Modelling and Simulation of Active Power Filters for Harmonic Compensation, Voltage Sags and Swells Mitigation and Power Factor Correction

Michael C. Pacis, Jesus M. Martinez Jr., and Jaypee V. Tecson

Abstract— **The two major problems in the electrical industry today are sagging and swelling of line voltage and harmonic currents. Voltage sagging and swelling may result to equipment malfunction and shut down. Harmonics also affect the electrical equipment to fail and deteriorate the waveform of the current. To mitigate the voltage sags and swells, uninterrupted power supply was used. But uninterrupted power supply is an example of non-linear load which creates harmonics in the power system. Active power filters were used to eliminate the harmonics in the system. This study aims to create three models of active power filters that compensate the harmonics, mitigate the voltage sags and swells, and also correct the power factor. The models were simulated to know which of the three active power filter models gives the best performance. The simulation tools that were used in this study were MATLAB/Simulink and TINA PRO. Based on the results, the active power filter models compensate the harmonics, mitigate the voltage sags and swells, and correct the power factor of the system. Evaluating the models, the active power filter Model-A gave the best performance by reducing the total harmonic distortion of the system.**

Index Terms— **active power filter, harmonics, voltage sags and swells, power factor correction**

I. Introduction

As time passes by, the world of technology evolves to a more advance and becomes widely developed. Different devices were formed such as high-end personal computers, laser printers and other electronic equipment. These devices are very sensitive to voltage sags and swells. Bingham defined voltage sags in his study as "the decrease in voltage lower than a user defined low limit" while voltage swells was defined as "voltage that surpass the user defined high limit" [1]. The more advanced and sophisticated the equipment is, the more it is sensitive to sagging and swelling of voltages.
Voltage sags and swells are the most occurring power system problems today that can cause electrical equipment to fail or shut down [3]. To mitigate the voltage sags and swells, uninterrupted power supply (UPS) were used. Uninterrupted power supply is an example of non-linear loads. Other examples of non-linear loads are laptop, stereo, fax machines, television set and telephone system [5],[6]. Non-linear loads create harmonic current and increase the deterioration of the power systems voltage and current waveforms. These loads causes the sine wave of the current o deform [2]. Harmonics in the power system can be measured through the measurement of total harmonic distortion (THD) [4]. Due to the current wide use of non-linear loads, harmonics became a major issue in the electrical industry. Active power filters were used to compensate the harmonics in the power system. This research paper focused on modelling and simulating active power filters that can compensate both harmonics and voltage sags & swells which both cause severe problems in the electrical power system.

A study was conducted by M. Tarafdar Haque [7] regarding simulation of active power filter as an efficient and economical way of eliminating harmonics in the power system. The controls of the active filter were based on the instantaneous active and reactive power theory. MATLAB was used as a simulation tool for the active power filter. The study turned out that the active filter produced better results for correction of power factor and elimination of harmonics compared to the usual method which is passive filter for conditioning current harmonics and capacitors for correcting the power factor. This study offers to solve other major electrical power system problem. Not only that the active power filter models can compensate harmonic and correct power factor but rather it can also mitigate voltage sags and swells. This study will also widen up the features of an active power filter and will serve as a new solution for the power system problems. The researcher created three different models of active power filter. At the end of this study, the researcher will choose which of the three active power filter models gave the best performance. From the models generated in this study, interested researchers could innovate and enhance it by creating a complete equivalent circuit or a prototype of the active power filter models. The purpose of this study is to create three different models of active power filters and evaluate their performance on different harmonic conditions. Simulating tools such as MATLAB/Simulink and TINA PRO can be used to evaluate the performance of the active power filter models. After simulating each active filter model one by one, each model must compensate the harmonics, correct the power factor and mitigate the voltage

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sags and swells. At the end of this study, the researcher will evaluate and compare the results of the simulation of the models and choose the best active power filter model among the three models. Another purpose of this research paper is to construct an equivalent circuit for the voltage sags and swells submodel.

Furthermore, this study will help the electrical power system from the generation side up to the distribution side because this will serve as a solution for harmonics, voltage sags and swells, and power factor correction in the power system. There will be reduction of voltage drop in long transmission lines. There will also be reduction of losses, therefore, wasted energy will be minimized [6]. There will be extra apparent power available for additional loads that may be inserted in the power system. Commercial and industrial customers will save more money because their electricity bills will be reduced. There will be continuous production and service because electrical disturbance will be mitigated. All the end users will benefit because the equipment will be protected at the same time its life will be extended. The simulation tools to be used in this study are MATLAB/Simulink and TINA PRO. This study focuses mainly on the creating three different active power filter models and evaluating each model's performance in seven different harmonic cases. The harmonic currents to be compensated by the Simulink filter model will range from second harmonic current to seventh harmonic current. For the Simulink model for voltage sags and swells, there will be two cases for voltage sags mitigation and two cases for voltage swells mitigation. For the TINA pro simulation, there will be ten cases for power factor correction. Since the usual load in the industry is an inductive load, the simulation for power factor correction in tina pro will cover lagging power factor. The simulation for Simulink power factor correction model will cover both lagging and leading power factor. However, this study is only limited to single phase circuits and single phase active power filter models.

II. METHODOLOGY

The methodology of the study was based on Figure 1. Three active power filter models were simulated to eliminate the problems. Each active power filter model was composed of submodels for voltage sags and swells mitigation, harmonic compensation and power factor correction. The researcher decided to simulate separately the submodel for voltage sags and swells since all three active power filters have the same voltage sags and swells mitigation submodel. The researcher used two different softwares to simulate hand in hand the models. MATLAB/Simulink was used first to simulate the voltage sags and swells submodel and harmonic compensating submodel combined with power factor correction submodel. TINA PRO was used to simulate the circuit for the power factor correction.

A. MATLAB Simulink model for voltage sags and swells mitigation

The first submodel generated was the voltage sags and swells mitigation. The block diagram of the voltage sags and swells mitigation submodel was composed of the rectifier, switch mode DC to DC regulator and inverter [4]. Figure 2 shows the block diagram of voltage sags and swells mitigation submodel while Figure 2 shows the Simulink model for the voltage sags and swells mitigation. The model of the voltage sags and swells shown in Figure 3 was the equivalent of the block diagram in Figure 2. The block diagram was used to serve as a guide to build the voltage sags and swells mitigation submodel.

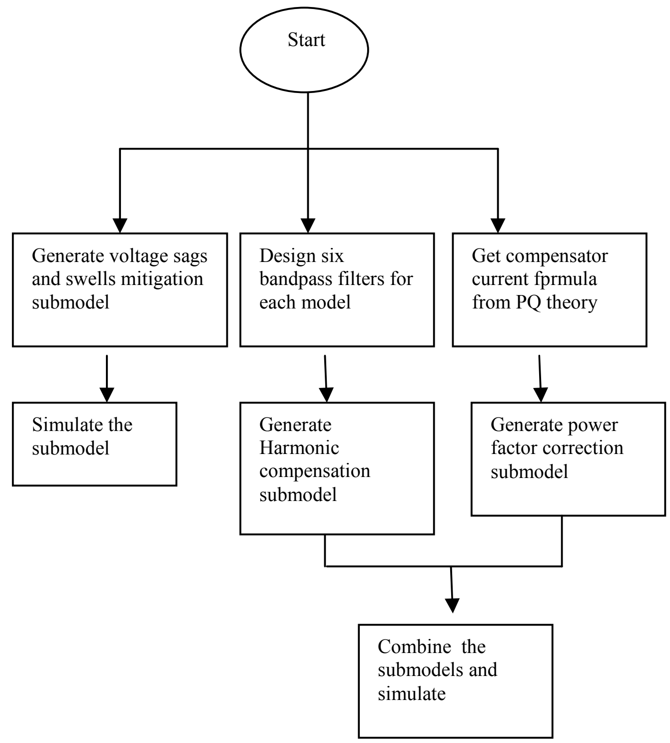

Fig. 1. Matlab/Simulink Methodology Outline

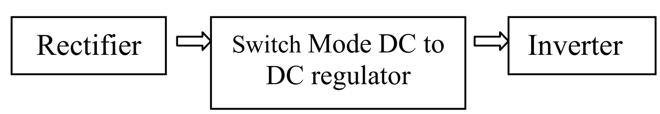

Fig. 2. Block diagram of voltage sags and swells mitigation submodel

The voltage sags and swells mitigation model was simulated in four cases. Two cases were simulated for voltage sags and two cases for voltage swells. In every case for the voltage sags mitigation, there was a twenty volt amplitude decrease from 311 volt amplitude. In every case for the voltage swells mitigation, there was a twenty volt amplitude increase from 311 volt amplitude. The amplitude of the output voltages were all computed by getting the average of ten consecutive peak values of the output voltages.

B. MATLAB/Simulink model for harmonic compensation and power factor correction

The second and third stage of the active power filter is the harmonic compensation submodel and power factor correction submodel respectively. Figure 3 shows the Simulink model intended for harmonic compensation and power factor correction. In designing bandpass filters, the frequencies of the bandpass filters depend on the frequencies of the harmonic currents in the line. All three active power

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filter models were created with different types of bandpass filter. For active power filter Model-A, the researcher used a butterworth type bandpass filters. For the active power filter Model-B and Model-C, the researcher used the chebyshev type one bandpass filter and chebyshev type two bandpass filter respectively.

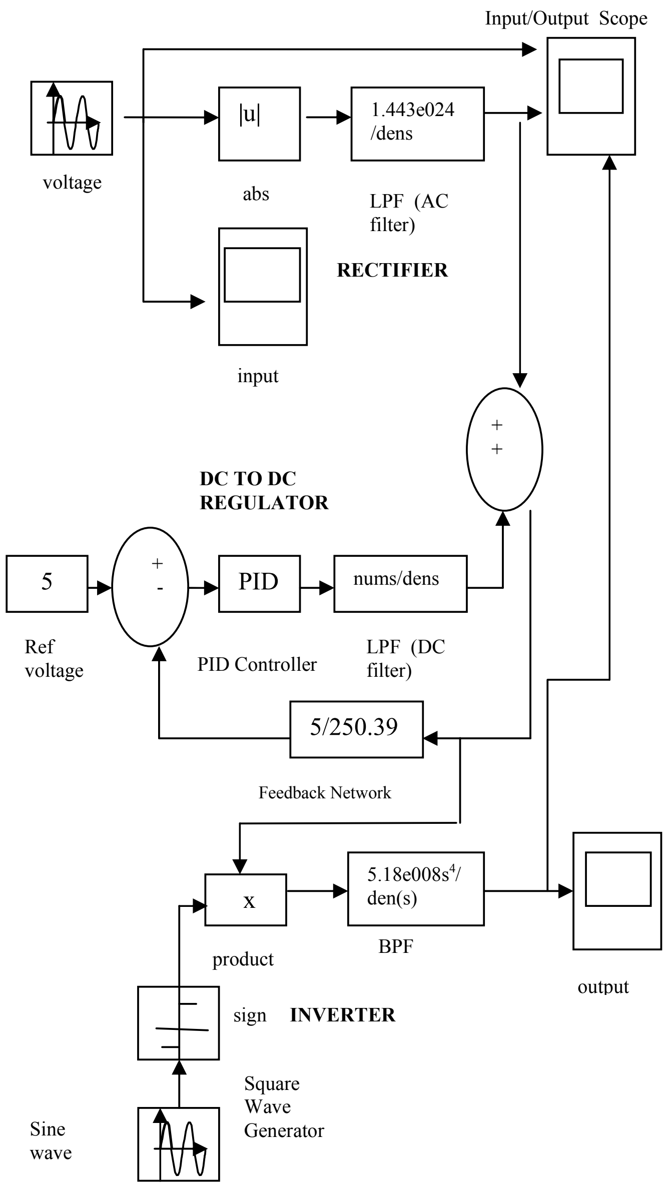

Fig. 3. Simulink model for the voltage sags and swells mitigation
Block diagram of voltage sags and swells mitigation submodel

The transfer function of the designed filters was inputted in the simulink transfer function block followed by a transport delay. The delay was used to create a signal with a phase angle of 180 degrees with respect to the original harmonic sine wave. Harmonic delay 2, harmonic delay 3, harmonic delay 4, harmonic delay 5, harmonic delay 6 and harmonic delay 7 delay the filter current that passed through BPF2, BPF3, BPF4, BPF5, BPF6 and BPF7 respectively to create an out of phase signal that will compensate each harmonic currents. Every delay depends on response of the designed band pass filter. Then all filter currents were added to the load current. The resulting current was expected to reduce all the harmonic currents and have a new total harmonic distortion (THD) percentage that is smaller compared to the original total harmonic distortion (THD) percentage. The original THD percentage is the percentage of the system without the active power filter model. The output of the harmonic compensation sub model was used as an input of the submodel for power factor correction. A derived equation of the compensating current in his study entitled single phase P-Q theory for active filters [3], [4]. The compensating current equation was converted into a Simulink power factor correction submodel. From the matrix form of the single phase instantaneous active and reactive power equation shown below (1).

$$\begin{bmatrix} p_{1\emptyset}(t) \\ q_{1\emptyset}(t) \end{bmatrix} = \begin{bmatrix} V_r(t) & V_i(t) \\ -V_i(t) & V_r(t) \end{bmatrix} \begin{bmatrix} I_r(t) \\ I_i(t) \end{bmatrix} \quad (1)$$

The compensator current was derived from it. The equation of the compensator current is (2). The compensator current equation was directly converted to a Simulink model in Figure 4. It shows the converted power factor correction model from the compensating current equation in the single phase active and reactive power theory. The researcher simulated the model after combining the harmonic compensation sub model and power factor correction sub model.

$$I_{comp} = \frac{V_i(t)V_i(t)I_r(t) - V_i(t)V_r(t)I_i(t)}{V_r^2(t) + V_i^2(t)} \quad (2)$$

C. TINA PRO power factor correction simulation

There were ten cases of power factor correction for the tina pro simulation. For all ten cases, the voltage was 311 volts. Initially, the power factor for case one was 0.50. In every case for the power factor correction, there was a 0.05 power factor increase. There were two trials for every case. For trial one, capacitor switches were opened to see the old power factor. For trial two, the capacitor switches were closed to give a correct capacitance that will correct the old power factor to unity. Initially, the power factor for case one was 0.50. In every case for the power factor correction, there was a 0.05 power factor increase. There were two trials for every case. For trial one, capacitor switches were opened to see the old power factor. For trial two, the capacitor switches were closed to give a correct capacitance that will correct the old power factor to unity.

III. RESULTS AND DISCUSSION

By observing the result of the simulation for voltage sag and swells mitigation in Table 1, all the output voltages in all cases were all above 311 volts. Given that the output decimal values were small, the decimal values can be treated as negligible. Since all output voltages have amplitude of 311, the model for voltage sags and swells mitigation is very effective. It can be verified in the figures 4 and 5. This model can give us an output voltage (magenta colored sine wave) amplitude value of 311 volts even if the input voltage (yellow colored sine wave) is sagged or swelled. The Matlab abs block of the Simulink model performs the full-wave rectification on the input AC signal.

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The low pass filter that acts as an AC filter can be represented as capacitor that eliminates the 60Hz frequency and the harmonics. The second low pass filter that acts as a DC filter in the DC to DC regulator eliminates the switching frequency and the harmonics. The control adjusts the resistor value R2 for the voltage divider in the circuit. The second switch can be controlled by an internal clock or a 555 square wave oscillator. The bandpass filter is designed for the fundamental frequency to pass through the circuit while rejecting other components. The output voltage must have an RMS value of 220 volts. Tables 2 to 6 shows the results for case one of the three filter models. Figure 6 to 12 show the output graphs for case one. Based from the tables, the active power filter reduces the harmonic currents in the system. All the three active power filter models lessened the total harmonic distortion (THD) of the system. From a distorted waveform of the load current, it was improved by smoothening the waveform into a sinusoid.

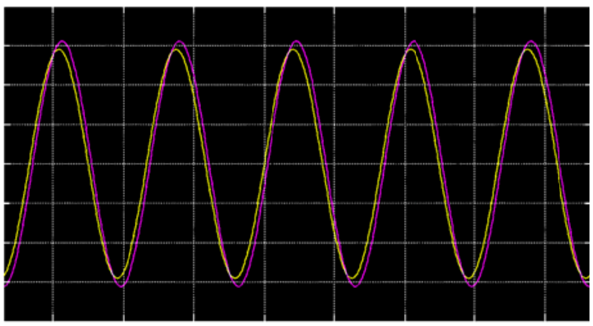

Fig. 4. Power factor correction submodel

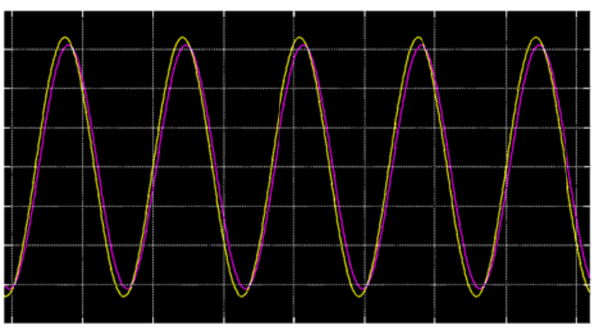

Fig. 5. Input and output voltage case 3

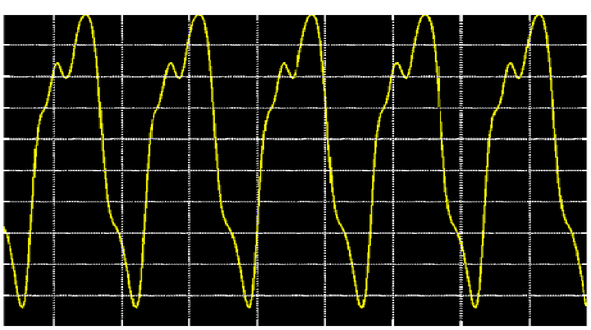

Fig .6 Load current without active power filter case 1

Table 1 Input and output voltages for case 1 and 3

Case	Input voltage	Output voltage
1	291	311.047
3	331	311.075

Table 2 Case 1 results without an active power filter

Harmonics	Load amplitude	Source amplitude
2nd	10.80	10.80
3rd	7.60	7.60
4th	4.80	4.80
5th	2.50	2.50
6th	1.90	1.90
7th	0.30	0.30

THD = 36.00

Table 3 Case 1 results with active power filter Model-A

Harmonics	Load amplitude	Filter amplitude	Source amplitude
2nd	10.80	10.64	0.16
3rd	7.60	7.60	0.00
4th	4.80	4.80	0.00
5th	2.50	2.50	0.00
6th	1.90	1.90	0.00
7th	0.30	0.26	0.04

THD = 0.41

Table 4 Case 1 results with active power filter Model-B

Harmonics	Load amplitude	Filter amplitude	Source amplitude
2nd	10.80	8.09	2.71
3rd	7.60	7.60	0.00
4th	4.80	4.69	0.11
5th	2.50	2.00	0.50
6th	1.90	1.08	0.82
7th	0.30	0.24	0.06

THD = 7.19

Table 5 Case 1 results with active power filter Model-C

Harmonics	Load amplitude	Filter amplitude	Source amplitude
2nd	10.80	10.34	0.46
3rd	7.60	6.70	0.90
4th	4.80	4.80	0.00
5th	2.50	1.85	0.65
6th	1.90	0.72	1.18
7th	0.30	0.28	0.02

THD = 4.21

Table .6 THD percentage reductions of the three models

Case	Filter Model	Old THD	New THD	% THD Reduction
	A	36.00	0.41	98.85
1	B	36.00	7.19	80.02
	C	36.00	4.21	88.30

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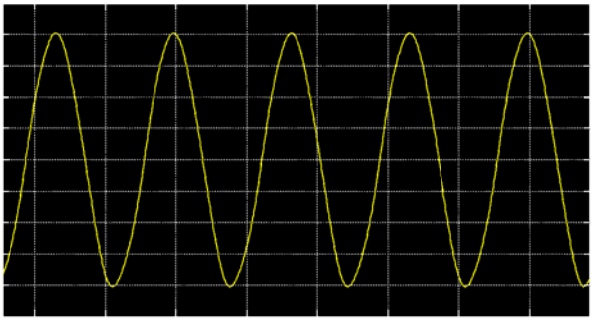

Fig .7 Load current with active power filter Model-A case 1

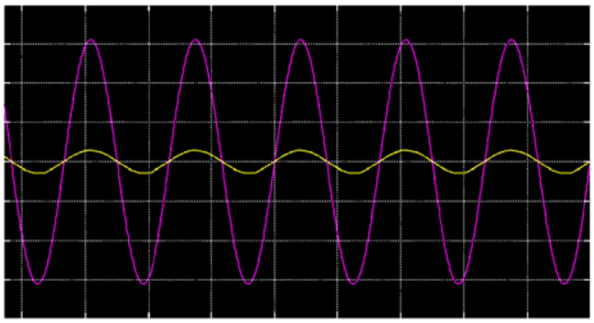

Fig. 8 Voltage and current with active power filter Model-A case 1

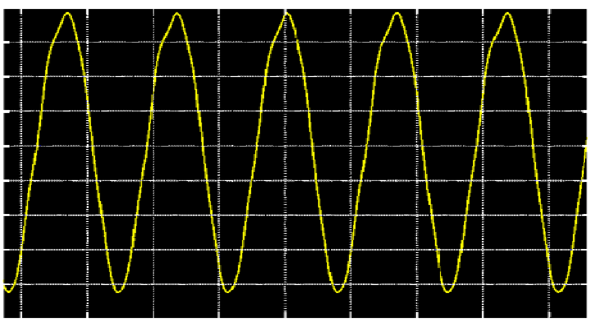

Fig. 9 Load current with active power filter Model-B case 1

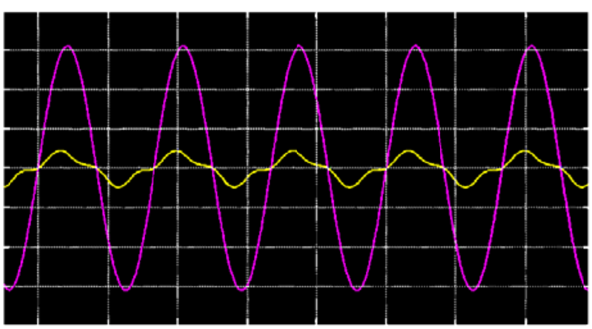

Fig. 10 Voltage and current with active power filter Model-B case 1

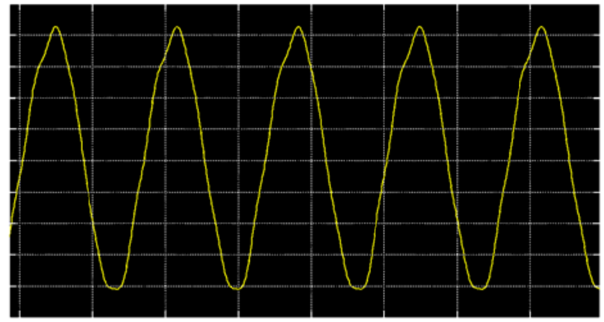

Fig.11 Load current with active power filter Model-C case 1

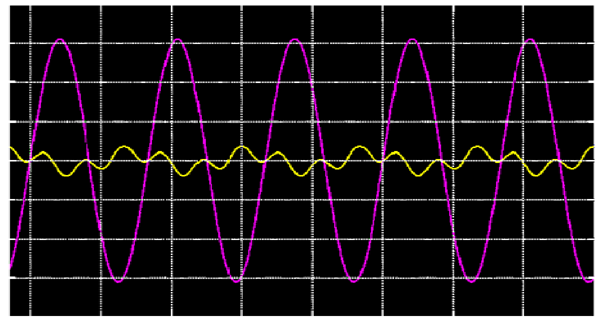

Fig. 12 Voltage and current with active power filter Model-C ase 1

IV. SIMULATION RESULTS USING TINA PRO

By looking at Table 7, the power factor from 0.50 was corrected to unity. The capacitance for case one was 192uF to correct the power factor of 0.5 to 1. For trial one, capacitor switches were opened to see the old power factor. For trial two, the capacitor switches were closed to give a correct capacitance that will correct the old power factor to unity. The computations matched the results of the TINA PRO simulation. TINA PRO simulation shows the implementation of the Simulink model for power factor correction.

Table .7 Power factor correction simulation settings

Case	Power factor	Load impedance (ohms)	Load resistance (ohms)	Load inductance (mH)
1	0.50	$12\angle 60.00$	6.00	27.56
2	0.55	$12\angle 56.63$	6.60	26.58
3	0.60	$12\angle 53.13$	7.20	25.46
4	0.65	$12\angle 49.46$	7.80	24.19
5	0.70	$12\angle 45.57$	8.40	22.73
6	0.75	$12\angle 41.41$	9.00	21.06
7	0.80	$12\angle 36.87$	9.60	19.10
8	0.85	$12\angle 31.79$	10.20	16.76
9	0.90	$12\angle 25.84$	10.80	13.87
10	0.95	$12\angle 18.19$	11.40	9.95

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V. CONCLUSION

Initially, the active power filter mitigated the voltage sags and swells of the circuit then it compensated the harmonic currents in the line current. The sagged or swelled voltage was rectified to convert AC voltage to DC by using the bridge type rectifier and capacitor. The DC output of the rectifier was controlled by the switch mode DC to DC regulator. The feedback comprising of a multiplier, a constant block that acts as a reference voltage, a PID controller and a low pass filter circuit was the error checker of the DC to DC regulator to maintain a certain DC value. For the practical application of this, voltage divider was used to regulate the voltage which was showed on the equivalent circuit of the voltage sags and swells mitigation model labelled as Figure 8.

The first low pass filter which was interpreted as a capacitor and acts as an AC filter eliminates the fundamental frequency and harmonics while the second low pass filter that acts as a DC filter eliminates the harmonics and the switching frequency. The output of the regulator was multiplied to a square wave generator in order to change DC back to AC. The square wave of the circuit can be an internal clock or a 555 square wave oscillator. Since the model for voltage sags and swells mitigation is very effective, the output of this circuit will always be an RMS voltage of 220V because of the DC to DC regulator. Regulating the voltage was done in DC to utilize the available DC – DC switching technique which is popular today. The active power filter compensates all harmonic currents and reduces the total harmonic distortion of the system. It also smoothens the distorted waveform of the load current into a pure sinusoid. Among the three active power filter models, active power filter Model-A gave the best performance compared to the other two models. Model-A reduced the percentage of total harmonic distortion of the systems greater than the two remaining models.

Since all the voltage and current whether distorted or not became in phase with each other in all cases, the power factor of the system were all corrected to near unity. Tina pro simulation was the implementation of the MATLAB/Simulink model for the power factor correction. The active power filter will switch on the correct capacitance to correct the power factor to unity once the active power filter detects the load voltage and load current. Therefore the active power filter models were effective in correcting the power factor of the system to near unity.

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