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An Investigation on Harmonic Problems for N-1 Contingency in Industrial Distribution and Its Mitigation Using Fuzzy Controlled Hybrid Filter

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Abstract

The electric distribution structure of modern industries is rapidly changing and becomes complex and complex as a result of increase in demand and market competition. Effective nonlinear electronic device were introduced recently to increase productivity and efficiency. However, installing devices such as; programmable logic controllers (PLCs), adjustable-speed drives (ASDs), energy efficient motors and other power electronic devices are creating a power quality related problem namely harmonic distortion. Harmonic means the multiple of fundamental frequencies resulting in excessive current flow on lines due to power electronic devices, short circuits and other contingency effect. This has a great threat for industrial consumers, results in equipment damages, poor power factor and excessive neutral currents. Considering the economic consequence of harmonic problems due to damaging of electric equipment and increase of electric bill due to poor power factor in Industries, this research paper presents modelling of an industrial distribution named Coca-Cola Share Company using Matlab Simulink for an investigation of harmonic distortion level. Then harmonic distortion level at both PCC and IPC were computed for normal operating conditions as well as for N-1 contingency cases. The result were compared with the IEEE 519-2 and IEC 61000-2-4 for class 2 standards and found don't comply with the standards. A fuzzy logic hybrid filter were designed to reduce the harmonic distortion level that satisfies the standards.

Keywords: Total harmonic distortion (THD), Point of common coupling (PCC), In plant point of coupling (IPC), Variable Frequency Drive (VFD), Generalized Fryze Current Control Strategy

INTRODUCTION

The modern industries are constantly exposed of power quality related problems results in an unscheduled plant shutdown [1]. Power quality is a kind of disturbance or interruptions in electric supply caused by a power system equipment. For instance, transients, voltage sags or swells, electrical noise ,harmonic distortion, voltage notching and flickering lights are some of power quality related disturbances [2]. From all those power quality related disturbances, harmonic distortion is critical as it represents the steady state problem. It is always available as long as the harmonic producing equipment is there [3]. Moreover, during switching on of large industrial loads there is maximum fluctuation of current which results in harmonics.

Non-linear load devices create harmonics when they convert AC to DC, DC to DC, DC to AC, and AC to AC.Now a days ,these converters are widely used in the modern industrial equipment's such as programmable logic controllers (PLCs), adjustable-speed drives (ASDs), energy efficient motors and other electronic devices to improve productivity and efficiency. Hence, These Nonlinear loads are the main contributors of harmonic distortion and producing great destruction in industrial companies worldwide[4].

The distorted current produced by the nonlinear loads propagate through all the impedance between the load and power source. It causes voltage drops for each harmonic frequency based on ohms law and thereby producing total voltage distortion at the point of common coupling (PCC) due to the vector sum of the individual voltage drops. This distortion is quantified by Total Harmonic Distortion (THD) which is a function of the impedance between the power source and the load [5]. If any change happens in the impedance due to any sort of fault in the distribution system such as pure wiring practice, geographical or weather conditions, and effect of neighboring customers, it thus affects the THD [3]. In general the THD at the PCC depends up on load, type of load, Configuration (resonances depending on capacitive or inductive character of the elements in the network),network impedance and the fault level [6] [7] [8][9].

Understanding the economic impact of harmonic distortion in industry, various researchers have made a contribution in an investigation and mitigation of harmonic problems based on hybrid filter using different control strategies [10][11][12][13][14][15].However, As per the report of various researchers, majority of the work done on the design of power filter is based on fixed load conditions, or for small range of load variations. But in practical life a part from small load variation due to the activities of customers, power system distribution is exposed to various types of faults. Hence, it changes the loads greatly. Consequently, it exacerbates the harmonic distortion level. Moreover, many researchers as referred [16][17] have used power quality analyzers to quantify the harmonic distortion level at different buses and designed suitable filters accordingly. These methods are costly and time-consuming as they need to take harmonic measurements systematically. They only consider the circumstances in which they were taken, therefore can't be assured to reflect the worst possible operating conditions of a system. Measurements can also be inaccurate due to measuring errors or flawed use of instruments[18].Therefore, there is a need of developing a model which gives relative flexibility to investigate Harmonic distortion at PCC considering various operating conditions of the plant and designing a fuzzy logic controlled hybrid filter that can maintain the THD well with in IEEE standards taking contingency under consideration, so that it can effectively mitigate the harmonic levels even in the worst case operation of the plant. Therefore, this study focuses on an investigation of harmonic distortion at both PCC and IPC of an industry named Coca cola Share Company in Eritrea for N-1 contingency and Designing of a fuzzy logic controlled hybrid filter.

DEVELOPING THE MODEL OF THE INDUSTRIAL DISTRIBUTION

The utility or substation

The data needed is the line to line voltage (VLL), short-circuit MVA (SC MVA), and X/R. Obtaining the voltage is simple enough. SC MVA is the power available at a bolted three phase fault. Bolted means all three phases connected together with no added impedance. X/R is the ratio of reactance to resistance in the supply. SC MVA and X/R may need to be derived from other data [19].

$$SCMVA = \sqrt{3} * I_{SC} * V_{LL}, \quad (1)$$

Where I_{sc} is expressed in KA and V_{LL} –in KV

$$X/R = \tan(\cos^{-1} PF) \quad (2)$$

Transformer modelling

Transformers are specified by output voltage (V), KVA rating, percent impedance (%Z), and X/R ratio. All this information apart X/R, is usually available on the transformer nameplate. If the X/R is not specified 4.9 can be used for calculations. Therefore the impedance(Z) can be calculated from V,KVA, and %Z [20].

$$Z = \frac{Z * V^2}{kVA * 100{,}000} \quad \text{Or} \quad Z = \frac{Z}{100} * \frac{V^2}{VA} \quad (3)$$

Transformer impedance

Z%=4% S=630KVA Secondary voltage =V_s=400v f=50hz

Since

$$Z_t^{\ 2} = R_t^{\ 2} + X_t^{\ 2}$$

$$Z = \frac{V_s^{\ 2}}{SKVA} * Z\% = \frac{400^2}{630 * 10^3} * 0.04 = 0.01\Omega \quad (4)$$

Assuming $\frac{X_t}{R_t} = 4.9$

Therefore $R_t = 4.12 * 10^{-3}\Omega$ and $X_t = 0.02\Omega$

then $L_t = \frac{X_t}{2 * \Pi * 50} = \frac{0.02}{2 * \Pi * 50} = 63.7\mu\Omega$

The transformer data for modeling is

$R_t = 4.12 * 10^{-3}\Omega$ $X_t = 0.02\Omega$

$L_t = 63.7\mu\Omega$

Computing of the transmission line parameters

The transmission line extends 3728 meters from the substation to the factory transformer.it is 95mm^2 aluminum type conductor.

The resistance of the cable can be calculated as follows

The resistivity of aluminum is $\rho = 2.65 * 10^{-8}\Omega m$

$$R_C = \rho \frac{L}{A} = 2.65 * 10^{-8} \frac{3728}{95} = 1.04\Omega \quad (5)$$

Similarly the inductance can be calculated

$$L = 2l[2.303\log(4l/d) - 1 + \mu/4 + (d/2l)] \quad \text{Or}$$
$$L = 2L[\ln(2L/r) - 0.75]nH \quad (6)$$

In the above equation, L is the inductance in nH (10-9 henry), l is the length and d is the diameter of the wire/rod (both in cm). µ is the permeability of the material (=1.0, except for iron and other ferromagnetic materials) [21].

Therefore L=9969188 nH the inductive reactance would be

$$X_L = 2*\Pi*f*L = 2*\Pi*50*0.009969 = 3.13 \quad (7)$$

Modeling of loads

VFD modeling

A Variable Frequency Drive (VFD) is a type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor. Hence, the VFD consists of three major components; the first is the front end, which is usually a 6 or 12 pulse rectifier. The second is the inverter stage that converts the generated DC voltage to controllable frequency AC voltage to control the speed of the motor. The last stage is the DC link (shunt capacitor) that couples the two main stages and help in reducing the ripples of the DC voltage in case of VSI and PWM topologies. The DC link capacitor in case of VSI can block the propagation of the harmonics generated from the inverter side from entering the AC system. This conclusion calls for a simple representation of the converter and the motor collectively by a DC current source instead of a harmonic current source. The most common rectifier circuit in three-phase PWM drives, 6-pulse VFD uses six-pulse diode rectifier. A 6-pulse rectifier is the most robust and cost effective solution in the VFD industry as of today, even though input current contains some amount of low order harmonics. The capacitor and resistor depends up on the active power of the inverter. It can be modelled as shown in the fig1 [22][23][24][25][26].

Since the capacitive reactance affects the THD [27]

As a general rule $\omega R_{SR}C = 1, \approx [12\%]$,

$$\omega R_{SR}C = 2, \approx [6\%], \qquad \omega R_{SR}C = 3, \approx [4\%] \qquad (8)$$

Assuming the lowest distortion

The capacitance value would be

$$\omega R_{SR}C = 3, \approx [4\%] \qquad (9)$$

The general formula is

$$C_x = \frac{Q_T}{2\Pi f(R_{SR})}, \text{ where } 1 < Q_T < 3 \qquad (10)$$

$$R_{SR} = \frac{(V_{in})^2(\eta)}{P_{out}} \qquad (11)$$

Therefore for VFD motor having power rating of 15KW the capacitance value would be

$R_{SR} = \dfrac{400^2 * 0.85}{15000} = 9.067$ Thus the capacitance value would be $C_x = \dfrac{3}{2*\Pi*50*9.07} = 1.053mF$

Therefore it can be modelled as shown in the fig.1

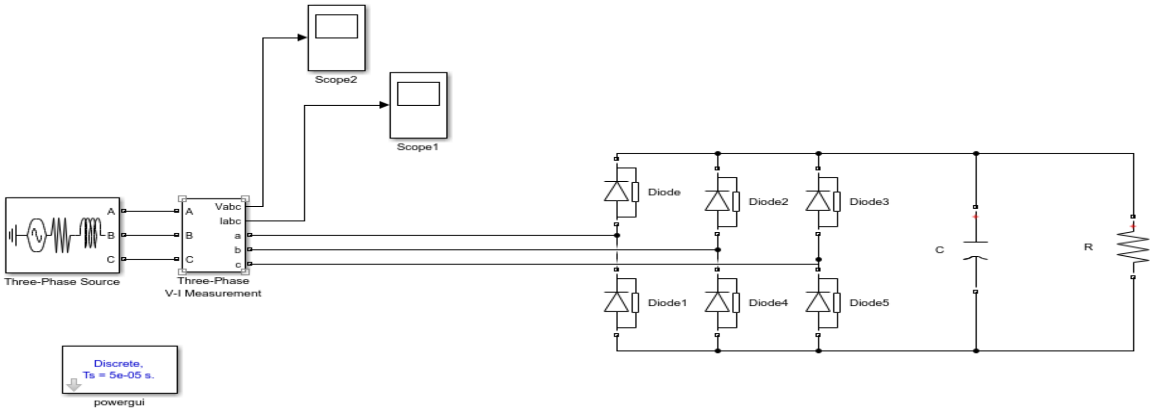

Figure 1: Six pulse variable frequency drive (VFD)

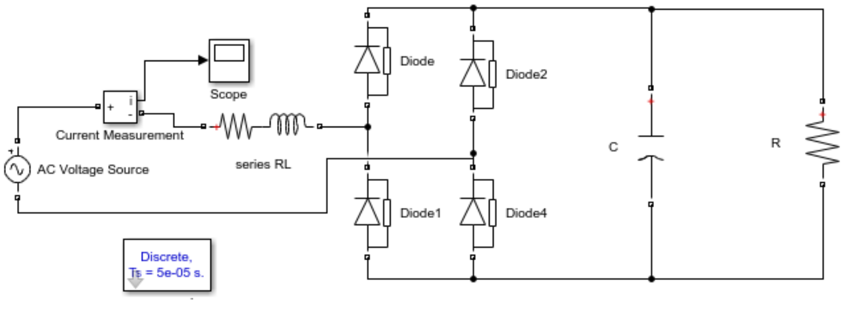

Figure 2: Switch mode power supplies (SMPS)

Similarly all the VFD available in the industry can modelled likewise.

Switched-Mode Power Supplies.

These power supplies are the "front-end" of single-phase 120V loads such as PCs and home entertainment equipment. Typically, they have a full-wave diode rectifier connected between the AC supply system and a capacitor, and the capacitor serves as a low-ripple “battery” for the DC load. Unfortunately, low ripple means that the AC system charges the capacitor for only a fraction of each half-cycle, yielding an AC waveform that is highly peaked[28]

The capacitor and resistor can found out using the following formulas[29].

$R = \frac{V_{dc}^2}{P_{rated}}$ Where V_{dc} the instantaneous value of the DC is link voltage and P_{rated} is the rated power of the modelled SMPS device.

Similarly the capacitor value can computed as shown below

$$Rf = \frac{1}{\left[\sqrt{2}\left(2 * f_r * RC - 1\right)\right]} [30]$$

(12)

Where Rf the ripple is factor and f_r is the ripple frequency

Therefore the Switch mode power supplies (SMPS) can be modelled as shown below

Model of the whole industrial network for harmonic study

The normal induction motors are modelled as a constant RL load being assumed as linear passive loads, because an Induction motor is basically a large inductor in which the current doesn’t change very fast as per the inductive property[31] [32]. The induction motor of each department are lumped, whereas the VFD motors are preferred not to be lumped, because the harmonics generated by each VFD drives has canceling property that reduces the overall harmonic distortion at the PCC. Hence, considering the above stated cases the overall model of the plant with both active and passive filter is as shown below

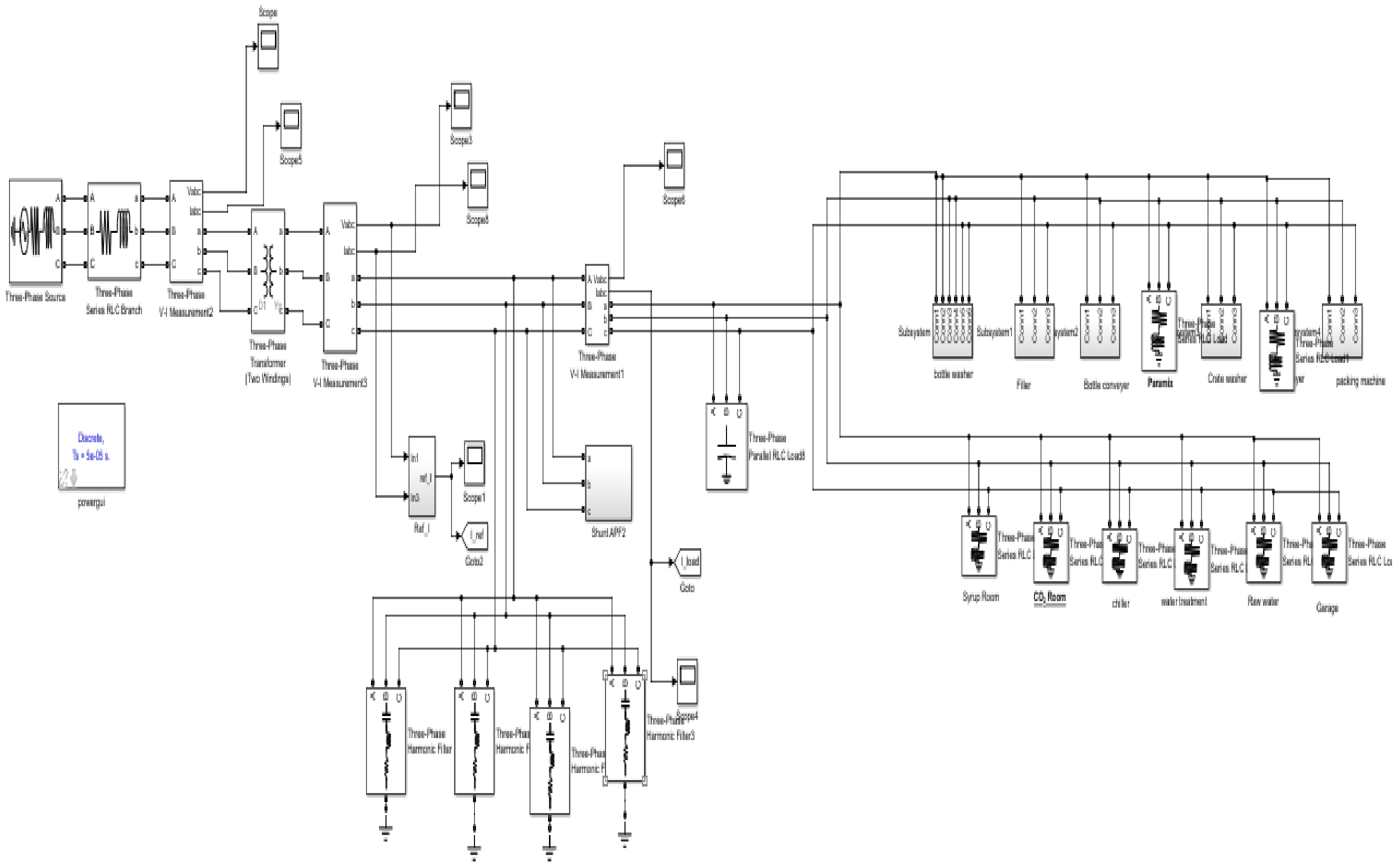

Figure 3: Model of the industrial network (SMPS)

Proposed control algorism

The control algorism used in this research is generalized fryze current control strategy .This strategy is concise and requires less computational efforts, since it deals directly with the abc phase voltages and line currents. The elimination of the clark transformation makes this control strategy simple [33]

The hybrid filter generates appropriate compensating currents based on the load currents, DC bus voltage and peak voltage of AC source (Vsm).

The instantaneous voltages of AC source can be represented as in equation below.

$$\begin{aligned} V_{sa}(t) &= V_{sm}\sin(wt) \\ V_{sb}(t) &= V_{sm}\sin(wt-120) \\ V_{sc}(t) &= V_{sm}\sin(wt-240) \end{aligned} \tag{13}$$

The ultimate role of the proposed hybrid filter is to eliminate harmonics and compensate the current unbalance and reactive power of the load. After compensation, the AC source feeds the fundamental active power component of load current and loss of inverter for regulating the DC capacitor voltage. Hence the peak of source reference current I_{sm} has two components .The first part derived from the average load active power and the second component is derived from the DC capacitor voltage regulator [33].

The instantaneous power is given by

$$p(t) = \sum_{k=1}^{m} v_k(t)i_k(t) \tag{14}$$

By definition the active power P_{DC} equals the average value (DC components) over one period T of the instantaneous power $p(t)$.

$$P_{DC} == \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T v(t)i(t)dt = V_{RMS}I_{RMS}COS\theta \tag{15}$$

This average power can be obtained by passing the $p(t)$ through the low pass filter or moving average filter.

Considering the unity power factor the average active power of the of the AC source can be represented as below

$$P_s = 3/2V_{sm}I_{smp} = P_{DC} \tag{16}$$

Where V_{sm} is the maximum amplitude voltage source and can be calculated at sampling frequency fs from the source phase voltages V_{sa}, V_{sb} , V_{sc} , at each sampling instant, it can be expressed as shown below

$$V_{sm} = \sqrt{2/3\left(V_{sa}^2 + V_{sb}^2 + V_{sc}^2\right)}, \tag{17}$$

From this equation the first part of AC side current can be derived

$$I_{smp} = 2/3*(P_{DC}/V_{sm}) \tag{18}$$

The second component of AC current source is obtained from DC link capacitor

The reference stored energy on the DC link capacitor is given by

$$E_{dcn} = \frac{1}{2}CV_{dcn}^2 \tag{19}$$

Where V_{dcn} is the reference or nominal voltage across the capacitor C.

When the capacitor is charged with a V_{dc} voltage the energy unbalance in the DC link capacitor is [34]

$$\Delta E_{dc} = \frac{1}{2}C\left(V_{dcn}^2 - V_{dc}^2\right) \tag{20}$$

This energy unbalance must be supplied by the AC source. Imposing a sinusoidal input current, the change in the capacitor energy must satisfy

$$\Delta E_{dc} = \int_0^T\left[\sum_{i=0}^{2} V_{sm}\sin\left(\omega_s t - \frac{2\Pi}{3}i\right)I_{smd}in\left(\omega_s t - \frac{2\Pi}{3}i\right)dt\right] \tag{21}$$

The I_{smd} is the active current supplied to the DC link capacitor.

So the reference current to maintain the DC voltage is given by

$$I_{smd} = \frac{2}{3}\frac{\Delta E_{dc}}{TV_{sm}} = C\frac{V_{dcn}^2 - V_{dc}^2}{3TV_{sm}} \tag{22}$$

The desired peak current of AC source is then obtained using the equation below.

$$I_{sm} = I_{smp} + I_{smd} \tag{23}$$

The AC source current must be sinusoidal and in-phase with source voltages. Therefore the desired currents of AC source can be calculated by multiplying peak source current with unity sinusoidal signal and these unity signals. Therefore the desired or reference source current can be obtained by the using equations below.

$$I_{ref\_a} = I_{sm} * \left(\frac{V_a}{V_{mag}})\right)$$

$$I_{ref\_b} = I_{sm} * \left(\frac{V_b}{V_{mag}}) \right) \tag{24}$$

$$I_{ref\_c} = I_{sm} * \left(\frac{V_c}{V_{mag}}) \right)$$

Finally, the reference currents of the hybrid filter can be obtained by subtracting the reference source current from load current as shown below.

$$i_{ca} = I_{la} - I_{ref\_a}$$

$$i_{cb} = I_{lb} - I_{ref\_b} \tag{25}$$

$$i_{cc} = I_{lc} - I_{ref\_c}$$

These reference currents i_{ca}, i_{cb}, i_{cc} will be fed to the switching circuit of carrier-less hysteresis controller for producing the necessary PWM pulse to the voltage source inverter. So the voltage source inverter with the closed loop system acts as a controlled current source and produces the exact reference waveform at the output. This output of the shunt active filter compensates the line harmonics and the line current becomes sinusoidal.

Design of DC link capacitor and AC link inductor

The selection of DC link capacitor and AC link inductor affects the performance of the active filter. Therefore they have to be properly selected to get best result.

AC link inductor

The standard inductor differential equation is given by

$$\frac{di}{dt} = \frac{\Delta V}{L_{flter}} \tag{26}$$

The maximum possible inductance should be used to achieve the lowest average switching frequency

Therefore the maximum value of the inductor can be obtained using the equation below

$$L_{filter} = \frac{\Delta V}{\max\left(\frac{di}{dt}\right)} \tag{27}$$

The maximum $\frac{di}{dt}$ of the actual compensating current has to be determined for each harmonic component based on its amplitude and frequency. Hence the maximum value of the inductor to be considered is as shown below

$$L_{filter} = \frac{\left(\frac{V_{dc}}{\sqrt{2}}\right) - \left(\frac{V_{line}}{\sqrt{2}}\right)}{n * \omega * I_n} \tag{28}$$

Where $\omega = 2 * \Pi * f$ (f is the fundamental frequency and I_n is the current of n^{th} harmonic order.

The inductor should allow the flow of compensating current which includes the harmonic components of load current simultaneously it should block the high frequency signals generated by the switching inverter to the supply[35].

Table below shows the amplitude of each harmonic in the FFT of load current. Neglecting Tripelen and third harmonics up to 19th order are considered for inductor design.

Table 1

Order of harmonics	Amplitude
5th	0.013
7th	0.0033
11th	0.0029
13th	0.0012
17th	0.0011
19th	0.0003

Other Important parameters for the design are

$I_L = 438.7A$ and $V_{line} = 400V$

$V_{dc} = \sqrt{2} * V_{line} = \sqrt{2} * 400 = 565.7$, Therefore V_{dc} can be considered 600

$$I_L = \frac{\frac{600}{\sqrt{2}} - \frac{400}{\sqrt{2}}}{\left(\begin{array}{l} 5*2\Pi*50*0.013*438.7 + 7*2\Pi*50*0.0033*438.7 + 11*2\Pi*50*0.0029*438.7 + \\ 13*2\Pi*50*0.0012*438.7 + 17*2\Pi*50*0.0011*438.7 + 19*2\Pi*50*0.0003*438.7 \end{array}\right)} = 6.4mH$$

Design of DC link capacitor

$$C = \frac{P*T}{\frac{1}{2}\left(V_{dc}{}^{2}\right)}; \qquad \text{Where} \qquad P = \frac{V_{line}}{\sqrt{2}}*I$$

(29)

Therefore the capacitor value would be

$$C = \frac{124083*40*10^{-3}}{\frac{1}{2}\left(V_{dc}\right)^{2}} = 27574\mu F$$

Design of the passive filter

The capacitive reactance needed to improve from power factor with θ_1 to power factor with θ_2 is defined by

VARs= P (tan θ_2– tan θ_1) (30)

Where

P= (V) (I) cos θ_2 (31)

The capacitive reactance would be calculated using the equation below

$$X_C = \frac{V^2}{VARs} \tag{32}$$

The capacitor value will be [36]

$$C = \frac{Q_C}{V^2 w}\frac{n^2-1}{n^2} \tag{33}$$

Similarly the inductance formula is

$L = \frac{1}{h^2 w_1^2 c}$, and $R = \frac{X_L}{Q_f}$ where the Q_f is the quality factor (34)

Using the above formulas the computed parameters of the passive filter are as shown below

Table 2

Filter type	R(mΩ)	L(μH)	C(mF)
5th single tuned	41	4.88	83
7th single tuned	55.8	4.06	50.9
11th single tuned	52.5	2.43	34.4
13th single tuned	89.3	3.5	17.2

Design of fuzzy logic based DC Voltage control

$$I_{smd} = C\frac{V_{dcn}^2 - V_{dc}^2}{3TV_{sm}} \tag{35}$$

From the equation (35) the block diagram of the control system is

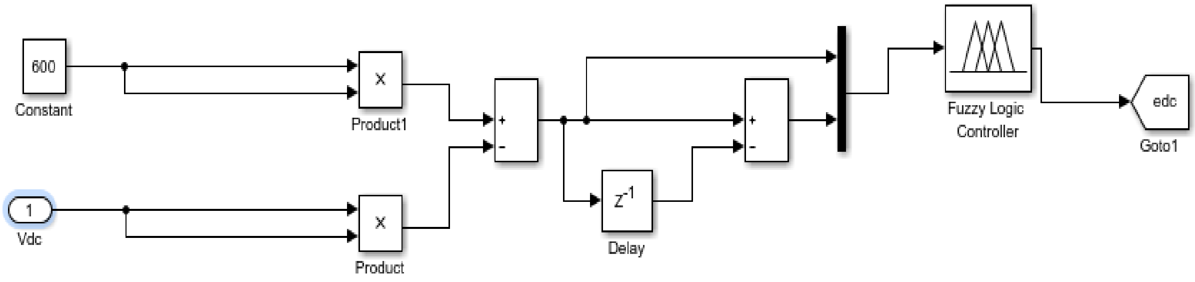

Figure 4. Design of the control system

Where the output of the controller is $edc = V_{dcn}^2 - V_{dc}^2 = 600^2 - V_{dc}^2$ (36)

\

The input member function are

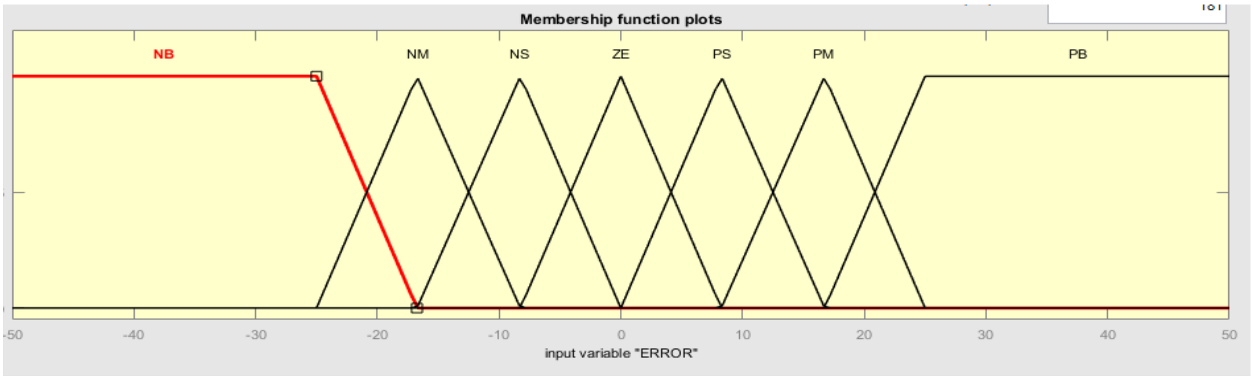

Figure 5: Input Error membership function

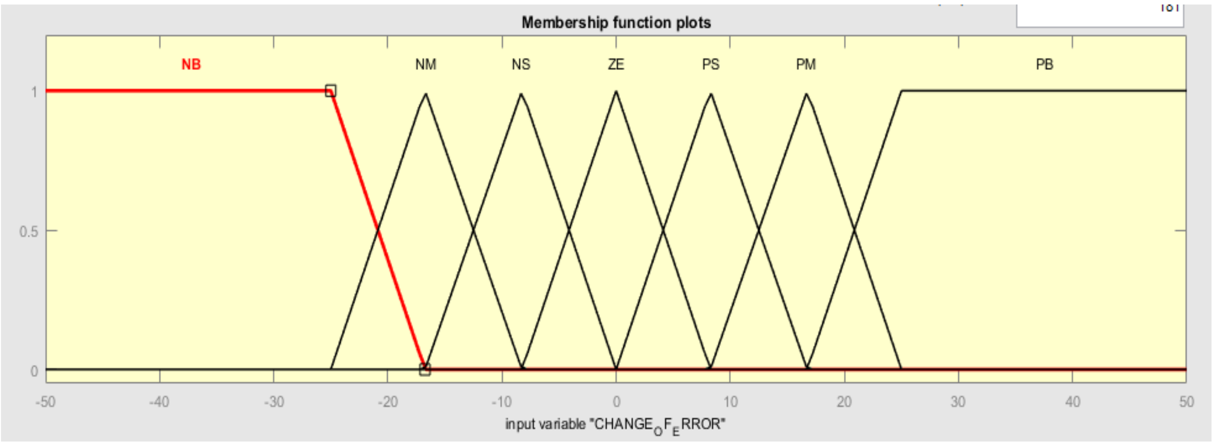

Figure 6: Input change of Error membership function

Similarly the output membership function is

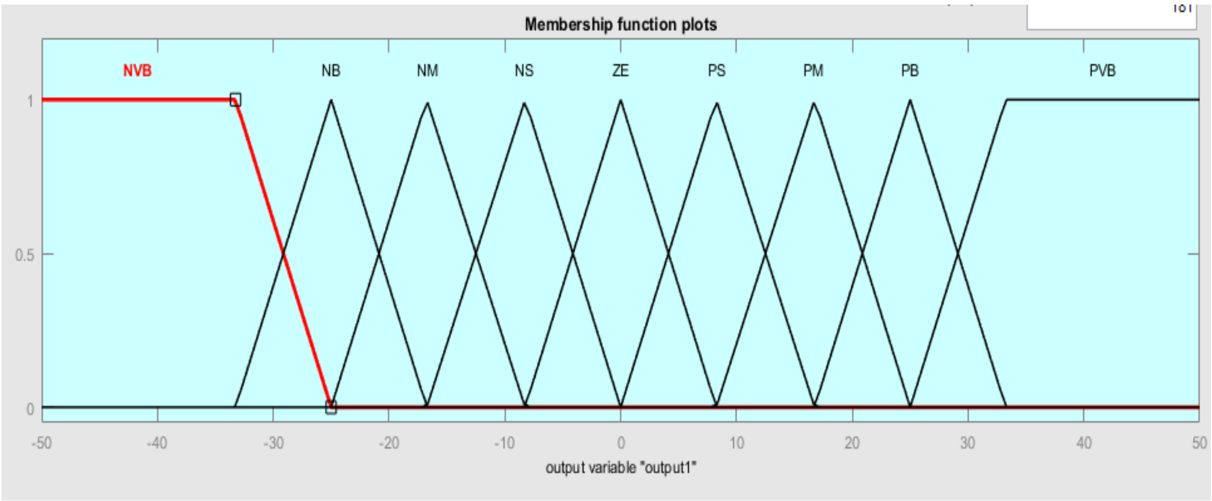

Figure 7: Output membership function

The rule is constructed based on concept shown in the graph below

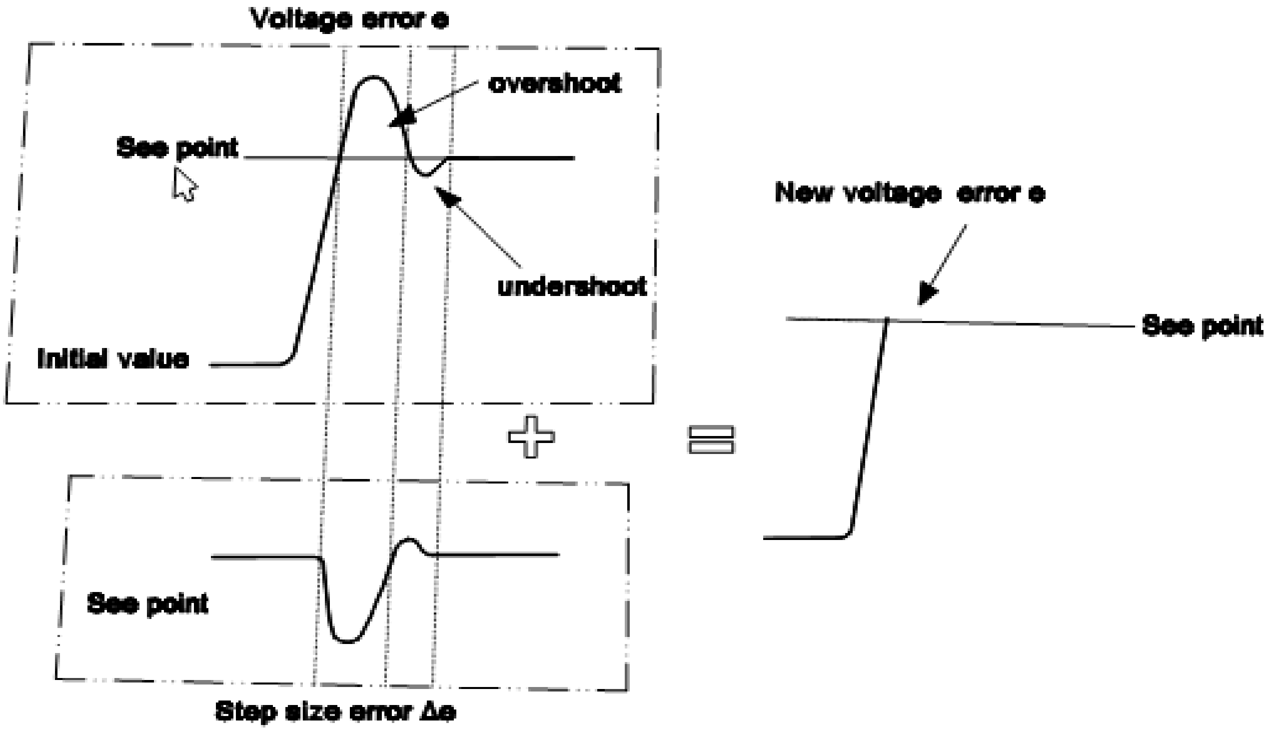

Figure 8: Concept of generating rule base

The Rule base for this controller is

Table 3

e Δe	NB	NM	NS	Z	PS	PM	PB
NB	NVB	NVB	NVB	NB	NM	NS	Z
NM	NVB	NVB	NB	NM	NS	Z	PS
NS	NVB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PVB
PM	NS	Z	PS	PM	PB	PVB	PVB
PB	Z	PS	PM	PB	PVB	PVB	PVB

SIMULATION RESULTS

Considering all the loads are working and loaded 100%, the measured THDV and THDI at point both PCC and IPC before compensation is

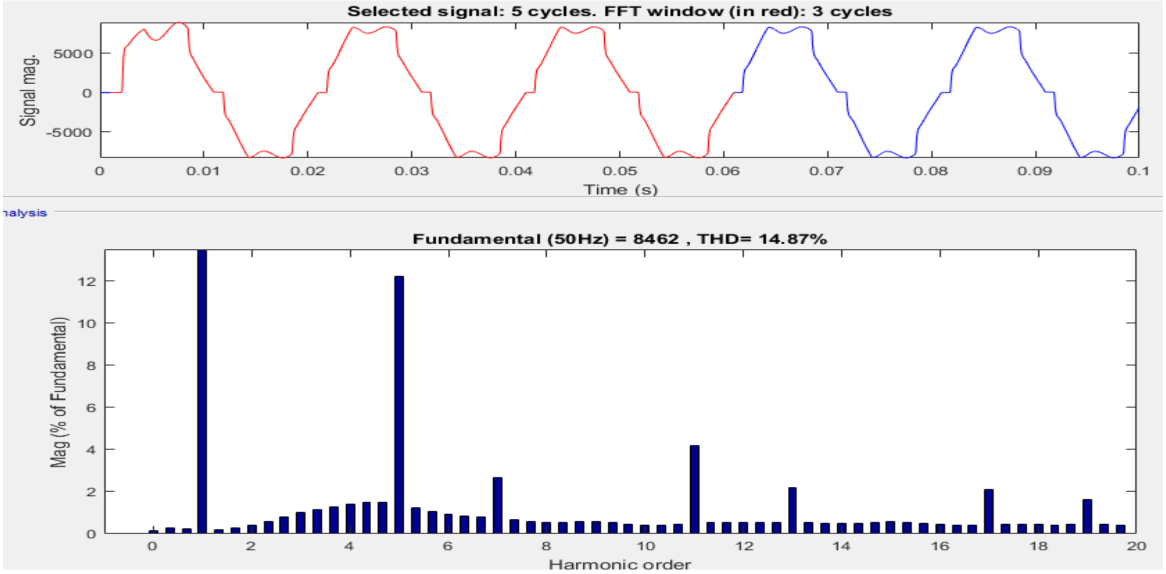

Figure 9: Voltage distortion at the PCC before compensation

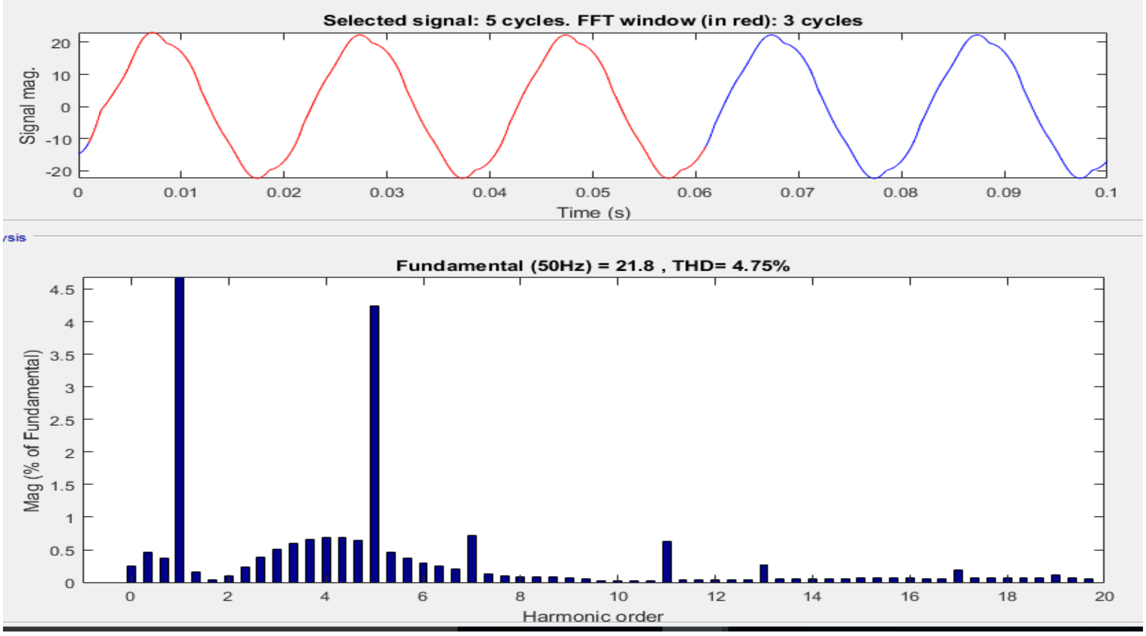

Figure 10: Current distortion at the PCC before compensation

Table 4

Point	THDV (%)	THDI (%)
PCC	14.87	4.75
IPC	14.60	5.59

The THDV at the IPC is above the limit as per defined by the IEC 61000-2-4 for class 2 [37]

Since $\mathrm{THDV}_{\mathrm{IPC}} \geq \mathrm{THDV}_{\mathrm{IPC\_Permitted}}$

$14.60\% \geq 8\%$

Therefore a filter has to be designed to reduce the harmonic distortion level to the limit. Similarly we have to calculate the short circuit ratio at the PCC of the primary side of the transformer to determine whether the voltage and harmonic distortion level at the PCC are within the limit as per defined by IEEE 519-2[38].

Computing the short-circuit ratio $\frac{I_{sc}}{I_L}$

I_{sc} can be calculated from the utility information based on this formula

$$I_{sc} = \frac{KVA_{sc} * 1000}{V_{LL} * \sqrt{3}} = \frac{6000000 * 1000}{15000 * \sqrt{3}} = 230940A$$

(37)

Whereas I_L can be computed using this formula

$$I_L = \frac{Kw}{PF * \sqrt{3} * kV} \qquad (38)$$

Where PF is the power factor and KW is the average power demand that can be found out from the billing information of over the recent 12 months [39]

Average power demand =KW=

$$\frac{\text{kwh consumed in the period}}{\text{hours in the period}}$$

(39)

Assuming the maximum power consumption 70500KWH during the month of December

This month has 31 days therefore

The average power $KW = \frac{70500KWH}{24*31} = 94.76KW$

therefore $I_L = \frac{94.76KW}{0.8 * \sqrt{3} * 400} = 170.97$

Therefore $\frac{I_{sc}}{I_L} = \frac{230940}{170.97} = 1350.76$

As per defined by IEEE 519-2 THDI should not exceed the limit 20% therefore the THDI is within the limit. However THDV is out of the limit which is much greater than the standard. It should be lower than 5% .Therefore a filter is highly recommended to mitigate the harmonics so that the distortion will be reduced to the limit as per defined by IEEE 519-2.

The simulation result after compensation is as shown in table 5

Table 5

Point	THDV (%)	THDI (%)
PCC	4.58	4.83
IPC	4.26	4.72

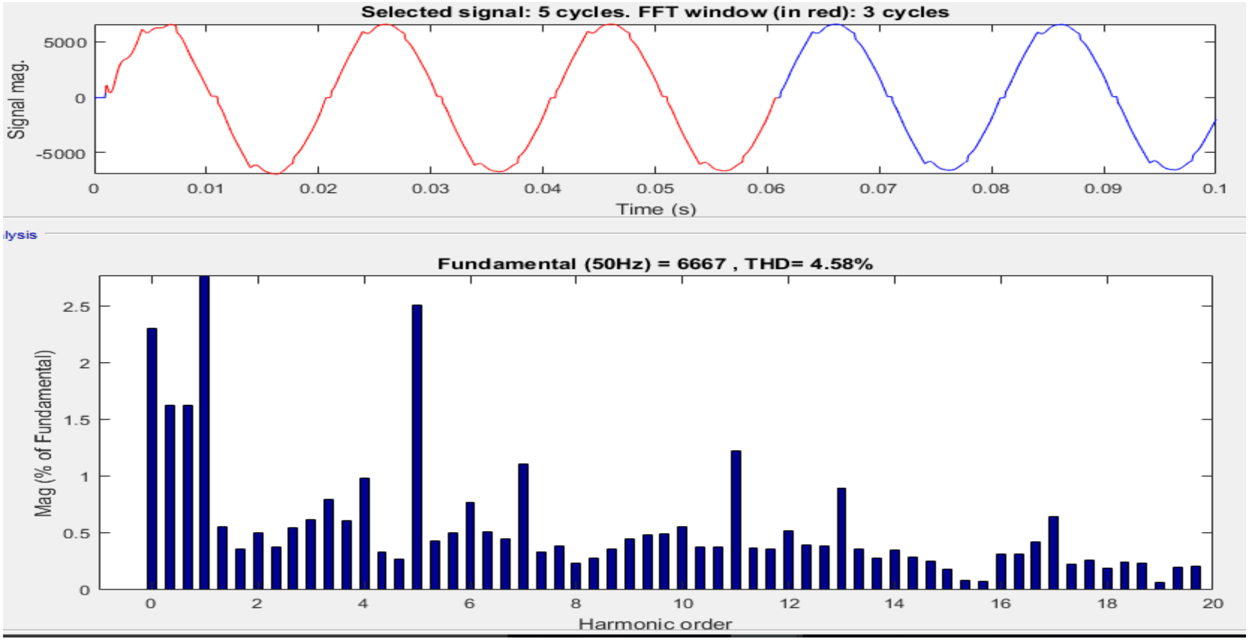

Figure 11: Voltage distortion at the PCC after compensation

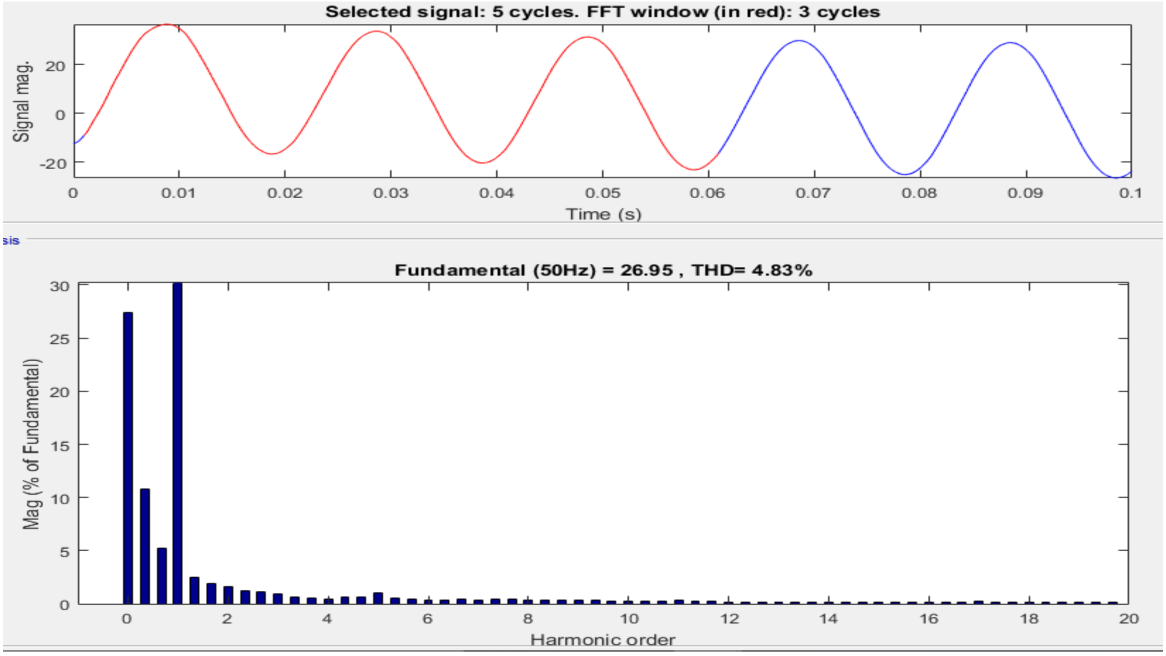

Figure 12: Current distortion at the PCC after compensation

The simulation result considering contingency that is loss of loads in one whole department.

Table 6

Point	THDV (%)	THDI (%)
PCC	4.47	5.91
IPC	4.42	5.62

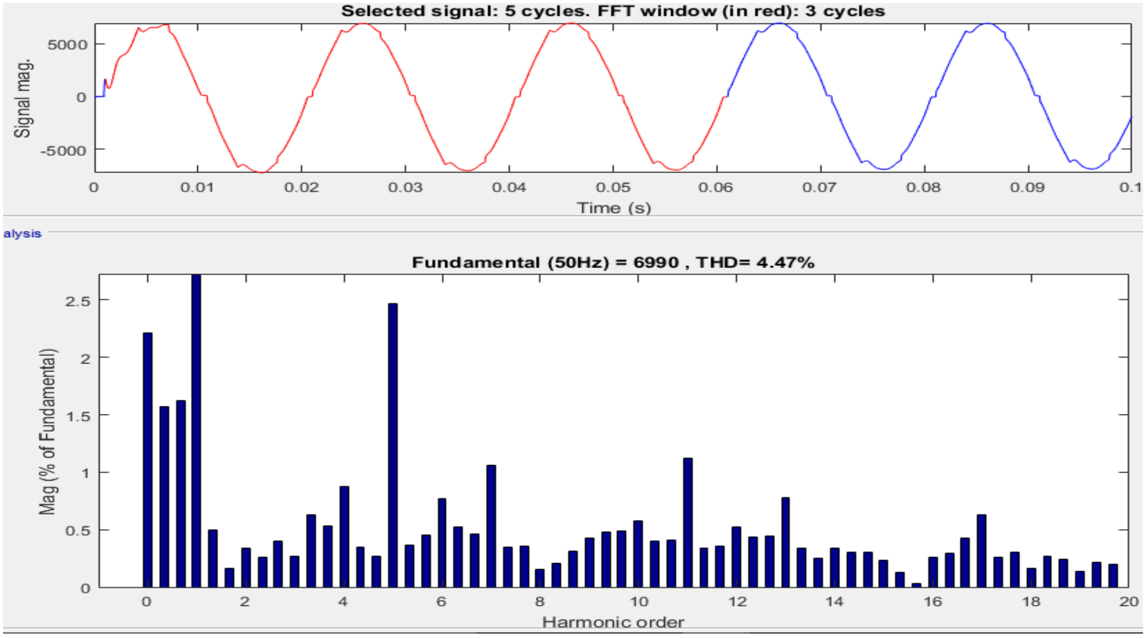

Figure 13: Voltage distortion at the PCC after compensation with a loss of single load

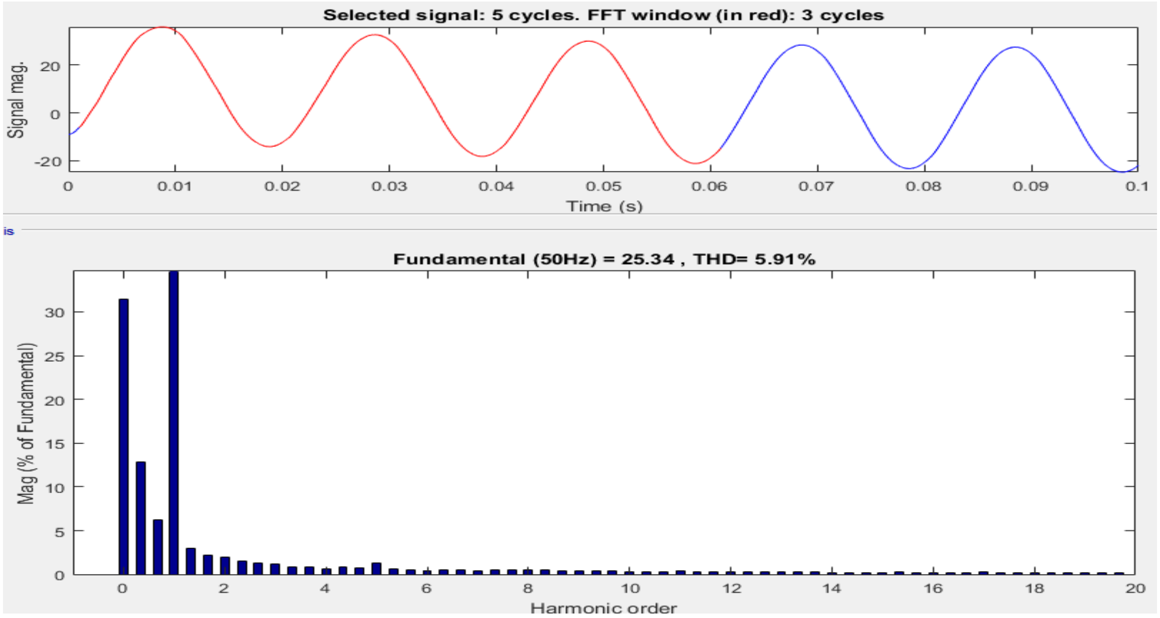

Figure 14: Current distortion at the PCC after compensation with a loss of single load

CONCLUSION

An industrial electrical distribution is modelled for harmonic study using mat lab Simulink. The harmonic distortion level at both PCC and IPC were measured for normal operating conditions and considering N-1 contingency i.e. single case loss of load in a particular department. In all these cases the harmonic distortion level does not meet the harmonic distortion as per the IEEE 519-2 and IEC 61000-2-4 for class 2 standards. To reduce the harmonic distortion level to the level that satisfies the stated standards a fuzzy logic based hybrid filter were designed using the concept of generalized fryze current control strategy. The designed filter were able to mitigate the harmonic distortion level regardless of the operating conditions of the industry i.e. loss of load or disconnecting any department.

REFERENCE

[1] S. Khalid and B. Dwivedi, “Power quality issues, problems, standards and their effects in industry with corrective means,” *Int. J. Adv. Eng. Technol.*, vol. 1, no. 2, pp. 1–11, 2011.

[2] K. Olikara, “Power Quality Issues , Impacts , and Mitigation for Industrial Customers,” 2015.

[3] B. G. P.Eng, C. E. Partners, A. Calgary, M. S. Rouse, and P.Eng, *POWER QUALITY Energy Effi ciency Guide*. NY, 1999.

[4] C. E. Commission, “Power Quality Solutions for Industrial Customers,” California, 2000.

[5] Nikunj Shah, “Harmonics in Power Systems,” 2013.

[6] P. Vukan and P. Jelica, “ALLOCATION OF HARMONIC DISTORTION MARGINS,” *21st Int. Conf. Electr. Distrib.*, no. 69, pp. 1–4, 2011.

[7] I. U. Marcus, A. E. Nestor, and P. Clarkson, “The Influence of the Network Impedance on the Nonsinusoidal (Harmonic) Network Current and Flicker Measurements,” *IEEE Trans. Instrum. Meas.*, vol. 60, no. 7, pp. 2202–2210, 2011.

[8] R. Pragale, T. J. Dionise, S. Member, and D. D. Shipp, “Harmonic Analysis and Multistage Filter Design for a Large Bleach Production Facility,” *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1201–1209, 2011.

[9] H. M. Transformers, “International Inc. 6805,” *MIRUS International Inc.*, Ontario, Canada, pp. 7–17, Jun-2003.

[10] Y. DJEGHADER and L. ZELLOUMA, “Using Hybrid Power Filter To Mitigate Currents and Voltages Harmonics in Three Phase System,” *Acta Electrotech. Inform.*, vol. 15, no. 4, pp. 37–43, 2015.

[11] S. K. Jain, P. Agrawal, and H. O. Gupta, “Fuzzy logic controlled shunt active power filter for power quality improvement,” *IEEE Proc. Electr. Power Appl.*, pp. 317–328, 2002.

[12] A. A. L. I. Sahito, S. M. Tunio, and A. N. Khizer, “Voltage Harmonics Mitigation through Hybrid Active Power Filer,” vol. 35, no. 1, pp. 101–110, 2016.

[13] A. Sharma and A. K. Upadhyay, “Harmonic Mitigation Using Inverter Based Hybrid Shunt Active Power Filter,” vol. 7, no. 8, pp. 787–798, 2014.

[14] K. Dewangan and P. C. Tapre, “Harmonic Reduction

by Using Shunt Hybrid Power Filter," *ISSN || Int. J. Comput. Eng. Res.*, vol. 4, no. 5, pp. 41–49, 2014.

[15] N. Tilwani and D. Sharma, "Series Hybrid Filter for Harmonic Compensation in Three Phase System," vol. 4, no. 5, pp. 266–272, 2015.

[16] C. M. Ndungu, J. N. Nderu, and L. Ngoo, "Analysis of Harmonic order levels at Power Lines to Improve the Power Quality," *Sustain. Res. Innov. Proceedings,2011 - journals.jkuat.ac.ke*, 2011.

[17] G. Nicholson, V. J. Gosbell, and A. Parsotam, "Analysis of harmonic distortion levels on a distribution network," *2007 Australas. Univ. Power Eng. Conf. AUPEC*, pp. 1–7, 2007.

[18] V. Lackovic, *Introduction to Harmonic Analysis*, no. 877. NY: Continuing Education and Development, Inc. 9 Greyridge Farm Court Stony Point, NY 10980, 2010.

[19] S. C. Program, "Short-Circuit Calculations," 2006.

[20] H. M. Umran, "PARAMETERS IDENTIFICATION OF A 3 - PHASE LC FILTER USED FOR VARIABLE FREQUENCY DRIVE," *Kufa J. Eng.*, vol. 6, no. 2, pp. 76–89, 2015.

[21] E. B. Rosa, "The self and mutual-inductances of linear conductors," *Bulletin of the Bureau of Standards*, vol. 4, no. 2. p. 301, 1908.

[22] ARMSTRONG, "6 Pulse Vs. 12 and 18 Pulse Harmonics Effect Reduction," *White Pap.*, 2015.

[23] C. Venkatesh and D. Kumar, "Modelling of Nonlinear Loads and Estimation of Harmonics in Industrial Distribution System," *Natl. Power Syst.*, vol. 2, no. December, pp. 592–597, 2008.

[24] W. Wichakool, A. T. Avestruz, R. W. Cox, and S. B. Leeb, "Modeling and estimating current harmonics of variable electronic loads," *IEEE Trans. Power Electron.*, vol. 24, no. 12, pp. 2803–2811, 2009.

[25] T. Hidaka, M. Ishida, T. Hori, and H. Fujita, "High-Frequency Equivalent Circuit of an Induction Motor Driven by a PWM Inverter," vol. 119, no. 12, pp. 65–76, 2001.

[26] L. Hu and R. E. Morrison, "AC side equivalent circuit-based method for harmonic analysis of a converter system," *IEE Proc. - Electr. Power Appl.*, vol. 146, no. 1, p. 103, 1999.

[27] C. W. M. T. Mclyman, *TRANSFORMER AND INDUCTOR DESIGN HANDBOOK*, Third Edit. California,USA: Marcel Dekker, 2004.

[28] P. M. Grady and M. Grady, "Understanding Power System Harmonics," no. April, 2012.

[29] A. J. Collin, C. E. Cresswell, and S. ?? Djoki??, "Harmonic cancellation of modern switch-mode power supply load," *ICHQP 2010 - 14th Int. Conf. Harmon. Qual. Power*, 2010.

[30] S. Pyakuryal and M. Matin, "Filter Design for AC to DC Converter," *Int. Ref. J. Eng. Sci.*, vol. 2, no. 6, pp. 42–49, 2013.

[31] Task Force on Harmonics Modeling and Simulation, "Modeling and simulation of the propagation of harmonics in electric power networks. I. Concepts, models, and simulation techniques," *IEEE Trans. Power Deliv.*, vol. 11, no. 1, pp. 452–465, 1996.

[32] R. A. Mequon, "Straight Talk About PWM AC Drive Harmonic Problems and Solutions."

[33] T. Manigandan, "Implementation of a Novel Control Strategy Using Fuzzy Logic Controller to Shunt Active Filter for Line Harmonic Reduction Department of EEE , Kongu Engineering College , P . A College of Engineering and Technology , Pollachi , Tamilnadu , India," vol. 8, no. 5, pp. 737–746, 2012.

[34] J. F. and H. A. Antonio Martins, "Active Power Filters for Harmonic Elimination and Power Quality Improvement," *World's Larg. Sci. Technol. Med. Open Access B. Publ.*, 2011.

[35] M. C. Shah, S. K. Chauhan, P. N. Tekwani, and R. R. Tiwari, "Analysis, design and digital implementation of a shunt active power filter with different schemes of reference current generation," *IET Power Electron.*, vol. 7, no. 3, pp. 627–639, 2013.

[36] F. C. De la Rosa, *Harmonics and Power Systems*. Missouri: CRC Press Taylor & Francis Group, 2006.

[37] H. U. Boksberger, "Electrical network and power converters," *Paul Scherrer Institute,* pp. 347–362.

[38] IEEE, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*. 1993.

[39] "Understanding Demand / Energy Rates and Managing Your Electricity Costs," in *An information guide for commercial and industrial customers*, St. John's, Newfoundland and Labrador, Canada: NEWFOUNDLAND POWER A FORTIS COMPANY.