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REDUCTION OF HARMONIC EFFECT ON GENERATORS AND MOTORS USING MODULATED POWER FILTER COMPENSATOR

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Abstract - Modulated Power Filter Compensator (MPFC) is a new approach to harmonic mitigation for power system generators and motors that is introduced in this study. Several problems, including digital device malfunctions, overheating, and protective device tripping, can be caused by harmonics in electrical systems. To determine what produces harmonics in motors and generators in particular, the study conducted experimental investigations. The impact of voltage harmonics was investigated mathematically, which resulted in an expression for Total Harmonic Distortion (THD). With a focus on a plastic processing industry that uses several types of motors, a Matlab/Simulink model was developed to examine harmonics in generators and motors. With a THD of 14.93%, the results were found to violate the IEEE-1992 standard for harmonics. The integrated modulated power filter, which was created in MATLAB's Simulink environment and incorporated into the model, reduced total current to a level that is consistent with industry standards (4.77%). It was concluded that the Modulated Power Filter Compensator is very effective in reducing the Total Harmonics Distortion in Power System Generators and Motors. This research shows that MPFCs are great for reducing harmonic impacts and making sure power systems are up to code.

KEYWORDS: **MPFC, Total Harmonics Distortion (THD), Harmonics, Generator, Load**

I. Introduction

Non-linear loads pose a significant threat to modern electrical demand because they draw non-sinusoidal currents, which in turn generate harmonic currents and voltages that can skew waveforms. Increased heating, more audible noise emissions, and harmonic currents in the rotor are some of the negative effects that harmonics can have on generators and motors. The harmonics in the stator winding are to blame for these problems, which can lead to overheating of the rotor and compromised torque. To complicate matters, harmonics, especially triple harmonics, can be generated by generators and then transmitted to neighboring transformers. An important problem with power quality is harmonic distortion which are voltage or current waveforms in an electrical system that occur at integer multiples of the fundamental frequency (the main frequency at which the system operates, usually 50 Hz or 60 Hz). A rise in non-linear loads in contemporary electrical distribution systems has made this a more common occurrence. Due to their extremely non-linear characteristics, power electronic loads are both the origin and destination of power quality issues. Defects in equipment, overheated neutrals, potential fire risks, and inefficient energy use can result from harmonics, voltage sag/swell, and dynamic switching excursions. Additionally, when paired with power electronic devices for speed control, AC motors—typically linear loads—can induce harmonic current distortion. To fix these problems, methods like the modulated power filter compensator can be used.

2.1 Research Gap

Several studies by other scholars have been analyzed and discussed in this paper. Review articles and studies on the topic of dynamic characterization of power system harmonics and the reduction of their effects with chains have also addressed similar notions. Additionally, Markov; Stnakovic; A and Edwin M. (2020) were reviewed. There was a 25% improvement in harmonic reduction efficiency as a result of this effort. This new effort will make it better.

3. Methodology

3.1 Materials

i. The materials used were
ii. Dc motor and Generator
iii. Laptop
iv. Harmonic analyzer software
v. Electrical Transient Aanlyzer Program(ETAP) software
vi. MATLAB
vii. Excell software.

3.2 Methodology

This study employed the experimental method and the simulation approach as its major techniques. Motors and generators were studied experimentally to identify their operating characteristics and the impact of harmonics. It should be noted that the generators have a harmonic impact comparable to that of motors. To model and simulate the DC motor and generator, Matlab and Simulink were Helpful. Following these procedures precisely will help you learn how harmonics impact your motor and generator operations. A Simulink model of a modulated power filter compensation was created to mitigate the effects of harmonic losses on generators and motors while they are in operation. In the end, we had to correlate the models we had built and evaluate how well they worked.

3.3 Characterization of generator and determination of Harmonics

To examine the impact of harmonics on a three-phase Permanent Magnet (PM) Motor, the experimental apparatus seen in Figure 1 was employed. An incremental encoder, a power supply, a three-phase PM motor, a microcontroller-equipped control board, a low-voltage power inverter, and a piezoelectric element for vibration measurement were all parts of the setup. The research took place at a plastic processing company that uses a variety of motors and electrical components, some of which are classified as linear loads and others as non-linear. Initially, a power control center panel and portable measurement devices were used to evaluate harmonic qualities, and a modulated power filter compensator was not utilized. The harmonic content was measured using the Owon HDS 1022M-N power quality analyzer meter. To conduct harmonic testing, additional tools such as power analyzers, harmonic analyzers, and programmable loads were utilized. The test device was first configured, and then the harmonic content was measured. The results were compared to the standard limits defined by IEEE 519-1992, and any necessary adjustments were made. Power system harmonics can be better understood and controlled with the help of IEEE Standard 519-1992.

Figure 3.1: Experimental Determination of the effects of Harmonics at SEDI Enugu.

Power: apparent, active, reactive are related by

$S = \sqrt{Q^2 + P^2}$ 1

Where S, apparent power
Q, reactive power
P, active power.
D = Distortion power
For harmonic supply,

S = P + JQ = V I (cosφ + j sin φ); 2

Current THD (THDi) - the Total Harmonic Distortion for current will be:

$S = \sqrt{P^2 + Q^2 + D^2}$ 3

With a nearly sinusoidal voltage at the fundamental frequency and a highly distorted current, we can recover Irms as a function of THDi in such a system or installation.

$$P \approx P_1 \approx U_1 I_1 cos\phi_1;$$

$$I_{rms} = I_1\sqrt{1 + THD_i^2} \quad 4$$

(Alejandro et al., 2021)

A relationship between THDi (current distortion) and Power Factor can be written as (Daniel and Kabiru, 2016):

$$PF \approx \frac{cos\phi_1}{\sqrt{1+THD_i^2}} \quad 5$$

Since harmonics is presented in the form of voltage as;

• Voltage THD (THDv) – similarly, the Total Harmonic Distortion of voltage is expressed as (Elprocus, 2019):

$$THD_v = \sqrt{\sum_{n=2}^{N}\left(\frac{U_n}{U_1}\right)^2} \quad 6$$

The modified equation for the total harmonics distortion becomes harmonic distortion

$$THD_v = \sqrt{\sum_{n=2}^{N}\left(\frac{I_n(R_g + j2\pi f_n L_g)}{I_1(R_g + j2\pi f_1 L_g)}\right)^2}$$

$$THD_v = \sqrt{\sum_{n=2}^{N}\left(\frac{I_n \times \sqrt{R_g^2 + (2\pi f_n L_g)^2}}{I_1 \times \sqrt{\left(R_g^2 + (2\pi f_1 L_g)\right)^2}}\right)^2} \quad 7$$

3.4 Design of the Modulated Power Filter Compensator

Some parameters required for the design are:
Supply frequency f in Hz (50Hz)
Supply Voltage Vs in Volts (Low voltage-230V)
Harmonic order h Number (it was gotten by multiplying the supply frequency by every odd number from 3 to 23)
Quality Factor Q Number (The Q factor of the pMUT can be determined by the real part of the impedance frequency spectrum, which is defined as Q = fr/Δf, where the resonance frequency fr is the frequency at which the real part of the impedance reaches its maximum, Δf is the width of the peak at its half height, so-called 3 dB bandwidth)

The design steps adopted during calculating the Passive modulated power filter are;

i. The capacitance reactance was calculated using Equation 8

$Xc = \frac{Vs^2}{N} x \frac{h^2}{h^2 - 1}$ 8

ii. The capacitance C was calculated using Equation 9

$C = \frac{1}{2\pi Xc}$ 9

The inductive reactance was calculated using Equation 10

$XL = \frac{Xc}{h^2}$ 10

The relationship between X_l and X_c is $Z = \sqrt{X_l^2 + X_c^2}$ 11

iii. The inductance was calculated

iv. $L = \frac{Xl}{2\pi f}$ 12

v. Resistance was calculated using

$R = \frac{Xl}{Q}$ 13

$N = \sqrt{H^2 + Q^2} = \sqrt{S^2 - P^2} = \sqrt{(1865)^2 - (1492)^2} = 1119$

N = 1119Var

For that, the calculation of the values of the required passive power harmonic filter is as follows:

$Xc = \frac{Vs^2}{N} \times \frac{h^2}{h^2 - 1} = \frac{220^2}{1119} x \frac{3^2}{3^2 - 1} =$ 435,600/8952 = 48.66Ω

Where,
Vs = Supply Voltage =220V
h = Harmonic Order = 3
N = 1119Var
Xc = Capacitive reactance

$C = \frac{1}{2\pi f Xc} = \frac{1}{2x3.142\ x\ 50\ 48.66}$ = 6.54μF

XL = $\frac{Xc}{h^2}$ = $\frac{48.66}{3^2}$ = 4.41Ω

L = $\frac{Xl}{2\pi f}$ = $\frac{4.41}{2 \ x \ 3.142 \ x \ 50}$ = 14.04mH

R = $\frac{Xl}{Q}$ = $\frac{4.41}{50}$ = 0.0882Ω

Similarly, the modulated power filter designed is capable of suppressing odd harmonics.

The LC filter's impedance can be calculated using Equation 14.

$$:Z_{filter} = \sqrt{\frac{L}{C}} \qquad 14$$

$$Ish = \frac{Z_{filter}}{K + sL + Z_{filter}} ILH \qquad 15$$

If the filter K is less than or equal to the Z filter in equation (28), then the passive filter is the source of all the harmonic current. Because of this, the harmonics are removed at their source. According to Akagi et al. (2007), if K is less than or equal to sL, then K acts as a resistor in order to remove the source-filter harmonic resonance. Filter inductor and capacitor parameters.

By incorporating input and output inductances, the harmonic current produced by the non-linear load can be significantly reduced. A high rating was given to the input and output inductors. Incorporating the LCL filter solved the issue with input/output inductance. Issues with stability and insufficient filtering efficacy could arise from improperly chosen and rated power components. The aforementioned issues can be resolved in two ways. The passive technique involves connecting a resistor to the capacitor in series; the active method employs a lead-lag compensator. The passive dampening approach involved connecting the capacitor and resistor in series. With this setup, the system will remain stable. When using passive damping, there are a lot of losses in the system. In order to lessen the losses, active dampening techniques were implemented. The active damping method made use of a lead-lag compensator. This lead-lag compensator also made use of a band stop filter. The overall inductance value served as the foundation for the filter inductor's design. (Omorogiuwa and Bello, 2023) Equation (14) gives the total inductor:

$$L = \frac{V_r \times 0.04}{i_r \times 2\pi f} \qquad 16$$

In Equation 16, Vr is the rated voltage of the system, ir is the rated current and f is the fundamental frequency. The equation of the resonance frequency is given by Equation (17):

$$F = \frac{1}{2\pi\sqrt{L_f \ C_f}} \qquad 17$$

F is the resonance frequency, Lf is the filter inductor, and Cf is the filter capacitor in the preceding equation. These are the main points of the rationale behind choosing the 13th-order harmonic frequency:

The 13th-order LC filter is shorter, thinner, and less expensive than LC filters tuned for 5, 7, and 11th-order harmonic frequencies. One can greatly enhance the 13th-order harmonic frequency-tuned passive filter's filtering capability.

The passive filter adjusts to the 13th-order harmonic frequency, displaying lower impedance. Lesser-order harmonics are suppressed to reduce phase voltage harmonics without employing a passive LC filtering technique.

3.5 Integration of the developed models of Modulated power filter compensator and that of Synchronous Generator and then determine its performance

In order to minimize harmonics, the modulated power filter compensator is driven by a triloop dynamic error-driven PI controller. Modulated power filter compensators are crucial in lowering overall harmonic distortion, as shown before. The term "total harmonic distortion" (THD) describes the degree to which the total harmonic component of a voltage or current wave compares to the fundamental component. The connectivity of the modulated power filter compensator to the network in which the generator operates is illustrated in Figure 3.3, while the block diagram is shown in Figure 3.2.

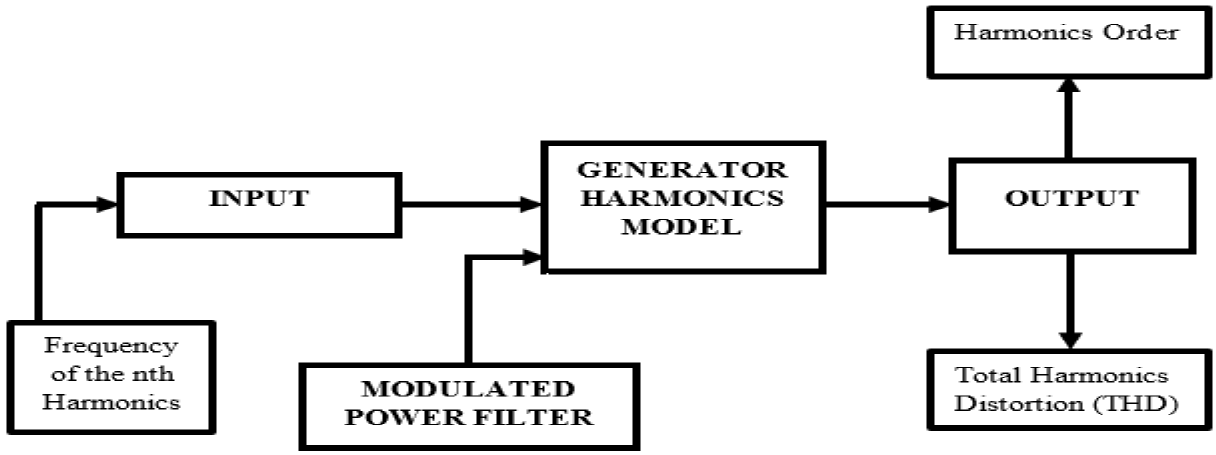

Figure 3.2: Block Diagram representation of Figure 3.3

1. **Input:** Receives harmonic signals and their corresponding frequencies for analysis.
2. **Generator Harmonics Model:** Simulates the harmonic behavior of the generator, analyzing how different harmonic orders affect performance.
3. **Modulated Power Filter:** Filters and mitigates unwanted harmonic components to improve power quality.
4. **Output:** Displays results, including the harmonic order and the Total Harmonic Distortion (THD), which indicates the system's harmonic performance.

This diagram represents a system for analyzing and optimizing harmonic distortions in power generators.

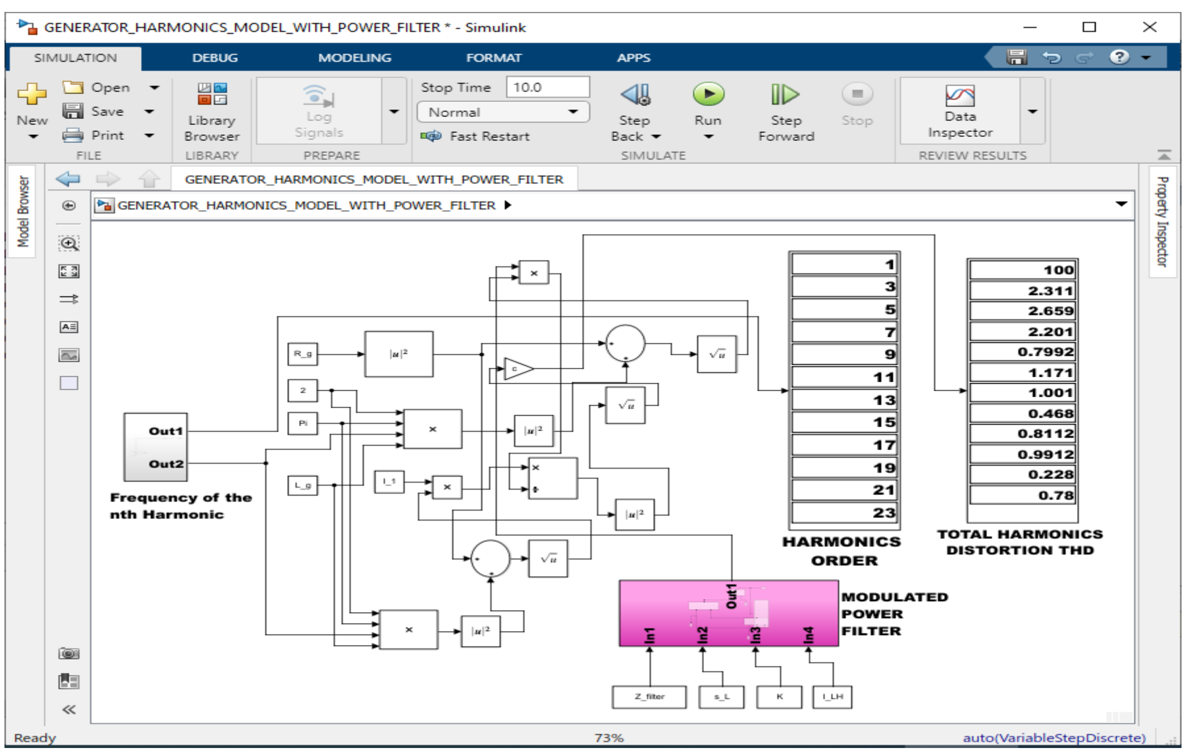

Figure 3.3: Integration of the modulated power filter

The **Generator Harmonics Model with Power Filter** is a Simulink-based system designed to analyze and mitigate harmonic distortions in power systems.

1. **Frequency Input:** Receives frequencies of various harmonic components.
2. **Harmonics Simulation:** Models the harmonic orders and their impact on the generator's performance.
3. **Modulated Power Filter:** Filters specific harmonic frequencies, reducing distortion and improving power quality.
4. **Output:** Displays harmonic orders and computes the Total Harmonic Distortion (THD), which quantifies the system's harmonic performance.

This model provides an effective approach for optimizing power systems by minimizing harmonic effects and ensuring efficient operation.

Figure 3.4 shows the integration of Generator harmonics model with the Modulated power filter compensator. The Simulink model was realized using equation 18 and with the help of the math operations and signal routing tool box of Simulink. The varying input to the generator harmonics model was the frequency of the nth harmonic whereas the corresponding output was the harmonics order and the Total Harmonics Distortion (THD). The outputs were obtained by simulating the Simulink model with all inputs to the model specified in Matlab Command.

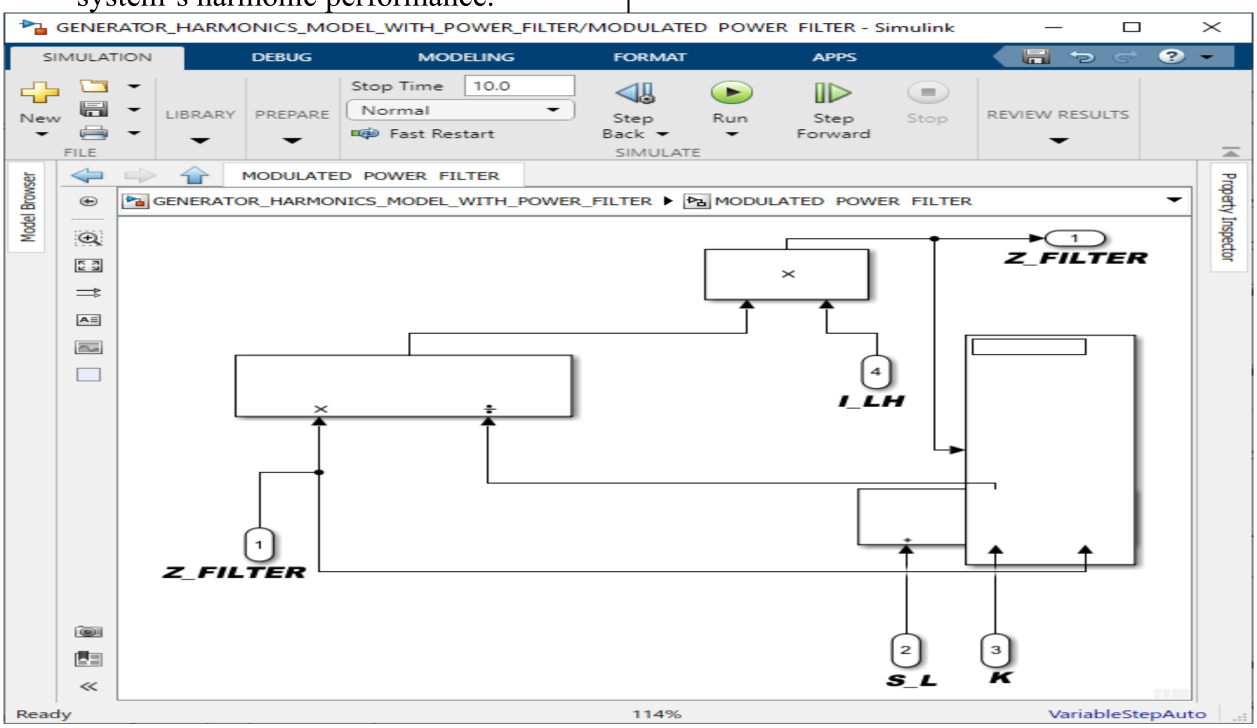

Figure 3.4: Internal Circuitry of the Modulated Power Filter

4. Results

Table 2 of the measurement findings shows that the motor plastic processing industry load achieved a THDi current harmonic content of 14.93%. Because the permissible THDi is greater than 5%, this condition does not conform to the IEEE 519-1992 standard. As a result, the harmonics generated surpass the limits set by the IEEE 519-1992 standard.

Table 1: Results of harmonic simulation without modulated power filter.

Individual harmonic Distortion (IHD) Order	Measured Harmonics	Simulation result without Power Filter.	IEEE 519-1992 Standard
1	100.00	100	
3	2.20	2.35	7.0
5	14.22	14.99	7.0
7	02.35	2.48	7.0
9	0.84	0.91	7.0
11	1.21	1.25	3.5
13	1.03	1.03	3.5
15	0.49	0.52	3.5
17	0.84	0.85	2.5
19	1.02	1.03	2.5
21	0.24	0.28	2.5
23	0.81	0.82	1.0
THD	**14.95**	**15.57**	

The results of the simulation run without the modulated power filter are displayed in Table 1.

From the table, the total recorded current harmonic was 15.55% while the difference of 0.6% was obtained from real measurement which was 14.95%. Individual harmonic Distortion (IHD) values exceed the IEEE 519-1992 standard limits as seen from the Table 1. That means, effort must be made to reduce the harmonic effect.

Table 2: harmonic results after integration of modulated Power filter compensator.

Individual harmonic Distortion (IHD) Order	Simulation result with Power Filter.	IEEE 519-1992 Standard
1	100.00	
3	2.31	7.0
5	2.66	7.0
7	2.20	7.0
9	0.80	7.0
11	1.17	3.5
13	1.00	3.5
15	0.47	3.5
17	0.81	2.5
19	0.99	2.5
21	0.23	2.5
23	0.78	1.0
Total THD	4.77	

It is shown in Table 2 how the amount of each harmonic flow changes when the current harmonics are reduced through simulation using a modulated power filter compensator. Table 2 shows a simulated reduction of motor current harmonics using a modulated power filter compensator. The modulated power filter compensator reduces the overall current harmonics from 15.55% to 4.77%. Simulated results reveal that all IHD harmonic orders have reached the IEEE 519-1992 standard when looking at individual harmonic currents.

From Figure 8, it is clear that modulated power filter has reduced the effect of harmonic effect in motors and generators. By comparing with IEEE 519 – 1992 Standard, the use of modulated power filter has meet the standard limit.

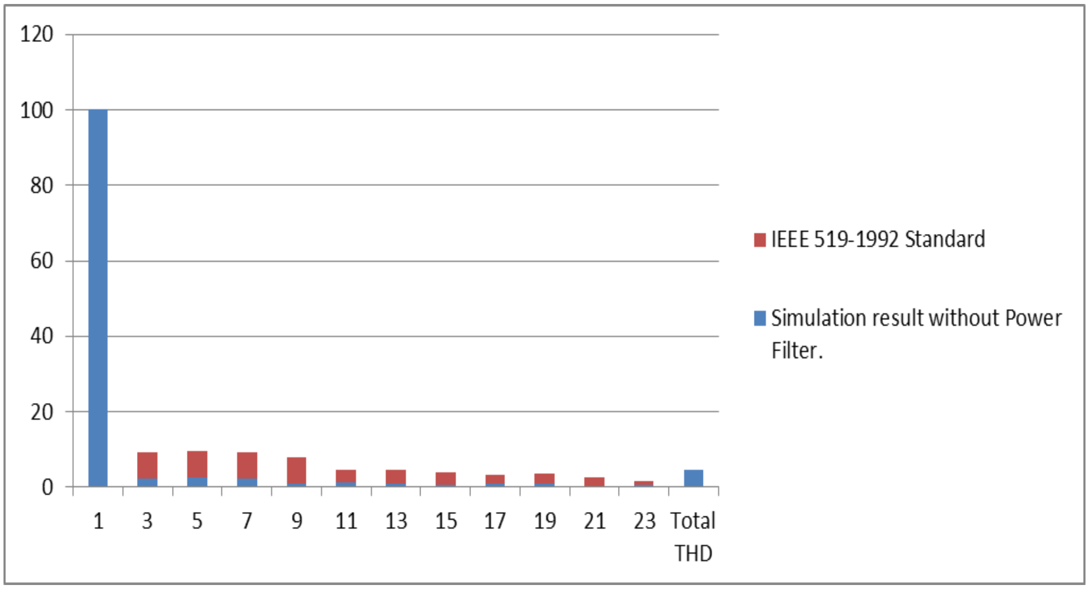

Figure 4.1: Bar chart of the integration of modulated power filter and developed Simulink model.

5. Conclusion

To prevent operational issues and equipment degradation, it is helpful to measure and restrict harmonics in electric power systems. From this investigation, we derive the following conclusions:1. In the simulation studies, the use of a modulated power filter reduced the Total Harmonic Distortion (THD) Current from 15.55% to 4.77%. To meet the criteria of the IEEE 519-1992 standard, the modulated power filter has reduced the system's total harmonic distortion (THD). A modulated power filter can boost power system performance while simultaneously lowering the target harmonic order.

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