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A Perception to Digital Control Schemes for Active Power Filters

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ABSTRACT

*Most of the pollution issues created in power systems are due to the non-linear characteristics and fast switching of power electronic equipment. The use of the power electronic devices in power distribution system gives rise to harmonics and reactive power disturbances From more than a decade, there is lots of effective research contribution towards introducing a technique for suppression such harmonics using filters. However, till date there is no evidence of any standard model or framework or any landmark ideas that has solved the issue of harmonic suppression in total it. The harmonics and reactive power cause a number of undesirable effects in the power system. Active Power Filters(APF) have been developed over the years to solve these problems to improve power quality . Hence, the purpose of this manuscript is to discuss about harmonics with respect to active power filters where the prominent focus is laid down to understand the effectiveness of priorly introduced techniques. The study presents a state-of-art review of techniques of harmonic suppression with an aid of research gap***.**

Keywords-component, Harmonic, Active Power Filter,p-q theory

I. INTRODUCTION

With the increasing adoption of the modern electrical appliance, the area of power electronics as well as power distribution encounters a significant challenging factor. Owing to the usage of power components like diode bridge, DC capacitors, it is highly feasible that such devices can consume current to highest point of the main source voltage in an interface circuits. It is known that electrical devices mainly draw non-sinusoidal currents irrespective of the applied voltage being sinusoidal [1]. Owing to non-appropriate features of the source of voltage, voltage distortion surfaces up in electrical devices due to harmonics. In the present era, the consumers heavily uses cyclo-converters, rectifier, arc furnaces, variable speed drives, asymmetrical loads that can significant produce maximized disturbances in the existing as well as in upcoming power supply system [2]. Presence of harmonics are always detrimental to power system that results in irreversible failure of the electrical components sometimes apart from frequently known heating issues in it. Usually, it degrades the power quality system resulting in spikes, sags, swell, transients etc [3]. In order to mitigate adverse effect of harmonics in power system, adoption of inductive reactors, active filter, passive filters, phase-shifting transformers, etc are increasingly considered. It was also seen that there is a frequent adoption of three-four phase wire systems in majority of the commercial applications for power distribution. In presence of imprecisely distributed loads as well as uncompensated loads, it is highly possible that such electrical system will undergo unnecessary damage owing to non-linear loads. Hence, voltage-source is the most frequently adopted consideration compared to current source for designing the parallel active filters owing to its potential advantages. For better power quality, maximized level of voltages over DC bus is highly preferred and can be accomplished by using multi-level inverter. The reference current for the filter node need to cater up conditions for eliminating harmonics, correcting power factors, voltage regulation, and compensating load unbalance..

This paper therefore studies various techniques for harmonic compression in past decade and extracts a significant research gap. Section 2 discusses about the fundamentals of harmonics filter followed by Section 3 discusses about recently existing review papers. Section 4 discusses some of the prominent techniques used by researchers to suppress harmonics with an aid of methods, outcomes, experimental environments. Section 5 discusses about the research gap and finally section 6 makes some concluding remakes.

II. HARMONIC FILTERS

With the modernization of modern power electronics, various types of system consume various types of loads. Usually, with the use of applications like computers, laptops, and various other embedded system, the existence of usage of non-linear electric loads are high on use. Fig.1 exhibits the generation of multiple orders of harmonics with respect to amplitude and time. Hence, harmonic occurs owing to non-linear electric loads and effect the operational current and voltage design power filter that can minimize the side effects of harmonics on the power system and targets to enhance the power quality. Therefore, harmonics filters are developed to minimize problematic harmonics to a specific value to resist harmonic amplification.

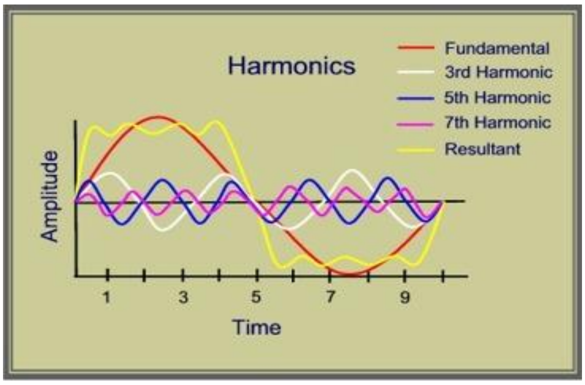

Figure 1 Harmonics Fundamentals [4]

A. *Causes of Harmonics in Power System*

At present time, the consumers uses various type of application that are based on power converters e.g. variable speed drives, rectifiers, inverters, soft-starter, switch-mode energy supply, uninterrupted power supply etc. Such types of frequently used devices in power electronics adopts switching mechanism using semi-conductor to precisely control speed, output, torque, as well as energy efficiency on electrical system. Compared to linear loads (e.g. capacitors, inductors, and resistors), such devices consumes continuous current from the source of supply. However, non-linear loads can consume short and rapid burst of current from the supply source. Another cause of harmonic is when the system apply a sinusoidal voltage to linear device and the current factor is found to sinusoidal too. When a system applies sinusoidal voltage to any non-linear device, it was seen that output will be non-sinusoidal thereby giving rise to harmonics. Therefore, the yielding non-sinusoidal waves that are disrupted by the presence of harmonics can be studied from various degrees of harmonics ranging from fundamental (1^{st} harmonic) to larger order (Fig.1). The significant causes of generation of harmonics are basically the frequency and amplitude of harmonic current generated, quantity as well as type of non-linear load integrated in power system, and strength of power supply as well as system impedance factor. Hence, these are some of the significant cause of harmonics that adverse effect power system.

B. Effect of Harmonics on Power System

Harmonics always have adverse effect on power system that can be discussed in multiple manners. The first physically sensed issues of harmonics are overheating of the power system that is followed by breakdown of insulation. Owing to overheating of electrical equipments (switchgear, transformer, conductors etc), it undergo irreversible operational failure. Another soft target of harmonics is capacitor bank, which are normally adopted for correcting the power factor as well as used for controlling voltage. It occurs owing to the low impedance at maximized level of harmonics. Some of the other effects of harmonics are malfunctioning of PLL circuits, loss of motor winding, perturbing torque on motor shaft, communication interference, blown fuse, and occasional tripping of circuit breaker. Active filters can optimize residual output to filter out the single maximized harmonics in the network, but it cannot deal with 5^{th} harmonics which is one of the most significant harmonics on distribution network. Hence, hybrid harmonic filters are designed by amalgamating the potential beneficial factors of both passive and active harmonic filters, where the passive filter can be used for minimizing lower order harmonics(5^{th} and 7^{th}), while active filter can be used for higher order harmonics. Hence, hybrid filters ensure better size and cost efficiency in the area of harmonic filters.

II. ACTIVE POWER FILTER

In the area of power filter, there are various types of power filters as seen in the prior section. However, adoption of active power filter is quite high as seen in topic of research-based investigation for minimizing harmonic distortion. Active Power Filter is designed for the purpose of optimizing the modern technologies of power electronics for generating particular components of current that can eliminate adverse harmonic current caused due to non-linear loads. Investigation shows that active power filter is better compared to conventional passive power filter in following manner e.g. i) active power filter can eliminate harmonics generated from both reactive current as well as supply currents, ii) Active power filter doesn't generates harmful resonance like passive power filter in any power distribution networks, iii) active power filter is free from any dependency from power distribution system properties. However, owing to novelty in technologies associated with active power filter, still investigation is an on-going process in power electronics. Fig.2 highlights the actual components used in any standard active power filters and their respective operation.

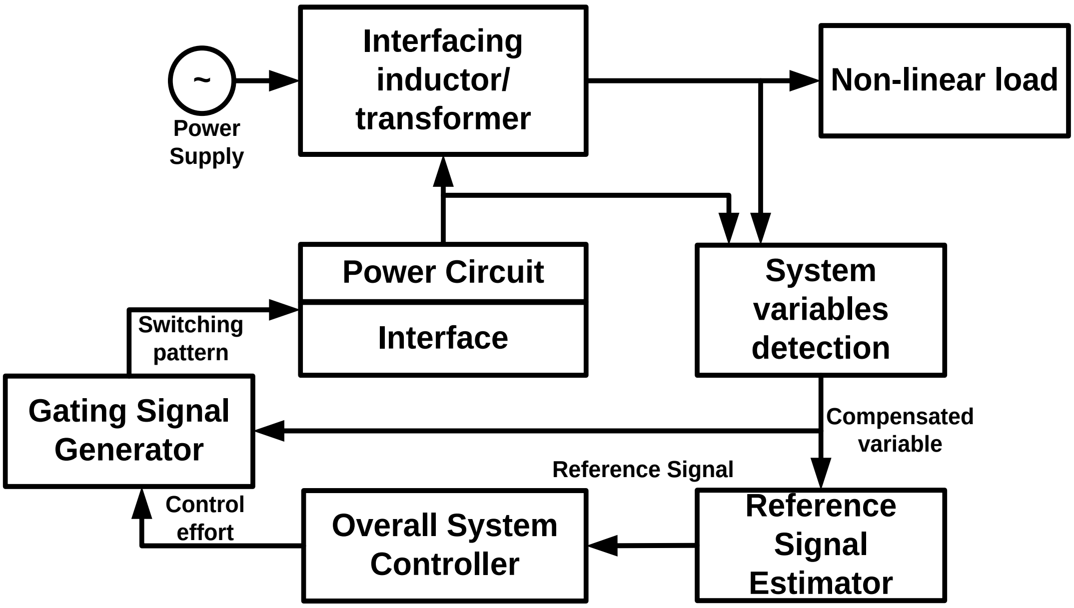

Figure 2 Active Power Filter Design

Fig.2 shows that overall system controller is driven by compensation reference signal that furnishes the cumulative control for the gating signal generator. The output signal generated from the gating signal generator actually controls the power circuit using an appropriate interface. Ultimately, the circuit design shown in Fig.2 can be of any form of connectivity (series, parallel, series-parallel etc) based on type of interfacing transformer or inductor to be used. However, active power filter has higher dependency on faster switching mechanism for higher current that can be considered as compensator for harmonics. The entire operation on active power filter is carried out by i) signal conditioning, ii) extraction of compensating signals, and iii) generation of gating signals.

The operation carried out in signal conditioning allows the filter to identify and sense the harmonics in the power distribution network. The reference signal is the prime component that guarantees the precise functionality of active power filter to be processed by controller. The current and voltage factors in electrical system are identified by using current transformer, potential transformers, and isolated amplifiers. The voltage factors to be identified in this process will be AC source voltage, DC bus voltage as well as voltage across interfacing transformer. After this, the time-domain or frequency-domain is adopted for evaluating feedbacks, reference signals. Active power filters are again classified into three types as discussed below:

- **Series Filters**: The series filters generates pulse width modulated voltage waveforms that are either subtracted or added on an instantaneous basis from/to the supply voltage for ensuring a pure sinusoidal voltage waveform over the load. A typical series active power filter design is shown in Fig 3. The system uses voltage-fed inverter for inverter configuration without any current-control loops. However, such types of filters are least adopted in commercial practices as compared to parallel active power filters. The prime reason behind this is issues of series circuits for handling maximized load current that maximizes the rating of their currents significantly as compared to parallel active power filters. Series filters are preferred for reducing harmonics of voltage-waveform for ensuring proper equilibrium of three-phase voltages. It can be

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also said that series filters can enhance the power quality for the benefit of load and furnishes load with an appropriate sinusoidal waveform that are critically required for voltage-sensitive devices.

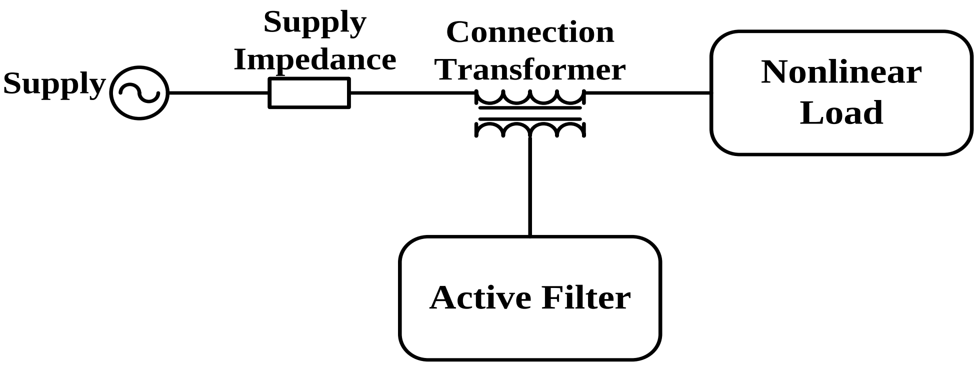

Figure 3 Series Active Power Filters

- **Shunt Filters**: This type of the filters is widely adopted for eliminating harmonics fed to the supply. The standard circuit design of series active power filter is shown in Figure 4. Shunt active power filters can be also used for compensating reactive power and ensuring proper equilibrium of three-phase currents. Shunt active power filter have potential advantages over passive active power filter. Such filters is capable of carrying specifically compensating current along with the small quantity of active fundamental currents that are supplied to compensate for the system losses. It is also feasible for integrating various filters in parallel for maximized currents for better power ratings.

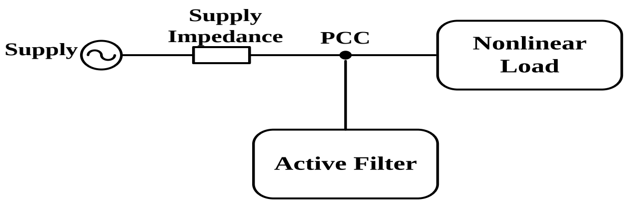

Figure 4 Shunt Active Power Filters

III. EXISTING REVIEW OF ACTIVE POWER FILTER

The investigation towards exploring the superior active power filter is not a new arena in research community. It was found that various researchers in most recent times have also performed reviewing various techniques of active power filter for harmonic suppression. The initial review towards the active power filter was published by Won [5] where the authors have discussed various issues of harmonics with respect to nature, impact, sources, and standards of harmonics. Chaturvedi et al [6] have also reviewed some of the techniques of active power filter with focus on non-linear loads. Most recently in 2014, the frequency of publications for review papers was seen to be quite high. Jacob et al. [7] have discussed about the theoretical understanding of power system harmonics with illustration of active power filter and its operations. The author have also discussed the classification of active power filter into three types i) Shunt, ii) Series, and iii) Hybrid. Raouf et al. [8] have investigated techniques towards improving power quality with an aid of active power filters and their respective controlling techniques. Ahmad and Jaglan [9] have discussed about the issues pertaining to harmonics and the techniques to

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eliminate them. Choudhary and Gaur [10] have discussed the control strategies towards active power filters exiting in the most recent times. The controlling techniques discussed by the author were signaling conditioning stage, derivation of compensation signal stage, and generation of gating signals. Apart from this authors have briefly hinted that in the existing system, various techniques frequently adopted for minimizing harmonics were neural network, wavelets, hysteresis control, fuzzy logic etc. Arthy and Marimuthu [11] have reviewed the control strategies for total harmonic distortion and theoretically discussed p-q theory, SRF (synchronous reference frame) Theory, SDM (synchronous detection method) theory, sliding mode controller, Pulse width modulation, and DSP-FPGA based schemes etc. Table 1. Summarizes existing reviews on active power filter.

Table 1 Summary of Existing Reviews on Active Power Filters

Index	Year	Discussion of theory	Discussion on research papers	Discussion on Research gap
[5]	2009	√	X	X
[7]	2014	√	X	X
[6]	2012	√	X	X
[8]	2014	√	√	X
[9]	2014	√	X	X
[10]	2014	√	X	X
[11]	2014	√	√	X

IV. EXISTING TECHNIQUES OF ACTIVE POWER FILTER

Afonso et al. [12] have developed a design of shunt active power filter that permits correction of dynamic power factor and effectively compensates both zero-sequence and harmonics. The design principle was mainly based on p-q theory. The simulation was performed in Simulink to evaluate shunt active filter. Study on adoption of shunt active power filter was also carried out by Kumar [13]. Designed on Simulink, the outcome of the study have exhibited better performance of controlled design where total harmonic current was reduced by 5% of the harmonics limit. Martinek et al. [14] have also adopted shunt active power filter for enhancing the power quality. The author has set novelty in their work by incorporating Artificial Intelligence method. Implemented in Simulink, the outcome of the study was evaluated using reference voltage process with respect to current, percentile of fundamentals with order of harmonics, and current with time. The outcome also exhibited that total harmonic distortion is enhanced by using ANFIS. Similar direction of the study was also performed by Poorvi et al. [15] and Daniel et al. [16]. However, Daniel et al. [16] have used hybrid active filter using reduced switch topology (B4) to ensure better cost minimization and bridge losses.

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Table 2 Summary of Existing Implementations on Active Power Filters

#	Year	Method	Real-Time	Simulated	Benchmarked
[12]	2000	PQ-theory	X	√ (Simulink)	X
[13]	2007	Fuzzy Controller-Shunt Active Power Filter	X	√ (Simulink)	X
[17]	2012	Shunt Active Power Filter	X	√ (Simulink)	X
[18]	2010	Two-level hysteresis controller	√ (IGBT switch + Texas Instruments TMS320F2812 Digital Signal Processor)	X	X
[14]	2013	Shunt Active Power Filter + ANFIS	√(intelligent electronics device)	√ (Simulink)	X
[15]	2013	Shunt Active Power Filter	X	√ (Simulink)	X
[19]	2007	SRF Controller + PQ Theory	X	√ (Simulink)	X
[20]	2010	Hybrid Active Power Filter	√(dSPACE DS1104 DSP controller)	X	X
[21]	2014	Comparative analysis of different active power filter	√(dSPACE control board of 750GX processor)	X	X
[22]	2012	7-level shunt active power filter + SDM circuit	X	√ (Simulink)	X
[16]	2013	Shunt Hybrid active power filter	X	√ (Simulink)	X
[23]	2008	Shunt Active Power Filter	√(Semikron IGBT Modules SKM50GB123D)	X	X
[28]	2009	Synchronous Generator	X	√	X
[29]	2014	Discrete Wavelet Transform	X	√ (Simulink)	X
[30]	2014	Comparative analysis of different active power filter	√(dSPACE Board-DS1104)		X
[31]	2011	FPGA + Fuzzy Logic	√(FPGA Board)	√ (Simulink)	X
[32]	2010	FPGA	√(Cyclone II-Altera)	√ (Simulink)+ Altera's Quartus II design software	X
[33]	2011	FPGA + Series Filters	√(TMS320F2812 DSP and	X	X

			3s400pq208-4– SPARTAN III FPGA)		
[34]	2005	FPGA+Newton climbing method	√(Altera FLEX 10K FPGA)	X	X
[35]	2013	Predictive Compensation	√(HIOKI PQA-HiView PRO 9624-50 power quality Analyzer)	X	X
[36]	2012	Neural Network + Shunt Active Power Filter	X	√ (Simulink)	X
[37]	2013	PQ-Theory	√(dSpace 1103 DSP system)		X
[38]	2004	PQ-Theory	X	√	X
[39]	2014	PQ-Theory + Shunt filter	X	√	X

Adoption of shunt active power filter was also witnessed in the study proposed by Routimo [23]. The study was more inclined to address voltage flickering problem. Xiao et al. [36] have investigated o shunt active power filter with split capacitor for reducing multi-repetitive errors. The outcome of the study was found to ensure total harmonic distortion minimization upto 4.35% and successfully caters up IEEE-519 standards. Gowtami et al. [37] have designed controlled using neural network for enhancing the power quality using shunt active power filter.Emphasis towards power quality enhancement was observed in the work being carried out by Ravindra et al. [22]. Various experiments were seen towards series active power. Owing to certain beneficial factors (e.g. current compensation caused by non-linear loads, high impedance, correction of voltage imbalance),Brandstetter et al. [23] have adopted real-time design of DSP to control active power filter. The outcome of the study was evaluated using two-level hysteresis current on 20 kHz IGBT switches with maximum current 78A.

Salmeron et al. [25] have designed a prototype of four different topologies of active power filter considering non-linear loads. Leela and Dash [26] have presented active power filter to generate seven voltage levels for minimizing the switching current ripple as well as load power factor using Simulink. Similar direction of the research is also found by the work carried out by Normanyo [27].Some of the studies introduced in most recent times have incorporated certain level of uniqueness. For an example-the study carried out by Salam et al. [24] have presented a hybrid version of active power filter considering the case study of a PV array. The model has been implemented on dSPACE DSII04 DSP controller and the outcome has been evaluated using spectrum analysis of source current on multiple scenarios. This work is the first of its kind that has attempted to integrate PV system with hybrid active power filter. However, the study was focused on high-order harmonics and adopts simpler compensation current reference. Hacil et al. [29] have adopted a case study of wind energy and targeted to enhance power generation and minimize harmonics using active power filter. The outcome of the study was

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found to minimize harmonics by 30%. Madhavi et al. [30] have adopted discrete wavelet transform as well as active power filter to ensure identification and location in time for both steady and transient state signals. Considering input voltage as 230 volts and simulated in Simulink, the outcome of the study was analyzed with respect to voltage sag and swell waveforms, and coefficient in DWT. Another unique study was proposed by Merabet et al. [31] most recently, where the author have adopted neural network to evaluate harmonics in dSPACE board. The outcome of the study was evaluated and compared with P-Q theory and diphase currents with respect to reactive power compensation, extent of harmonic compensation, and direct components needed. Simulated in Simulink model, the model considered unique values of utility source, non-linear loads, and active power filter.

Prusty [32] have adopted FPGA based approach to mitigate harmonics using active power filter using SRF theory and fuzzy logic. Adoption of FPGA based implementation was also carried out by Selvajyothi and Janakiraman [33] using single phase inverter. Darly et al. [34] have investigated on series active power filter using FPGA for improving the quality of power.Similar trend of the adoption of PQ-theory was also seen in the work of Bitoleanu and Popescu [38], Watanabe et al. [39] Table 2 summarizes the cumulative techniques introduced by various authors to enhancing the power quality factors ranging from publication year 1995-2014. The tabulated data basically highlights the methods of experiments and their adopted environment primarily focusing on their techniques being adopted. The next section will discuss about the research gap that has been identified after reviewing the research papers discussed in this manuscript.

V. RESEARCH GAP

From the discussion in all the prior sections, it was seen that evolution of harmonics and its significance in the research community is not new. The researchers from past decade have been attempting to showcase various techniques to eliminate harmonics for the purpose of enhancing power quality. In order to do so, it was seen that adoption of active power filter is quite higher even compared to hybrid active power filters for suppressing harmonics in electrical system. There are large scales of experiments being performed both real-time as well as in simulation environment to validate the outcomes accomplished by the researchers. Enough Studies have been done on Active Power Filter towards harmonic compensation during 1995-2014. Hence, following are the research gaps that have been explored after in-depth investigation of the outcomes highlighted in the studied prior techniques.

- **Ineffective review papers**: Before starting the write up of the proposed review manuscript, it was attempted to see if there are some existing review papers for harmonic elimination. However, in present paper, we choose to discuss only the most recent review papers on active power filters to narrow down our investigational focus (Section 4). It was found that all the existing review papers on active power filters as well as harmonic suppression are more or less the replica copy of each other. The review paper discussed by Jacob et al. [7], Chaturvedi et al [6], Raouf et al. [8] , Choudhary and Gaur [10] have only focused on theoretical operations of active power filter without any significant discussions on existing research contribution. We strongly believe that an objective of a review paper is to discuss about the prominent techniques discussed by prior researchers till date to understand the most effective techniques in this field of study. However, if someone reads all the existing review papers in this topic, the readers will only come to know about theoretical idea of domain and not the technical idea about the methods being adopted by researcher, their outcomes, their tools etc. Hence, proper decision cannot be made by the reader after reading the existing survey paper about the most effective techniques.

- **No Benchmarked works**: In the area of research, the reliability of the introduced model of researcher is determined by the performing comparative analysis of their outcomes with the most standards outcomes (or model) of other researchers but if the outcomes are compared on similar test bed and significant performance parameters, it become easy for the readers (or new researcher) to understand the most effective techniques. Tables 2 showcase that till date; very few studies were found to be benchmarked. To discuss a few e.g. Afonso et al. [12],Brandstetter et al. [23], Salam et al. [24], Salmeron et al. [25], Leela and Dash [26], Hacil et al. [29], Selvajyothi and Janakiraman [33]. In all the studies discussed in Table 2, the outcomes were compared by self-adopted hypothesis of the authors, which really makes a challenging task for a novel researcher to understand the best techniques of minimizing harmonics in power electronics.
- **Less Novel Work**: From Table 2, it can be seen that majority of the work are slight enhancement of each other with slight change in system variables and experimental test bed. Some of the studies e.g. Poorvi et al. [15], Leela and Dash [26], Prusty [31], Gowtami et al. [36] are just the minor amended version of priorly published studies in similar problems. The extent of novelty in this field is very few. However, few studies like Salam et al. [24] and Hacil et al. [28] were found with significant novelty and such studies were found with less repetition. We strongly believe that enhancing somebodies else work is always a novel idea, but it is better if the implemented enhanced model show some significant improvement. Majority of the work was found to enhance total harmonic distortion minimization in the mean range of 3% by slight change of research variables. If the extent of novelty is minimal, it becomes quite challenging task for the readers to get motivated for investigation in this field.
- **Repetitive Implementation Scenario**: In the area of power electronics, it is always a good idea to test the model in real-time environment for better realization of its outcomes. Table 2 shows that majority of the studies towards harmonic suppression is carried out in real-time and less in simulation environment. Some of the studies were also found to combinely use for real-time and simulation study. We strongly agree that a real-time implementation is effective, if the researchers showcase their observational outcomes by performing an extensive hardware based experiments. The commercial market has various types of hardware units for distribution of electricity which is not necessary to always match with the laboratory prototypes. Moreover, it was seen that till date there is no mathematical model (other than frequently used Simulink tool or some other proprietary tool) ever used for optimizing power quality in electrical system. We strongly believe that a mathematical modelling can greatly formulate the problems and can render better solution compared to real-time and simulation based model.

VI. CONCLUSION

This paper has review some of the most latent techniques found in the collected works that adopts mainly active power filters for significant suppression of harmonics in electrical devices. The paper has discussed the outcomes of various techniques and has presented a state-of-art comparative analysis (Table 1 and Table 2) of the current review and implementation techniques in similar field. It can be inferred that study towards active power filter have not seen much novelty and can be still said to be in early stages stage of development. Our future towards this paper is with an aid of mathematical modelling as well as effective benchmarking.

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