQ) issues by which the electrical devices may get affected with fluctuation causing equipment failure, power system failure, etc. In order to resolve the PQ related issues and harmonics mitigation occurred due to nonlinear load power filters were introduced in decades ago. This paper deals with the review of existing researches that uses power filters and other methods for power quality improvement. The paper also gives gaps and the current state of the art in the recent researches which have futuristic scope in the research domain.

***Keywords*: Harmonics, Power Quality, Hybrid Filter, Neuro-fuzzy, Power system**

I. INTRODUCTION

With the growing demand of power in today's world as witnessed the Power Quality (PQ) as a major concern in power system. The increased use of electronic equipment involving information technology and power electronics devices like adjustable speed drives (ASD), energy-saving lighting systems, programmable logic controllers (PLC) are considered as the main cause of power quality degradation as they bring variation like electric loads [1]. This non-linearity in all these loads is leading to the generation of disturbances within the voltage waveform. With technological advancement, the worldwide organizational economy has evolved with globalization, and profit level of various processes is decreasing [2]. The growing sensitivity of the process involved in industries, residential and services are leading to power quality issues into the availability of quality of power as a major factor for attractiveness in each activity sector. The major power quality affected areas are industry and information technology services as they involved with continuous processes. In order to overcome the concerns of power quality, various methods were presented in recent past. The power quality enhancement methods involve power conditioning devices, power filters, etc [3].

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This paper intends to perform the survey analysis on the existing researches, the current state of the art in the domain of power system dealing with power quality issues. Sectionally, this paper is organized as Essential reasons for degradation in power quality (Section II), existing Solutions/methods for power quality optimization (Section III), Review of existing research tries towards power quality enhancement (Section IV). Discussion of identified research gaps in current research (Section V), Analysis of the current state of the art in power system domain intending with power quality issues (Section VI) and finally, the significant points obtained from the survey are discussed in Section (VII).

II. REASONS OF POWER QUALITY DEGRADATION

As discussed above the use of electronic equipment and drives are inducing non-linear load into the power system which is generating power quality issues and by which the end user electrical device may get malfunctioned, fail or not operate at all. In that regards, various reasons are there in power quality degradation which has the impact of sensitive devices. Following are the few listed reasons for power quality degradation (as shown in Figure.1).

A. Voltage Spikes or Surges

These are rise due to non-linear load which can be instantaneous (known as a spike) or may exist for a longer duration (known as a surge). The surges mainly occur when the voltage becomes more than normal, and in this condition, the heavy power equipment may get turned off. In order to overcome these spikes/surges, the voltage regulators, surge suppressors, power conditioners, etc [4] can be used.

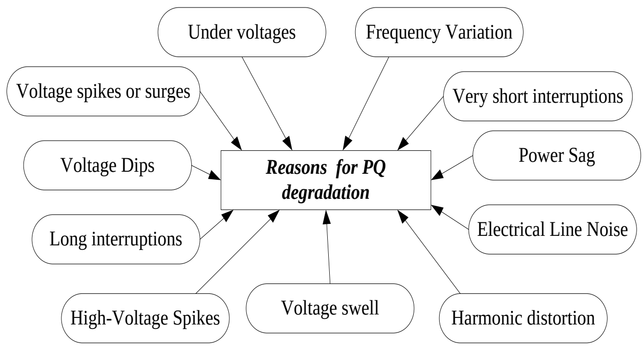


Fig.1 Reasons for PQ degradation

B. Voltage Dips

The limited duration of under voltages can be referred to as Voltage Sags/Dips. The sag in voltage is the minimization of supply voltage and recovery of voltage within a short duration.

The voltage dip is a fault in the power system. The sources of these dips are starting of huge loads and the supply of inductive loads. These inductive loads give an impact on the consumer's devices, and it may annoy with the continuous flickering of light and in some cases tripping loads may take place.

C. Under Voltages

The loss in the power generation, increased network loading, improper tapping of transformers and malfunctioning of voltage regulator causes this kind of under voltage issues. The loads having low power factor are the prime reason for under voltage which indirectly induces the overloading problems in which the equipment consumes more current to balance the output power [5, 6].

D. High-Voltage Spikes

These spikes take place if the voltage reaches to 6KV and the spikes results about lightning strikes and other problems. The problem on the electronic system can lead to data loss and circuit board malfunctioning. These spikes can be suppressed with voltage regulators, surge suppressors, power conditioners, etc [7].

E. Frequency Variation

This involves variation in the frequency from the normal frequency of 50Hz-60Hz based on geographic location. The frequency variation caused due to the sudden operation of generators or improper frequency sources. This variation can lead to data loss, equipment failure, program failure, etc. This can be suppressed with voltage regulators, surge suppressors, power conditioners, etc [7].

F. Power Sag

These are the prime reason for PQ degradation. The sages are mainly occurred by system faults and may result in load switching with highly demanding startup currents. These sags can be suppressed with voltage regulators, surge suppressors, power conditioners, etc[8].

G. Electrical Line Noise

These are the unwanted effects caused due to Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) in computer system circuits. The line noise occurs due to relays, motors controllers, broadcast transmissions, and microwave radiation, etc. Due to this problem, the equipment failure and data loss may take place. These can be suppressed with voltage regulators, surge suppressors, power conditioners, etc [9].

H. Very Short Interruptions

The interruption of few milliseconds can be considered as a very short interruption and are occurs due to opening or re-closing of protection devices due to decommissioning a faulty network. Due to this the insulation failure, lightning issues, and, etc. With this interruption, the protection device may get tripped, data malfunctioning, etc [10].

I. Long Interruptions

These are the interruption which occurs at the greater duration of more than 2 seconds. This interruption may be caused due to equipment failure in a power system, striking of objects to the lines, human errors, etc. [1].

J. Voltage Swell

The increment rate of voltage to a greater extent can be considered as voltage swell due to power frequency, more than normal tolerances just in few seconds. The reason behind is this swell is the improper operation of the heavy load, power sources, transformers, etc. With this issue, the system can cause damage to the sensing devices, data loss, etc [11].

K. Harmonic Distortion

The operation of the electric machines beyond the magnetic saturation, welding machines, DC brush motors, etc, is the main reasons for harmonic distortion. Along with these, the use of nonlinear load generating devices like electronic equipment causes higher distortion. Due to this issue the cable overheating, loss of efficiency, error in meter reading, etc, may take place. In order to overcome these issues, some of the following solutions were discussed.

III. SOLUTIONS FOR POWER QUALITY ISSUES

The power storage devices, distributed generation systems can be used to resolve the issues of power quality. The use of proper interfacing devices can be helpful in isolating the power disturbances. Some of the power conditioning devices include surge suppressors, power filters, etc., and are discussed below.

Over the decade of research has provided many PQ enhancement devices which play a major role in resolving the above-stated problems.

A. Surge Suppressors

The voltage surge suppressors are the easiest and low-cost power conditioning devices. These devices are mainly used interfacing with a power source and other sensitive loads hence transient voltage can be clamped with the suppressor before it reaches the load or equipment. The transient voltage with surge suppressor composed of non-linear resistance which limits the excess line voltage and performs grounding [12].

B. Filters

The filter is used to improve the power quality enhancement among them noise and harmonic filters play a significant role in avoiding unwanted frequency current/voltage signals and harmonics. The noise filter avoids the reaching of the unwanted signal to the equipment, and it has an integrated circuit of both capacitor and inductor which brings low impedance path between frequency levels. The harmonic filter is used to reduce the unwanted harmonics exist in the source. The harmonic filters can be classified into active power filters (APF) and passive power filters (PPF). The PPF builds a low impedance path for the frequency levels of harmonics which are caused due to passive components such as a capacitor, inductors, and resistors. Various passive filters are mainly connected in shunt manner to eliminate the harmonics to a greater extent. In case the components in the power system circuit, the PPF may fail to eliminate the harmonics. Hence APFs were evolved in recent researches which are more effective under dynamic load variation or non-linear load.

The APFs performs the analysis on current consumed at load end and eliminates the load generated harmonics. The recent advancement in the current research has evolved with both the active and PPF, i.e., a Hybrid filter which has got both the functionalities of both filters. The following Figure.2 gives the connection of APFs [13, 14].

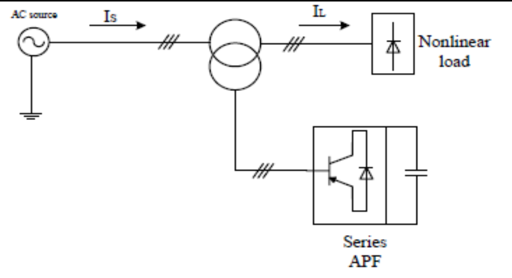
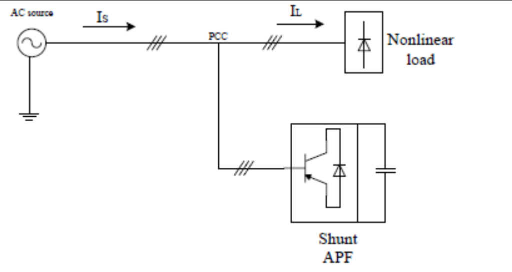
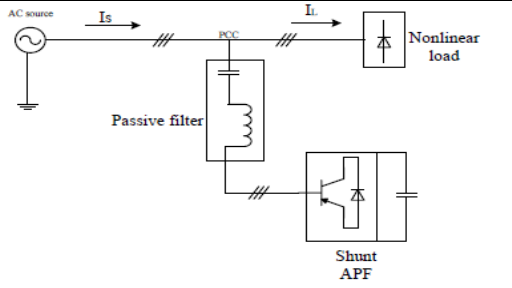
Type of Filter	Circuit
Series Filter: • This eliminates voltage harmonics • Balances voltages at both the terminals	
Shunt Filter: • This eliminates currents harmonics • Compensates reactive power • Balanced unbalanced currents at both the terminals	
Hybrid Filter: • Performs harmonics cancellation • Shares/balances both currents and voltage	

Fig.2 Different connections of power filters

IV. EXISTING RESEARCH TECHNIQUES FOR POWER QUALITY IMPROVEMENT

The techniques adapted and presented in recent past to evolve with power quality improvement are discussed below. The review is conducted by considering the official publications like IEEE, Springer, Elsevier, etc and selecting recent journal papers. An interesting work towards addressing power quality (PQ) issue and tried to improve PQ with Hybrid Power Filters (HPF) is observed in Temerbaev and Dovgun [1]. The filter adapts notch filter to mitigate the harmonics and improved PQ. The performance analysis through MATLAB based Simulink suggests that the [1] gives improved PQ. An integrated system having HPF and thyristor collected reactor is found in Rahmani et al. [2] with the aim of compensating harmonics and reactive power. The [2] have achieved satisfying results in harmonic mitigation and PQ enhancement. Towards the same concern for Wind Form Shahalami and Hosseini [3] have used ANN based HPF. The performance analysis suggests that [3] able to reduce the harmonics to a great extent with reduced processing time. The implementation of FPGA for PQ improvement with all on-chip controller is found in Sahu and Mahapatra [4]. The verified results of [4] give that the system can compensate both the balanced as well as unbalanced loads. A practical design of hybrid APF is given in Unnikrishnan et al. [5] which uses control mechanisms. The outcomes of [5] were compared with the existing system by which it is observed that it gives enhanced PQ. A comparative analysis of APF and HPF is found in Kedra [6] aiming with harmonics mitigation. From the analysis it is observed that HPF us more effective in mitigating harmonics and enhancing PQ. The implementation of Fuzzy logic for HPF is given in Kumar and Bhat [7] that also considered PQ improvement. The outcome of this [7] was able to stabilize the voltages of the DC link. Another comparative analysis of HPF with other compensation mechanism is found in Babu [8] in terms of PQ enhancement. The design and analysis of [8] were performed with different compensation mechanisms by which it is observed that HPF is efficient in minimizing total harmonics distortion and enhancing PQ. A current controller method for HPF is given in Chau [9] in which fuzzy- neural network, cost function, prediction model were used. The outcomes [9] suggests that it reduced the harmonics to a greater extent. The implementation of Fuzzy logic based PI controller is presented in Behera et al. [10]

which effectively improves the performance of the system by fulfilling the IEC and IEEE standards of harmonic mitigation. The performance analysis of HPF by using PQ theory is found in Balasubramanian and Palani [11] where the detailed analysis was performed in terms of harmonics reduction and voltage regulation. From the performance analysis, it is observed that [11] was able to improve the filtering performance of HPF. The work of Babu et al. [12] gives the modeling as well as analysis of HPF using Hysteresis current controller [12]. The [12] discussed various issues of PQ and performed compensation by using the PI controller. The performance analysis under different load scenario gives the effective PQ enhancement in [12].The combinational work of Tahmid and Ahmad [13] has introduced the PQ enhancement technique by adopting a synchronous reference frame (SRF) for HPF. The outcomes of HPF gives that the THD is reduced to a greater extent under both linear and nonlinear condition. The generated harmonics due to nonlinear load were minimized by Kaiwart and Raju [14] through the tuned filter. The performance analysis of the HPF with different inverter topology was given in Nandakumar and More [15]. Through this [15] significant PQ is achieved with reduced harmonics. The implementation of Recursive Least Square (RLS) for Harmonics mitigation and enhance PQ is given in Daset al. [16]. The system considered three levels of harmonics like low, intermediate and high and was estimated with error computation. Through this [16] significant amount of PQ is achieved. Review work in identifying the events of PQ and classifying them is performed by Ahsan et al. [17]. This [17] has reviewed more than 100 publications for classifying and detecting them. Another work of Balasubramanian et al. [18] discussed the simulation and analysis of the performance of HPF with fuzzy logic implementation under the non-linear condition for PQ enhancement. Compared to existing work better DC link regulation is achieved with better PQ. The work of Das et al. [19] has used fuzzy sliding mode based HPF for PQ enhancement. The outcomes were compared with the hysteresis current controller and are found that [19] has achieved better PQ. Further, some of the research tries on PQ enhancement, and harmonics mitigation is observed with FPGA implementation. One of such work is found in Panda et al. [20] which uses hysteresis current controller for HPF with Simulink and Xilinx system as a design platform. From the outcomes, it is mentioned that the acceptable THD is achieved and by which PQ is enhanced. Another kind of FPGA implementation for photovoltaic and wind grid systems is found in Damodhar and Kumar [21] by considering HPF. Through this technique better tracking and mitigation of fluctuation output power was achieved at steady state. An investigational analysis on HPF with fuzzy logic was found in Somlal et al. [22]. The controller-based on Fuzzy Logic generates the desired harmonic reference currents and are regulated with HPF. The outcomes of this give significant results in harmonics mitigation. Towards PQ improvement in the power system, the work of Rani et al. [23] has considered phase shift carrier PWM based shunt APF. The PWM technique was used to generate the gating signals, and its performance is analyzed by using MATLAB based Simulink, and the outcomes suggest that the system was able to balance both the linear and non-linear condition. Another work of Das et al. [24] has focused on improving PQ by using the RLS algorithm with HPF. By using the RLS algorithm, the amplitude as well as the phase angle of harmonic and fundamental currents. The analysis of [24] suggests that both the load and supply currents were improved with minimized THD at different conditions. The works of Zahira and Fathima [25] have given a technical review on different control mechanisms of APF. The discussion on a variety of control mechanism was observed with control mechanism advantages and limitations. The implementation of 3-phase auto tuned HPF is observed in Sindhu et al. [26] and experimentation is conducted at all load scenarios. The outcomes suggest that it achieves better harmonics mitigation and reactive power compensation. The continued work of Sindhu et al. [27] implemented exponential composition mechanism for compensating the power quality challenges like voltage sag, harmonics, and current harmonics. The outcomes of were verified by considering nonlinear load condition and achieved satisfactory results. An optimal approach of Fuzzy Particle Swarm Optimization (FPSO) for PQ enhancement is found in Esfahani et al. [28] which is found on both Fuzzy logic and particle swarm optimization (PSO) algorithm. The outcomes were analyzed with PQ enhancement. A compensation technique of Fatih et al. [29] gives the improved PQ and reactive power compensation. Similarly, to compute the noise level and eliminate the harmonics Dhineshkumar and Subramani [30] introduced Kalman filter and attained better computation of noise, harmonics elimination and improved PQ. The summarized form of review on existing research is given Table.1.

Table.1. Summary of existing researches

Author	Problem considered	Technique and Tool used	Outcome Limitations
Temerbaev and Dovgun [1]	Power Quality	HPF + adaptive system • MATLAB/Simulink	Enhanced PQ • Not benchmarked • Not considered Fuzzy logic
Rahmani et al. [2]	Power Quality	HPF + Thyrister controller Reactor • MATLAB/Simulink	Significant PQ • Not benchmarked • Not considered Fuzzy logic
Shahalami and Hosseini [3]	Power Quality	HPF + ANN • MATLAB/Simulink	Better PQ • Not benchmarked • Not considered Fuzzy logic
Sahu and Mahapatra [4]	Power Quality	HPF + Controller on a single chip • FPGA	Enhanced PQ, reduced THD • Not benchmarked • Not considered Fuzzy

Unnikrishnan et al. [5]	Power Quality	Shunt HPF • MATLAB/Simulink	Significant PQ • Not benchmarked • Not considered Fuzzy
Kedra [6]	Power Quality	HPF comparison • MATLAB/Simulink	Better comparative analysis • Not considered neuro-fuzzy
Kumar and Bhat [7]	Power Quality	Fuzzy logic + HPF • MATLAB/Simulink	Better PQ • Not benchmarked
Babu [8]	Power Quality	Comparative analysis of HPF • MATLAB/Simulink	Significant PQ • Enhanced comparative analysis • Not considered neuro-fuzyy
Chau [9]	Power Quality	Adaptive controller + APF MATLAB/Simulink	improved PQ • Not benchmarked • Not considered Fuzzy logic
Behera et al. [10]	Power Quality	Fuzzy logic + PI controller + HPF • MATLAB/Simulink	Significant PQ • Not benchmarked
Palani [11]	Power Quality	HPF + PQ theory • MATLAB/Simulink	Significant PQ • Not benchmarked • Not considered Fuzzy logic
Babu et al. [12]	Power Quality	HPF + Hysteresis current controller • MATLAB/Simulink	Better PQ • Not benchmarked • Not considered Fuzzy
Tahmid and Ahmad [13]	Power Quality	HPF + SRF • MATLAB/Simulink	Improved PQ • Not benchmarked • Not considered Fuzzy
Kaiwart and Raju [14]	Power Quality	Survey	Not an implementation work
Nandakumar and More [15].	Power Quality	HPF + inverter topology • MATLAB/Simulink	Significant PQ • Not benchmarked • Not considered Fuzzy logic
Das et al. [16].	Power Quality	HPF + RLS algorithm • MATLAB/Simulink	Better PQ • Not benchmarked • Not considered Fuzzy
Ahsan et al. [17]	Power Quality	• Survey	Not an implementation work
Balasubramanian et al. [18]	Power Quality	HPF + fuzzy logic • MATLAB/Simulink	Improved Not benchmarked • Not considered neuro-fuzzy
Das et al. [19]	Power Quality	HPF + Fuzzy logic + Sliding mode • MATLAB/Simulink	Better PQ • Not benchmarked • Not considered neuro-fuzyy
Panda et al. [20]	Power Quality	HPF + Hysteresis current controller • FPGA	Improved PQ, reduced THD • Not benchmarked • Not considered Fuzzy logic
Damodhar and Kumar [21]	Power Quality	Sinusoidal PWM + HPF • FPGA	Better PQ, reduced THD • Not benchmarked • Not considered Fuzzy logic
Somlal et al. [22]	Power Quality	Fuzzy logic + PWM + HPF • FPGA	Improved PQ • Not benchmarked
Rani et al. [23]	Power Quality	Shunt APF + PWM MATLAB/Simulink	Better PQ • Not benchmarked • Not considered Fuzzy
Das et al. [24]	Power Quality	HPF + RLS algorithm • MATLAB/Simulink	Improved PQ • Not benchmarked Not considered Fuzzy
Zahira and Fathima [25]	Power Quality	• Survey	Not an implementation work
Sindhu et al. [26]	Power Quality	3-phase HPF • MATLAB/Simulink	Better PQ • Not benchmarked • Not considered Fuzzy
Sindhu et al. [27]	Power Quality	HPF + Exponential Composition Algorithm • MATLAB/Simulink	Improved PQ • Not benchmarked • Not considered Fuzzy
Esfahani et al. [28]	Power Quality	HPF + fuzzy logic based PSO • MATLAB/Simulink	Better PQ • Not benchmarked • Not considered Fuzzy
Fatih et al. [29]	Power Quality	Hybrid passive filter • MATLAB/Simulink	Improved PQ • Not benchmarked • Not considered Fuzzy
Dhineshkumar and Subramani	Noise estimation + harmonic + power quality	HPF + Kalman Filter • MATLAB/Simulink	Better noise estimation, reduced harmonics, significant PQ • Not benchmarked • Not considered Fuzzy

Fatih et al. [29]	Power Quality	Hybrid passive filter • MATLAB/Simulink	Improved PQ • Not benchmarked • Not considered Fuzzy
Dhineshkumar and Subramani	Noise estimation + harmonic + power quality	HPF + Kalman Filter • MATLAB/Simulink	Better noise estimation, reduced harmonics, significant PQ • Not benchmarked • Not considered Fuzzy

V. RESEARCH GAP

After reviewing the recent existing researches in the domain of power quality enhancement and harmonics minimization, some of the following gaps were identified.

- **Lack of suitable techniques:** Various existing researches were not much effective under dynamically varying load, i.e., nonlinear conditions.
- **Lack of fuzzy logic based approaches:** Most of the existing researches are associated with traditional techniques, PI controllers, etc. From the survey, it is found that very rare works were evolved with fuzzy logic-based approaches.
- **Lack of neuro-fuzzy approaches:** The recent works were given much emphasis on either fuzzy or neural network approaches separately. The recent researches are less involved with neuro-fuzzy approaches.
- **More focus on APF based approaches:** The recent researches are much concentrated on active power filters than hybrid power filters.
- Very rare works are focused with THD minimization.
- Very rare work are considered with hardware implementation with FPGA and neuro-fuzzy logic technique.

VI. CURRENT STATE OF ART IN RESEARCH DOMAIN

The current state of the art in power quality enhancement and harmonics mitigation is analyzed by extracting the data from IEEE Xplore and Springer publication details till now. The keyword of "power quality + harmonics" and "power quality +power filter" is given for analysis and the obtained data is given in below table.2.

Table.2 Current state of the art in the research domain

Type of publications	Power Quality + harmonics		Power Quality +power filter	
	(IEEE)	(Springer)	(IEEE)	(Springer)
Conferences	195	-	7,220	-
Journals & Magazines	15	937	1,764	939
Standards	2	-	2	-
Books	1	29,920	7	31,229
Series	-	432	-	432
Web pages	-	251	-	253
Early access Articles	-	-	62	-
Courses			60	-

From table.2, it is observed that the research works published in Springer were more than IEEE. The springer has a good number of books, web pages, conferences, and series. Figure.3 gives the graphical representation of the tabulated research state.

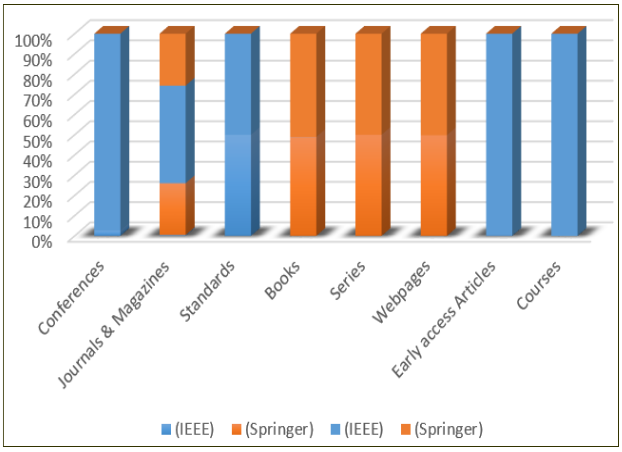


Fig.3 Graphical representation of current researches

VII. CONCLUSION AND FUTURE WORK/SCOPE

The available power supply in today's world is not up to mark which is failing to meet the growing power demand. Also, with rapid use of electronic devices are posing power quality problem due to nonlinearity at the load end. The low quality of power also leads to the malfunctioning of power equipment or power system failure. To overtake these problems and prevent the losses related to the PQ problems, the consumers need to take prevention actions. In that sense, this paper introduced various factors involved in power quality degradation, recent researches in the power quality enhancement, research gaps found after review analysis, the current state of the art in research domain with unaddressed problems.

Further, this review paper can be considered for futuristic research towards:

- Designing a hybrid power filter using an analytical approach.
- Designing a neuro-fuzzy based controller for hybrid power filter to enhance the power quality, reduce THD and suppress the harmonics.
- A hardware prototyping model can be designed by using FPGA and neuro-fuzzy logic technique.

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