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POWER SYSTEM HARMONIC ANALYSIS PROGRAMS FOR POWER QUALITY TEACHING AND STUDYING

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A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Engineering Program in Electrical Engineering

Department of Electrical Engineering

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สุละไซ แก้วคำพัน : โปรแกรมการวิเคราะห์ฮาร์มอนิกในระบบไฟฟ้ากำลัง เพื่อการเรียนการสอน ด้านคุณภาพไฟฟ้า. (POWER SYSTEM HARMONIC ANALYSIS PROGRAMS FOR POWER QUALITY TEACHING AND STUDYING) อ. ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ไชยะ แช่มช้อย, อ. ที่ปรึกษาวิทยานิพนธ์ร่วม: ผศ.ดร. ธวัชชัย เตชัสอนันต์, 136 หน้า.

วิทยานิพนธ์ นี้นำเสนอการพัฒนาโปรแกรมวิเคราะห์ฮาร์มอนิก โดยใช้ Graphic User Interface (GUI) ของโปรแกรม MATLAB โปรแกรมแบ่งได้เป็น 3 ส่วน ส่วนแรกเป็นการสังเคราะห์รูปคลื่นฮาร์มอนิก ผู้ใช้สามารถใส่ค่าขนาดและมุมเฟสของแต่ละฮาร์มอนิก แล้วดูรูปคลื่นที่สร้างขึ้นมาได้ ส่วนที่สองวิเคราะห์การตอบสนองทางฮาร์มอนิกโดยดูผลจากโหลดเชิงเส้นและไม่เป็นเชิงเส้น ตัวเก็บประจุ ตัวกรองฮาร์มอนิกชนิดดีจูนและจูน การคำนวณหลักในส่วนนี้ คือ การสแกนอิมพีแดนซ์ การไหลกระแสฮาร์มอนิก และ การคำนวณความผิดเพี้ยนทางฮาร์มอนิกแรงดัน การสแกนอิมพีแดนซ์ สามารถบอกการเกิดเรโซแนนซ์ได้ ส่วนสุดท้ายเกี่ยวกับการออกแบบตัวกรองฮาร์มอนิกและการจำลองแบบ การจำลองแบบของระบบหลังจากมีการติดตั้งตัวกรองฮาร์มอนิกมีความสำคัญในการที่จะตรวจสอบประสิทธิภาพการออกแบบตัวกรองฮาร์มอนิกโปรแกรมที่พัฒนาขึ้น สามารถนำไปใช้ในการเรียนการสอนเกี่ยวกับคุณภาพไฟฟ้าได้ กรณีศึกษาหลายกรณี ได้ถูกจำลองแบบเพื่อการทำความเข้าใจกับคุณสมบัติของฮาร์มอนิก โปรแกรมที่พัฒนาขึ้นใช้ง่ายสำหรับผู้ใช้ทั้งที่มีประสบการณ์และไม่มีประสบการณ์ในการเข้าใจการวิเคราะห์ทางฮาร์มอนิก.

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SOULAXAY KEOKHAMPHAN: POWER SYSTEM HARMONIC ANALYSIS PROGRAMS FOR POWER QUALITY TEACHING AND STUDYING. ADVISOR: ASSOC. PROF. CHAIYA CHAMCHOY, CO-ADVISOR: ASST. PROF. THAVATCHAI TAYJASANANT, Ph. D. 136-pp.

This thesis presents a graphic user interface (GUI)-based power system harmonic analysis program developed under MATLAB environment. The program can be divided into three parts. The first part performs harmonic waveform synthesis. A user can input various harmonic magnitudes and phase angles and then view the resultant distorted waveform. The second part analyzes the power system harmonic response with combination of linear and nonlinear loads, capacitor banks, a detuned filter and tuned filters. The major features of this part are impedance scan, harmonic current flow and harmonic voltage distortion calculation. The harmonic impedance scan can reveal resonance conditions of a power system. The last part deals with harmonic filter design and simulation. Simulations of system response after installation of harmonic filters are crucial in order to verify the effectiveness of the harmonic filter design. The developed program can be used for power quality teaching and studying. Various cases can be simulated for better understanding of harmonic characteristics. The developed program is user-friendly for non-experienced and experienced users in order to understand harmonic analysis.

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CHAPTER I

INTRODUCTION

1.1 Motivation

Power system harmonic is one of major power quality disturbances in a power system. The severity of harmonic level is increasing due to an increased utilization of nonlinear loads such as adjustable-speed drives, power converters, computers and other power electronic-based devices in industrial, commercial and residential consumers. Harmonics are voltages and currents whose frequencies are integral multiples of the fundamental frequency. On a 50-Hz system, this could include 2nd harmonic (100 Hz), 3rd harmonic (150 Hz), 4th harmonic (200 Hz), and so on. Harmonic can pollute a power system and result in negative effects on electrical equipments. Major effects of harmonics are losses in transformers, machines and electrical devices, mal-operation of electrical devices, power system resonances and severe overheating of neutral lines in commercial buildings. In order to better understand the nature of harmonics in a power system, there is a need to develop a program that can analyze their characteristics [1]. The developed program must be user-friendly and accurate enough to represent harmonic characteristics. MATLAB software contains many build- in functions widely used in engineering fields. Therefore, developing a program under MATLAB software is simple to program and suitable for this task. The program can be divided into 3 parts: 1) Harmonic waveform synthesis, 2) Harmonic response analysis and 3) Harmonic filter design.

1.2 Research objectives

Objectives of this research are

1) To develop harmonic analysis program for power quality teaching and studying
2) To understand harmonic characteristics in a power system through computer simulations

1.3 Scope of study

1) To perform waveform synthesis with various harmonic components and calculate important harmonic indices. The reconstructed waveform will show the effect of harmonic components in a signal. Harmonic indices that will be considered are RMS and THD values.
2) To analyze harmonic flow in a power system. Harmonic voltages at a bus and harmonic currents in branches will be calculated. Results can reveal how harmonics flow in the system.
3) To design passive harmonic filter to minimize harmonic level in a power system. Frequency response in the form of frequency scan plot will be evaluated in order to verify filter performance.
4) This research will focus only parallel resonance.

1.4 Research methodology

In order to achieve the objectives, the following research methodology will be carried out.

1) Studying effects of harmonics.
2) Studying harmonic models of system equipments in power system
3) Studying and analyzing the computation of harmonic in power system as well as writing a program to analyze when capacitor, detuned filter and tuned filters are installed.
4) Testing the program performance.
5) Evaluating test results and concluding results from the testing.
6) Writing thesis.

1.5 Expected outcomes

Power system harmonic analysis programs for power quality teaching and studying with graphic user interface (GUI) of MATLAB software will be developed. Users can adjust parameters and perform sensitivity studies in various issues of power system analysis such as waveform synthesis, harmonic flow and harmonic filter design. Developed programs can help users to understand harmonic characteristics for power quality teaching and studying.

1.6 Overview of thesis

Chapter 2 summarizes the fundamental background and related theoretical knowledge in analyzing and estimating the harmonic current in a power system and harmonic filter design method.

Chapter 3 deals with harmonic modeling of system components. Modeling of equipment for harmonic analysis and method of simulation

Chapter 4 describes details of developed program. The program consists of 3 parts, which are: waveform synthesis, harmonic power flow and harmonic filter design.

Chapter 5 displays outputs and summarizes case studies.

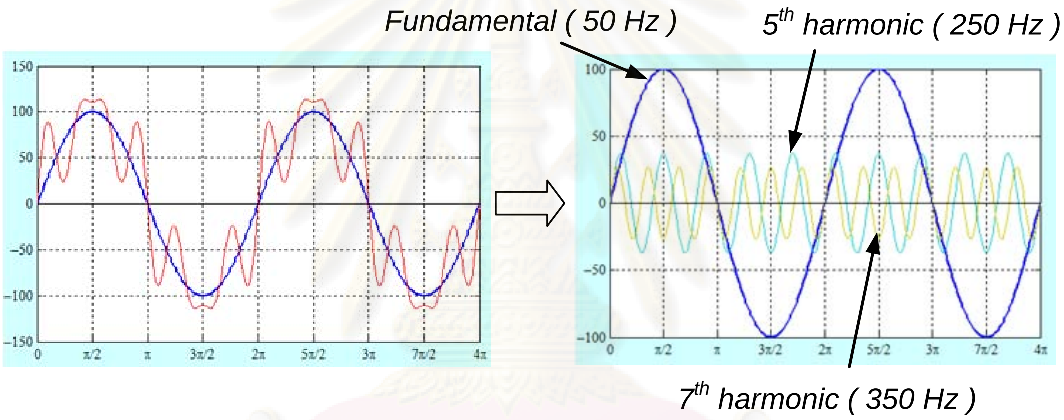
Chapter 6 concludes the research work.

CHAPTER II

LITERATURE REVIEW

2.1 Fourier series and waveform reconstruction

One method of describing the non-sinusoidal waveform is Fourier series. Jean Fourier was a French mathematician of the early 19th century who discovered a special characteristic of periodic waveforms. Periodic waveforms are those waveforms comprised of identical values that repeat in the same time interval, like those shown below.



(a) (b)

Figure 2. 1 (a) Distorted current waveform (b) Equivalent harmonic components

Fourier discovered that periodic waveforms can be represented by a series of sinusoids summed together. The frequency of these sinusoids is an integer multiple of the frequency represented by the fundamental periodic waveform.

The distorted (non-linear) waveform, however, deserves further consideration. This waveform meets the continuous, periodic requirement established by Fourier. It can be described, therefore, by a series of sinusoids. This example waveform is represented by only three harmonic components, but some real-world waveforms (square wave, for example) require hundreds of sinusoidal components to fully describe them. The magnitude of these sinusoids decreases with increasing frequency, often allowing the power engineer to ignore the effect of components above the 50th harmonic [2], [3].

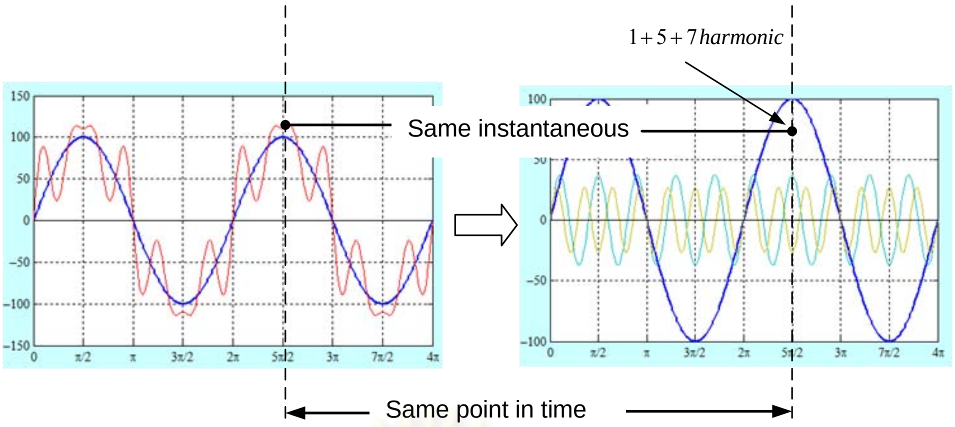


Figure 2.2 Distorted (non-linear) waveform

The general equation of the reconstructed current waveform is

$$I = \sum_{1}^{h} I_h \sin(h\omega t + \theta_h) \qquad (2.1)$$

where: h = 1, 2, 3, 4, 5, 6, 7…

The reverse process where the harmonic spectra can be computed from the distorted waveform is called waveform analysis which can be achieved through Fast Fourier Transform (FFT).

2.2 Power system quantities under non sinusoidal conditions

2.2.1 Root-mean-square (rms) Values

The rms values of the waveforms are computed as the square root of the sum of squares of all individual components [4].

$$\text{rms current: } I_{rms} = \sqrt{\sum_{h=1}^{N} I_h^2} = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \ldots} \qquad (2.2)$$

$$\text{rms voltage: } V_{rms} = \sqrt{\sum_{h=1}^{N} V_h^2} = \sqrt{V_1^2 + V_2^2 + V_3^2 + V_4^2 + \ldots} \qquad (2.3)$$

where: I_h The single frequency rms current at harmonic h

V_h The single frequency rms voltage at harmonic h

N Maximum harmonic order to be considered

2.2.2 Total harmonic distortion (THD)

Total harmonic distortion (THD) is an important index widely used to describe power quality issues in transmission and distribution systems. It considers the contribution of every individual harmonic component on the signal. THD is defined for voltage and current signals, respectively. Total harmonic distortion is calculated as the sum of all the harmonic components (except the fundamental), divided by the magnitude of the fundamental. This value is represented as THD [3], [4].

$$THD_V = \sqrt{\frac{\sum_{h=2}^{N} V_h^2}{V_1^2}} \tag{2.4}$$

$$THD_I = \sqrt{\frac{\sum_{h=2}^{N} I_h^2}{I_1^2}} \tag{2.5}$$

V_h The single frequency rms voltage at harmonic h

V_1 The fundamental line-to-neutral rms voltage

I_h The single frequency rms current at harmonic h

I_1 The fundamental rms current

THD can be computed in term of rms value as follows:

$$THD_V = \sqrt{\frac{\sum_{h=2}^{N} V_h^2}{V_1^2}} = \sqrt{\frac{\sum_{h=1}^{N} V_h^2 - V_1^2}{V_1^2}} = \sqrt{\left(\frac{V_{rms}}{V_1}\right)^2 - 1} \tag{2.6}$$

or

$$V_{rms} = V_{1rms}\sqrt{1+THD_V^2} \tag{2.7}$$

and

$$I_{rms} = I_{1rms}\sqrt{1+THD_I^2} \tag{2.8}$$

Note that the components are summed vectorially, not algebraically, because they have different phase angles. For a waveform represented by a fundamental current of 100 A, a 5th component of 20 A, and a 7th component of 12 A, for example, I_h would equal the square root of ($20^2 + 12^2$), or 23 A, not (20 + 12) = 32 A. The THD is, therefore, 23/100 = 0.23 or 23%.

2.2.3 Total demand distortion (TDD)

For current harmonics, using the THD value might mislead the harmonic current level when it is under a light-load condition, I_1 is small so THD_I is large. For this reason, TDD is proposed for the measure of harmonic current level. Instead of using I_1, the rated or maximum load current is applied [4].

Harmonic distortion is most meaningful when monitored at the point of common coupling (PCC) - usually the customer's metering point - over a period that can reflect maximum customer demand, typically 15 to 30 minutes as suggested in Standard IEEE-519. Weak sources with a large demand current relative to their rated current will tend to show greater waveform distortion. Conversely, stiff sources characterized for operating at low demand currents will show decreased waveform distortion. The total demand distortion is based on the demand current, I_L, over the monitoring period [3]:

$$TDD = \frac{\sqrt{\sum_{h=2}^{N} I_h^2}}{I_L} \tag{2.9}$$

where:

I_h The single frequency rms current at harmonic h

I_L Rated or maximum load current magnitude

2.2.4 Power, distortion power, displacement and power factors

- Active (Real or True) Power is measured in watts (W) and is the power drawn by the electrical resistance of a system doing useful work.
- Apparent Power is measured in volt-amperes (VA) and is the voltage on an AC system multiplied by all the current that flows in it. It is the vector sum of the active and the reactive power.
- Reactive power is measured in volt-amperes reactive (VAR). Reactive power is power stored in and discharged by inductive motors, transformers and solenoids

- Active and reactive powers

$$P = \sum_{h=1}^{N} V_h I_h \cos(\theta_h - \phi_h) \tag{2.10}$$

$$Q = \sum_{h=1}^{N} V_h I_h \sin(\theta_h - \phi_h) \tag{2.11}$$

The apparent power (S) is the product of V_{rms} and I_{rms} or:

$$S = V_{rms} I_{rms} \tag{2.12}$$

$$S = V_{1rms}\sqrt{1+THD_V^2}\,.I_{1rms}\sqrt{1+THD_I^2} \tag{2.13}$$

$$S = S_1\sqrt{1+THD_V^2}\,.\sqrt{1+THD_I^2} \tag{2.14}$$

where: S_1 is apparent power at the fundamental frequency

- When the harmonics are present, S is not only comprised of P and Q, but distortion power (D) as shown in Fig 2.3.

$$S^2 = P^2 + Q^2 + D^2 \quad \text{or} \quad D = \sqrt{S^2 - P^2 - Q^2} \tag{2.15}$$

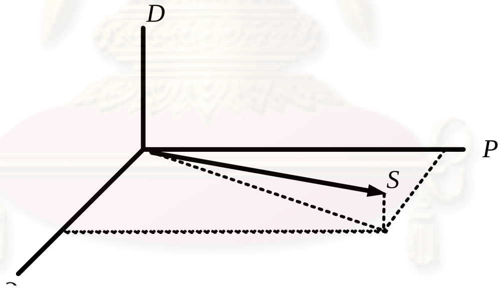


Figure 2.3 Relationship of components of the apparent power

- Power factor

It is common to define the Power Factor (PF) as the cosine of the phase angle between voltage and current or the "cosφ".

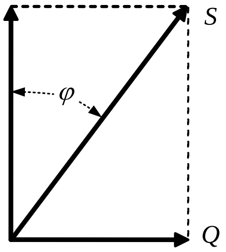


Figure 2.4 Relationship between P, Q, and S in sinusoidal condition

The power factor defined by IEEE and IEC is the ratio between the applied active (true) power - and the apparent power, and can in general be expressed as:

$$PF = P / S \tag{2.16}$$

where: PF = power factor

P = active (true or real) power (Watts)

S = apparent power (VA, volts amps)

With an increasing harmonic distortion environment, the conventional definition of power factor as the cosine of the angle between fundamental frequency voltage and current has progressed to consider the signal's rms values, which make up the contribution of components of different frequencies. Thus, displacement power factor (DPF) continues to characterize the power frequency factor, while distortion power factor (HPF) emerges as the index that tracks rms signal variations. True power factor (PF) thus becomes the product of displacement and distortion power factors [4]:

$$PF = \frac{P}{S} = \frac{P}{S_1}\left(\frac{1}{\sqrt{1+THD_V^2}}.\frac{1}{\sqrt{1+THD_I^2}}\right) \tag{2.17}$$

$$PF = PF_{disp}.PF_{dist} \tag{2.18}$$

where:

$$PF_{disp} = \frac{P}{S_1} \tag{2.19}$$

PF_{disp} = Displacement power factor (DPF)

and

$$PF_{dist} = \left(\frac{1}{\sqrt{1+THD_V^2}}.\frac{1}{\sqrt{1+THD_I^2}}\right) \tag{2.20}$$

$$PF_{dist} = \left(\frac{V_{1rms}}{V_{rms}}\frac{I_{1rms}}{I_{rms}}\right) = \frac{S_1}{S} \tag{2.21}$$

PF_{dist} = Distortion power factor (HPF)

2.3 Harmonic analysis in power system

2.3.1 Harmonic resonances

The current drawn by non-linear loads passes through all of the impedance between the system source and load. This current produces harmonic voltages for each harmonic as it flows through the system impedance. These harmonic voltages sum and produce a distorted voltage when combined with the fundamental. The voltage distortion magnitude is dependent on the source impedance and the harmonic voltages produced. Figure 2.5 illustrates how the distorted voltage is created. As illustrated, non-linear loads are typically modeled as a source of harmonic current [2].

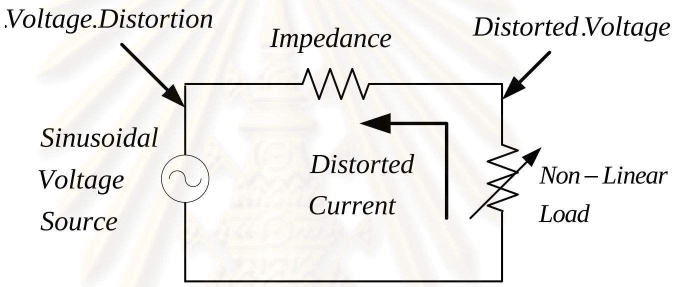
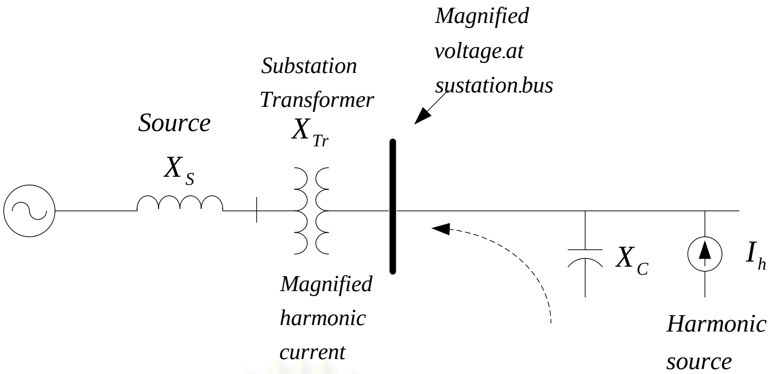


Figure 2.5 Creation of distorted current

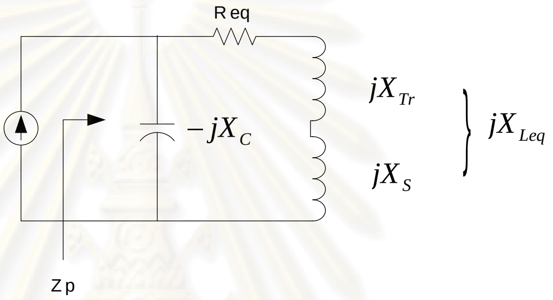
With low source impedance the voltage distortion will be low for a given level of harmonic current. If harmonic current increases, however, system impedance changes due to harmonic resonance (discussed below), voltage distortion can increase significantly.

2.3.1.1 Parallel resonance

- Resonance can happen when certain harmonic frequency produced by nonlinear loads is near the natural frequency of system [4].
- The potential parallel resonance occurs when the shunt capacitor appears in parallel with the equivalent system inductance (source and transformer) at harmonic frequencies as show in Figure 2.6. (a).



(a) Simplified distribution circuit



(b) The equivalent circuit of parallel resonance circuit

Figure 2.6 Parallel resonance

- Parallel resonance occurs when the reactance of X_c and the distribution system cancel out each other as show in figure2.6 (b).
- The frequency at which this phenomenon occurs is called the parallel resonant frequency (f_p).
- The apparent impedance as seen from the harmonic current source becomes very large. Reactance is computed at the resonant frequency Z_P.
- Therefore, during parallel resonance, a small harmonic current can cause a large voltage drop across the apparent impedance; V_p. The voltage near the capacitor bank will be magnified and heavily distorted. The current will also be magnified resulting capacitor failure, fuse blowing or transformer overheating.
- Power systems analysis typically does not have *L* and *C* readily available and prefer to use other forms of this relationship. They commonly compute the resonant harmonic h_p based on fundamental frequency impedances and ratings using one of the following h_p.
- The current behavior during the parallel resonance. Let the current flowing in the capacitor bank or into the power system be $I_{resonance}$

$$Z_p = \frac{-jX_C(jX_{Leq}+R_{eq})}{-jX_C+jX_{Leq}+R_{eq}} = \frac{-jX_C(jX_{Leq}+R_{eq})}{R_{eq}} \approx \frac{X_{Leq}^2}{R_{eq}} = \frac{X_C^2}{R_{eq}} \tag{2.22}$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{1}{L_{eq}C} - \frac{R_{eq}{}^2}{4L_{eq}^2}} \approx \frac{1}{2\pi}\sqrt{\frac{1}{L_{eq}C}} \tag{2.23}$$

$$h_p = \sqrt{\frac{X_C}{X_{SC}}} = \sqrt{\frac{MVA_{SC}}{MVAR_{cap}}} = \sqrt{\frac{kVA_{Tr} \times 100}{kVAR_{cap} \times Z_{Tr}(\%)}} \tag{2.24}$$

or $$h_p = \sqrt{\frac{X_C}{X_{Tr} + X_S}} \tag{2.25}$$

$$V_p = \frac{X_{Leq}^2}{R_{eq}}.I_h = \frac{X_C^2}{R_{eq}}.I_h \tag{2.26}$$

$$I_{resonance} = \frac{V_P}{X_C} = \frac{QX_C I_h}{X_C} = QI_h \tag{2.27}$$

or $$I_{resonance} = \frac{V_P}{X_{Leq}} = \frac{QX_{Leq} I_h}{X_{Leq}} = QI_h \tag{2.28}$$

where $Q = X_L/R_{eq} = X_C/R_{eq}$

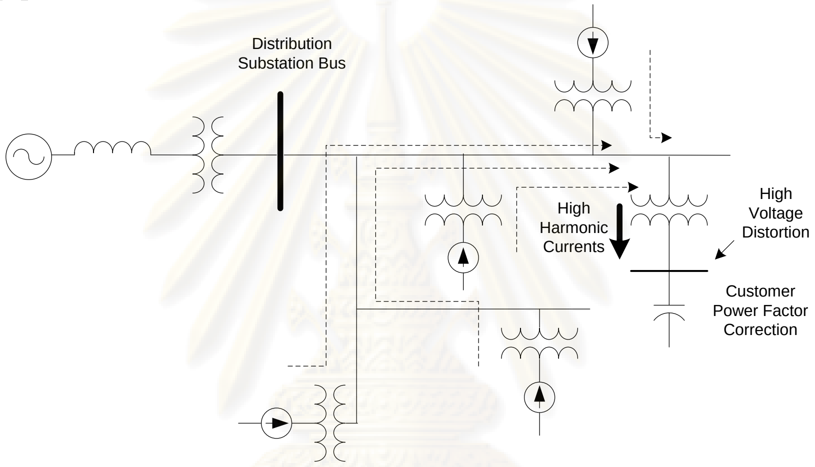
R_{eq}	Resistance of combined equivalent source and transformer
X_{Leq}	Reactance of transformer and System
X_{Tr}	Reactance of transformer at fundamental frequency
X_S	Reactance of system at fundamental frequency
I_h	Current at harmonic h^{th} from non-linear load
Z_p	Impedance at harmonic h^{th}
f_p	Frequency at parallel resonance
h_p	Parallel resonance order
X_C	Capacitor reactance at fundamental frequency
C	Capacitance of capacitor bank
L_{eq}	Inductance of combined equivalent source and transformer
X_{SC}	System short-circuit reactance
MVA_{SC}	System short-circuit MVA
$MVAR_{cap}$	Mvar rating of capacitor bank
$kVAR_{cap}$	kvar rating of capacitor bank
kVA_{Tr}	kVA rating of step-down transformer
Z_{Tr}	Impedance of transformer
Q	Quality factors of transformer and system at resonance frequency

- For example, for an industrial load bus where the transformer impedance is dominant, the resonant harmonic for a 1500-kVA, 6 percent transformer and a 500-kvar capacitor bank is approximately.

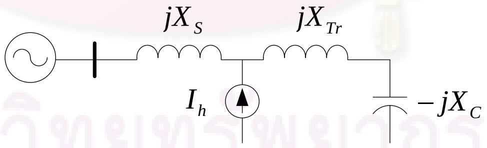
$$h_p \approx \sqrt{\frac{kVA_{tr} \times 100}{kVAr_{cap} \times Z_{tr}(\%)}} = \sqrt{\frac{1500 \times 100}{500 \times 6}} = 7.07$$

2.3.1.2 Series resonance

Shunt capacitors of customer and the inductance of a transformer or distribution line may appear as a series *LC* circuit to a source of harmonic currents as show in Figure 2.7 (a). If the resonance frequency corresponds to a characteristic harmonic frequency of the nonlinear loads, the *LC* circuit will attract a large portion of the harmonic current. The voltage at the PF factor correction capacitor is magnified and highly distorted [4].



(a) System with potential series resonance problems



(b) The equivalent circuit of a series resonance circuit.

Figure 2.7 Series resonance

- The voltage at PF capacitor bank is:

$$\frac{X_C}{X_T + X_C + R} V_h \approx \frac{X_C}{R} V_h \tag{2.29}$$

where: V_h is harmonic voltage corresponding to I_h

$$h_s = \sqrt{\frac{X_C}{X_T}} \tag{2.30}$$

where: h_s = Series resonant order.

In many systems with potential series resonance problems, parallel resonance also arises due to the circuit topology. One of these is shown in figure 2.8. Where the parallel resonance is formed by the parallel combination between X_{source} and a series between X_T and X_C. The resulting parallel resonant frequency is always smaller than its series resonant frequency due to the source inductance contribution. The parallel resonant frequency can be represented by the following equation:

$$h_p = h_r = \sqrt{\frac{X_C}{X_T + X_{source}}} \qquad (2.31)$$

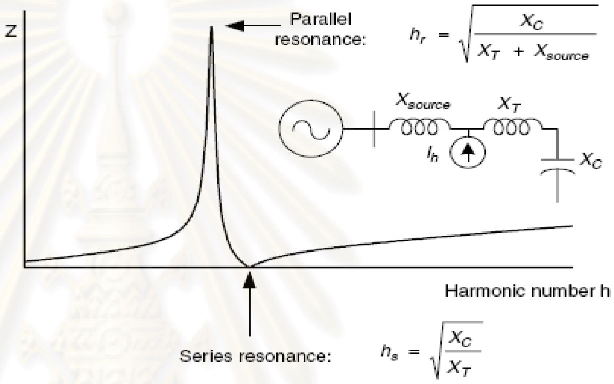


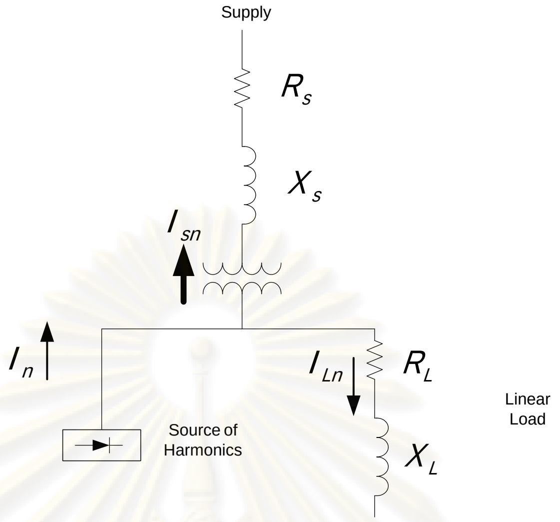
Figure 2.8 Parallel and series resonances

- Comparison between parallel and series resonances

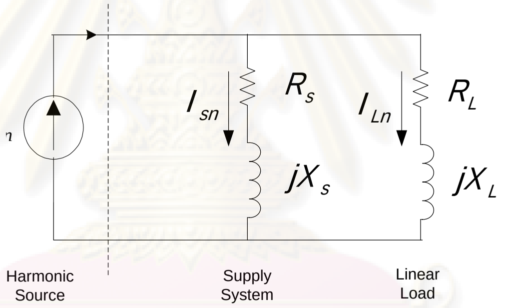
Parallel resonance	Series resonance
$Z_T = \infty$	$Z_T = 0$
Small I_h causes large voltage distortion	large harmonic current follow

2.3.2 Harmonic current flow

2.3.2.1 Inductive system



(a) Inductive system



(b) Equivalent circuit of an inductive system

Figure 2.9 Simple inductive system

Harmonic current in an inductive system can be calculated from

$$I_{sn} = \frac{(R_L + jX_L)}{(R_L + jX_L) + (R_s + jX_s)} \cdot I_n \tag{2.32}$$

$$I_{Ln} = \frac{(R_s + jX_s)}{(R_L + jX_L) + (R_s + jX_s)} \cdot I_n \tag{2.33}$$

$$I_n = I_{sn} + I_{Ln} \tag{2.34}$$

Load Impedance > Source Impedance

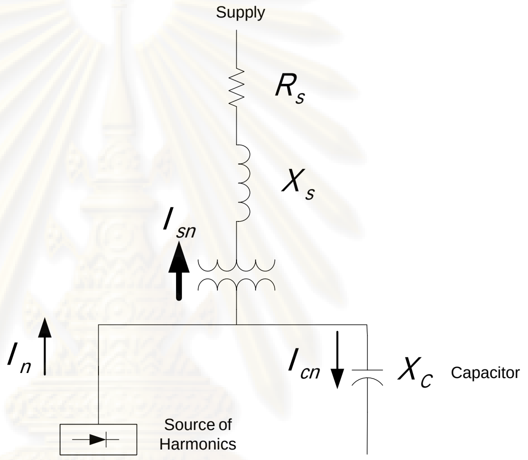
$$(R_L + jX_L) > (R_s + jX_s)$$

$$\frac{(R_L + jX_L)}{(R_L + jX_L) + (R_s + jX_s)} > \frac{(R_s + jX_s)}{(R_L + jX_L) + (R_s + jX_s)}$$

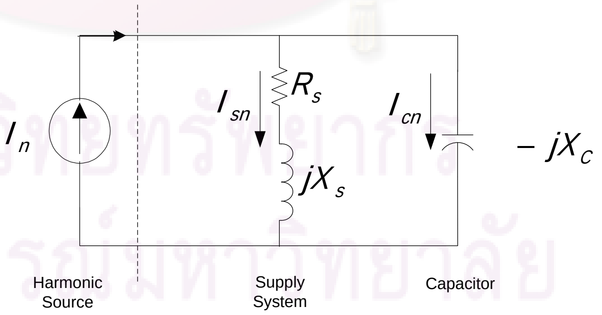
$$\Rightarrow \qquad I_{sn} \quad > \quad I_{Ln}$$

R_L	Load resistance
X_L	Load reactance
R_S	System resistance
X_S	Reactance of system at fundamental frequency
I_n	Harmonic current from non-linear load
I_{sn}	Harmonic current through System
I_{Ln}	Harmonic current through Load

2.3.2.2 System with a capacitor



(a)



(b) Equivalent circuit of system with capacitor

Figure 2.10 Simple system with a capacitor

$$Z_{total} = \frac{(R_s + jX_s)(-jX_c)}{R_s + jX_s - jX_c} \tag{2.35}$$

- At parallel resonance $|X_s| = |X_c|$

$$I_n = I_{sn} + I_{cn} \tag{2.36}$$

$$I_{cn} = \frac{R_s + jX_s}{R_s + jX_s - jX_c} \cdot I_n \tag{2.37}$$

$$I_{sn} = \frac{-jX_c}{R_s + jX_s - jX_c} \cdot I_n \tag{2.38}$$

At resonance

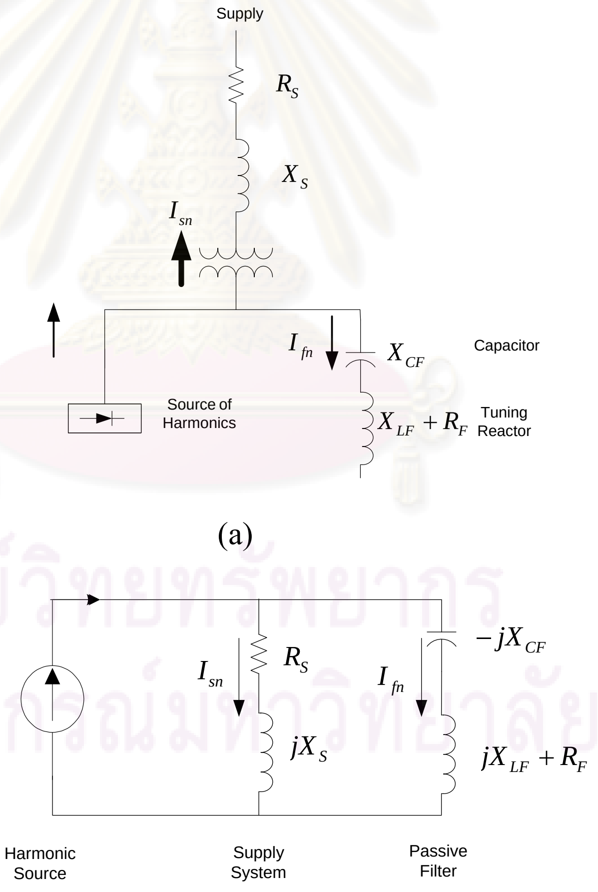
$$I_{cn} = \frac{R_s + jX_s}{R_s} \cdot I_n \qquad >> \qquad I_n$$

$$I_{sn} = \frac{-jX_c}{R_s} \cdot I_n \qquad >> \qquad I_n$$

X_c Capacitor reactance

I_{cn} Harmonic current through capacitor

2.3.2.3 System with a passive filter



(a)

(b) Equivalent circuit of system with a passive filter

Figure 2.11 Simple system with a passive filter

Harmonic currents in a system with a passive filter can be calculated from

$$I_n = I_{sn} + I_{fn} \tag{2.39}$$

$$I_{fn} = \frac{R_S + jX_S}{R_S + jX_S + R_F + jX_{LF} - jX_{CF}} \cdot I_n \tag{2.40}$$

$$I_{sn} = \frac{R_F + jX_{LF} - jX_{CF}}{R_S + jX_S + R_F + jX_{LF} - jX_{CF}} \cdot I_n \tag{2.41}$$

Tuned Filter: set $|X_{LF}| = |X_{CF}|$ and R_F are small

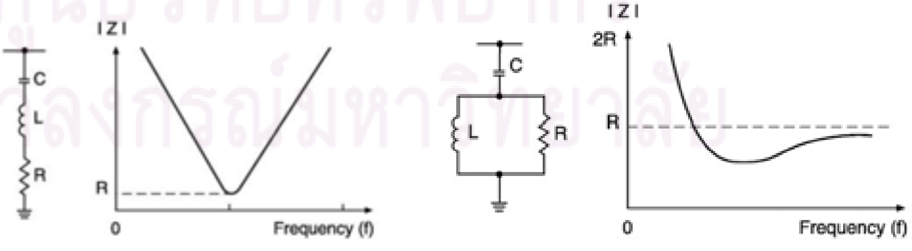
$$I_{fn} = \frac{R_S + jX_S}{R_S + jX_S + R_F} \cdot I_n \approx I_n \tag{2.42}$$

$$I_{sn} = \frac{R_F}{R_S + jX_S + R_F} \cdot I_n \approx 0 \tag{2.43}$$

R_F	Filter resistance
X_{LF}	Reactance of reactor
X_{CF}	Capacitive reactance of filter
I_{fn}	Harmonic current through filter

2.4 Mitigation of harmonics

The most common method for control of harmonic distortion in industry is the use of passive filtering techniques that make use of single-tuned or band-pass filters. Passive harmonic filters can be designed as single-tuned elements that provide a low impedance path to harmonic currents at a punctual frequency or as band-pass devices that can filter harmonics over a certain frequency bandwidth [6].



(a) Band Pass filter (b) High Pass filter

Figure 2.12 Impedance daigram of filters

2.5 Harmonic filter design and specification

Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics. They are commonly used and are relatively inexpensive compared with other means for eliminating harmonic distortion. However, they have the disadvantage of potentially interacting adversely with the power system, and it is important to check all possible system interactions when they are designed. They are employed either to shunt the harmonic currents off the line or to block their flow between parts of the system by tuning the elements to create a resonance at a selected frequency [6].

Passive filters are the most commonly used filters in industry. As illustrated in figure 2.13, the following can be found under this category:

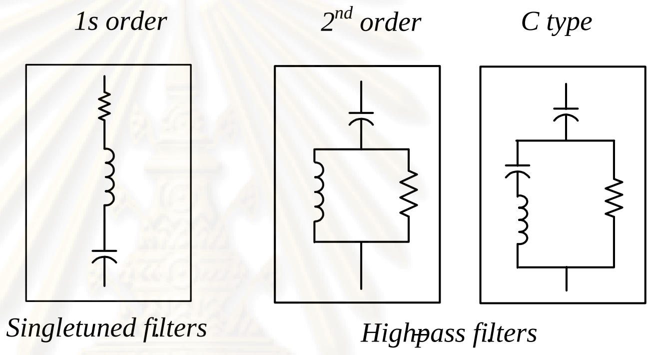


Figure 2.13 Electric diagrams of passive filters

2.5.1 Detuned filter design

Design equation for the detuned filter [7]:

$$n_h = \sqrt{\frac{X_{CF}}{X_{LF}}} = \sqrt{\frac{100}{\%X_{LF}}} \tag{2.44}$$

$$\%X_{LF} = \frac{100}{n_h^2} \tag{2.45}$$

where: n_h = Tuning point of filter

$f_{rs} = f_1 * n_h$ = frequency of series resonance (Hz)

Table 2.1 Frequency of tuning point at $\%X_{LF}$ (f_1=50 Hz)

$\%X_{LF}$	n_h	$f_{rs}(Hz)$
5.67	4.20	210
6	4.08	204
7	3.78	189

- The necessary data for detuned filter design:
  1) The system frequency (f_1) such as 50Hz
  2) The system voltage (V_s) that detuned filter be connected such as 380V, 400V
  3) Rated reactive power (Q_{Comp}) of detuned filter such as 25 kVAr, 50kVAr
  4) $\%X_L$ such as 5.67%, 6% or 7%
  5) The system voltage increase ($+\Delta V_s$) that detuned filter can use and not fail
  6) The maximum of harmonic voltage such as V_3, V_5, V_7, V_{11} and V_{13} causes harmonic current flow through the detuned filter

Table 2.2 Harmonic voltage limit in low voltage system (400 V)

Compatibility Level (CL)	Planning Level (PL)
[IEC 61000-2-2]	[ER G 5/4]
V_3= 5.0%	V_3 = 4.0%
V_5 = 6.0%	V_5 = 4.0%
V_7= 5.0%	V_7 = 4.0%
V_{11} =3.5%	V_{11} = 3.0%
V_{13} = 3.0%	V_{13} = 2.5%
THD = 8.0%	THD = 5.0%

- Specify rated of components:
  1) Capacitor

1.1) Reactive power rating of capacitor (Q_{cr} : kVAr)
1.2) Voltage rating of capacitor (V_{cr} : V)
1.3) Current rating of capacitor (I_{cr} : A)

2) Reactor
2.1) Inductance (L : mH)

2.2) Thermal current rating (I_{th} : A)

2.3) Maximum current that still causes the value of decrease less than 5% inductance (I_{Lin} : A)

- Thermal current rating (I_{th} : A) condition:
  (1) V_1 (50 Hz) = 110%
  (2) V_3 (150 Hz) = 0.5% of V_1
  (3) V_5 (250 Hz) = 6% of V_1
  (4) V_7 (350 Hz) = 5% of V_1
  (5) V_{11} (550 Hz) = 3.5% of V_1
  (6) V_{13} (650 Hz) = 3.0% of V_1

➢ Equation for detuned filter design

$$I_{cr} = \frac{Q_{cr} \times 1000}{\sqrt{3} \times V_{cr}} \tag{2.46}$$

$$X_{C,Y} = \frac{V_{cr}^2}{Q_{cr} \times 1000} \tag{2.47}$$

$$X_{Total} = \left[1 - \frac{\%X_{LF}}{100}\right] \frac{V_{cr}^2}{Q_{cr} \times 1000} \tag{2.48}$$

$$I_1 = \frac{V_s}{\sqrt{3}} \cdot \frac{100}{100 - \%X_{LF}} \cdot \frac{Q_{cr} \times 1000}{V_{cr}^2} \tag{2.49}$$

$$Q_{comp} = \frac{\sqrt{3} \cdot V_s \cdot I_1}{1000} = \left[\frac{100}{100 - \%X_{LF}}\right] \left[\frac{V_s}{V_{cr}}\right]^2 \times Q_{cr} \tag{2.50}$$

$$Q_{cr} = \left[\frac{100 - \%X_L}{100}\right] \left[\frac{V_{cr}}{V_s}\right]^2 \times Q_{comp} \tag{2.51}$$

$$Q_{comp} = P\left[\tan(\cos^{-1} PF_{old}) - \tan(\cos^{-1} PF_{new})\right] \tag{2.52}$$

$$\frac{Q_{cr}}{P} = \left[\frac{100 - \%X_{LF}}{100}\right] \left[\frac{V_{cr}}{V_s}\right]^2 \left[\tan(\cos^{-1} PF_{old}) - \tan(\cos^{-1} PF_{new})\right] \tag{2.53}$$

$$V_{cr} \geq \frac{V_s}{1-\frac{\%X_{LF}}{100}} \tag{2.54}$$

$$L = \frac{X_L}{2\pi f} \quad \text{(mH)} \tag{2.55}$$

$$I_{th} = \sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_{11}^2 + I_{13}^2} \quad \text{(A)} \tag{2.56}$$

$$I_{Lin} = 1.9 I_1 \quad \text{(A)} \tag{2.57}$$

$$X_L = \frac{\%X_L}{100} \times X_C \tag{2.58}$$

I_{cr}	Rated current of capacitor (A)
V_S	Voltage of system (V)
$X_{C,Y}$	Reactance of capacitor (Ω)
Q_{comp}	Reactive power compensation (kVAr)
P	Real power of load (W)
Q_{cr}	Rated reactive power of capacitor (kVAr)
V_{cr}	Rated voltage of capacitor (V)
PF_{old}	Old power factor
PF_{new}	New power factor (target)

2.5.2 Tuned harmonic filter design

If harmonic filter is needed, on top of resonance prevention, tuned reactors are applied. The capacitor/reactor filter is tuned to absorb particular harmonic and reduce the Total Harmonic Distortion (THD).

Tuned filter design steps [7]

1) Calculate the value of reactive power (Q_{FT}) which needs to increase the power factor of power system.
2) Determine the number of set for harmonic filters. For example,
   - 2 sets of 5th harmonic filter and 1 set of 7th harmonic filter.
   - 2 sets of 5th harmonic filter, 1 set of 7th harmonic filter and 1 set of 11th harmonic filter.
3) Divide Q_{FT} in step 1 for each filter (Q_{Fhi}).
4) Specify the tuning point of each filter. For example, set a tuning point at 4.7 to 4.9 for 5th harmonic and 6.7 to 6.85 for 7th harmonic.

5) Select voltage rating of a capacitor, e.g. 480 V, 500 V or 525 V.
6) Calculate reactive power of a capacitor to be used.

$$Q_{Crhi} = Q_{Fhi}\left(\frac{V_{Cr}}{V_s}\right)^2\left(\frac{n_{hi}^2-1}{n_{hi}^2}\right) \tag{2.59}$$

7) Calculate C value (μF) and X_C at 50Hz from steps 5 and 6:

$$C = \frac{Q_{Crhi}\times 1000}{2\pi V_{Cr}^2} = 3.183 Q_{Crhi}/V_{Cr}^2 \quad (\mu F) \tag{2.60}$$

$$X_C = \frac{V_{Cr}^2}{Q_{Crhi}\times 1000} \quad (\Omega) \tag{2.61}$$

8) Calculate reactor (L_{hi}) of each filter unit

$$L_{hi} = \frac{10^9}{(2\pi f n_{hi})^2 \times C} \quad (mH) \tag{2.62}$$

9) Consider *Q-Factor* and calculate *R*. Normally *Q-Factor* of a harmonic filter in a low voltage system is 40 to 60.

$$R = \frac{2\pi f L_{hi}\times n_{hi}}{Q-Factor} \quad (\Omega) \tag{2.63}$$

10) Analyze harmonic current flow
11) Check working conditions of the capacitor
12) Specify current rating of reactor *L*

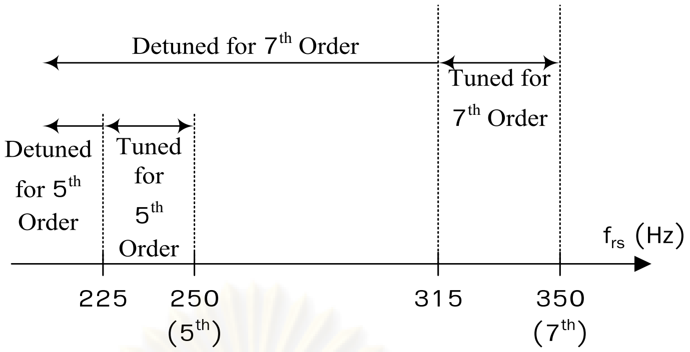
$$I_L = \sqrt{(1.1 I_1)^2 + \sum I_h^2} \tag{2.64}$$

Q_{Fhi}	Reactive power of each filter unit
Q_{Factor}	Q-factor of the filter
n_h	Tuning point
V_s	Voltage of system (V)

Note that :

Certain voltage rating of a capacitor is available. And designed filter parameters might not be available in practice. This thesis does not consider this limitation.

2.5.3 Tuning frequency range for detuned and tuned filter



- Detuned Filter: A filter with a tuning frequency more than 10% below the lowest harmonic frequency with considerable current / voltage amplitude.
- Tuned Filter: A filter with a tuning frequency with differs by no more than 10% from the frequency with is to be filtered.

CHAPTER III

HARMONIC MODELING OF SYSTEM COMPONENTS

In this research all parameters are calculated per phase and all models of system components are simplified models, the skin effect is not involved in calculation so the resistance does not change at harmonic frequency but capacitive reactance and inductive reactance will change depending on the harmonic frequency. The models of system components in power system used in this thesis consist of supply system, transformer, linear load, non-linear load, capacitors, detuned filters and tuned filters [15], [17].

3.1 Supply system

This model is determined from point of common coupling (PCC) into system, the model is represented by resistance series with reactance. The resistance has relationship with reactance in form ratio of X/R.

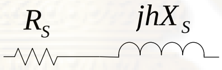


Figure 3.1 Model of supply system

$$Z_S = \frac{V_S^2}{MVA_{SC}} \tag{3.1}$$

$$R_S = \frac{Z_S}{\sqrt{\left(\frac{X}{R}\right)^2 + 1}} \tag{3.2}$$

$$X_S = \left(\frac{X}{R}\right) \times R_S \tag{3.3}$$

$$Z_{Sh} = R_S + jhX_S \tag{3.4}$$

Z_S	The supply impedance (Ω)
Z_{Sh}	Impedance of system at harmonic frequency (Ω)
R_S	Resistance of system (Ω)

X_S	Reactance of system at fundamental frequency (Ω)
V_S	Voltage of system (kV)
MVA_{SC}	Short circuit of system (MVA)
X/R	X to R ratio
h	Harmonic order

3.2 Transformer

Transformer model is represented by impedance that has resistance series with reactance, whose change due to harmonic order. So at various harmonic the value of impedance can be calculated as follows:

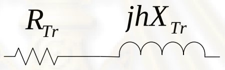


Figure 3.2 Model transformer

$$Z_{Tr} = \frac{\%Z}{100}\frac{V^2}{S_{Tr}} \tag{3.5}$$

$$R_{Tr} = \left(\frac{P_k}{3}\right) \times \left(\frac{\sqrt{3}V}{S_{Tr}}\right)^2 \Rightarrow R_{Tr} = P_k \times \frac{V^2}{\left(S_{Tr}\right)^2} \tag{3.6}$$

$$Z_{Tr}^2 = R_{Tr}^2 + X_{Tr}^2 \Rightarrow X_{Tr} = \sqrt{Z_{Tr}^2 - R_{Tr}^2} \tag{3.7}$$

$$Z_{Trh} = R_{Tr} + jhX_{Tr} \tag{3.8}$$

V	Voltage of transformer (V)
Z_{Tr}	Impedance of transformer at fundamental frequency (Ω)
Z_{Trh}	Harmonic impedance of transformer (Ω)
R_{Tr}	Resistance of transformer (Ω)
X_{Tr}	Reactance of transformer at fundamental frequency (Ω)
P_k	Transformer load loss (W)
$\%Z$	Percent impedance of transformer (%)
S_{Tr}	Rated power of transformer (VA)

3.3 Linear load

Linear load data is generally in the form of active power (*P*) and reactive power (*Q*) which are used for calculating the impedance. The impedance consists of resistance series/parallel with reactance depends on that linear load.

This thesis use the parallel model for linear load. The resistance and the reactance are obtained from active power (*P*) and reactive power (*Q*) according to equation (3.9) and (3.10)

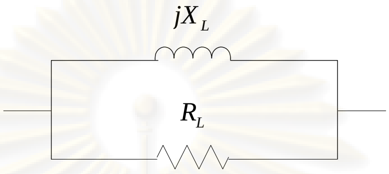


Figure 3.3 Model of linear load

$$R_L = \frac{V_S^2}{P_1} \tag{3.9}$$

$$X_L = h \cdot \frac{V_S^2}{Q_1} \tag{3.10}$$

V_S	Voltage system (V)
R_L	Resistance of load (Ω)
X_L	Reactance of load at harmonic order(Ω)
P_1	Active power of load at fundamental frequency (W)
Q_1	Reactive power of load at fundamental frequency (VAR)

3.4 Capacitor

Capacitor can be represented by the capacitive reactance which obtained from equation (3.11)

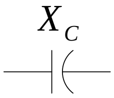


Figure 3.4 Model of capacitor

$$X_C = -j\frac{V_{cr}^2}{hQ_{cr}} \tag{3.11}$$

X_C	Capacitor reactance at harmonic order (Ω)
V_{cr}	Rated voltage of capacitor (V)
Q_{cr}	Reactive power of capacitor (VAR)
h	Harmonic order

3.5 Non-linear load

The source of harmonic is non-linear load. The non-linear loads are devices in system that make distorted current waveforms such as power electronic devices, arc furnace, rectifier etc. The model of non-linear load in figure 3.5 is harmonic current source.

The distorted harmonic current data can be obtained from measurement or equipment producer.

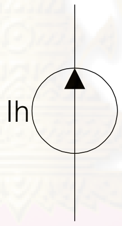


Figure 3.5 Model of harmonic current source

3.6 Harmonic filter

The harmonic filter is device used to filter harmonic current out of the system. When there are harmonics in power system, it may cause the problem of resonance between systems with capacitor at harmonic order which is the same as harmonic in system. Normally it is among the harmonic order 5th, 7th, 11th, 13th.

One of methods that can solve the problem is to change the capacitor in the system to be harmonic filter by adding the reactor series with capacitor.

- Harmonic filter will play two roles as follows:
    1. Reactive power compensation at fundamental frequency to improve power factor.

2. Reduce or filter harmonic current out of the system.

- Harmonic filter is divided into two types
    1. Detuned filter
    2. Tuned filter
- The steps of calculation are provided chapter 2.

This research uses model of single tuned filter as show in fig. 3.6.

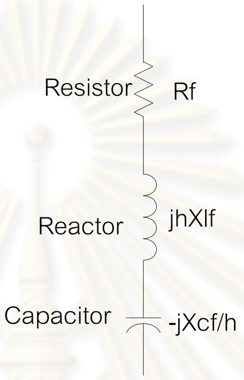


Figure 3.6 Model of harmonic filter

$$X_{CFi} = \frac{V_{Cri}^2}{Q_{Cri}} \tag{3.12}$$

$$L_i = \frac{1}{(2\pi fn_i)^2 C_{Cri}} \tag{3.13}$$

$$X_{Li} = 2\pi fL_i \tag{3.14}$$

$$Z_{Fi} = R_{Fi} + j(hX_{LFi} - \frac{X_{CFi}}{h}) \tag{3.15}$$

$$R_i = \frac{2\pi fn_i L_i}{Q - factor} \tag{3.16}$$

CHAPTER IV

DETAILS OF DEVELOPED PROGRAM

This chapter presents a graphic user interface (GUI)-based power system harmonic analysis program developed under MATLAB environment. The program can be divided into three parts. The first part performs harmonic waveform synthesis. The second part analyzes the power system harmonic response with combination of linear and nonlinear load, capacitor banks, a detuned filter and tuned filters. The last part deals with harmonic filter design and simulation. The developed program can also be used for power quality teaching and studying. Various cases can be simulated for better understanding of harmonic characteristics. The developed program is user-friendly for non-experienced and experienced users in order to understand harmonic analysis.

4.1 Harmonic waveform synthesis

The first part of program performs harmonic waveform synthesis. A user can input various harmonic magnitudes and phase angles and then view the resultant distorted waveforms. The shape of the distorted waveform depends on harmonic magnitudes and phase angles. Distorted waveform with certain harmonics will show typical wave shapes. This can give a clue of the major harmonic component when an actual waveform is recorded from a field measurement**.**

The general equation of the reconstructed waveform is

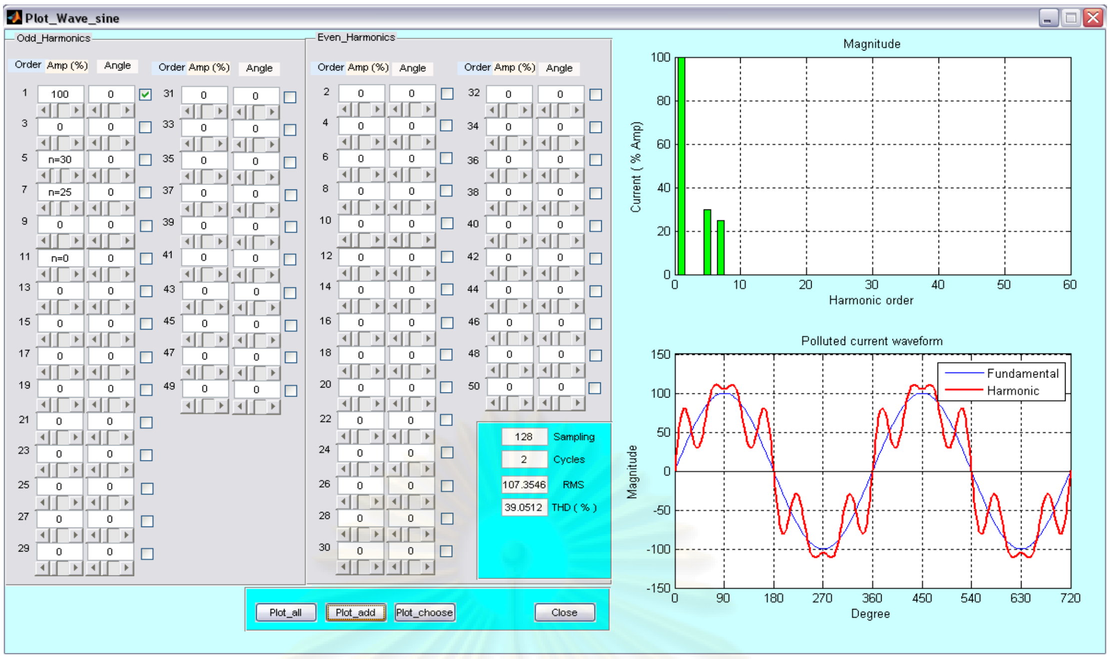
$$I = \sum_{1}^{h} I_h \sin(h\omega t + \theta_h) \tag{4.1}$$

where: h=1, 2, 3, 4, 5, 6, 7…

The reverse process where the harmonic spectra can be computed from the distorted waveform is called waveform analysis which can be achieved through Fast Fourier Transform (FFT).

$$I_{rms} = \sqrt{(100\sin(\omega t))^2 + (A_3\sin(3\omega t + \theta_3))^2 + (A_5\sin(5\omega t + \theta_5))^2 \ldots} \tag{4.2}$$

where: $\omega = 2 * \pi * f$ and $f = 50Hz$



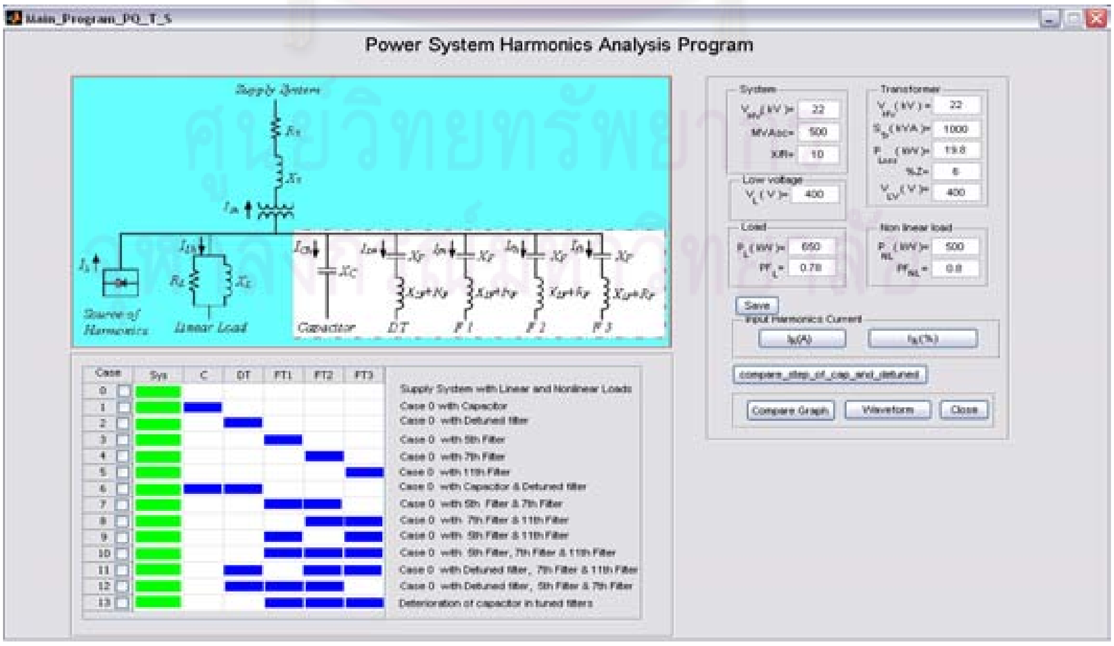
Order 1: Amp (%) 100, Angle 0 ☑
Order 5: n=30, Angle 0
Order 7: n=25, Angle 0
Order 11: n=0, Angle 0

128 Sampling
2 Cycles
107.3546 RMS
39.0512 THD (%)

Figure 4.1 Synthesis of a waveform from harmonics

4.2 Harmonic response analysis and harmonic filter design

The second part of the program analyzes the power system harmonic response with combinations of linear and nonlinear loads, capacitor banks, a detuned filter and tuned filters. The major features of this part are 1) system harmonic impedance scan, 2) harmonic current flow between each devices and 3) harmonic voltage and current distortion calculation.



System
V_{HV}(kV)= 22
MVAsc= 500
X/R= 10

Transformer
V_{HV}(kV)= 22
S_n(kVA)= 1000
P_{Loss}(kW)= 19.8
%Z= 6
V_{LV}(V)= 400

Low voltage
V_L(V)= 400

Load
P_L(kW)= 650
PF_L= 0.78

Non linear load
P_{NL}(kW)= 500
PF_{NL}= 0.8

Case		Sys	C	DT	FT1	FT2	FT3	
0	☐	🟩						Supply System with Linear and Nonlinear Loads
1	☐	🟩	🟦					Case 0 with Capacitor
2	☐	🟩		🟦				Case 0 with Detuned filter
3	☐	🟩			🟦			Case 0 with 5th Filter
4	☐	🟩				🟦		Case 0 with 7th Filter
5	☐	🟩					🟦	Case 0 with 11th Filter
6	☐	🟩	🟦	🟦				Case 0 with Capacitor & Detuned filter
7	☐	🟩			🟦	🟦		Case 0 with 5th Filter & 7th Filter
8	☐	🟩				🟦	🟦	Case 0 with 7th Filter & 11th Filter
9	☐	🟩			🟦		🟦	Case 0 with 5th Filter & 11th Filter
10	☐	🟩			🟦	🟦	🟦	Case 0 with 5th Filter, 7th Filter & 11th Filter
11	☐	🟩		🟦		🟦	🟦	Case 0 with Detuned filter, 7th Filter & 11th Filter
12	☐	🟩		🟦	🟦	🟦		Case 0 with Detuned filter, 5th Filter & 7th Filter
13	☐	🟩			🟦	🟦	🟦	Deterioration of capacitor in tuned filters

Figure 4.2 Main display of program

- **Case studies**

Twelve case studies are simulated in this work. Possible scenarios at an industrial plant fall into these these twelve cases. Details of case studies are summarized in table 4.1. For case studies 3-6 and 7-12, harmonic filters have to be designed as previously explained before the harmonic flows can be simulated.

Table 4.1 Case studies

Case 0	Supply System with Linear and Nonlinear Loads
Case 1	Case 0 with Capacitor
Case 2	Case 0 with Detuned filter
Case 3	Case 0 with 5th Filter
Case 4	Case 0 with 7th Filter
Case 5	Case 0 with 11th Filter
Case 6	Case 0 with Capacitor & Detuned filter
Case 7	Case 0 with 5th Filter & 7th Filter
Case 8	Case 0 with 7th Filter & 11th Filter
Case 9	Case 0 with 5th Filter & 11th Filter
Case10	Case 0 with 5th Filter, 7th Filter & 11th Filter
Case11	Case 0 with Detuned filter, 7th Filter & 11th Filter
Case12	Case 0 with Detuned filter, 5th Filter & 7th Filter

4.2.1 Input parameters

On the main display, following input parameters are required from a user.

4.2.1.1 Supply system

In high voltage want to input parameters such as:

1) (MVA) short circuit
2) (kV) high voltage
3) X/R ratio

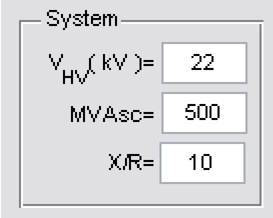
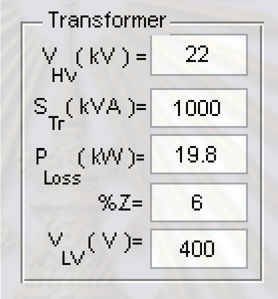

System
V_{HV}(kV)= 22
MVAsc= 500
X/R= 10

Figure 4.3 Supply system

4.2.1.2 Transformer

Need input parameters such as:

1) Rated (kVA)
2) Primary Voltage (kV)
3) Secondary Voltage (V)
4) Percent Impedance (%Z)
5) Power Loss (kW)



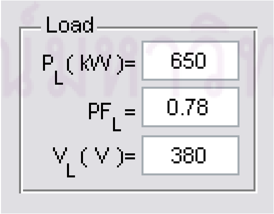
V_{HV} (kV) = 22
S_{Tr} (kVA)= 1000
P_{Loss} (kW)= 19.8
%Z= 6
V_{LV} (V)= 400

Figure 4.4 Transformer

4.2.1.3 Linear load

Need input parameters such as:

1) Active Power (kW)
2) Power Factor
3) Load Voltage (V)



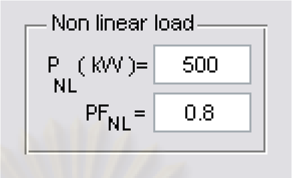
P_L (kW)= 650
PF_L = 0.78
V_L (V)= 380

Figure 4.5 Linear load

4.2.1.4 Non-linear load

Need input parameters such as:

1) Active Power (kW)
2) Power Factor



P_{NL} (kW)= 500

PF_{NL} = 0.8

Figure 4.6 Non-linear load

Odd

Ih1= 902.11
Ih3= 0
Ih5= 169.03
Ih7= 107.30
Ih9= 0
Ih11= 80.72
Ih13= 66.47
Ih15= 0
Ih17= 48.43
Ih19= 39.88
Ih21= 0
Ih23= 31.34
Ih25= 25.64
Ih27= 0
Ih29= 19.94
Ih31= 14.24
Ih33= 0
Ih35= 0
Ih37= 0
Ih39= 0
Ih41= 0
Ih43= 0
Ih45= 0
Ih47= 0
Ih49= 0

Even

Ih2= 0
Ih4= 0
Ih6= 0
Ih8= 0
Ih10= 0
Ih12= 0
Ih14= 0
Ih16= 0
Ih18= 0
Ih20= 0
Ih22= 0
Ih24= 0
Ih26= 0
Ih28= 0
Ih30= 0
Ih32= 0
Ih34= 0
Ih36= 0
Ih38= 0
Ih40= 0
Ih42= 0
Ih44= 0
Ih46= 0
Ih48= 0
Ih50= 0

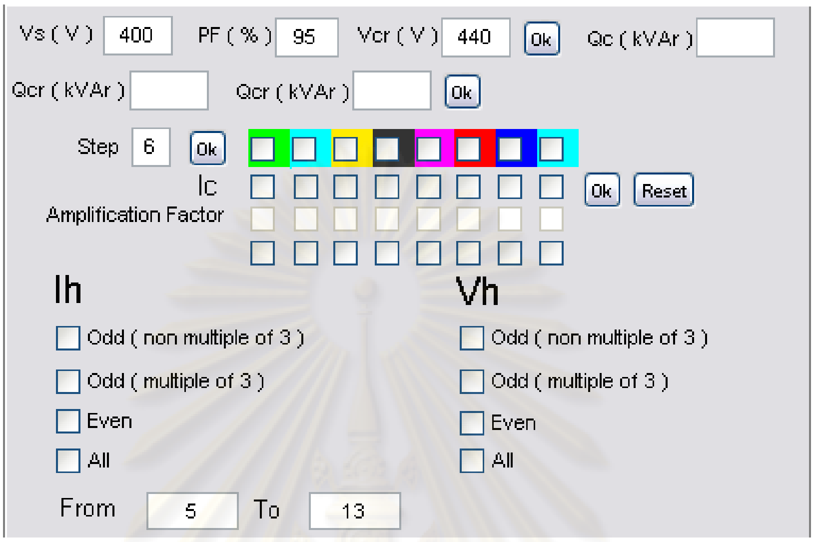
Figure 4.7 Display for input harmonic data

4.2.1.5 Capacitor

Figure 4.8 shows a page which a user can select the number of steps for capacitors to be applied.

Needed input parameters are:

1) Target power factor
2) Voltage rated of capacitor
3) Reactive power of capacitor
4) Step of capacitor



Vs (V) 400
PF (%) 95
Vcr (V) 440
Qc (kVAr)
Qcr (kVAr)
Qcr (kVAr)
Step 6
From 5 To 13

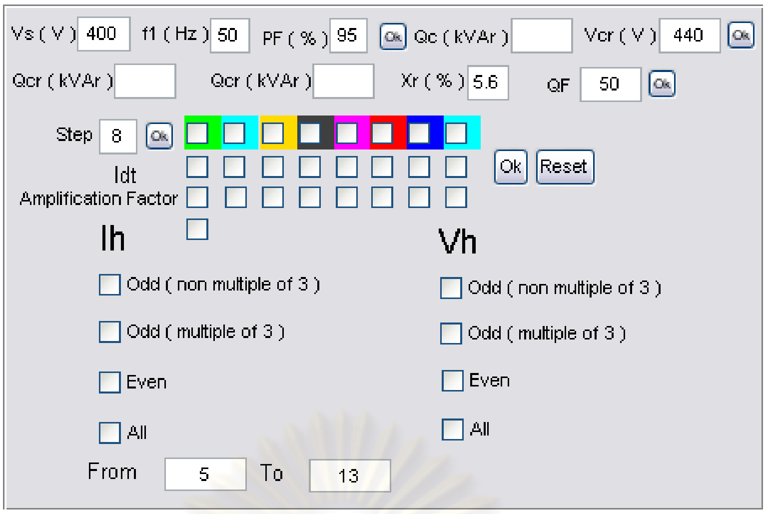
Figure 4.8 Display to input capacitor parameters and select steps

4.2.1.6 Detuned filter

Figure 4.9 shows a display which a user can select the number of steps for detuned filter to be applied and step of calculation as shown in chapter 2.

Required inputs are:

1) Target power factor
2) Voltage rated of capacitor
3) Reactive power of detuned filter
4) Percent X_r (%)
5) Q-factor
6) Step of detuned filter



Vs (V) 400 f1 (Hz) 50 PF (%) 95 Qc (kVAr) Vcr (V) 440

Qcr (kVAr) Qcr (kVAr) Xr (%) 5.6 QF 50

Step 8

From 5 To 13

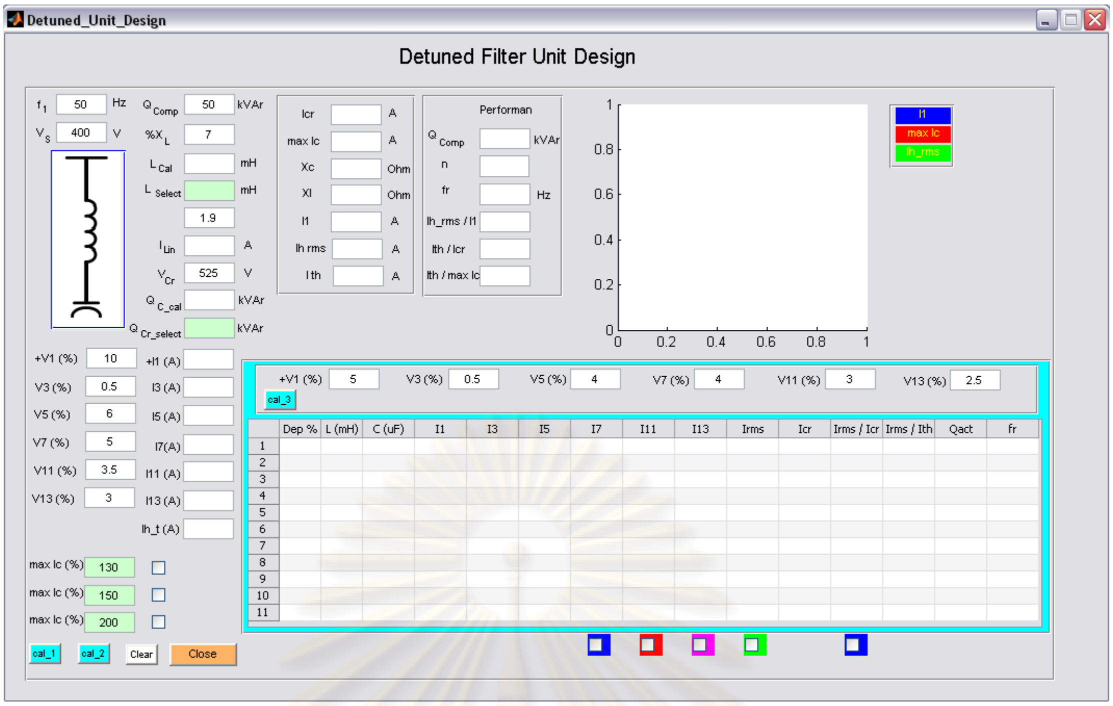
Figure 4.9 **Display to input detuned filter parameters and select steps**

4.2.2 Harmonic filter design

4.2.2.1 Detuned filter unit design

Following parameters are required as inputs:

1) Fundamental frequency (f_1) such as 50Hz
2) System voltage (Vs) that detuned filter connected such as (400V)
3) Reactive power compensate (Q_{comp}) such as (50 kVAr, 90 kVAr)
4) Voltage rated of capacitor
5) Percent reactance (% X_L) such as 5.65%, 6%, 7%.
6) Voltage increasing (+ΔV) 10%
7) Maximum harmonic voltage in order (V_3, V_5, V_7, V_{11},V_{13})
8) Percent of maximum current


Detuned_Unit_Design

Detuned Filter Unit Design

f_1 50 Hz
V_S 400 V
Q_{Comp} 50 kVAr
$\%X_L$ 7
1.9
V_{Cr} 525 V
+V1 (%) 10
V3 (%) 0.5
V5 (%) 6
V7 (%) 5
V11 (%) 3.5
V13 (%) 3
max Ic (%) 130 ☐
max Ic (%) 150 ☐
max Ic (%) 200 ☐

+V1 (%) 5
V3 (%) 0.5
V5 (%) 4
V7 (%) 4
V11 (%) 3
V13 (%) 2.5

Figure 4.10 Display for input parameters of detuned filter unit design

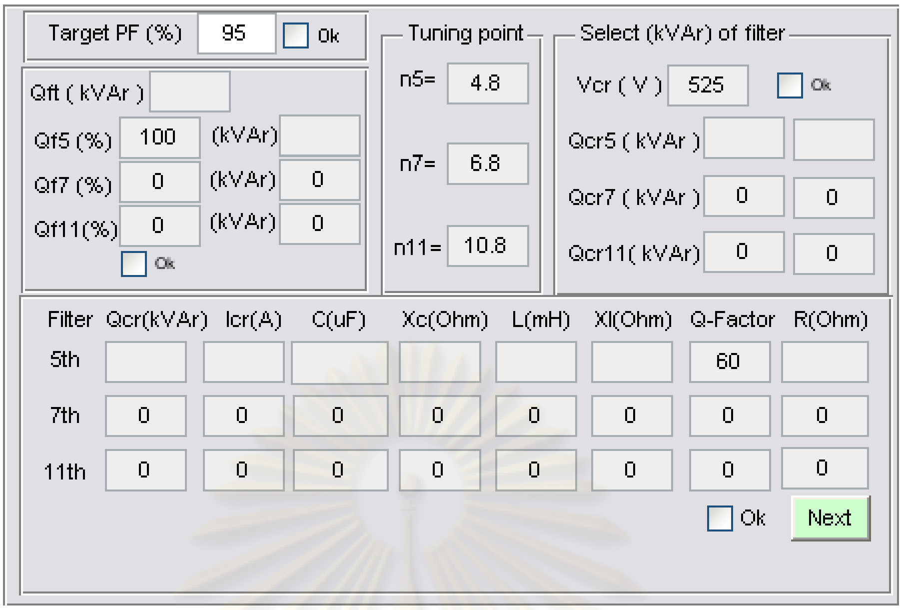
4.2.2.2 Tuned filter design

Proper design is required for harmonic filters in order to lower harmonic levels in a power system. Various types of harmonic filters are available. Tuned filters and detuned filters will be considered in the developed program. Proper selection and engineering experience plays an important role in a decision. Simulations of system response after installation of harmonic filters are also crucial in order to verify the effectiveness of the harmonic filter design. The developed program will be useful for power system harmonic analysis for various aspects. The program can also be used for power quality teaching and studying. Various cases can be simulated for better understanding of harmonic characteristics. The developed program is user-friendly for non-experienced and experienced users in order to understand harmonic analysis.

After parameters of filter are determined, harmonic flows of harmonic currents between system component and harmonic filter are required. Figure 4.11 shows the design page of harmonic filter in the developed program.

- In harmonic filter design page following input parameters are required:
  1) Target power factor
  2) Tuning point
  3) Reactive rated of capacitor
  4) Voltage rated of capacitor

5) Q-factor



Target PF (%) 95 ☐ Ok

Qft (kVAr)

Qf5 (%) 100 (kVAr)

Qf7 (%) 0 (kVAr) 0

Qf11(%) 0 (kVAr) 0

☐ Ok

Tuning point

n5= 4.8

n7= 6.8

n11= 10.8

Select (kVAr) of filter

Vcr (V) 525 ☐ Ok

Qcr5 (kVAr)

Qcr7 (kVAr) 0 0

Qcr11(kVAr) 0 0

Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th							60	
7th	0	0	0	0	0	0	0	0
11th	0	0	0	0	0	0	0	0

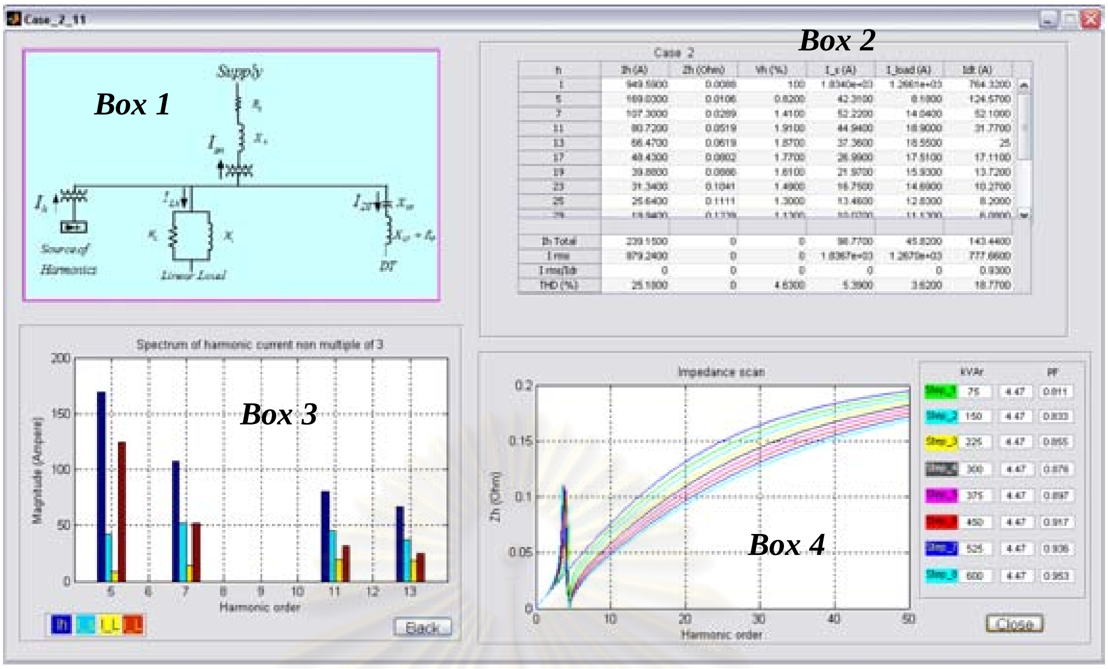
☐ Ok

Figure 4.11 Display for input parameters of tuned filter design

4.3 Outputs

4.3.1 Outputs of 14 cases studies

The output display of case study can be shown in figure 4.14. Box 1 illustrates the diagram of the case study chosen. Box 2 tabulates necessary results from the simulation. Harmonic currents from harmonic source (I_h), harmonic currents flow in the system (I_{Sh}), harmonic currents flow in a linear load (I_{Lh}), harmonic currents flow in capacitor (I_{Ch}), harmonic currents flow in detuned filters (I_{Dh}), harmonic currents flow in tuned filters (I_{Fh}) are tabulated in Box 2 with harmonic impedance (Z_h) and voltage (V_h) values at the main bus. I_{rms} value , I_{rms}/I_{cr} value, THD values of voltage and current are also provided at the bottom of Box 2. These harmonic currents and harmonic voltages are presented in a bar chart in Box 3. Box 4 shows an impedance scan of a case study and amplification factor.



h	Ih (A)	Zh (Ohm)	Vh (%)	I_s (A)	I_load (A)	Idt (A)
1	949.5900	0.0088	100	1.8340e+03	1.2661e+03	764.3200
5	169.0300	0.0106	0.8200	42.3100	8.1800	124.5700
7	107.3000	0.0289	1.4100	52.2200	14.0400	52.1000
11	80.7200	0.0519	1.9100	44.9400	18.9000	31.7700
13	66.4700	0.0619	1.8700	37.3600	18.5500	25
17	48.4300	0.0802	1.7700	26.9900	17.5100	17.1100
19	39.8800	0.0886	1.8100	21.9700	15.9300	13.7200
23	31.3400	0.1041	1.4900	16.7500	14.6900	10.2700
25	25.6400	0.1111	1.3000	13.4600	12.8300	8.2000
Ih Total	239.1500	0	0	98.7700	45.8200	143.4400
I rms	979.2400	0	0	1.8367e+03	1.2670e+03	777.6600
I rms/Idr	0	0	0	0	0	0.9300
THD (%)	25.1800	0	4.6300	5.3900	3.6200	18.7700

	kVAr		PF
Step_1	75	4.47	0.811
Step_2	150	4.47	0.833
Step_3	225	4.47	0.855
Step_4	300	4.47	0.876
Step_5	375	4.47	0.897
Step_6	450	4.47	0.917
Step_7	525	4.47	0.936
Step_8	600	4.47	0.953

Figure 4.12 Example output of 14 case studies

- Harmonic current flow and harmonic voltage distortion are also important parameters for harmonic analysis. They can provide the information of how harmonic currents propagate in a power system. Areas with high harmonic voltage distortions need mitigation methods in order to reduce the harmonic level under the limit.

  Figure 4.13 illustrates harmonic values compared with the planning level of voltage in G 5/4 standard (Harmonic Voltage Limited).

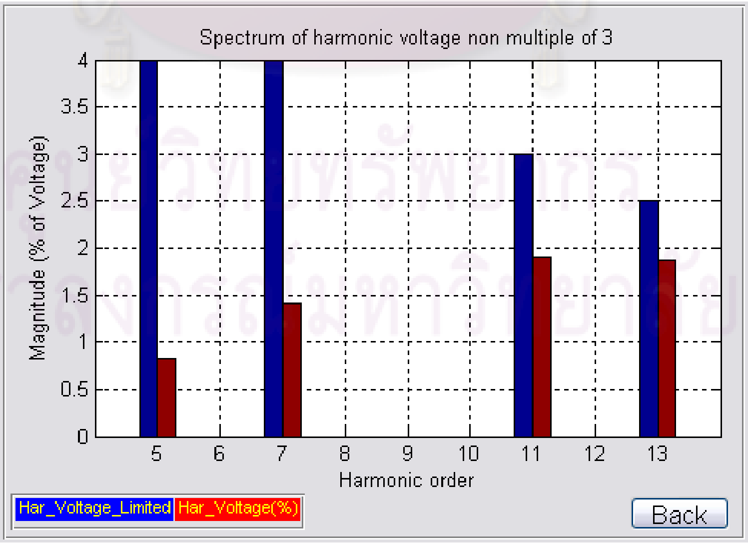


Figure 4.13 Spectrum of harmonic voltage comparison with planning level (G 5/4 standard)

- Amplification factor of harmonic current is the ratio between harmonic current which flows in each eqiupment divided by harmonic current from source.

  Figure 4.14 shows amplification factors of harmonic currents from system, load and detuned filter.

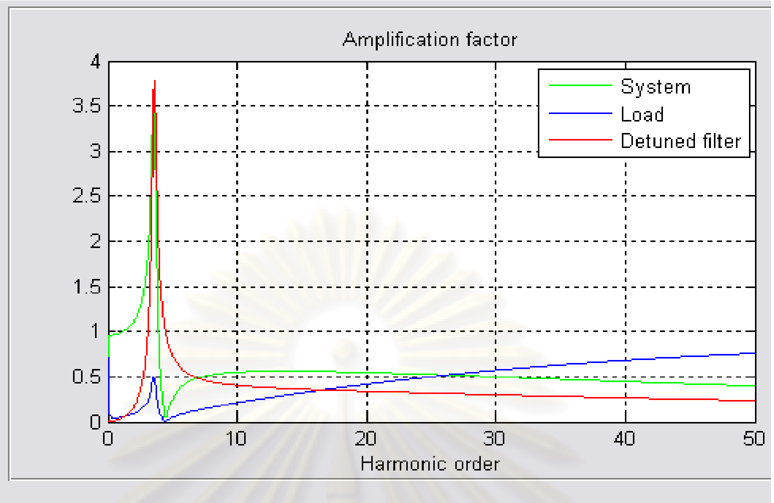
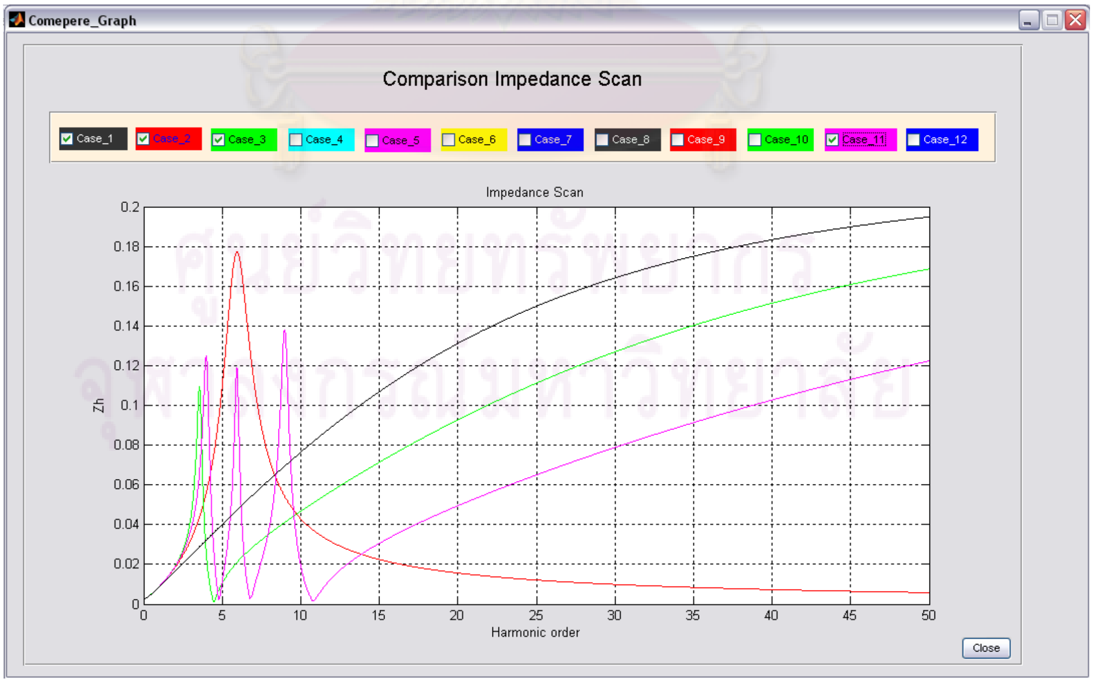


Figure 4.14 Amplification factor current

- The system harmonic impedance scan can reveal resonance conditions of a power system. This information helps us avoid damages from harmonic resonances.

  Figure 4.15 compares frequency scan of case studies.

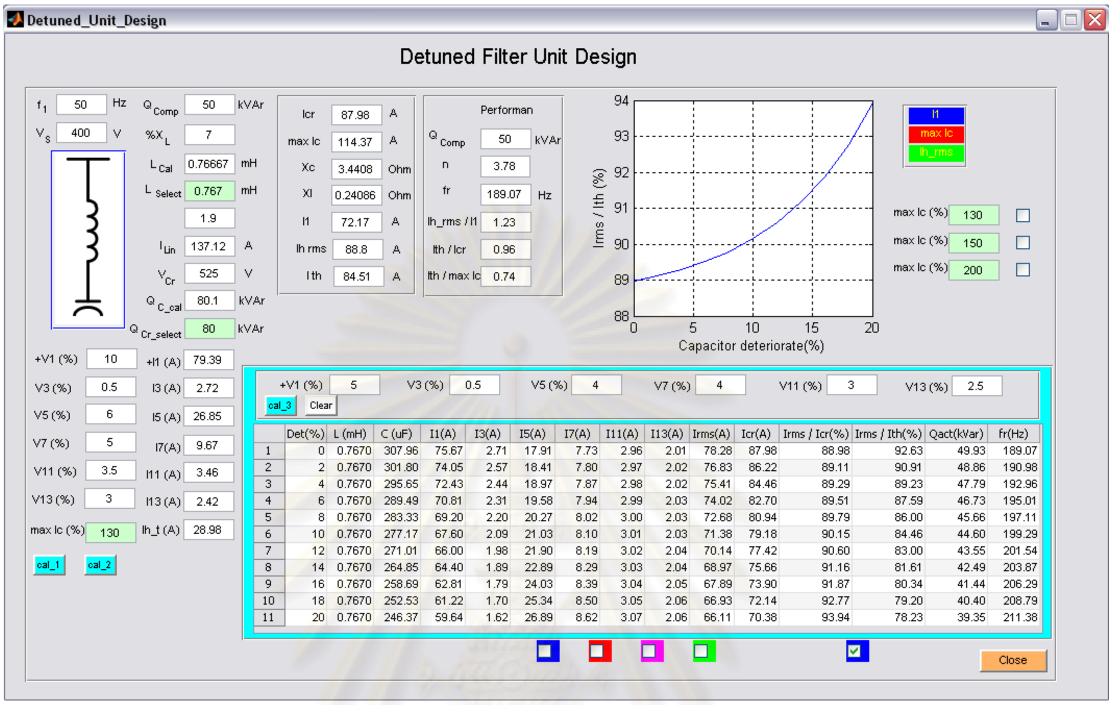


☑ Case_1 ☑ Case_2 ☑ Case_3 ☐ Case_4 ☐ Case_5 ☐ Case_6 ☐ Case_7 ☐ Case_8 ☐ Case_9 ☐ Case_10 ☑ Case_11 ☐ Case_12

Figure 4.15 Impedance scans of case studies

4.3.2 Outputs of detuned filter unit design

Detuned filter unit design is necessary for reactive power compensation in order to improve power factor and solve the harmonic problem.


Detuned_Unit_Design

Detuned Filter Unit Design

f_1 50 Hz
V_s 400 V
Q_{Comp} 50 kVAr
$\%X_L$ 7
L_{Cal} 0.76667 mH
L_{Select} 0.767 mH
1.9
I_{Lin} 137.12 A
V_{Cr} 525 V
Q_{C_cal} 80.1 kVAr
Q_{Cr_select} 80 kVAr

Icr 87.98 A
max Ic 114.37 A
Xc 3.4408 Ohm
Xl 0.24086 Ohm
I1 72.17 A
Ih rms 88.8 A
I th 84.51 A

Performan
Q_{Comp} 50 kVAr
n 3.78
fr 189.07 Hz
Ih_rms / I1 1.23
Ith / Icr 0.96
Ith / max Ic 0.74

+V1 (%) 10
V3 (%) 0.5
V5 (%) 6
V7 (%) 5
V11 (%) 3.5
V13 (%) 3
max Ic (%) 130

+I1 (A) 79.39
I3 (A) 2.72
I5 (A) 26.85
I7(A) 9.67
I11 (A) 3.46
I13 (A) 2.42
Ih_t (A) 28.98

max Ic (%) 130 ☐
max Ic (%) 150 ☐
max Ic (%) 200 ☐

+V1 (%) 5
V3 (%) 0.5
V5 (%) 4
V7 (%) 4
V11 (%) 3
V13 (%) 2.5

	Det(%)	L (mH)	C (uF)	I1(A)	I3(A)	I5(A)	I7(A)	I11(A)	I13(A)	Irms(A)	Icr(A)	Irms / Icr(%)	Irms / Ith(%)	Qact(kVar)	fr(Hz)
1	0	0.7670	307.96	75.67	2.71	17.91	7.73	2.96	2.01	78.28	87.98	88.98	92.63	49.93	189.07
2	2	0.7670	301.80	74.05	2.57	18.41	7.80	2.97	2.02	76.83	86.22	89.11	90.91	48.86	190.98
3	4	0.7670	295.65	72.43	2.44	18.97	7.87	2.98	2.02	75.41	84.46	89.29	89.23	47.79	192.96
4	6	0.7670	289.49	70.81	2.31	19.58	7.94	2.99	2.03	74.02	82.70	89.51	87.59	46.73	195.01
5	8	0.7670	283.33	69.20	2.20	20.27	8.02	3.00	2.03	72.68	80.94	89.79	86.00	45.66	197.11
6	10	0.7670	277.17	67.60	2.09	21.03	8.10	3.01	2.03	71.38	79.18	90.15	84.46	44.60	199.29
7	12	0.7670	271.01	66.00	1.98	21.90	8.19	3.02	2.04	70.14	77.42	90.60	83.00	43.55	201.54
8	14	0.7670	264.85	64.40	1.89	22.89	8.29	3.03	2.04	68.97	75.66	91.16	81.61	42.49	203.87
9	16	0.7670	258.69	62.81	1.79	24.03	8.39	3.04	2.05	67.89	73.90	91.87	80.34	41.44	206.29
10	18	0.7670	252.53	61.22	1.70	25.34	8.50	3.05	2.06	66.93	72.14	92.77	79.20	40.40	208.79
11	20	0.7670	246.37	59.64	1.62	26.89	8.62	3.07	2.06	66.11	70.38	93.94	78.23	39.35	211.38

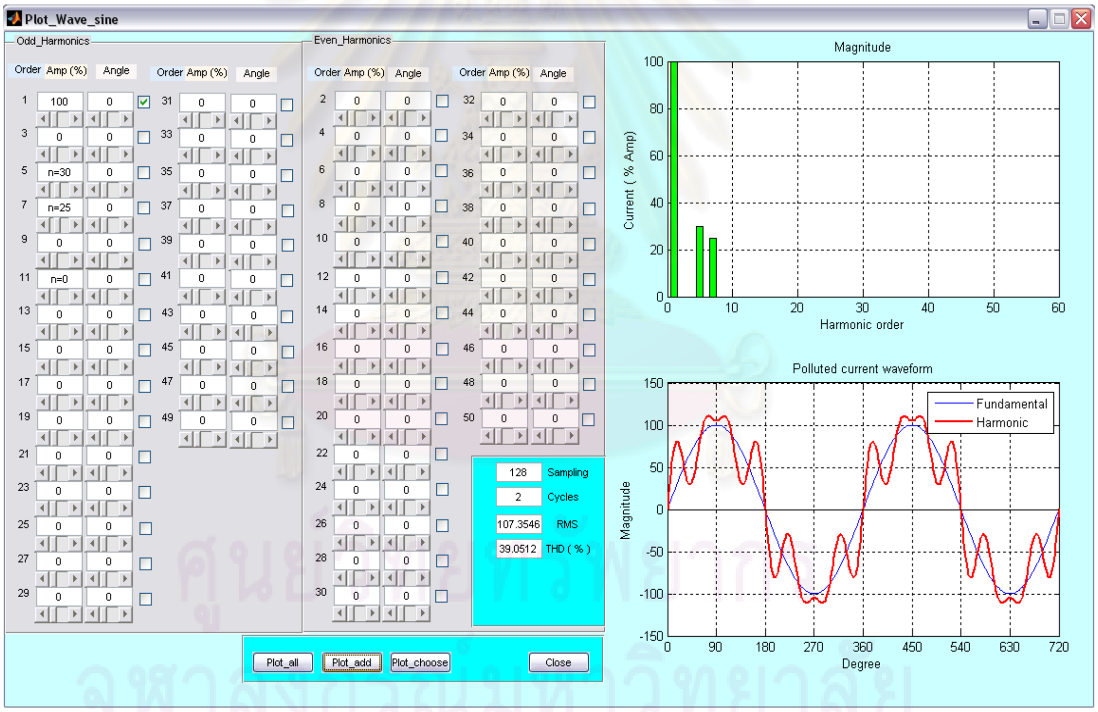
Figure 4.16 Output of detuned filter unit

CHAPTER V

OUTPUTS AND CASE STUDIES

This chapter presents the results from three parts of the developed program. The first part performs harmonic waveform synthesis. A user can input various harmonic magnitudes and phase angles and then view the resultant distorted waveform. The second part analyzes the power system harmonic response with a combination of linear and nonlinear loads, capacitor banks, detuned filters and tuned filters. The last part deals with detuned filter unit design.

5.1 Waveform synthesis



Odd_Harmonics

Order	Amp (%)	Angle		Order	Amp (%)	Angle	
1	100	0	☑	31	0	0	☐
3	0	0	☐	33	0	0	☐
5	n=30	0	☐	35	0	0	☐
7	n=25	0	☐	37	0	0	☐
9	0	0	☐	39	0	0	☐
11	n=0	0	☐	41	0	0	☐
13	0	0	☐	43	0	0	☐
15	0	0	☐	45	0	0	☐
17	0	0	☐	47	0	0	☐
19	0	0	☐	49	0	0	☐
21	0	0	☐				
23	0	0	☐				
25	0	0	☐				
27	0	0	☐				
29	0	0	☐				

Even_Harmonics

Order	Amp (%)	Angle		Order	Amp (%)	Angle	
2	0	0	☐	32	0	0	☐
4	0	0	☐	34	0	0	☐
6	0	0	☐	36	0	0	☐
8	0	0	☐	38	0	0	☐
10	0	0	☐	40	0	0	☐
12	0	0	☐	42	0	0	☐
14	0	0	☐	44	0	0	☐
16	0	0	☐	46	0	0	☐
18	0	0	☐	48	0	0	☐
20	0	0	☐	50	0	0	☐
22	0	0	☐				
24	0	0	☐				
26	0	0	☐				
28	0	0	☐				
30	0	0	☐				

Sampling: 128
Cycles: 2
RMS: 107.3546
THD (%): 39.0512

Figure 5.1 Main display of distorted waveform program

Non-linear equipment or components in the power system cause distortion of the current and to a lesser extent of the voltage. These sources of distortion can be divided in three groups:

- Loads
- The power system itself (HVDC, SVC, transformers, etc)
- The generation stage (synchronous generators)

The characteristic of the distorted current waveform, most devices are only producing odd harmonics but some devices have a fluctuating power consumption, from half cycle to half cycle or shorter, which then generates odd, even and interharmonic currents. The current distortion, for each device, changes due to the consumption of active power, background voltage distortion and changes in the source impedance.

5.1.1 Odd harmonic order

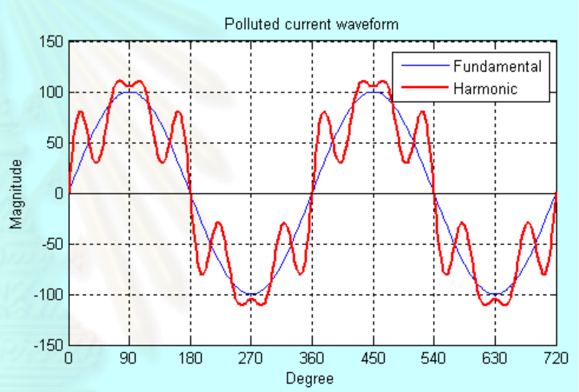
$$I = \sum_{1}^{h} I_h \sin(h\omega t + \theta_h) \tag{5.1}$$

$$I_{rms} = \sqrt{(100\sin(\omega t))^2 + (A_5 \sin(5\omega t + \theta_5))^2 + (A_7 \sin(7\omega t + \theta_7))^2} \tag{5.2}$$

Where: h=1, 2, 3, 4, 5, 6, 7…

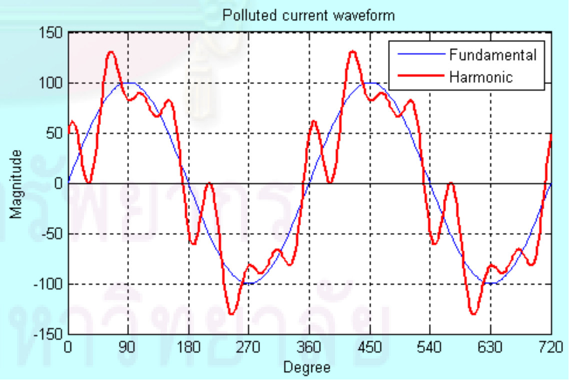
$$\omega = 2 * \pi * f \quad \text{and} \quad f = 50Hz$$

Harm (order)	Amp (%)	Angle (degree)
1	100	0
3		
5	A_5=30	0
7	A_7=25	0
RMS (%)	107.35	
THD (%)	39.05	



(a) (angle = 0)

Harm (order)	Amp (%)	Angle (degree)
1	100	0
3		
5	A_5=30	90
7	A_7=25	45
RMS (%)	107.35	
THD (%)	39.05	



(b) (angle $\neq$ 0)

Figure 5.2 Distorted waveform of odd harmonics (Symmetrical waveform)

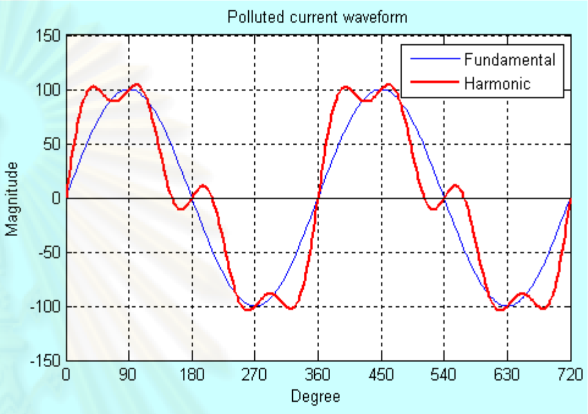
5.1.2 Even harmonic order

$$I_{rms} = \sqrt{(100\sin(\omega t))^2 + (A_2 \sin(2\omega t + \theta_2))^2 + (A_4 \sin(4\omega t + \theta_4))^2} \qquad (5.3)$$

Where:

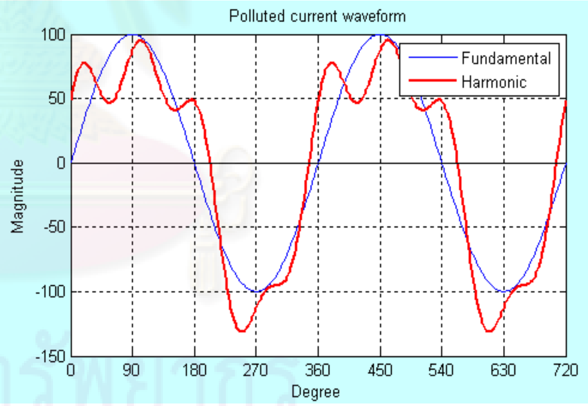
$$\omega = 2 * \pi * f$$
$$f = 50Hz$$

Harm (order)	Amp (%)	Angle (degree)
1	100	0
2	A_2=30	0
4	A_4=25	0
RMS (%)	107.35	
THD (%)	39.05	



(a) (angle = 0)

Harm (order)	Amp (%)	Angle (degree)
1	100	0
2	A_2=30	90
4	A_4=25	45
RMS (%)	107.35	
THD (%)	39.05	

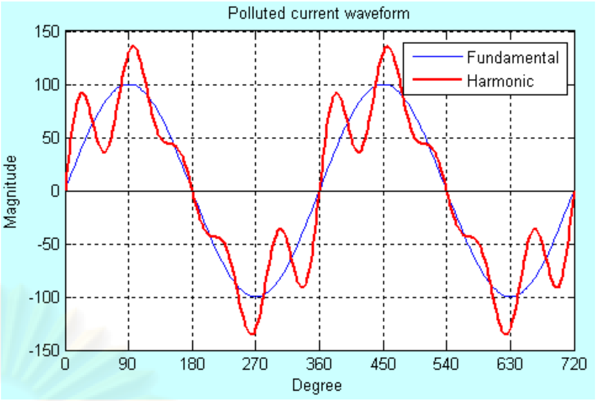


(b) (angle ≠ 0)

Figure 5.3 Distorted waveform of even harmonic (Asymmetrical waveform)

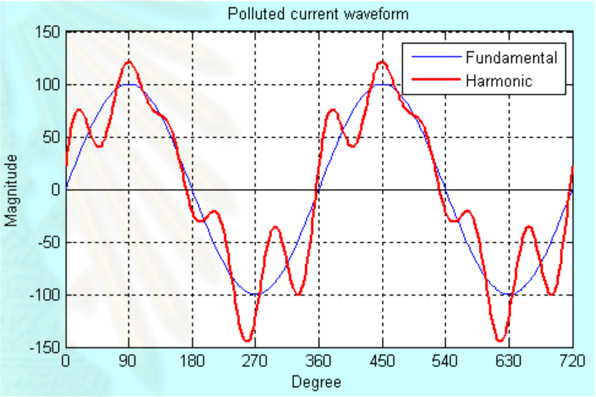
5.1.3 Odd and even harmonic order

Harm (order)	Amp (%)	Angle (degree)
1	100	0
4	A_4=25	0
5	A_5=30	0
RMS (%)	107.35	
THD (%)	39.05	



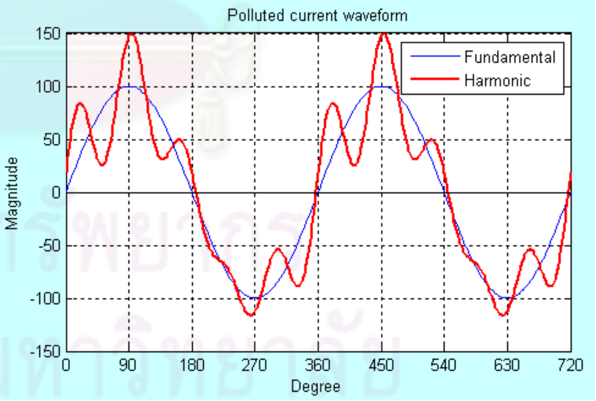
(a)

Harm (order)	Amp (%)	Angle (degree)
1	100	0
4	A_4=25	0
5	A_5=30	45
RMS (%)	107.35	
THD (%)	39.05	



(b)

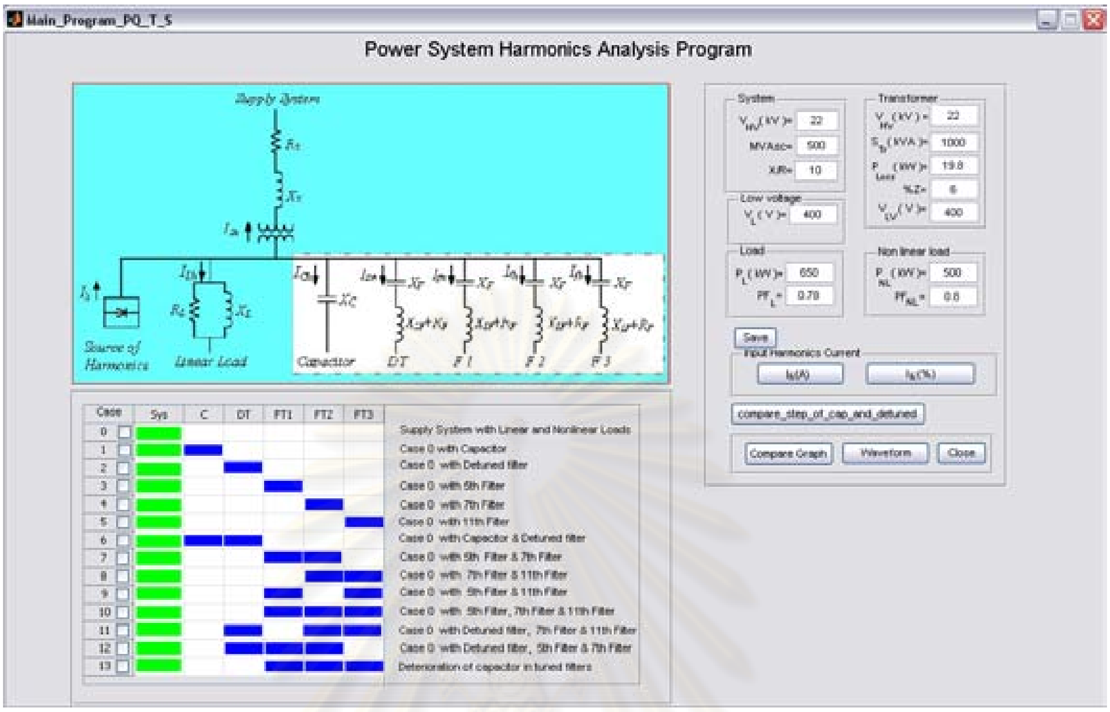
Harm (order)	Amp (%)	Angle (degree)
1	100	0
4	A_4=25	45
5	A_5=30	0
RMS (%)	107.35	
THD (%)	39.05	



(c)

Figure 5.4 Distorted waveform of odd and even harmonic

5.2 Harmonic response analysis



System
V_{HV} (kV)= 22
MVAsc= 500
X/R= 10

Transformer
V_{HV} (kV)= 22
S_{tr} (kVA)= 1000
P_{loss} (kW)= 19.8
%Z= 6
V_{LV} (V)= 400

Low voltage
V_L (V)= 400

Load
P_L (kW)= 650
PF_L= 0.78

Non linear load
P_{NL} (kW)= 500
PF_{NL}= 0.8

Case		Sys	C	DT	FT1	FT2	FT3	
0	☐	🟩						Supply System with Linear and Nonlinear Loads
1	☐	🟩	🟦					Case 0 with Capacitor
2	☐	🟩		🟦				Case 0 with Detuned filter
3	☐	🟩			🟦			Case 0 with 5th Filter
4	☐	🟩				🟦		Case 0 with 7th Filter
5	☐	🟩					🟦	Case 0 with 11th Filter
6	☐	🟩	🟦	🟦				Case 0 with Capacitor & Detuned filter
7	☐	🟩			🟦	🟦		Case 0 with 5th Filter & 7th Filter
8	☐	🟩				🟦	🟦	Case 0 with 7th Filter & 11th Filter
9	☐	🟩			🟦		🟦	Case 0 with 5th Filter & 11th Filter
10	☐	🟩			🟦	🟦	🟦	Case 0 with 5th Filter, 7th Filter & 11th Filter
11	☐	🟩		🟦		🟦	🟦	Case 0 with Detuned filter, 7th Filter & 11th Filter
12	☐	🟩		🟦	🟦	🟦		Case 0 with Detuned filter, 5th Filter & 7th Filter
13	☐	🟩			🟦	🟦	🟦	Deterioration of capacitor in tuned filters

Figure 5.5 Main display of program

- System and equipment data:

a) System: 22 kV, 500 MVA_{SC}, X/R=10

b) Transformer: 22 kV/400V, 1000kVA, 6%Z, $P_{cu\ loss}$ 19.8kW

c) Low voltage side: 400 V

d) Linear load: 400 V, 650 kW, 0.78 PF

e) Non linear load: 400 V, 500 kW, 0.80 PF, harmonic current show in table 5.1

Table 5.1 Harmonic current source

h	5	7	11	13	17	19	23	25	29	31
Ih(%I1)	18.74	11.89	8.95	7.36	5.37	4.42	3.47	2.84	2.21	1.58
Ih(A)	169.0	107.3	80.72	66.47	48.43	39.88	31.34	25.64	19.94	14.24

5.2.1 Case study 0 (supply system with linear and nonlinear load)

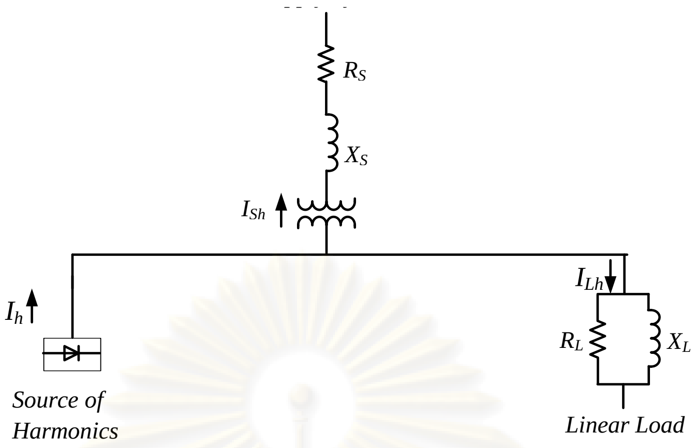
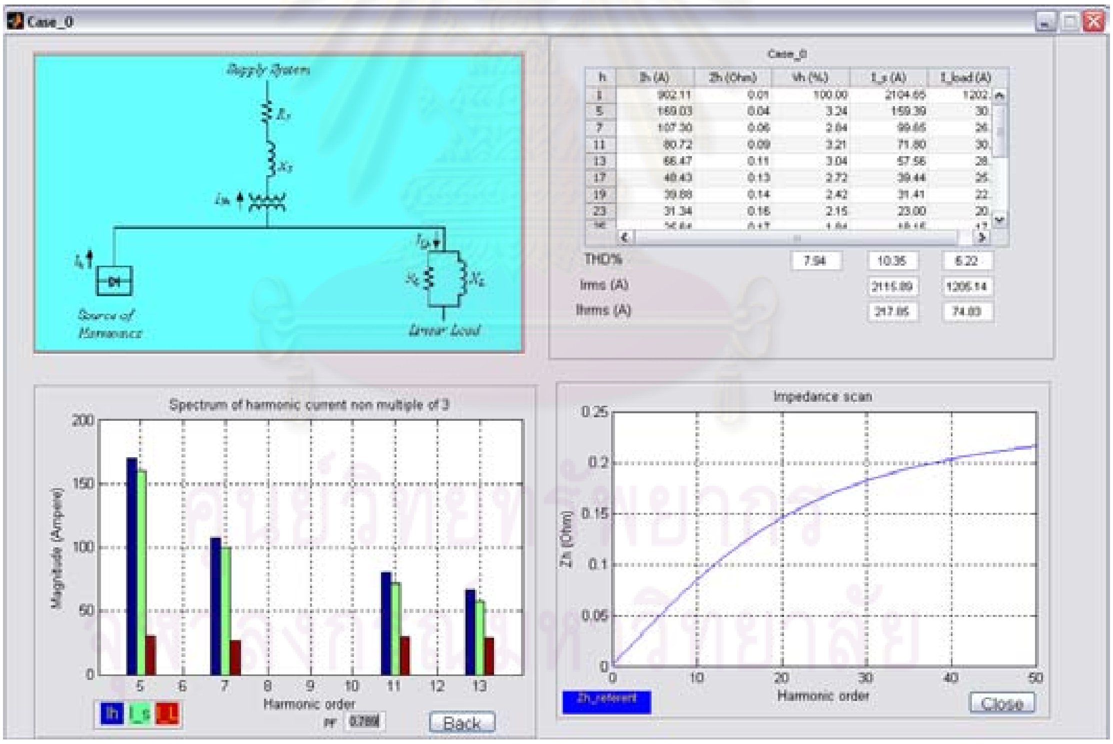


Figure 5.6 Single-line diagram of case study 0



Case_0

h	Ih (A)	Zh (Ohm)	Vh (%)	I_s (A)	I_load (A)
1	902.11	0.01	100.00	2104.65	1202.
5	169.03	0.04	3.24	159.39	30.
7	107.30	0.06	2.04	99.65	26.
11	80.72	0.09	3.21	71.80	30.
13	66.47	0.11	3.04	57.56	28.
17	48.43	0.13	2.72	39.44	25.
19	39.88	0.14	2.42	31.41	22.
23	31.34	0.16	2.15	23.00	20.

THD% 7.94 10.35 6.22
Irms (A) 2115.89 1205.14
Ihrms (A) 217.05 74.03

PF 0.789

Figure 5.7 The result of case study 0

The case study 0 is the reference case; it consists of a supply system, linear and non linear loads. Power factor from the analysis is 0.789, it is lower than the limited (it should improve) and the total harmonic voltage distortion value (THD_V) at low voltage bus is 7.94%, it is over the planning level of standard (for the planning level of standard $THD_V \leq 5\%$)

5.2.2 Case study 1 (case study 0 with capacitors)

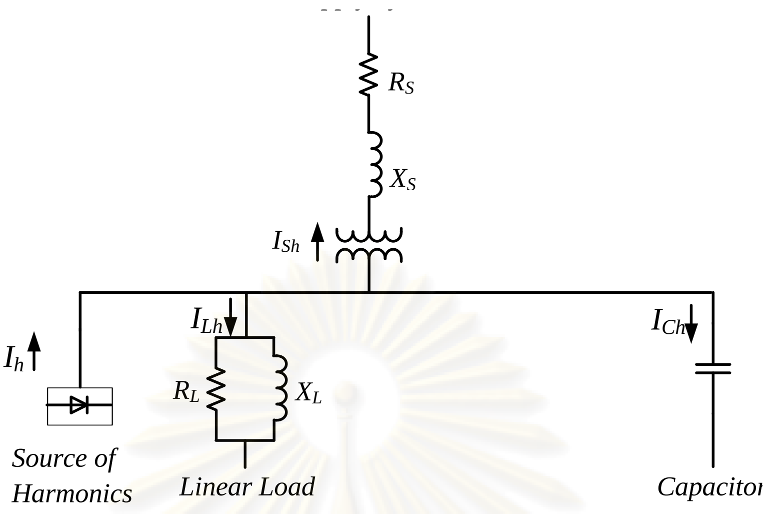


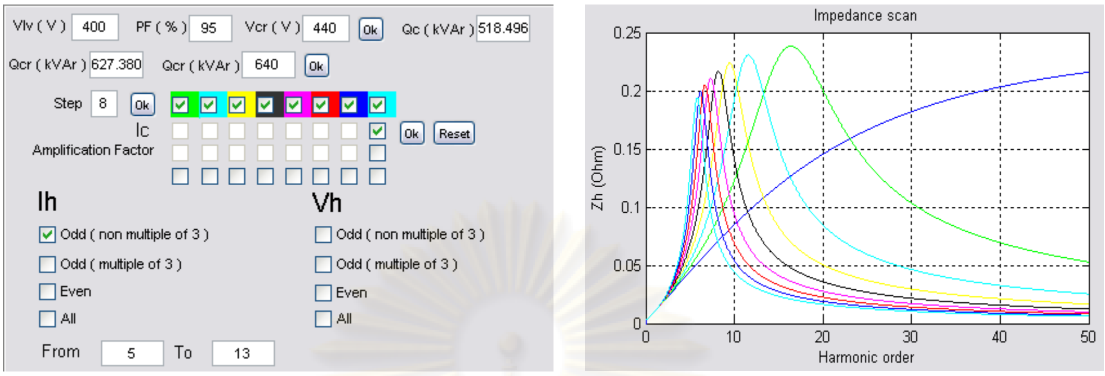
Figure 5.8 Single-line diagram of case study 1

Table 5.2 The input parameters for case study 1

System	Transformer	LV Bus	Non-Linear Load	Linear Load	Capacitor
500 MVA_{SC} 22 kV X/R 10	1000 kVA 22 kV/400 V %Z = 6 P_{LOSS} = 19.8 kW	400 V	500 kW PF = 80 %	650 kW PF = 75 %	80 kVAr / 440 V or 115 kVAr / 525V 8 Steps

Case study 1 is case study 0 with capacitors. This case considers two conditions as (80 kVAr / 440 V, 8 steps) and (115 kVAr / 525 V, 8 steps).

5.2.2.1 Results of case study 1 for 640 kVAr / 440 V capacitor



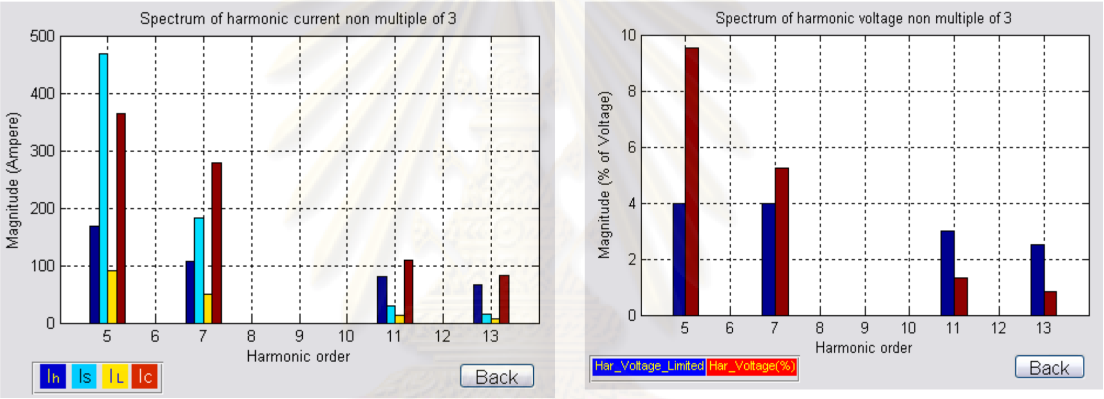
Vlv (V) 400
PF (%) 95
Vcr (V) 440 Ok
Qc (kVAr) 518.496
Qcr (kVAr) 627.380
Qcr (kVAr) 640 Ok
Step 8 Ok ☑ ☑ ☑ ☑ ☑ ☑ ☑ ☑
Ic ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☑ Ok Reset
Amplification Factor ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

Ih
☑ Odd (non multiple of 3)
☐ Odd (multiple of 3)
☐ Even
☐ All

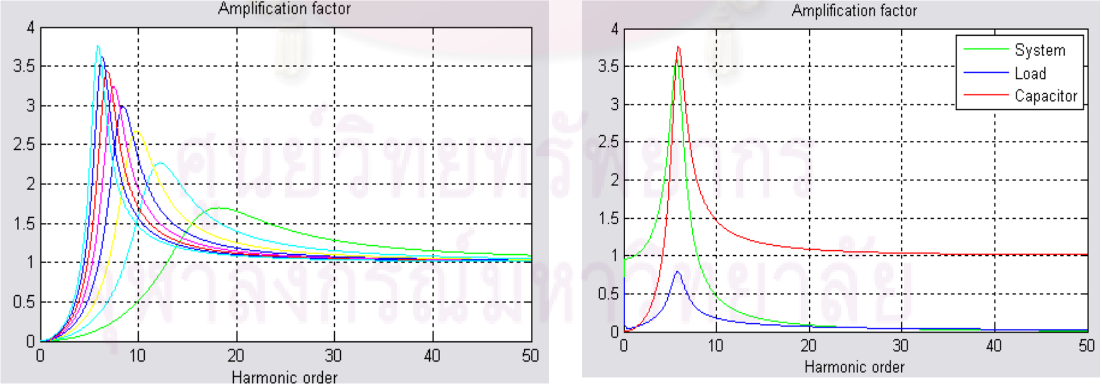
Vh
☐ Odd (non multiple of 3)
☐ Odd (multiple of 3)
☐ Even
☐ All

From 5 To 13

(a) Capacitor step selection **(b)** Impedance scan for case study 1



(c) Spectra of harmonic currents for case study 1 **(d)** Spectra of harmonic voltages for case study 1



(e) Harmonic current amplification in each step of capacitor **(f)** Harmonic current amplification in system, load and capacitor 8th step

Figure 5.9 Results of case study 1

Table 5.3 Harmonic current flow in capacitors 80x8 kVAr / 440 V

Order (h)	Ih (A)	I_C (A) at X^{th} step							
		1	2	3	4	5	6	7	8
1	902.11	95.43	190.86	286.29	381.72	477.15	572.58	668.01	763.44
5	169.03	16.99	37.6	63.06	95.14	136.52	191.14	264.72	363.95
7	107.3	22.76	56.54	109.89	196.84	313.54	365.59	327.05	279.27
11	80.72	52.66	164.83	193.33	157.95	136.15	123.42	115.32	109.76
13	66.47	67.79	147.06	121.97	104.06	94.44	88.65	84.81	82.1
17	48.43	80.5	78.49	67.13	61.74	58.72	56.81	55.49	54.53
19	39.88	67.34	58.2	51.46	48.24	46.41	45.23	44.41	43.81
23	31.34	47.44	40.2	37.09	35.57	34.68	34.1	33.69	33.38
25	25.64	36.65	31.57	29.52	28.51	27.92	27.53	27.25	27.04
29	19.94	26.07	23.21	22.11	21.56	21.23	21.01	20.86	20.74
31	14.24	18	16.25	15.58	15.24	15.04	14.9	14.81	14.74
$I_{h\ total}$	239.15	154.23	257.62	280.07	304.12	390.72	448.49	452.89	486.44
I_{rms}	933.27	181.37	320.62	400.5	488.06	616.71	727.31	807.06	905.24
I_{Cr}	0	104.97	209.95	314.92	419.89	524.86	629.84	734.81	839.78
I_{rms} / I_{Cr}	0	1.73	1.53	1.27	1.16	1.17	1.15	1.1	1.08

In table 5.3, as 1st step is on, harmonic currents from 13th -31st are amplified and I_{rms} / I_{Cr} value is more than 130%. as 8th step is on, 5th and 7th harmonic currents are amplifies (for 5th harmonic current is amplified from 169.03 to 363.59 A and 7th harmonic current is amplified from 107.3 to 279.27 A. For this condition could make capacitors to fail.

Table 5.4 The results of harmonic current calculation (640 kVAr / 440 V capacitors)

Cap Step	Q (kVAr)	PF	Low Voltage Side									
			I_C				I_S			I_L		
			Ihrms (A)	Irms (A)	Irms/Icr	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)
0	0	0.789	0	0	0	0	217.85	2115.89	10.35	74.83	1205.14	6.22
1	80	0.811	154.23	181.37	1.73	161.62	276.63	2066.0	13.51	105.66	1207.4	8.78
2	160	0.833	257.62	320.62	1.53	134.98	323.74	2019.1	16.24	111.51	1208.0	9.27
3	240	0.855	280.07	400.50	1.27	97.83	327.48	1969.2	16.86	94.96	1206.6	7.89
4	320	0.876	304.12	488.06	1.16	79.67	368.62	1929.6	19.64	94.18	1206.5	7.83
5	400	0.897	390.72	616.71	1.17	81.89	438.33	1901.2	23.69	108.17	1207.7	8.99
6	480	0.917	448.49	727.31	1.15	78.33	461.28	1867.7	25.49	109.39	1207.8	9.09
7	560	0.936	452.89	807.06	1.10	67.80	462.16	1833.2	26.50	101.86	1207.1	8.47
8	640	0.953	486.44	905.24	1.08	63.72	504.21	1814.1	28.93	104.33	1207.3	8.67

Table 5.5 The results of harmonic voltage calculation (640 kVAr/440 V capacitors)

Cap Step	PF	Low Voltage Side THDv (%)		
		Results	PL (ERG5/4)	(%) of PL
0	0.789	7.94	5	158.8
1	0.811	11.23	5	224.6
2	0.833	11.84	5	236.8
3	0.855	10.06	5	201.2
4	0.876	9.97	5	199.4
5	0.897	11.44	5	228.8
6	0.917	11.56	5	231.2
7	0.936	10.75	5	215.0
8	0.953	11.00	5	220.0

The analysis results of case study 1 a:

The calculation results of case study 1 for the first condition (80kVAr / 440V, 8 step), from table 5.4 we can see that when using capacitors for improved power factor in the system that has a high harmonic current source, the capacitors cannot work from the 1st to 2nd step because rms current are more than rated current of the capacitor (I_{rms} / I_{cr} > 1.3), as shown in figure 5.8.e. and the total harmonic voltage distortion value (THD_V) at low voltage bus 400V is more than planning level of standard as shown in table 5.5.

5.2.2.2 Results of case study 1 for 920 kVAr / 525 V capacitor

Table 5.6 The results of harmonic current calculation (920 kVAr / 525 V capacitors)

Cap Step	Q (kVAr)	PF	Low Voltage Side									
			I_C				I_S			I_L		
			Ihrms (A)	Irms (A)	Irms/Icr	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)
0	0	0.789	0	0	0	0	217.85	2115.9	10.35	74.83	1205.14	6.22
1	115	0.811	155.35	182.81	1.45	161.22	277.14	2065.5	13.54	105.73	1207.5	8.79
2	230	0.833	259.08	322.4	1.28	134.44	324.18	2018.2	16.27	111.40	1208.0	9.26
3	345	0.855	279.94	402.40	1.06	96.84	327.85	1967.9	16.90	94.54	1206.5	7.86
4	460	0.877	306.52	492.45	0.97	79.53	371.18	1928.3	19.26	94.60	1206.5	7.87
5	575	0.898	395.25	623.17	0.99	82.04	441.08	1899.8	23.87	108.73	1207.7	9.04
6	690	0.918	449.32	732.21	0.96	77.72	460.93	1865.5	25.50	108.91	1207.7	9.05
7	805	0.937	453.67	812.86	0.92	67.26	463.56	1831.4	26.16	101.65	1207.1	8.45
8	920	0.954	491.23	914.07	0.90	63.73	509.20	1813.3	29.26	104.97	1207.4	8.73

Table 5.7 The result of calculation

Cap Step	PF	Low Voltage Side THDv (%)		
		Results	PL (ERG5/4)	(%) of PL
0	0.789	7.94	5	158.8
1	0.811	11.23	5	224.6
2	0.833	11.83	5	236.6
3	0.855	10.02	5	200.4
4	0.877	10.01	5	200.2
5	0.898	11.50	5	230.0
6	0.918	11.51	5	230.2
7	0.937	10.73	5	214.6
8	0.954	11.06	5	221.2

The resulted of calculation case study 1 for the second condition (115kVAr / 525V, 8 steps). As shown in table 5.6, the capacitor 1st step cannot operate because of over load from harmonic current amplification (I_{rms} / I_{Cr} > 1.30). THD_V at a low voltage bus from table 5.7 is more than planning level of standard.

Table 5.8 Comparison step of capacitor when used V_{cr} = 440V and V_{cr} = 525V

V_{Cr}(V)	Irms/Icr (for X^{th} step)							
	1	2	3	4	5	6	7	8
440	1.73	1.53	1.27	1.16	1.17	1.15	1.1	1.08
525	1.45	1.28	1.06	0.97	0.99	0.96	0.92	0.90

5.2.3 Case study 2 (Case study 0 with Detuned filter)

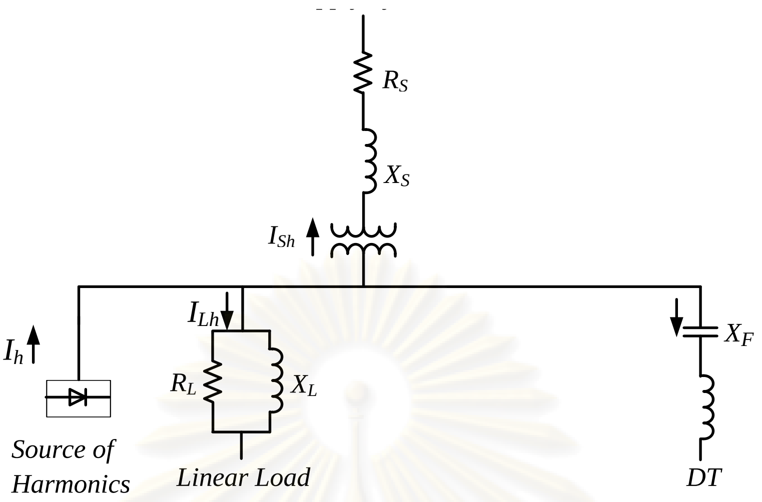


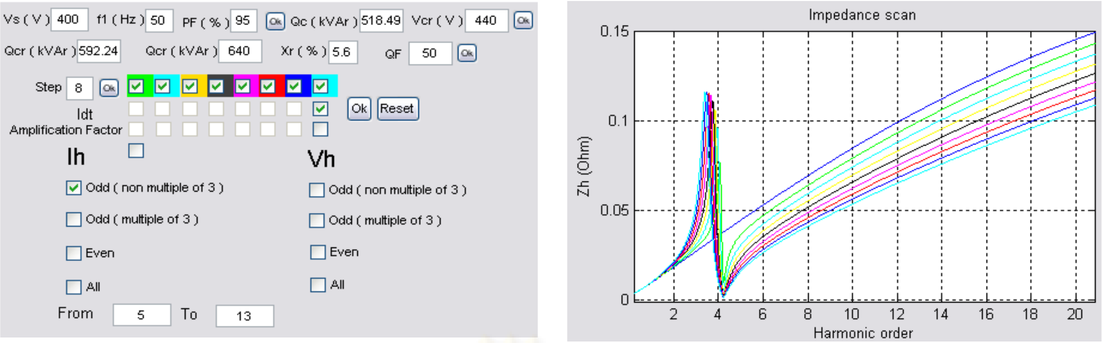
Figure 5.10 Single-line diagram of case study 2

Table 5.9 The input parameters for case study 2

System	Transformer	LV Bus	Non-Linear Load	Linear Load	Detuned filter
500 MVA_{SC}	1000 kVA	400 V	500 kW	650 kW	640 kVAr / 440 V or
22 kV	22 kV/400 V		PF = 80 %	PF = 75 %	920 kVAr / 525V
X/R 10	%Z = 6				8 Steps
	P_k = 19.8 kW				$\%X_L$=5.6 & $\%X_L$=7

Case study 2 is case study 0 with detuned filters which analyzing 4 conditions such as: (640kVAr / 440V, X_L=5.6%), (640kVAr / 440V, X_L=7%), (920kVAr / 525V, X_L=5.6%) and (920kVAr / 525V, X_L=7%).

5.2.3.1 Result of case study 2 for 640kVAr / 440 V, 5.6%X_L



Vs (V) 400 f1 (Hz) 50 PF (%) 95 Qc (kVAr) 518.49 Vcr (V) 440

Qcr (kVAr) 592.24 Qcr (kVAr) 640 Xr (%) 5.6 QF 50

Step 8

Ih

☑ Odd (non multiple of 3)

☐ Odd (multiple of 3)

☐ Even

☐ All

Vh

☐ Odd (non multiple of 3)

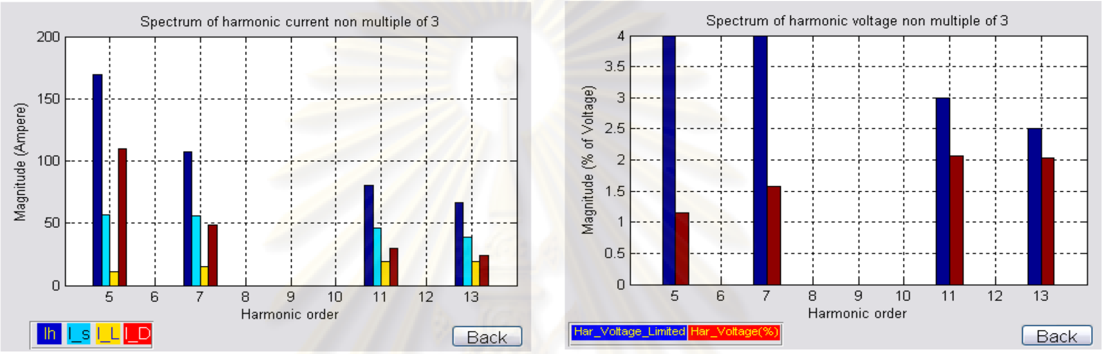
☐ Odd (multiple of 3)

☐ Even

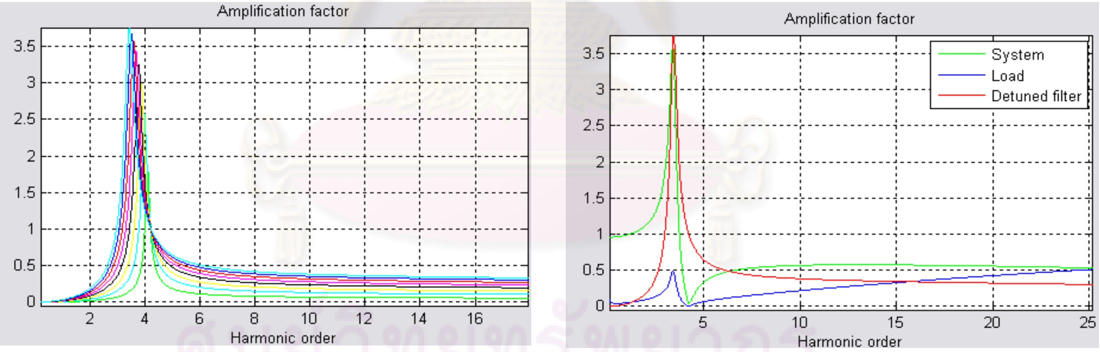
☐ All

From 5 To 13

(a) Detuned filter step selection **(b)** Impedance scan for case study 2



(c) Spectra of harmonic currents for case study 2 (d) Spectra of harmonic voltages for case study 2



(e) Harmonic current amplification in each step of detuned filter (f) Harmonic current amplification in system, load and detuned filter 8th step

Figure 5.11 Results of case study 2

Table 5.10 Harmonic current flow in detuned filter 80x8 kVAr / 440 V, 5.6%X_L

Order (h)	Ih (A)	I_{DT} (A) at X^{th} step							
		1	2	3	4	5	6	7	8
1	902.11	95.43	190.86	286.29	381.72	477.15	572.58	668.01	763.44
5	169.03	31.53	53.23	69.05	81.09	90.55	98.18	104.46	109.72
7	107.3	9.9	18.17	25.17	31.18	36.38	40.92	44.93	48.48
11	80.72	5.47	10.28	14.55	18.36	21.77	24.84	27.61	30.14
13	66.47	4.2	7.95	11.3	14.31	17.03	19.49	21.73	23.78
17	48.43	2.77	5.28	7.55	9.63	11.52	13.25	14.84	16.3
19	39.88	2.18	4.18	6	7.66	9.19	10.59	11.88	13.08
23	31.34	1.58	3.05	4.4	5.65	6.8	7.87	8.86	9.78
25	25.64	1.25	2.4	3.48	4.48	5.4	6.26	7.07	7.81
29	19.94	0.9	1.74	2.53	3.27	3.96	4.61	5.22	5.79
31	14.24	0.62	1.2	1.75	2.26	2.75	3.2	3.63	4.03
$I_{h\ total}$	239.15	34.02	58.29	76.65	91.15	102.97	112.83	121.22	128.48
I_{rms}	933.27	101.31	199.56	296.37	392.45	488.13	583.59	678.92	774.17
I_{Cr}	0	104.97	209.95	314.92	419.89	524.86	629.84	734.81	839.78
I_{rms} / I_{Cr}	0	0.97	0.95	0.94	0.93	0.93	0.93	0.92	0.92

When turn on detuned filters from 1st – 8th, all harmonic current is not amplified and I_{rms} / I_{Cr} value is less than 1, so detuned filter can operat safety as shown in table 5.10.

Table 5.11 The results of harmonic current calculation (640 kVAr / 440V, 5.6%X_L)

Cap Step	Q (kVAr)	PF	Low Voltage Side									
			I_{DT}				I_S			I_L		
			Ihrms (A)	Irms (A)	Irms/Icr	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)
0	0	0.789	0	0	0	0	217.85	2115.89	10.35	74.83	1205.14	6.22
1	80	0.812	34.02	101.31	0.97	35.65	189.68	2052.8	9.28	69.14	1204.8	5.75
2	160	0.835	58.29	199.58	0.95	30.54	169.41	1994.0	8.53	64.60	1204.5	5.37
3	240	0.859	76.65	296.37	0.94	26.77	153.89	1939.2	7.96	60.80	1204.4	5.05
4	320	0.881	91.15	392.45	0.93	23.88	141.49	1888.6	7.51	57.52	1204.2	4.78
5	400	0.903	102.97	488.13	0.93	21.58	131.26	1842.3	7.14	54.63	1204.1	4.54
6	480	0.924	112.83	583.59	0.93	19.71	122.61	1800.8	6.82	52.05	1203.9	4.33
7	560	0.943	121.22	678.92	0.92	18.15	115.19	1764.2	6.54	49.72	1203.8	4.13
8	640	0.960	128.48	774.17	0.92	16.83	108.71	1732.8	6.29	47.6	1203.8	3.96

Table 5.12 The results of harmonic voltage calculation (640 kVAr / 440V, 5.6%X_L)

Detuned Step	PF	Low Voltage Side THDv (%)		
		Results	PL (ERG5/4)	(%) of PL
0	0.789	7.94	5	158.8
1	0.812	7.34	5	146.8
2	0.835	6.86	5	137.2
3	0.859	6.46	5	129.2
4	0.881	6.11	5	122.2
5	0.903	5.81	5	116.2
6	0.924	5.53	5	110.6
7	0.943	5.29	5	105.8
8	0.960	5.06	5	101.2

5.2.3.2 Result of case study 2 for 640 kVAr / 440V, 7%X_L

Table 5.13 The results of harmonic current calculation (640 kVAr / 440V, 7%X_L)

Cap Step	Q (kVAr)	PF	Low Voltage Side									
			I_{DT}				I_S			I_L		
			Ihrms (A)	Irms (A)	Irms/Icr	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)
0	0	0.789	0	0	0	0	217.85	2115.89	10.35	74.83	1205.14	6.22
1	80	0.812	20.82	97.68	0.93	21.82	200.07	2052.9	9.79	70.81	1204.9	5.89
2	160	0.836	38.00	194.61	0.93	19.91	185.30	19933.7	9.33	67.29	1204.7	5.59
3	240	0.860	52.46	291.06	0.92	18.33	172.81	1938.4	8.95	64.16	1204.5	5.33
4	320	0.883	64.83	387.19	0.92	16.98	162.07	1887.3	8.62	61.35	1204.4	5.10
5	400	0.905	75.56	483.10	0.92	15.84	152.71	1840.7	8.32	58.81	1204.3	4.89
6	480	0.926	84.97	578.85	0.92	14.84	144.46	1768.9	8.06	56.48	1204.1	4.70
7	560	0.945	93.28	674.49	0.92	13.96	137.13	1762.2	7.81	54.34	1204.0	4.52
8	640	0.962	100.71	770.05	0.92	13.19	130.56	1703.9	7.56	52.37	1204.0	4.35

Table 5.14 The results of harmonic voltage calculation (640 kVAr / 440V, 7%X_L)

Detuned Step	PF	Low Voltage Side THDv (%)		
		Results	PL (ERG5/4)	(%) of PL
0	0.789	7.94	5	158.8
1	0.812	7.52	5	150.4
2	0.836	7.15	5	143.0
3	0.860	6.82	5	136.4
4	0.883	6.52	5	130.4
5	0.905	6.25	5	125.0
6	0.926	6.00	5	120.0
7	0.945	5.77	5	115.4
8	0.962	5.57	5	111.4

5.2.3.3 Result of case study 2 for 920kVAr / 525 V, 5.6%X_L

Table 5.15 The results of harmonic current calculation (920 kVAr / 525V, 5.6%X_L)

Cap Step	Q (kVAr)	PF	Low Voltage Side									
			I_{DT}				I_S			I_L		
			Ihrms (A)	Irms (A)	Irms/Icr	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)
0	0	0.789	0	0	0	0	217.85	2115.89	10.35	74.83	1205.14	6.22
1	115	0.812	34.29	102.28	0.81	35.59	187.45	2052.2	9.27	69.09	1204.8	5.74
2	230	0.836	58.69	201.45	0.80	30.46	169.07	1992.9	8.51	64.52	1204.5	5.36
3	345	0.859	77.12	299.18	0.79	26.68	153.49	1937.6	7.95	60.70	1204.3	5.05
4	460	0.882	91.65	396.17	0.78	23.78	141.05	1886.7	7.50	57.40	1204.2	4.77
5	575	0.904	103.49	492.77	0.78	21.48	130.80	1840.2	7.13	54.50	1204.0	4.53
6	690	0.925	113.36	589.15	0.78	19.61	122.15	1798.5	6.81	51.91	1203.9	4.32
7	805	0.944	121.74	685.39	0.77	18.05	114.72	1761.9	6.52	49.57	1203.8	4.12
8	920	0.961	128.99	781.57	0.77	16.73	108.23	1730.6	6.27	47.45	1203.8	3.94

Table 5.16 The results of harmonic voltage calculation (920 kVAr / 525V, 5.6%X_L)

Detuned Step	PF	Low Voltage Side THDv (%)		
		Results	PL (ERG5/4)	(%) of PL
0	0.789	7.94	5	158.8
1	0.812	7.34	5	146.8
2	0.836	6.85	5	137.0
3	0.859	6.45	5	129.0
4	0.882	6.10	5	122.0
5	0.904	5.79	5	115.8
6	0.925	5.52	5	110.4
7	0.944	5.27	5	105.4
8	0.961	5.05	5	101.0

5.2.3.4 Result of case study 2 for 920kVAr / 525 V, 7%X_L

Table 5.17 The results of harmonic current calculation (920 kVAr / 525V, 7%X_L)

Cap Step	Q (kVAr)	PF	Low Voltage Side									
			I_{DT}				I_S			I_L		
			Ihrms (A)	Irms (A)	Irms/Icr	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)
0	0	0.789	0	0	0	0	217.85	2115.89	10.35	74.83	1205.14	6.22
1	125	0.813	21.00	98.62	0.78	21.80	199.91	2052.3	9.79	70.77	1204.9	5.88
2	250	0.837	38.31	196.48	0.78	19.88	185.05	1992.6	9.33	67.22	1204.7	5.59
3	375	0.860	52.86	293.86	0.77	18.28	172.48	1936.9	8.94	64.08	1204.5	5.33
4	500	0.884	65.29	390.91	0.77	16.94	161.68	1885.5	8.61	61.25	1204.4	5.09
5	625	0.906	76.05	487.75	0.77	15.79	152.28	1838.6	8.31	58.68	1204.2	4.88
6	750	0.927	85.48	584.42	0.77	14.78	144.01	1796.7	8.04	56.35	1204.1	4.68
7	875	0.946	93.81	680.98	0.77	13.91	136.66	1759.9	7.79	54.20	1204.0	4.51
8	1000	0.963	101.25	777.47	0.77	13.13	130.07	1728.7	7.55	52.22	1203.9	4.34

Table 5.18 The results of harmonic voltage calculation (920 kVAr / 525V, 7%X_L)

Detuned Step	PF	Low Voltage Side THDv (%)		
		Results	PL (ERG5/4)	(%) of PL
0	0.789	7.94	5	158.8
1	0.813	7.52	5	150.4
2	0.837	7.14	5	142.8
3	0.860	6.81	5	136.2
4	0.884	6.51	5	130.2
5	0.906	6.24	5	124.8
6	0.927	5.99	5	119.8
7	0.946	5.76	5	115.2
8	0.963	5.55	5	111.0

From the results of calculation of case study 2 for all four conditions, when use detuned filters are used to increase power factor and partially filter harmonic current from the system, detuned filter can operate safety because the ratio of rms current to rated current of detuned filters is less than 1 (Irms / Icr < 1) as shown in table 5.11, 5.13, 5.15 and 5.17. The power factor can be improved to the target value (PF ≥ 0.95). But total harmonic voltage distortion (THD_V) at low voltage bus 400V still is over the planning level value as shown in table 5.12, 5.14, 5.16 and 5.18.

Table 5.19 Comparison of detuned filter lading

V_{Cr} (V)	%XL	I_{rms} / I_{Cr} (for X^{th} step)							
		1	2	3	4	5	6	7	8
440	5.6	0.97	0.95	0.94	0.93	0.93	0.93	0.92	0.92
440	7.0	0.93	0.93	0.92	0.92	0.92	0.92	0.92	0.92
525	5.6	0.81	0.80	0.79	0.78	0.78	0.78	0.77	0.77
525	7.0	0.78	0.78	0.77	0.77	0.77	0.77	0.77	0.77

5.2.4 Impedance scan comparison between capacitor and detuned filter

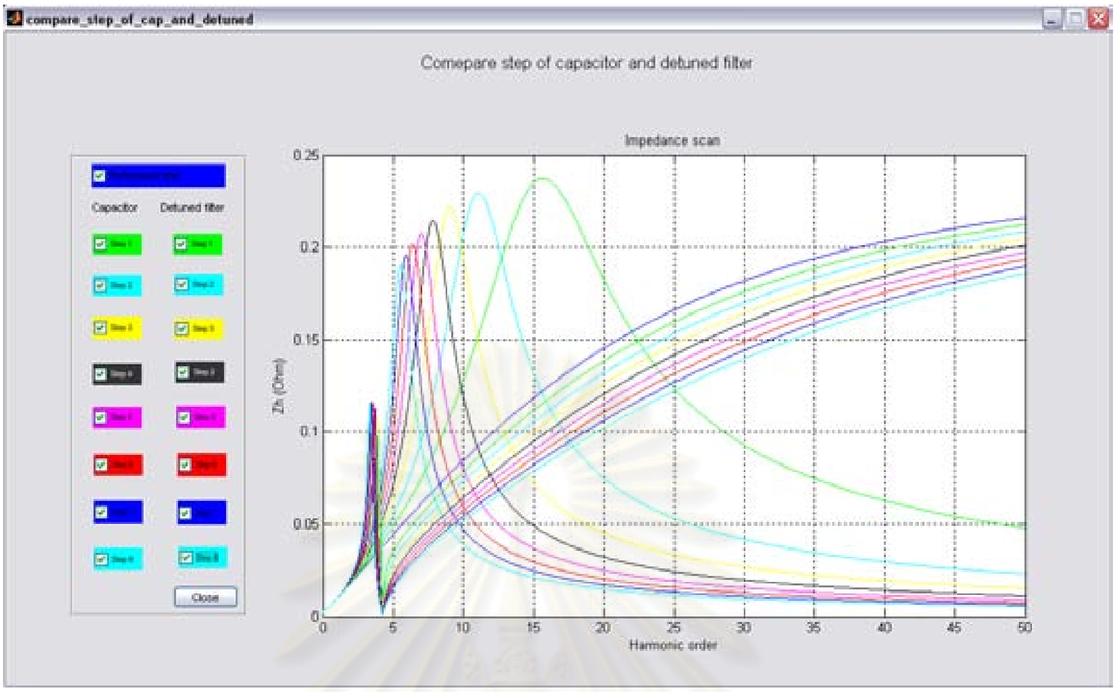


Figure 5.12 Comparison between step selection of capacitor and detuned filter

After change capacitors to detuned filters by connecting the reactor in series with the capacitor, it can avoid the damage that occurs from amplification of harmonic current and detuned filter can improve more value of THD_V than using the capacitor.

5.2.5 Case study 3 (case study 0 with 5th order tuned filter)

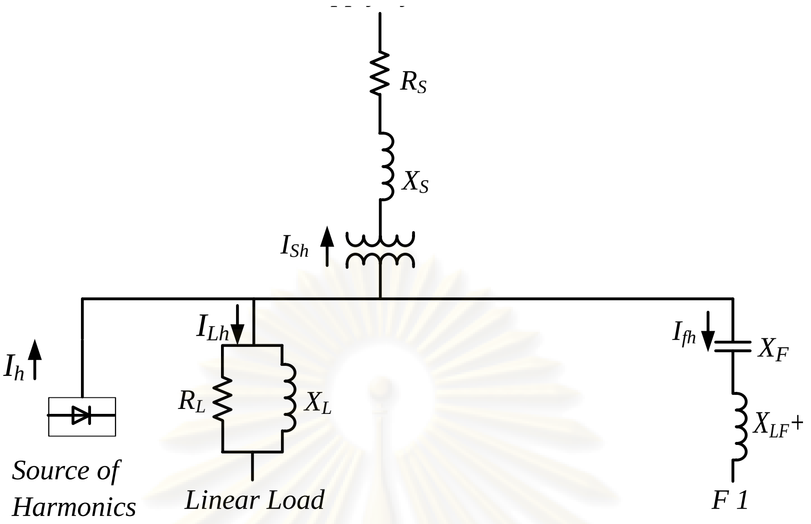


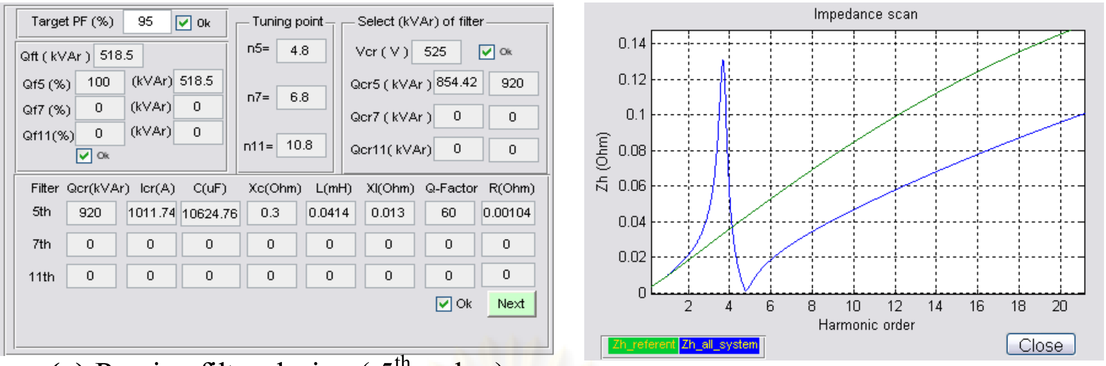
Figure 5.13 Single-line diagram of case study 3

Table 5.20 The input parameters for 5th tuned filter

System	Transformer	LV Bus	Non-Linear Load	Linear Load	Tuned filter
500 MVA_{SC}	1000 kVA	400 V	500 kW	650 kW	640 kVAr / 440 V or
22 kV	22 kV/400 V		PF = 80 %	PF = 75 %	920 kVAr / 525V
X/R 10	%Z = 6				Tuning point (n) 4.8
	P_k = 19.8 kW				Q-Factor 50

Case study 3 is case study 0 with 5th order tuned filters, which analyzing 2 conditions such as: (640kVAr / 440V, n = 4.8) and (920kVAr / 525V, n = 4.8).

5.2.5.1 Results of case study 3



Target PF (%) 95 ☑ Ok

Qft (kVAr) 518.5

Qf5 (%) 100 (kVAr) 518.5

Qf7 (%) 0 (kVAr) 0

Qf11(%) 0 (kVAr) 0

☑ Ok

Tuning point

n5= 4.8

n7= 6.8

n11= 10.8

Select (kVAr) of filter

Vcr (V) 525 ☑ Ok

Qcr5 (kVAr) 854.42 920

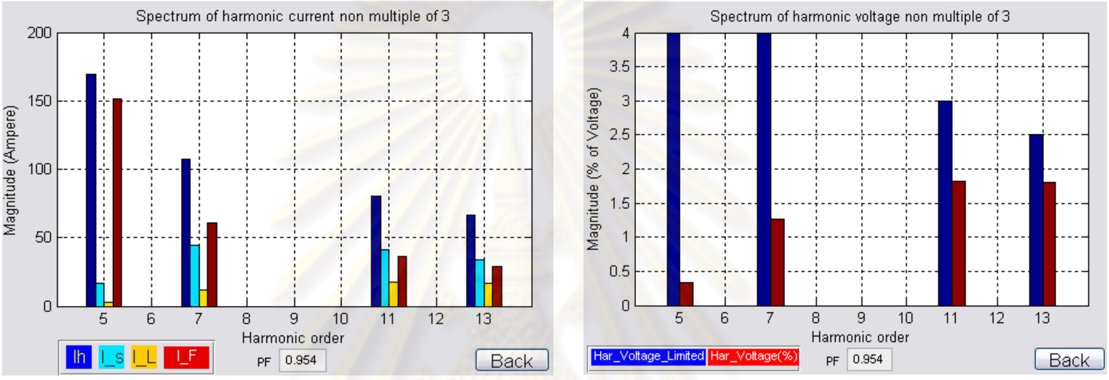
Qcr7 (kVAr) 0 0

Qcr11(kVAr) 0 0

Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	920	1011.74	10624.76	0.3	0.0414	0.013	60	0.00104
7th	0	0	0	0	0	0	0	0
11th	0	0	0	0	0	0	0	0

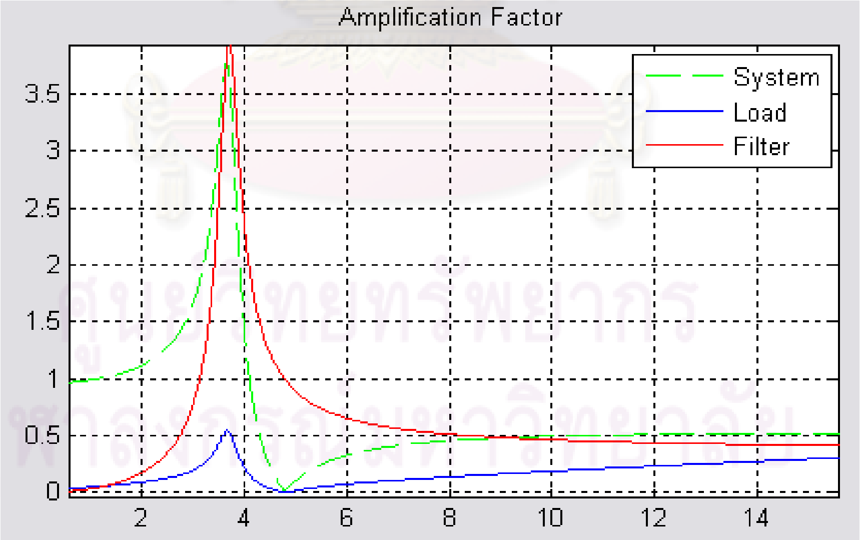
☑ Ok Next

(a) Passive filter design (5th order) **(b)** Impedance scan for case study 3



(c) Spectra of harmonic currents for case study 3

(d) Spectra of harmonic voltages for case study 3



(e) Harmonic current amplification in system, load and 5th order tuned filter

Figure 5.14 Results of case study 3

Table 5.21 The results of calculation for case study 3

V_{CR} (V)	Q (kVAr)	PF	Low Voltage Side										
			$I_{5th\ flter}$				I_S		I_L		THD_V (%)		
			Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	Irms (A)	THD (%)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
440	640	0.953	171.82	816.36	0.97	1.07	1734.3	4.74	1203.5	3.47	4.44	5	88.8
525	920	0.964	172.15	824.00	0.81	0.89	1732.1	4.72	1203.5	3.46	4.42	5	88.4

Table 5.22 The design parameters of 5th order tuned filters

Capacitor			Reactor		
Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
640	440	839.78	0.0418	894.54	1516.3
920	525	1011.74	0.0414	902.97	1531.1

Table 5.21 shows the results of calculation for case study

First condition (640kVAr / 440V, n =4.8), the power factor is 0.953, the ratio of rms current to rated current of tuned filter (I_{rms} / I_{cr} =0.97) and total harmonic voltage distortion THD_V =4.44%

Second condition (920kVAr / 525V, n=4.8), when increase rated voltage of capacitor from 440V to 525V, the power factor is 0.964, value of I_{rms} / I_{cr} =0.81, I_L / I_{cr} =0.89 and THD_V =4.42% which 5th order tuned filter can operate safely and the design parameters shown in table 5.22.

5.2.6 Case study 4 (case study 0 with 7th order tuned filter)

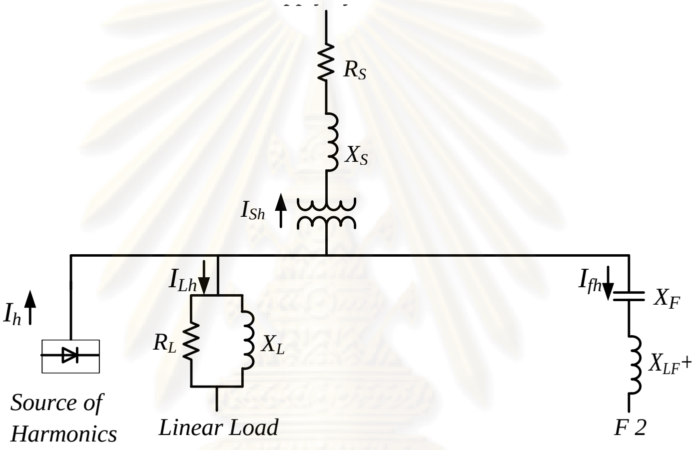


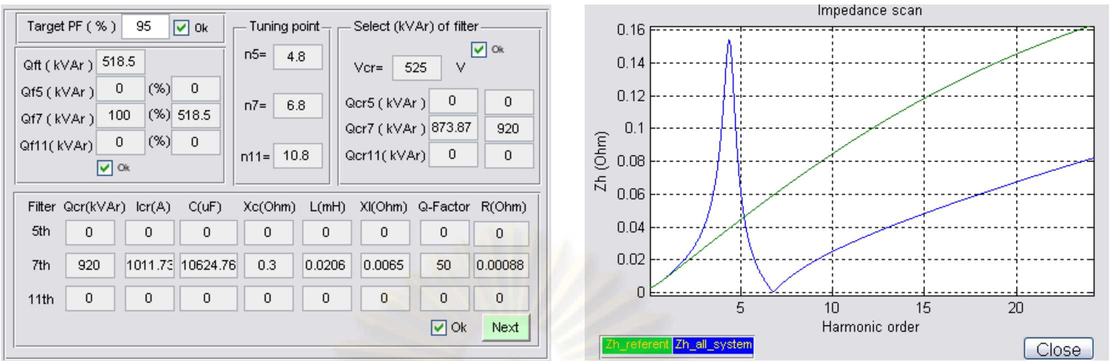
Figure 5.15 Single-line diagram of case study 4

Table 5.23 The input parameter of case study 4

System	Transformer	LV Bus	Non-Linear Load	Linear Load	Tuned filter
500 MVA_{SC} 22 kV X/R 10	1000 kVA 22 kV/400 V %Z = 6 P_k = 19.8 kW	400 V	500 kW PF = 80 %	650 kW PF = 75 %	640 kVAr / 440 V or 920 kVAr /525V Tuning point (n) 6.8 Q-Factor 50

Case study 4 is case study 0 with 7th order tuned filters, which analyzing 2 conditions such as: (640kVAr / 440V, n = 6.8) and (920kVAr / 525V, n =6.8).

5.2.6.1 Result of case study 4


Target PF (%) 95 ☑ Ok

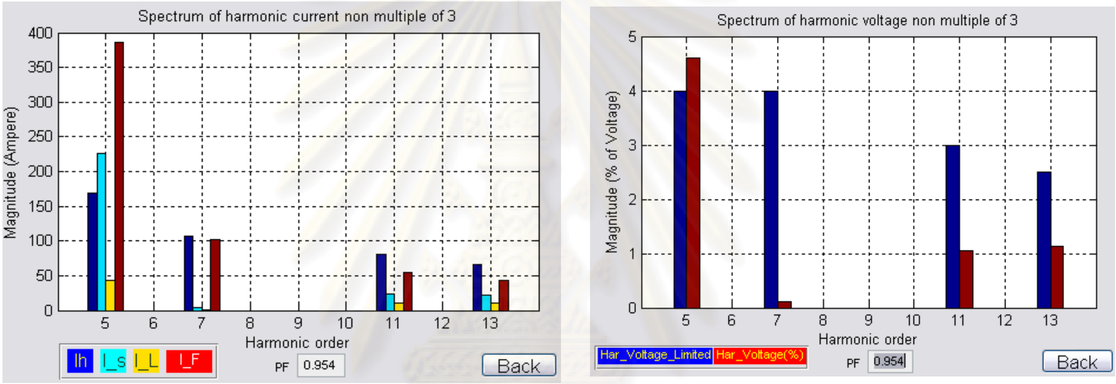
Qft (kVAr) 518.5
Qf5 (kVAr) 0 (%) 0
Qf7 (kVAr) 100 (%) 518.5
Qf11(kVAr) 0 (%) 0
☑ Ok

Tuning point
n5= 4.8
n7= 6.8
n11= 10.8

Select (kVAr) of filter
☑ Ok
Vcr= 525 V
Qcr5 (kVAr) 0 0
Qcr7 (kVAr) 873.87 920
Qcr11(kVAr) 0 0

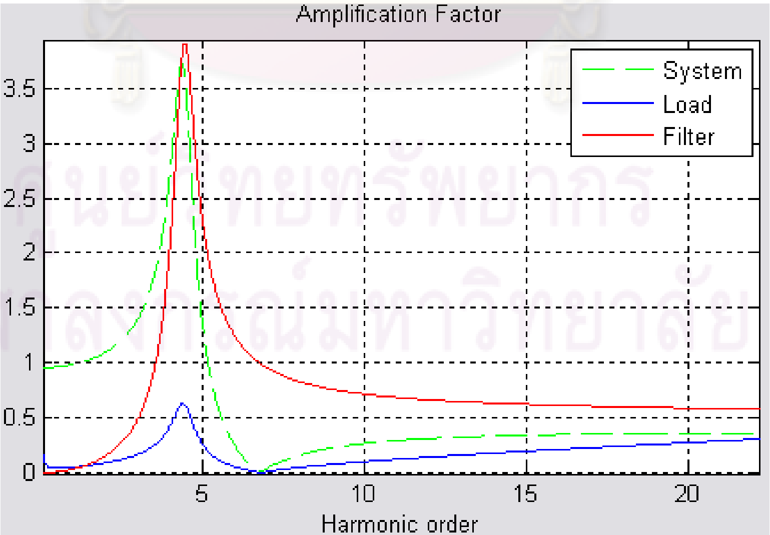
Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	0	0	0	0	0	0	0	0
7th	920	1011.73	10624.76	0.3	0.0206	0.0065	50	0.00088
11th	0	0	0	0	0	0	0	0

(a) Passive filter design (7th) **(b)** Impedance scan for case study 4



(c) Spectra of harmonic currents for case study 4

(d) Spectra of harmonic voltages for case study 4



(e) Harmonic current amplification in system, load and 7th order tuned filter

Figure 5.16 Results of case study 4

Table 5.24 Harmonic current flow in 7^{th} order tuned filter

Order (h)	Ih (A)	Filter current (A)	
		640 kVAr / 440 V	920 kVAr / 525 V
1	902.11	780.31	787.88
5	169.03	390.44	386.27
7	107.3	102.71	102.75
11	80.72	55.31	55.48
13	66.47	42.97	43.12
17	48.43	29.3	29.42
19	39.88	23.6	23.69
23	31.34	17.88	17.96
25	25.64	14.4	14.47
29	19.94	10.86	10.92
31	14.24	7.64	7.68
$I_{h\ total}$	239.15	412.33	408.46
I_{rms}	933.27	882.55	887.47
I_{Cr}	0	839.78	1011.7
I_{rms} / I_{Cr}	0	1.05	0.88

Note: 5^{th} order current is amplified.

Table 5.25 The result of calculation for case study 4

V_{CR} (V)	Q (kVAr)	PF	Low Voltage Side										
			$I_{7th\ filter}$				I_S		I_L		THD_V (%)		
			Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	Irms (A)	THD (%)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PF
440	640	0.953	412.33	882.55	1.05	1.13	1753.4	13.52	1203.9	4.34	5.51	5	110.2
525	920	0.954	408.46	887.47	0.88	0.95	1750.5	13.27	1203.9	4.27	5.42	5	108.4

Table 5.25 shows the results of calculation for case study 4

First condition (640kVAr / 440V, n = 6.8), the power factor is 0.953, the ratio of rms current to rated current of tuned filter (I_{rms} / I_{cr} = 1.05) and the total harmonic voltage distortion value at low voltage bus 400V THD_V = 5.51%, which higher than the planning level.

Second condition (920kVAr / 525V, n= 6.8), when increase rated voltage of capacitor from 440V to 525V, the power factor is 0.954, value of I_{rms} / I_{cr} = 0.88, I_L / I_{cr} = 0.95, which 7th order tuned filter can operate safely but the total harmonic voltage distortion value at low voltage bus 400V THD_V = 5.42% is still higher than the planning level.

Table 5.26 The design parameters of 7^{th} order tuned filters

Capacitor			Reactor		
Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
640	440	839.78	0.0208	952.25	1482.6
920	525	1011.73	0.0206	958.11	1497.0

5.2.7 Case study 5 (case study 0 with 11^{th} order tuned filter)

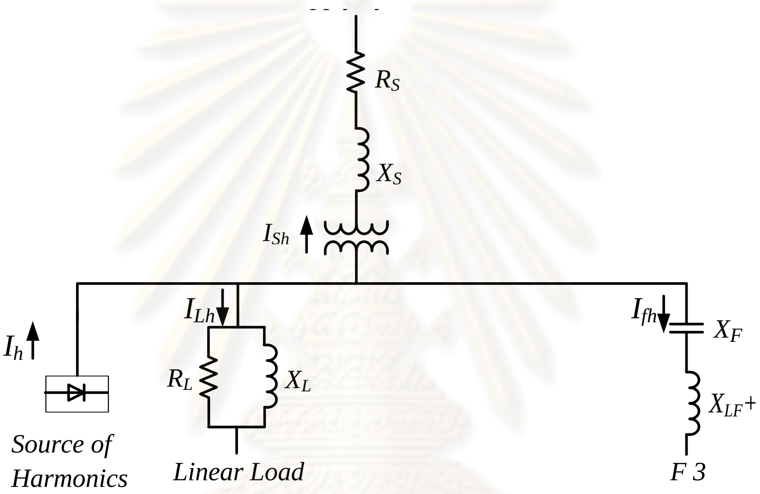


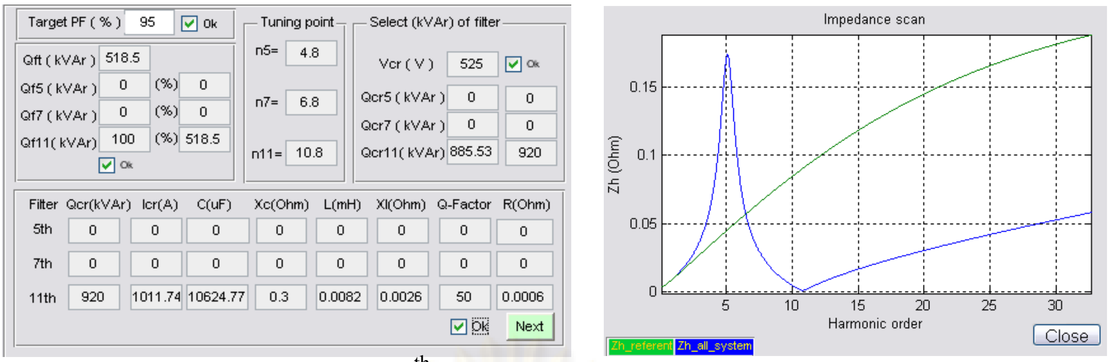
Figure 5.17 Single-line diagram of case study 5

Table 5.27 The input parameters for case study 5

System	Transformer	LV Bus	Non-Linear Load	Linear Load	Tuned filter
500 MVA_{SC} 22 kV X/R 10	1000 kVA 22 kV/400 V %Z = 6 P_{LOSS}= 19.8kW	400 V	500 kW PF = 80 %	650 kW PF = 75 %	640 kVAr /440 V or 920 kVAr / 525V Tuning point (n)10.8 Q-Factor 50

Case study 5 is case study 0 with 11^{th} order tuned filters, which analyzing 2 conditions such as: (640kVAr / 440V, n = 10.8) and (920kVAr / 525V, n = 10.8).

5.2.7.1 Results of case study 5



Target PF (%) 95 ☑ Ok

Qft (kVAr) 518.5
Qf5 (kVAr) 0 (%) 0
Qf7 (kVAr) 0 (%) 0
Qf11(kVAr) 100 (%) 518.5
☑ Ok

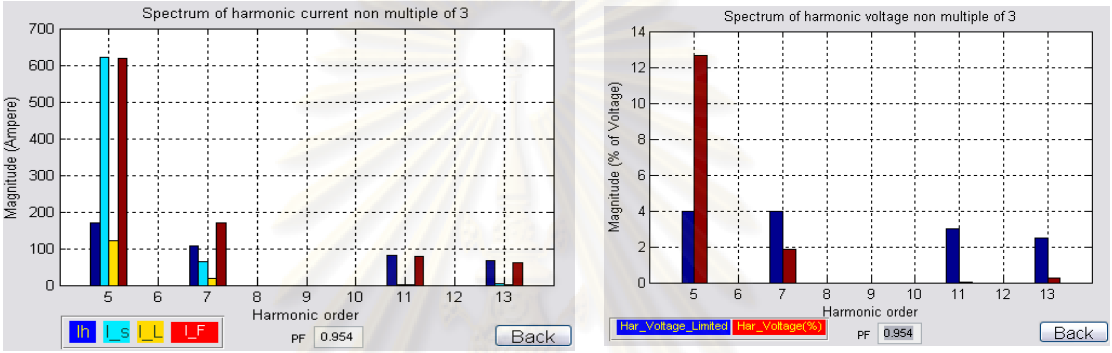
Tuning point
n5= 4.8
n7= 6.8
n11= 10.8

Select (kVAr) of filter
Vcr (V) 525 ☑ Ok
Qcr5 (kVAr) 0 0
Qcr7 (kVAr) 0 0
Qcr11(kVAr) 885.53 920

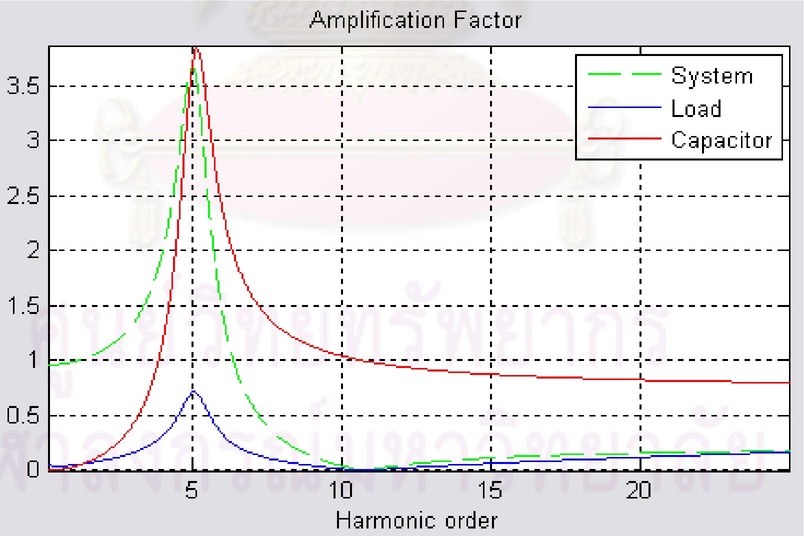
Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	0	0	0	0	0	0	0	0
7th	0	0	0	0	0	0	0	0
11th	920	1011.74	10624.77	0.3	0.0082	0.0026	50	0.0006

☑ Ok Next

(a) Passive filter design (11th order) **(b)** Impedance scan for case study 5



(c) Spectra of harmonic currents for case study 5 **(d)** Spectra of harmonic voltages for case study 5



(e) Harmonic current amplification in system, load and 11th order tuned filter

Figure 5.18 Results of case study 5

Table 5.28 Harmonic current flow in 11th order tuned filter

Order (h)	Ih (A)	Filter current (A)	
		640 kVAr / 440 V	920 kVAr / 525 V
1	902.11	770.04	777.51
5	169.03	611.08	619.51
7	107.3	172.01	171.07
11	80.72	79.71	79.72
13	66.47	60.91	60.96
17	48.43	41.15	41.21
19	39.88	33.16	33.21
23	31.34	25.30	25.35
25	25.64	20.47	20.51
29	19.94	15.63	15.67
31	14.24	11.08	11.10
$I_{h\ total}$	239.15	645.98	653.73
I_{rms}	933.27	1005.1	1015.8
I_{Cr}	0	839.78	1011.7
I_{rms} / I_{Cr}	0	1.2	1

Note: the 5th and 7th order current are amplified

Table 5.29   The result of calculation for case study 5

V_{CR} (V)	Q (kVAr)	PF	Low Voltage Side										
			$I_{11th\ filter}$				I_S		I_L		THD_V (%)		
			Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	Irms (A)	THD (%)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
440	640	0.953	645.98	1005.1	1.20	1.27	1848.2	35.71	1208.9	10.08	12.77	5	255.4
525	920	0.954	653.73	1015.8	1.00	1.06	1826.9	35.89	1209.0	10.12	12.81	5	256.2

Table 5.29 shows the results of calculation for case study 5

First condition (640kVAr / 440V, n =10.8), the power factor is 0.953, the ratio of rms current to rated current of tuned filter (I_{rms} / I_{cr} =1.20) and the total harmonic voltage distortion value at low voltage bus 400V THD_V =12.77%, which higher than the planning level.

Second condition (920kVAr / 525V, n=10.8), when increase rated voltage of capacitor from 440V to 525V, the power factor is 0.954, value of I_{rms} / I_{cr} =1.00, I_L / I_{cr} =1.06, which 11th order tuned filter can operate safely but the total harmonic voltage distortion value at low voltage bus 400V THD_V =12.81% is still higher than the planning level.

Table 5.30 The design parameter of 11th order tuned filters

Capacitor			Reactor		
Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
640	440	839.78	0.0083	1065.4	1463.1
920	525	1011.73	0.0082	1076.5	1477.3

5.2.8 Case study 6 (case study 0 with detuned filter and capacitor)

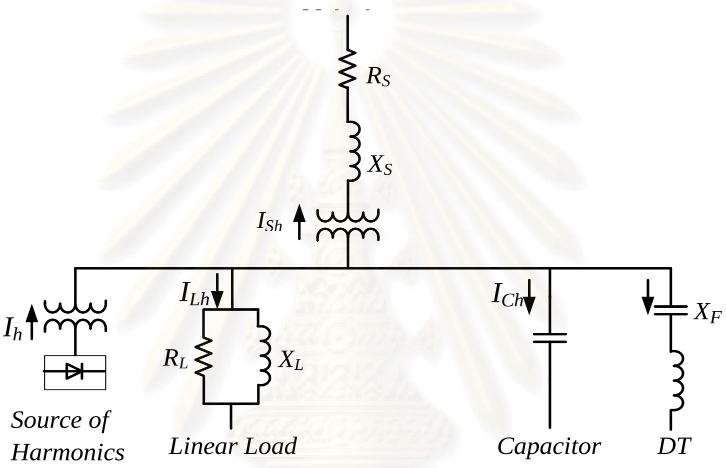


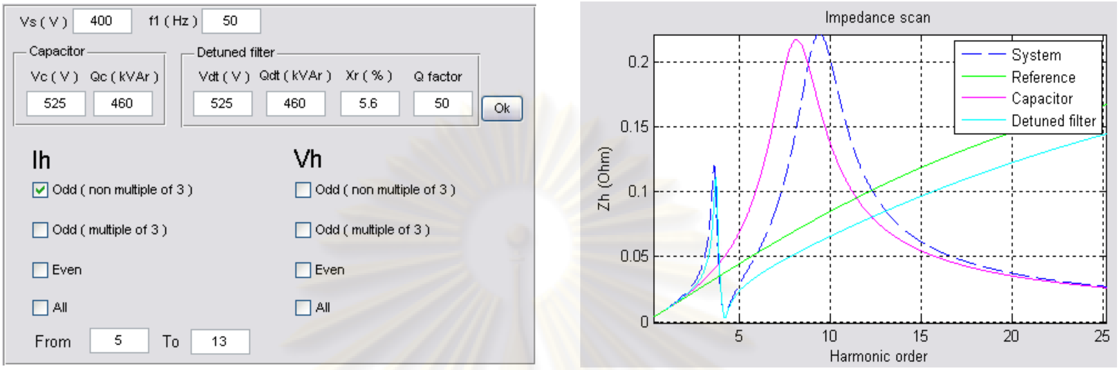
Figure 5.19 Single-line diagram of case study 6

Table 5.31 The input parameters

System	500 MVA_{SC}	22 kV	X/R 10	
Transformer	1000 kVA	22 kV/400 V	%Z = 6	P_k = 19.8 kW
LV Bus	400 V			
Non-Linear Load	500 kW	PF = 80 %		
Linear Load	650 kW	PF = 75 %		
Detuned filter	300,460, 620 kVAr	V_{cr} 525 V, Q-Factor 50, 5.6%X_L		
Capacitor	300,460, 620 kVAr	V_{cr} 525 V		

Case study 6 is case study 0 with capacitor and detuned filter. Which it's analyzing 3 conditions: first, for the capacitor (300kVAr / 525V), and detuned filter (620kVAr / 525V, %X_L=5.6). Second, for the capacitor (460kVAr / 525V), and detuned filter (460kVAr / 525V, %X_L=5.6) and third the capacitor (620kVAr / 525V), and detuned filter (300kVAr / 525V, %X_L=5.6).

5.2.8.1 Results of case study 6


Vs (V) 400
f1 (Hz) 50

Capacitor
Vc (V) 525
Qc (kVAr) 460

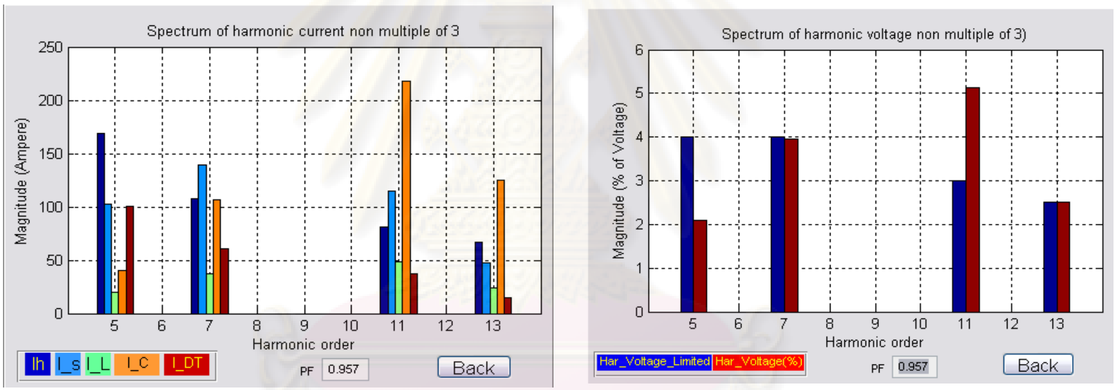
Detuned filter
Vdt (V) 525
Qdt (kVAr) 460
Xr (%) 5.6
Q factor 50

Ih
☑ Odd (non multiple of 3)
☐ Odd (multiple of 3)
☐ Even
☐ All

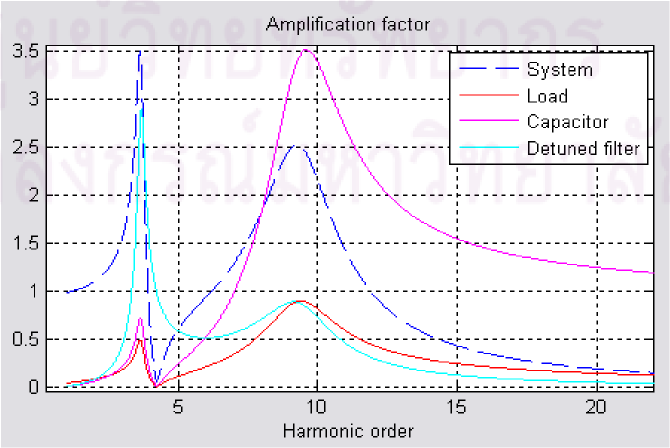
Vh
☐ Odd (non multiple of 3)
☐ Odd (multiple of 3)
☐ Even
☐ All

From 5 To 13

(a) Capacitor and detuned filter selection **(b)** Impedance scan for case study 6


PF 0.957

(c) Spectra of harmonic currents for case study 6 **(d)** Spectra of harmonic voltages for case study 6



(e) Harmonic current amplification in system, load, capacitor and tuned filter

Figure 5.20 Results of case study 6

Table 5.32 The result of calculation for case study 6

V_{CR} (V)	Q (kVAr)		Low Voltage Side									
			PF	I_C				I_{DT}				
	Cap	Detuned		Ihrms (A)	Irms (A)	Irms/Icr	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)
525	300	620	0.959	304.69	394.99	1.20	121.21	146.16	569.37	0.84	0.91	26.56
525	460	460	0.957	293.52	484.46	0.96	76.15	124.64	426.88	0.84	0.92	30.53
525	620	300	0.956	337.56	619.52	0.91	64.98	117.63	291.10	0.88	0.96	44.18

Low Voltage Side								
I_S			I_L			THD_V (%)		
Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
231.24	1726.2	13.52	94.51	1206.5	7.86	10.05	5	201.0
213.56	1716.1	12.4	69.55	1204.8	5.78	7.38	5	147.6
296.91	1721.3	17.51	78.76	1205.4	6.55	8.34	5	166.8

The results of case study 6 are summarized in table 5.32.

- The first condition: the power factor value is 0.959, for the capacitor (I_{rms} / I_{cr}=1.20), capacitor may fail due to high current flow in the capacitor. For detuned filter (I_{rms} / I_{cr} =0.84, I_L / I_{cr} =0.91) so it can operate safely and the total harmonic voltage distortion THD_V=10.05% which higher than planning level.
- The second condition: the power factor value is 0.957, for capacitor (I_{rms} / I_{cr}=0.96). For detuned filter (I_{rms} / I_{cr} =0.84, I_L / I_{cr} =0.92) so both capacitor and detuned filter can operate safely but total harmonic voltage distortion at low voltage bus THD_V=7.38% is still higher than planning level.
- The third condition: the power factor value is 0.956, for capacitor (I_{rms} / I_{cr}=0.91). For detuned filter (I_{rms} / I_{cr} =0.88, I_L / I_{cr} =0.96) so both capacitor and detuned filter can operate safely and total harmonic voltage distortion at low voltage bus THD_V=8.34% is still higher than planning level.

5.2.9 Case study 7 (case study 0 with 5th and 7th tuned filter)

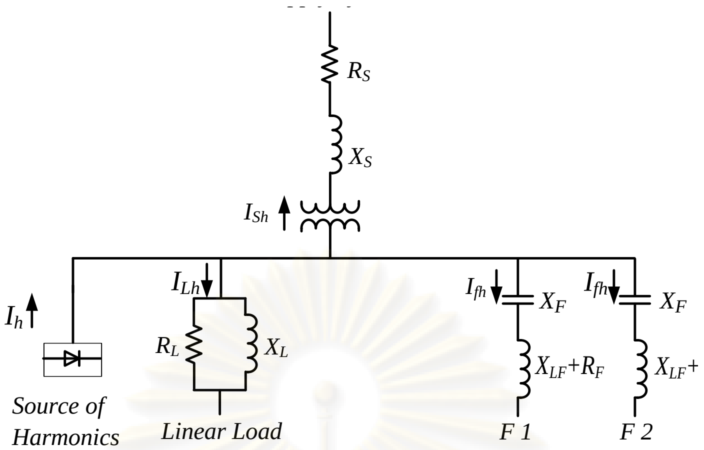


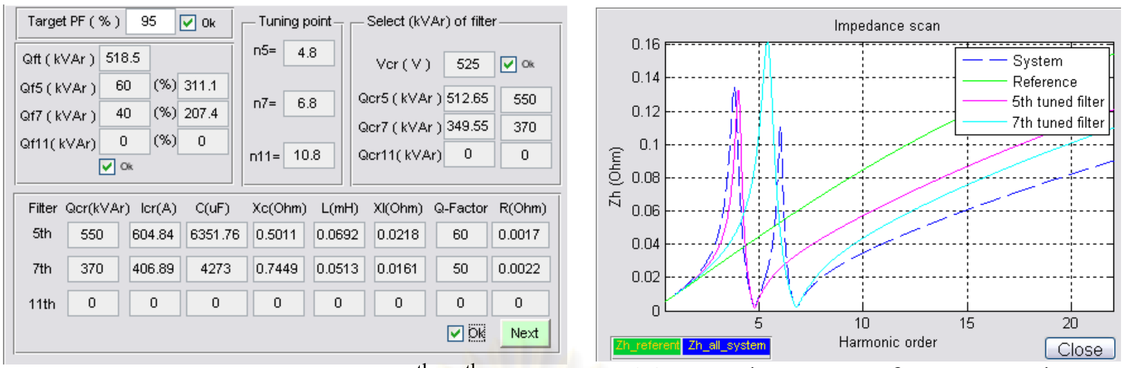
Figure 5.21 Single-line diagram of case study 7

Table 5.33 The input parameters

System	500 MVA_{SC}	22 kV	X/R 10	
Transformer	1000 kVA	22 kV/400 V	%Z = 6	P_k = 19.8 kW
LV Bus	400 V			
Non-Linear Load	500 kW	PF = 80 %		
Linear Load	650 kW	PF = 75 %		
5th tuned filter	50 % 460 kVA 60 % 550 kVAr	V_{cr} 525 V, Q-Factor 60		
7th tuned filter	50 % 460 kVAr 40 % 370 kVAr	V_{cr} 525 V, Q-Factor 50		

Case study 7 is case study 0 with 5th tuned filter and 7th tuned filter. Which it's analyzing 2 conditions: first condition 5th tuned filter (460kVAr / 525V, n=4.8), 7th tuned filter (460kVAr / 525V, n=6.8). Second condition 5th tuned filter (550kVAr / 525V, n=4.8), 7th tuned filter (370kVAr / 525V, n=6.8).

5.2.9.1 Results of case study 7


Target PF (%) 95 ☑ Ok

Qft (kVAr) 518.5
Qf5 (kVAr) 60 (%) 311.1
Qf7 (kVAr) 40 (%) 207.4
Qf11(kVAr) 0 (%) 0
☑ Ok

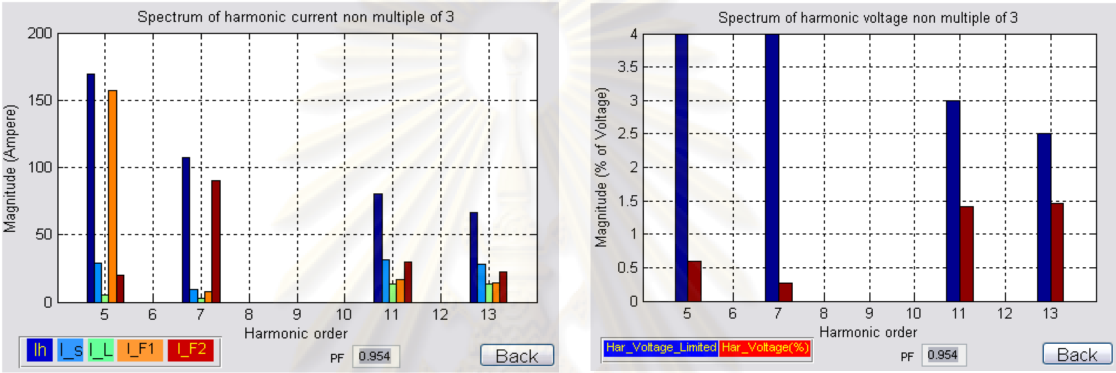
Tuning point
n5= 4.8
n7= 6.8
n11= 10.8

Select (kVAr) of filter
Vcr (V) 525 ☑ Ok
Qcr5 (kVAr) 512.65 550
Qcr7 (kVAr) 349.55 370
Qcr11(kVAr) 0 0

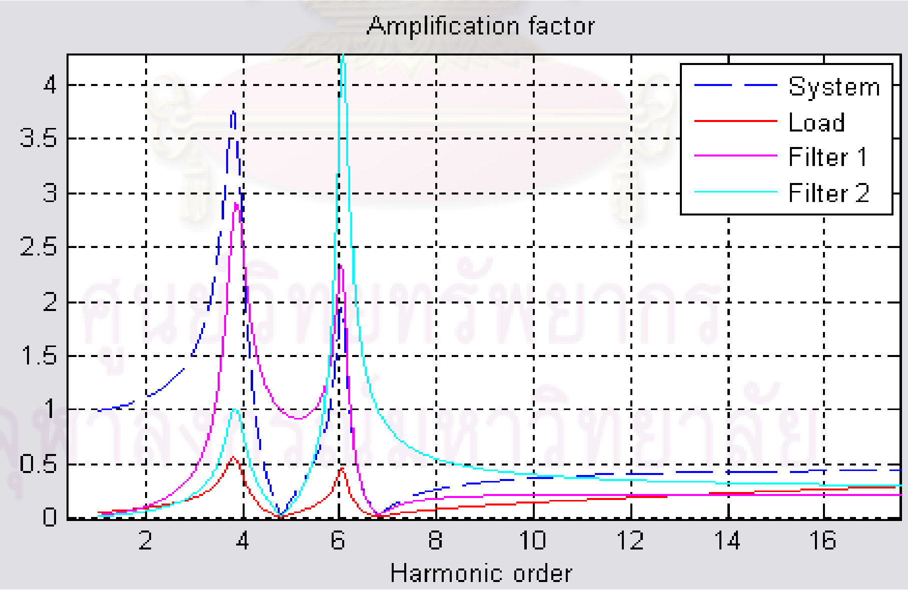
Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	550	604.84	6351.76	0.5011	0.0692	0.0218	60	0.0017
7th	370	406.89	4273	0.7449	0.0513	0.0161	50	0.0022
11th	0	0	0	0	0	0	0	0

☑ Ok Next

(a) Passive filter design (5th, 7th) **(b)** Impedance scan for case study 7



(c) Spectra of harmonic currents for case study 7 **(d)** Spectra of harmonic voltages for case study 7



(e) Harmonic current amplification in system, load and tuned filters

Figure 5.22 Result of case study 7

Table 5.34 The result of calculation for case study 7

V_{CR} (V)	Q (kVAr)		Low Voltage Side										
				$I_{5th\ filter}$					$I_{7th\ filter}$				
	5th	7th	PF	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)
525	460	460	0.954	162.18	434.33	0.86	0.93	40.25	111.48	409.41	0.81	0.88	28.30
525	550	370	0.955	159.97	507.60	0.84	0.92	33.21	102.16	332.93	0.82	0.89	32.24

Low Voltage Side								
I_S			I_L			THD_V (%)		
Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
63.36	1733.9	3.66	32.76	1203.3	2.72	3.49	5	69.8
62.23	1733.3	3.59	33.79	1203.3	2.81	3.60	5	72

From the results of both conditions, the filters can work safely as shown in table 5.34.

- The first condition, the power factor value is 0.954, for 5th tuned filter (I_{rms} / I_{cr} =0.86, I_L / I_{cr} =0.93), for 7th tuned filter (I_{rms}/ I_{cr} =0.81, I_L / I_{cr} =0.88) and the total harmonic voltage distortion at low voltage bus 400V THD_V=3.49% which lower than the planning level.
- The second condition, the power factor value is 0.955, for 5th tuned filter (I_{rms} / I_{cr} =0.84, I_L / I_{cr} =0.92), for 7th tuned filter (I_{rms}/ I_{cr} =0.82, I_L / I_{cr} =0.89) and the total harmonic voltage distortion at low voltage bus 400V THD_V=3.60% which lower than the planning level.
- Note: When operate both 5th and 7th tuned filter, it should turne on 5th tuned filter first, because if turn on 7th tuned filter first, it will amplify 5th harmonic current as shown in figure 5.21.b. and when turned off the filters, it must turn off 7th tuned filter first and following by 5th tuned filter.

Table 5.35 The design parameters of 5th and 7th tuned filters

5th tuned filter (%)	7th tuned filter (%)	5th tuned filter						7th tuned filter					
		Capacitor			Reactor			Capacitor			Reactor		
		Q_{cr}(kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr}(kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
50%	50%	460	525	505.87	0.0828	471.94	765.53	460	525	505.87	0.0412	447.45	748.49
60%	40%	550	525	604.84	0.0692	553.53	915.30	370	525	406.98	0.0513	363.22	602.05

5.2.10 Case study 8 (case study 0 with 7th and 11th tuned filter)

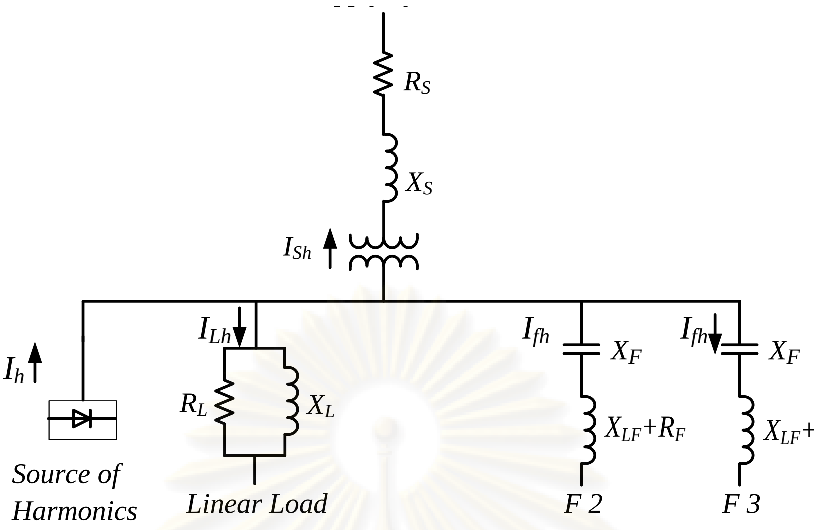


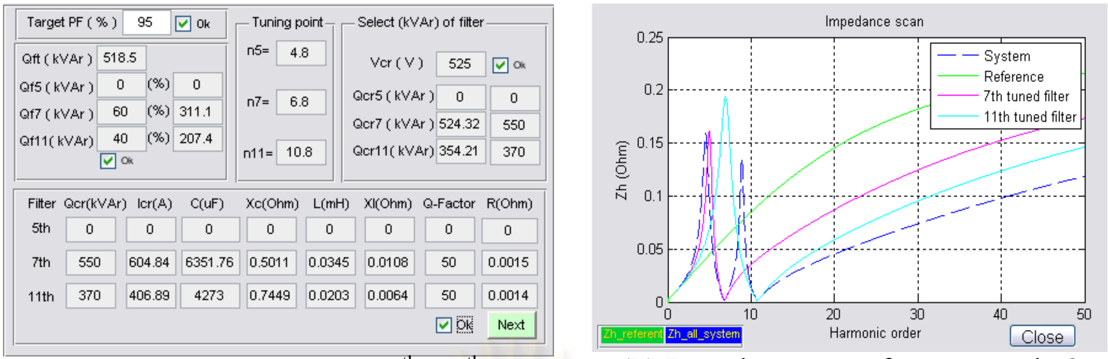
Figure 5.23 Single-line diagram of case study 8

Table 5.36 The input parameters for case study 8

System	500 MVA_{SC}	22 kV	X/R 10	
Transformer	1000 kVA	22 kV/400 V	%Z = 6	P_k = 19.8 kW
LV Bus	400 V			
Non-Linear Load	500 kW	PF = 80 %		
Linear Load	650 kW	PF = 75 %		
7th tuned filter	50 % 460 kVA 60 % 550 kVAr	V_{cr} 525 V, Q-Factor 50		
11th tuned filter	50 % 460 kVAr 40 % 370 kVAr	V_{cr} 525 V, Q-Factor 50		

Case study 8 is case study 0 with 7th tuned filter and 11th tuned filter. Which it's analyzing 2 conditions: first condition 7th tuned filter (460kVAr / 525V, n=6.8), 11th tuned filter (460kVAr / 525V, n=10.8). Second condition 7th tuned filter (550kVAr / 525V, n=6.8), 11th tuned filter (370kVAr / 525V, n=10.8).

5.2.10.1 Results of case study 8



Target PF (%) 95 ☑ Ok

Qft (kVAr) 518.5
Qf5 (kVAr) 0 (%) 0
Qf7 (kVAr) 60 (%) 311.1
Qf11(kVAr) 40 (%) 207.4
☑ Ok

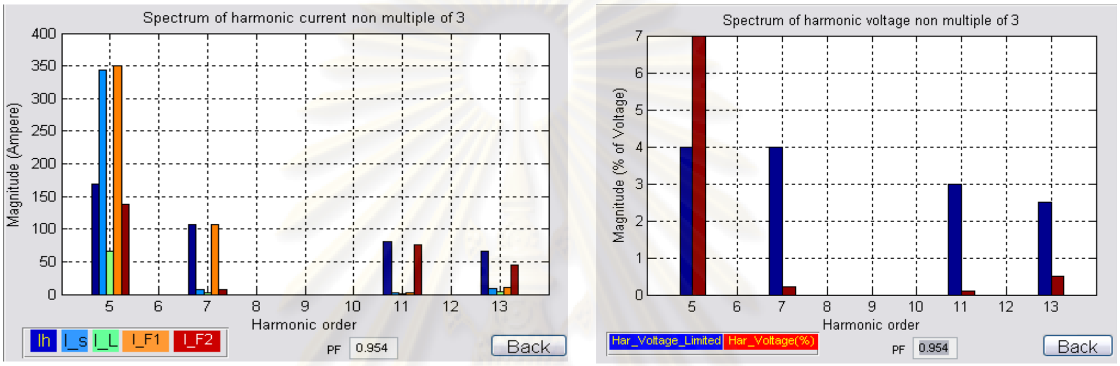
Tuning point
n5= 4.8
n7= 6.8
n11= 10.8

Select (kVAr) of filter
Vcr (V) 525 ☑ Ok
Qcr5 (kVAr) 0 0
Qcr7 (kVAr) 524.32 550
Qcr11(kVAr) 354.21 370

Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	0	0	0	0	0	0	0	0
7th	550	604.84	6351.76	0.5011	0.0345	0.0108	50	0.0015
11th	370	406.89	4273	0.7449	0.0203	0.0064	50	0.0014

☑ Ok Next

(a) Passive filter design (7th, 11th) **(b)** Impedance scan for case study 8

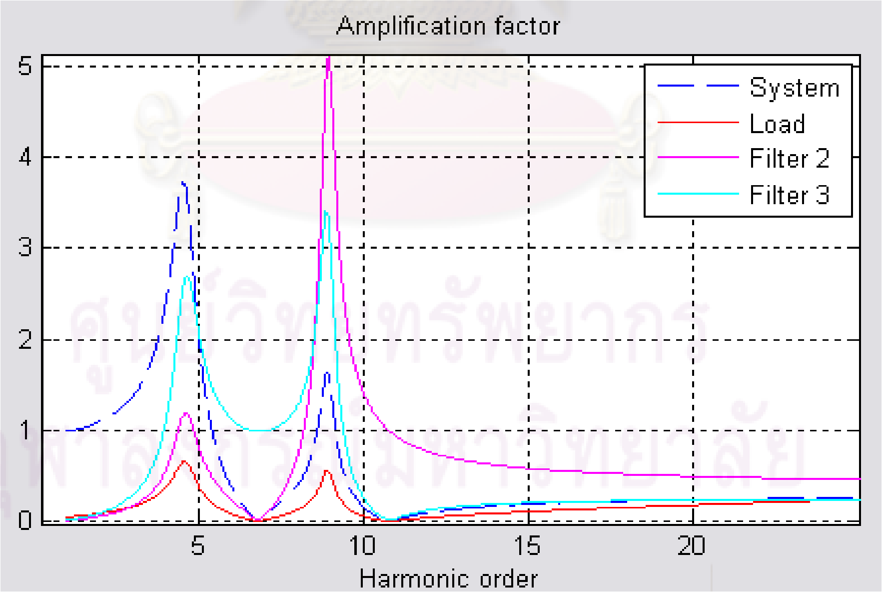


PF 0.954

PF 0.954

(c) Spectra of harmonic currents for case study 8

(d) Spectra of harmonic voltages for case study 8



(e) Harmonic current amplification in system, load and tuned filters

Figure 5.24 Results of case study 8

Table 5.37 The result of calculation for case study 8

V_{CR} (V)	Q (kVAr)		Low Voltage Side												
			PF	$I_{7th\ filter}$					$I_{11th\ filter}$				
	7th	11th		Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)
525	460	460	0.954	348.43	525.92	1.04	1.10	88.45	218.97	446.18	0.88	0.95	56.33
525	550	370	0.954	366.79	596.98	0.99	1.05	77.87	168.47	355.19	0.87	0.94	53.88

Low Voltage Side								
I_S			I_L			THD_V (%)		
Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
387.90	1779.6	22.33	76.40	1205.2	6.35	8.04	5	160.8
343.90	1770.3	19.80	68.31	1204.8	5.68	7.19	5	143.8

From the results of both conditions, the filters can work safely as shown in table 5.37.

- The first condition, the power factor value is 0.954, for 7th tuned filter (I_{rms} / I_{cr} =1.04 < 1.30, I_L / I_{cr} =1.10), for 11th tuned filter (I_{rms}/ I_{cr} =0.88, I_L / I_{cr} =0.95) and the total harmonic voltage distortion at low voltage bus 400V THD_V=8.04% which higher than the planning level.

- The second condition, the power factor value is 0.954, for 7th tuned filter (I_{rms} / I_{cr} =0.99, I_L / I_{cr} =1.05), for 11th tuned filter (I_{rms}/ I_{cr} =0.87, I_L / I_{cr} =0.94) and the total harmonic voltage at low volt bus 400V THD_V=7.17% which higher than the planning level.

- Note: It should not be operated this case to solve the problem from harmonic current because when turn on 7th tuned filter, it will amplify 5th harmonic current and cause to failure of a capacitor in 7th tuned filter.

Table 5.38 The design parameters of 7th and 11th tuned filters

7th tuned filter (%)	11th tuned filter (%)	7th tuned filter						11th tuned filter					
		Capacitor			Reactor			Capacitor			Reactor		
		Q_{cr}(kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr}(kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
50%	50%	460	525	505.87	0.04124	556.04	748.49	460	525	505.87	0.01635	480.44	738.64
60%	40%	550	525	604.84	0.03449	634.81	894.93	370	525	406.89	0.02032	383.01	594.12

5.2.11 Case study 9 (case study 0 with 5th and 11th tuned filter)

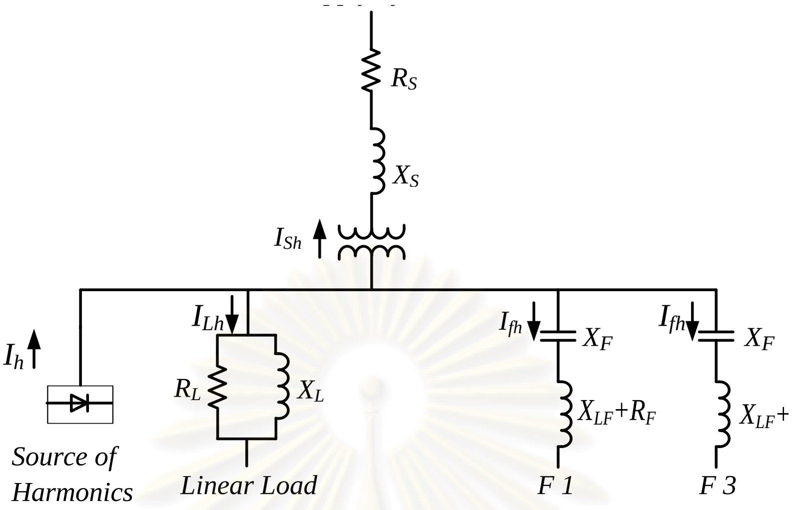


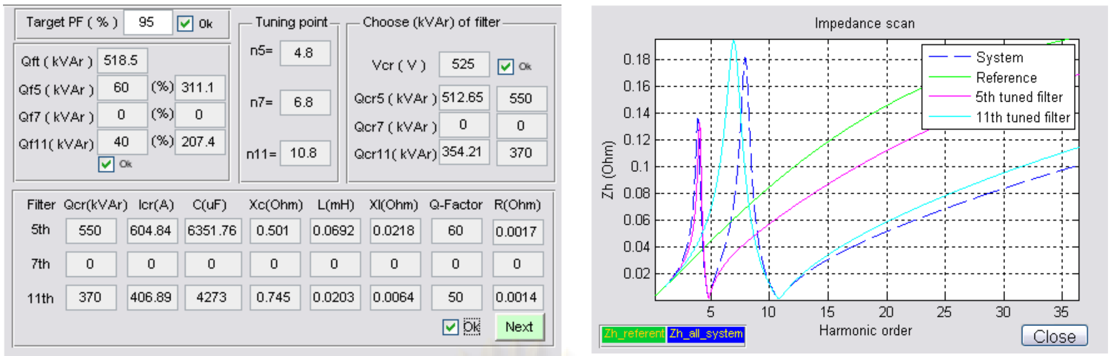
Figure 5.25 Single-line diagram of case study 9

Table 5.39 The input parameters case study 9

System	500 MVA_{SC}	22 kV	X/R 10	
Transformer	1000 kVA	22 kV/400 V	%Z = 6	P_k = 19.8 kW
LV Bus	400 V			
Non-Linear Load	500 kW	PF = 80 %		
Linear Load	650 kW	PF = 75 %		
5th tuned filter	50 % 460 kVA 60 % 550 kVAr	V_{cr} 525 V, Q-Factor 60		
11th tuned filter	50 % 460 kVAr 40 % 370 kVAr	V_{cr} 525 V, Q-Factor 50		

Case study 9 is case study 0 with 5th tuned filter and 11th tuned filter. Which it's analyzing 2 conditions: first condition 5th tuned filter (460kVAr / 525V, n=4.8), 11th tuned filter (460kVAr / 525V, n=10.8). Second condition 5th tuned filter (550kVAr / 525V, n=6.8), 11th tuned filter (370kVAr / 525V, n=10.8).

5.2.11.1 Results of case study 9



Target PF (%) 95 ☑ Ok

Qft (kVAr) 518.5
Qf5 (kVAr) 60 (%) 311.1
Qf7 (kVAr) 0 (%) 0
Qf11(kVAr) 40 (%) 207.4
☑ Ok

Tuning point
n5= 4.8
n7= 6.8
n11= 10.8

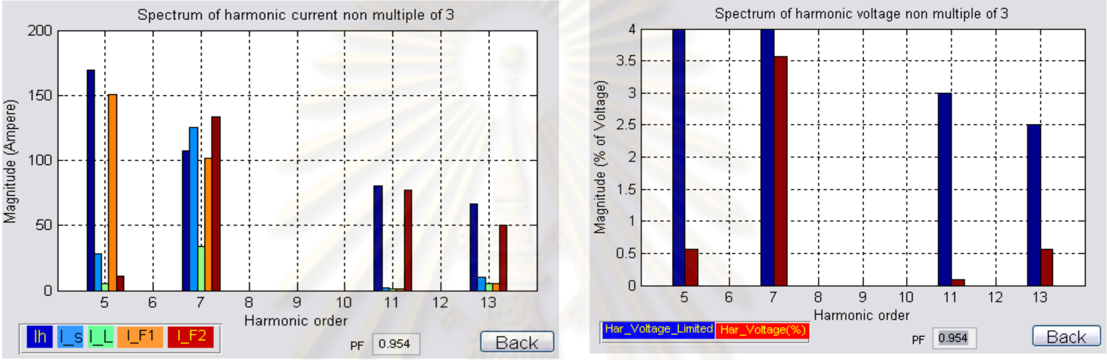
Choose (kVAr) of filter
Vcr (V) 525 ☑ Ok
Qcr5 (kVAr) 512.65 550
Qcr7 (kVAr) 0 0
Qcr11(kVAr) 354.21 370

Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	550	604.84	6351.76	0.501	0.0692	0.0218	60	0.0017
7th	0	0	0	0	0	0	0	0
11th	370	406.89	4273	0.745	0.0203	0.0064	50	0.0014

☑ Ok

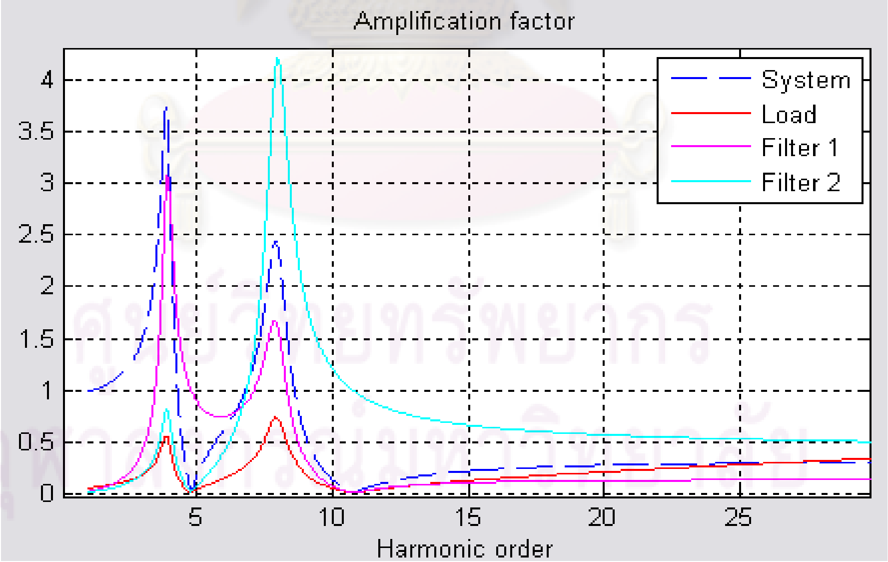
(a) Passive filter design (5th, 11th)

(b) Impedance scan for case study 9



(c) Spectra of harmonic currents for case study 9

(d) Spectra of harmonic voltages for case study 9



(e) Harmonic current amplification in system, load and tuned filters

Figure 5.26 Results of case study 9

Table 5.40 The result of calculation for case study 9

V_{CR} (V)	Q (kVAr)		Low Voltage Side										
			PF	$I_{5th\ filter}$					$I_{11th\ filter}$				
	5^{th}	11^{th}		Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)
525	460	460	0.954	204.21	451.70	0.89	0.96	50.68	289.73	484.85	0.96	1.02	74.53
525	550	550	0.954	183.08	515.00	0.85	0.93	37.80	168.50	355.21	0.87	0.94	53.89

Low Voltage Side								
I_S			I_L			THD_V (%)		
Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
206.77	1746.5	11.92	57.31	1204.2	4.76	6.07	5	121.4
130.41	1738.3	7.52	38.61	1203.4	3.21	4.09	5	81.8

From the results of both conditions, the filters can work safely as shown in table 5.40.

- The first condition, the power factor value is 0.954, for 5th tuned filter (I_{rms} / I_{cr} =0.89, I_L / I_{cr} =0.96), for 11th tuned filter (I_{rms}/ I_{cr} =0.96, I_L / I_{cr} =1.02) and the total harmonic voltage distortion at low voltage bus 400V THD_V=6.07% which higher than the planning level.
- The second condition, the power factor value is 0.954, for 5th tuned filter (I_{rms} / I_{cr} =0.85, I_L / I_{cr} =0.93), for 11th tuned filter (I_{rms}/ I_{cr} =0.87, I_L / I_{cr} =0.94) and the total harmonic voltage distortion at low voltage bus 400V THD_V=4.09% which lower than the planning level
- Note: When operate both 5th and 11th tuned filter, it should turn on 5th tuned filter first, because if turn on 11th tuned filter first, it will be amplify 5th harmonic current as shown in figure 5.25.b. and when turn off the filters, it must turn off 11th tuned filter first and following by 5th tuned filter.

Table 5.41 The design parameters of 5th and 11th tuned filters

Tuned filter 5th (%)	Tuned filter 11th (%)	5th tuned filter						11th tuned filter					
		Capacitor			Reactor			Capacitor			Reactor		
		Q_{cr}(kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr}(kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
50%	50%	460	525	505.87	0.0828	487.99	765.53	460	525	505.87	0.0164	516.54	738.64
60%	40%	550	525	604.84	0.0692	560.32	915.30	370	525	406.89	0.0203	383.02	594.12

5.2.12 Case study 10 (case study 0 with 5th, 7th and 11th tuned filter)

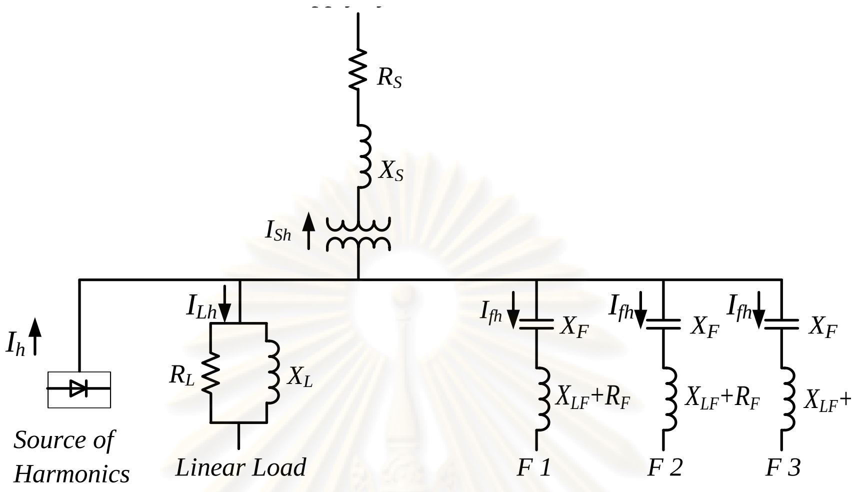


Figure 5.27 Single-line diagram of case study 10

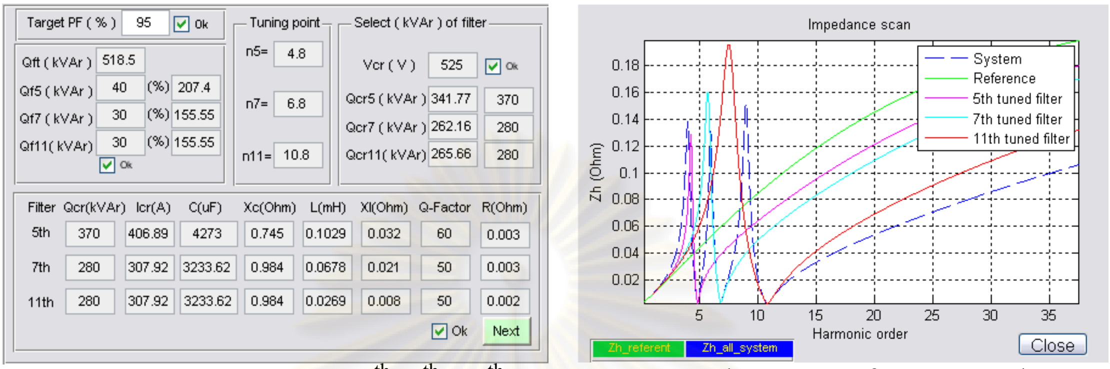
Table 5.42 The input parameters for case study 10

System	500 MVA$_{SC}$	22 kV	X/R 10	
Transformer	1000 kVA	22 kV/400 V	%Z = 6	P$_k$ = 19.8 kW
LV Bus	400 V			
Non-Linear Load	500 kW	PF = 80 %		
Linear Load	650 kW	PF = 75 %		
5th tuned filter	33 % (310 kVAr) 40 % (370 kVAr)	V$_{cr}$ 525 V, Q-Factor 60		
7th tuned filter	33 % (310 kVAr) 30 % (280 kVAr)	V$_{cr}$ 525 V, Q-Factor 50		
11th tuned filter	33 % (310 kVAr) 30 % (280 kVAr)	V$_{cr}$ 525 V, Q-Factor 50		

Case study10 is case study 0 with 5th, 7th and 11th tuned filters. Which it's analyzing 2 conditions: first condition 5th tuned filter (310kVAr / 525V, n=4.8), 7th tuned filter (310kVAr / 525V, n=6.8) and 11th tuned filter (310kVAr / 525V, n=10.8).

Second condition 5th tuned filter (370kVAr / 525V, n=6.8), 7th tuned filter (280kVAr / 525V, n=6.8) and 11th tuned filter (280kVAr / 525V, n=10.8).

5.2.12.1 Results of case study 10



Target PF (%) 95 ☑ Ok

Qft (kVAr) 518.5
Qf5 (kVAr) 40 (%) 207.4
Qf7 (kVAr) 30 (%) 155.55
Qf11(kVAr) 30 (%) 155.55
☑ Ok

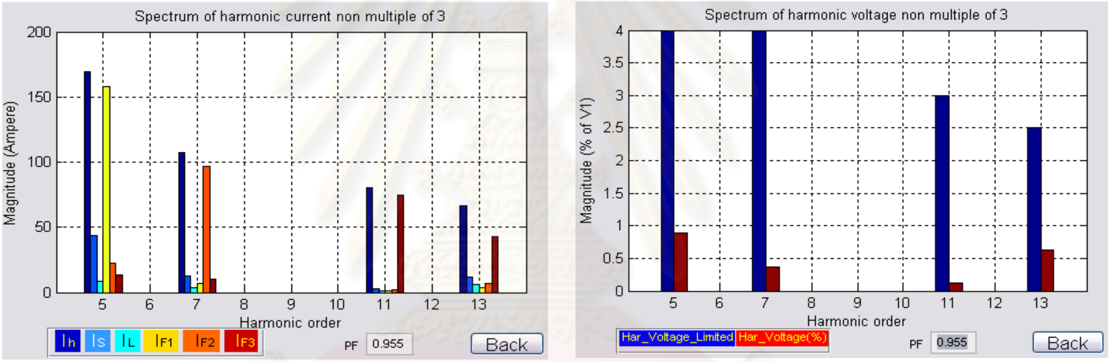
Tuning point
n5= 4.8
n7= 6.8
n11= 10.8

Select (kVAr) of filter
Vcr (V) 525 ☑ Ok
Qcr5 (kVAr) 341.77 370
Qcr7 (kVAr) 262.16 280
Qcr11(kVAr) 265.66 280

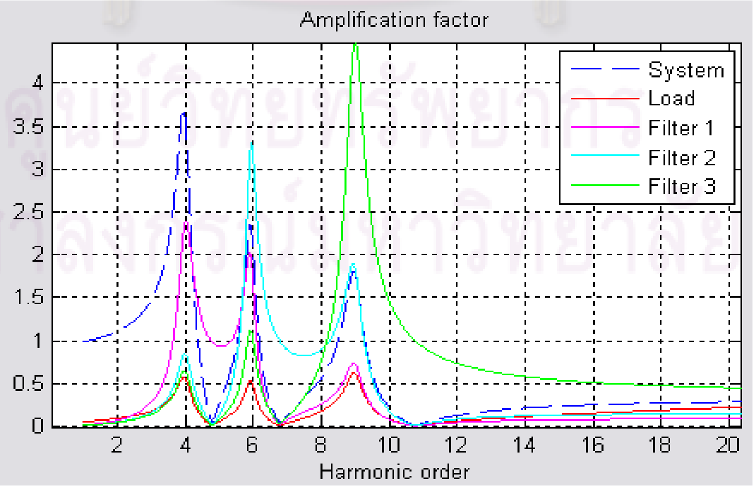
Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	370	406.89	4273	0.745	0.1029	0.032	60	0.003
7th	280	307.92	3233.62	0.984	0.0678	0.021	50	0.003
11th	280	307.92	3233.62	0.984	0.0269	0.008	50	0.002

☑ Ok

(a) Passive filter design (5th, 7th, 11th) **(b)** Impedance scan for case study 10



(c) Spectra of harmonic currents for case study 10 **(d)** Spectra of harmonic voltages for case study 10



(e) Harmonic current amplification in system, load and tuned filters

Figure 5.28 Results of case study 10

Table 5.43 The result of calculation for case study 10

V_{CR} (V)	Q (kVAr)			Low Voltage Side										
				PF	$I_{5th\ filter}$					$I_{7th\ filter}$				
	5^{th}	7^{th}	41.63		Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD(%)
525	310	310	310	0.955	159.78	315.05	0.92	0.99	58.85	104.53	285.32	0.84	0.91	39.37
525	370	280	280	0.955	157.96	360.52	0.89	0.96	48.74	99.83	259.74	0.84	0.92	41.63

Low Voltage Side													
$I_{11th\ filter}$					I_S			I_L			THD_V (%)		
Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%)of PL
97.38	279.50	0.82	0.89	37.17	58.88	1733.1	3.40	21.03	1203.0	1.75	2.23	5	44.6
94.84	254.93	0.83	0.90	40.08	51.83	1732.5	2.99	21.08	1203.0	1.75	2.24	5	44.8

The summarized of the results of case study 10 in two conditions is illustrated in table 5. 43. It is noticed that the 5th, 7th and 11th tuned filters can operate safely and the THD_V values of two conditions are within planning level.

- If compare two conditions, the second condition 5th (40%), 7th (30%) and 11th detuned filter (30%) can operate better than the first condition.

  Note: In case of using all 5th, 7th and 11th tuned filter, work in the same time. There should be divided kVAr which followed harmonic current data in the system, in order to get high capacity.

When there will utilize all of tuned filters, it suggests that should be switched on the 5th tuned filter first and follows by 7th and 11th tuned filter respectively. In case, if 11th is firstly turned on it will trigger the amplification of the 5th, 7th respectively or if 7th tuned filter is switched on first, it will cause the amplification of the 5th harmonic current as a show in figure 5.27.b.

In case the 5th, 7th and 11th tuned filters are operated in the same time, when turn off, it is recommended to switch off the 11th first, 7th and 5th tuned filter must be there after turned off respectively. In order to prevented the amplification of harmonic current.

Table 5.44 The design parameters of 5th, 7th and 11th tuned filters

Tuned filter 5th (%)	Tuned filter 7th (%)	Tuned filter 11th (%)	5th tuned filter						7th tuned filter					
			Capacitor			Reactor			Capacitor			Reactor		
			Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
33%	33%	33%	310	525	340.9	0.123	338.73	515.9	310	525	340.9	0.0612	310.2	504.4
40%	30%	30%	370	525	406.9	0.103	389.92	615.8	280	525	307.9	0.0678	282.0	455.6

Table 5.44 The design parameters of 5^{th}, 7^{th} and 11^{th} tuned filters (cont.)

11^{th} tuned filter					
Capacitor			Reactor		
Q_{cr}(kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
310	525	340.91	0.0243	304.19	497.78
280	525	307.92	0.0269	277.04	449.60

5.2.13 Case study 11 (case study 0 with detuned filter, 7^{th} and 11^{th} tuned filter

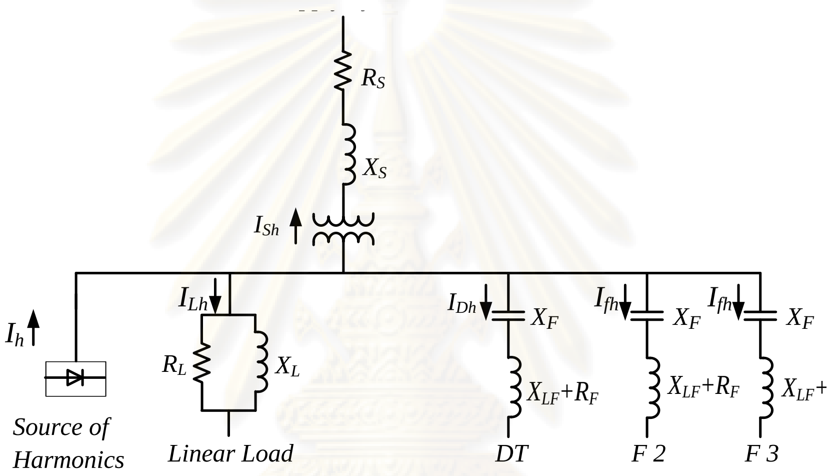


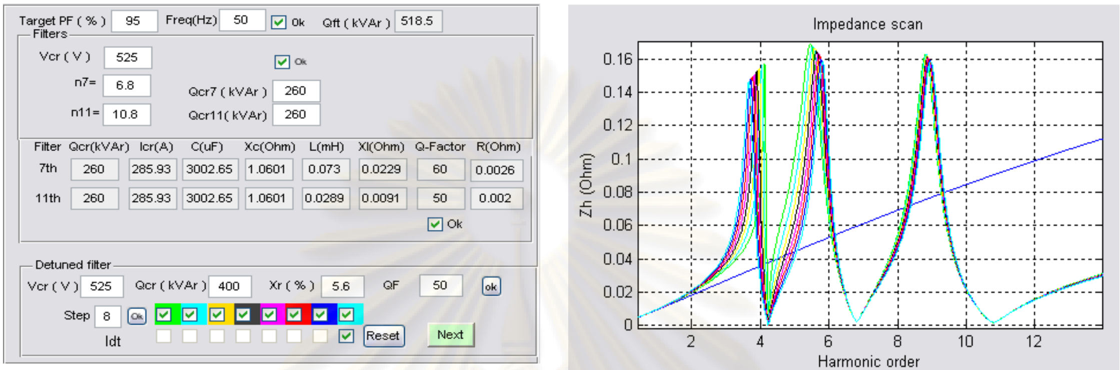
Figure 5.29 Single-line diagram of case study 11

Table 5.45 The input parameters for case study 11

System	500 MVA_{SC}	22 kV	X/R 10	
Transformer	1000 kVA	22 kV/400 V	%Z = 6	P_k = 19.8 kW
LV Bus	400 V			
Non-Linear Load	500 kW	PF = 80 %		
Linear Load	650 kW	PF = 75 %		
Detuned filter	400 kVAr / 525 V	Q-Factor 50, $\%X_L$ (5.6 & 7)		
7^{th} tuned filter	260 kVAr / 525 V	Q-Factor 50, Tuning point 6.8		
11th tuned filter	260 kVAr / 525 V	Q-Factor 50, Tuning point 10.8		

Case study 11 is case study 0 with detuned filters, 7th and 11th tuned filters. Which it's analyzing 2 conditions: first condition detuned filter (50kVAr / 525V, $\%X_L$=5.6, 8 step), 7th tuned filter (260kVAr / 525V, n=6.8), 11th tuned filter (260kVAr / 525V, n=10.8). Second condition detuned filter (50kVAr / 525V, $\%X_L$= 7, 8 step), 7th tuned filter (260kVAr / 525V, n=6.8), 11th tuned filter (260kVAr / 525V, n=10.8).

5.2.13.1 Results of case study 11 for detuned filter 5.6% XL



Target PF (%) 95 Freq(Hz) 50 ☑ Ok Qft (kVAr) 518.5

Filters

Vcr (V) 525 ☑ Ok

n7= 6.8 Qcr7 (kVAr) 260

n11= 10.8 Qcr11(kVAr) 260

Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
7th	260	285.93	3002.65	1.0601	0.073	0.0229	60	0.0026
11th	260	285.93	3002.65	1.0601	0.0289	0.0091	50	0.002

☑ Ok

Detuned filter

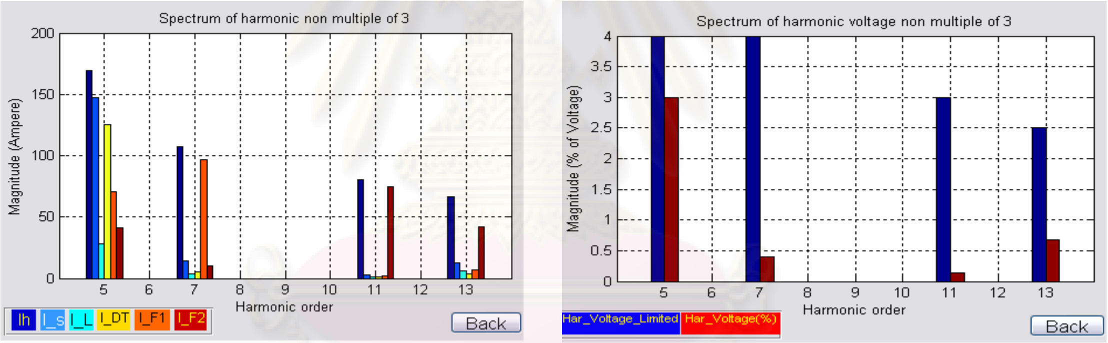
Vcr (V) 525 Qcr (kVAr) 400 Xr (%) 5.6 QF 50

Step 8 ☑ ☑ ☑ ☑ ☑ ☑ ☑ ☑

Idt ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☑

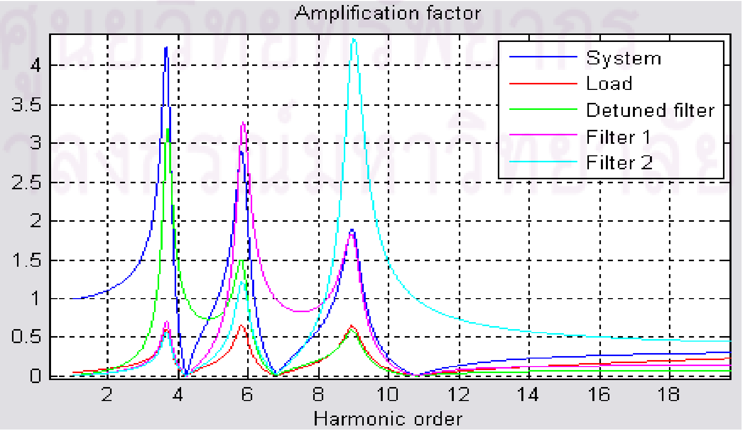
(a) Passive filter design (detuned filter, 7th, 11th)

(b) Impedance scan for case study 11



(c) Spectra of harmonic currents for case study 11

(d) Spectra of harmonic voltages for case study 11



(e) Harmonic current amplification in system, load, detuned filters and tuned filters

Figure 5.30 Results of case study 11

Table 5.46 The results of calculation for case study 11(detuned filter 5.6%X_L)

Step	V_{CR} (V)	Q (kVAr)			Low Voltage Side										
					PF	DT					$I_{7th\ filter}$				
		DT	7th filter	11th filter		Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)
1	525	50	260	260	0.899	39.07	59.12	1.08	1.14	88.03	204.22	302.14	1.06	1.12	91.72
2	525	100	260	260	0.909	65.48	110.30	1.00	1.07	73.78	179.65	286.10	1.00	1.06	80.68
3	525	150	260	260	0.918	83.85	157.34	0.95	1.02	62.98	161.83	275.26	0.96	1.03	72.68
4	525	200	260	260	0.927	97.11	202.34	0.92	0.99	54.70	148.77	267.79	0.94	1.00	66.82
5	525	250	260	260	0.935	107.02	246.36	0.90	0.97	48.23	139.01	262.49	0.92	0.98	62.43
6	525	300	260	260	0.943	114.67	289.92	0.88	0.95	43.07	131.54	258.61	0.90	0.97	59.07
7	525	350	260	260	0.951	120.74	333.29	0.87	0.94	38.87	125.68	255.68	0.89	0.96	56.44
8	525	400	260	260	0.958	125.65	376.61	0.86	0.93	35.39	120.99	253.41	0.89	0.96	54.34

Table 5.46 The results of calculation for case study 11(detuned filter 5.6%X_L)(continues)

Step	Low Voltage Side													
	$I_{11th\ filter}$					I_S			I_L			THD_V (%)		
	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
1	140.97	261.06	0.91	0.98	64.15	367.70	1882.0	19.92	74.14	1205.1	6.16	7.81	5	156.2
2	128.92	254.76	0.89	0.96	58.65	308.57	1852.7	16.89	63.19	1204.5	5.25	6.66	5	133.2
3	120.49	250.60	0.88	0.94	54.83	263.85	1827.8	14.59	55.02	1204.1	4.57	5.80	5	116.0
4	114.49	247.77	0.87	0.94	52.10	229.61	1806.2	12.82	48.86	1203.8	4.06	5.15	5	103.0
5	110.11	245.78	0.86	0.93	50.11	202.88	1786.9	11.43	44.12	1203.6	3.67	4.66	5	93.2
6	106.82	244.32	0.85	0.92	48.61	181.59	1769.4	10.32	40.41	1203.5	3.36	4.27	5	85.4
7	104.28	243.22	0.85	0.92	47.46	164.31	1753.5	9.41	37.45	1203.4	3.11	3.96	5	79.2
8	102.26	242.36	0.85	0.92	46.54	150.05	1739.0	8.66	35.04	1203.3	2.91	3.70	5	74.0

5.2.13.2 Results of case study 11 for detuned filter 7% X_L

Table 5.47 The result of calculation for case study 11(detuned filter 7%X_L)

Step	V_{CR} (V)	Q (kVAr)			Low Voltage Side										
					PF	DT					$I_{7th\ filter}$				
		DT	7th filter	11th filter		Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)
1	525	50	260	260	0.899	22.76	50.47	0.92	0.99	50.53	218.54	311.99	1.09	1.15	98.15
2	525	100	260	260	0.909	41.18	99.06	0.90	0.98	45.71	202.21	300.78	1.05	1.11	90.82
3	525	150	260	260	0.918	56.13	146.33	0.89	0.96	41.53	188.35	291.64	1.02	1.08	84.59
4	525	200	260	260	0.927	68.36	192.72	0.88	0.95	37.94	176.66	284.23	0.99	1.06	79.34
5	525	250	260	260	0.936	78.47	238.51	0.87	0.95	34.84	166.80	278.21	0.97	1.04	74.91
6	525	300	260	260	0.944	86.92	283.91	0.86	0.94	32.16	158.46	273.29	0.96	1.02	71.16
7	525	350	260	260	0.952	94.05	329.06	0.85	0.93	29.83	151.36	269.24	0.94	1.01	67.98
8	525	400	260	260	0.959	100.14	374.03	0.85	0.93	27.79	145.28	265.87	0.93	1.00	65.25

Table 5.47 The result of calculation for case study 11(detuned filter 7%X_L) (continues)

Step	Low Voltage Side													
	$I_{11th\ filter}$					I_S			I_L			THD$_V$ (%)		
	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
1	148.14	265.0	0.93	0.99	67.42	401.30	1888.6	21.75	80.41	1205.5	6.68	8.47	5	169.4
2	139.90	260.49	0.91	0.98	63.67	363.21	1862.0	19.89	73.28	1205.0	6.09	7.72	5	154.4
3	133.04	256.87	0.90	0.96	60.55	330.24	1837.8	18.27	67.14	1204.7	5.58	7.07	5	141.4
4	127.36	253.97	0.89	0.96	57.96	301.84	1815.8	16.85	61.88	1204.4	5.14	6.52	5	130.4
5	122.65	251.64	0.88	0.95	55.82	277.38	1795.7	15.63	57.39	1204.2	4.77	6.05	5	121.0
6	118.72	249.75	0.87	0.94	54.03	256.23	1777.3	14.57	53.53	1204.0	4.45	5.64	5	112.8
7	115.42	248.20	0.87	0.94	52.53	237.84	1760.5	13.64	50.19	1203.9	4.17	5.29	5	105.8
8	112.63	246.92	0.86	0.93	51.26	221.78	1745.2	12.81	47.30	1203.7	3.93	4.99	5	99.8

The results of calculation case study 11, when using detuned filters together with 7th and 11th tuned filters, are concluded in table 5.46 and 5.47. All filters can be operated satisfactory because the ratio of I_{rms} / I_{Cr} < 1.30.

Table 5.48 The design parameters of detuned filters, 7th and 11th tuned filters

Detuned filter							7th tuned filter						11th tuned filter					
Capacitor			Reactor				Capacitor			Reactor			Capacitor			Reactor		
Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	$\%X_L$	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
8x50	525	55	5.6	0.981	58.9	84.47	260	525	285.9	0.073	340.3	423.1	260	525	285.9	0.029	288.4	417.5
8x50	525	55	7.0	1.24	52.07	84.47	260	525	285.9	0.073	340.3	423.1	260	525	285.9	0.029	288.4	417.5

5.2.14 Case study 12 (case study 0 with detuned filter, 5th and 7th tuned filters)

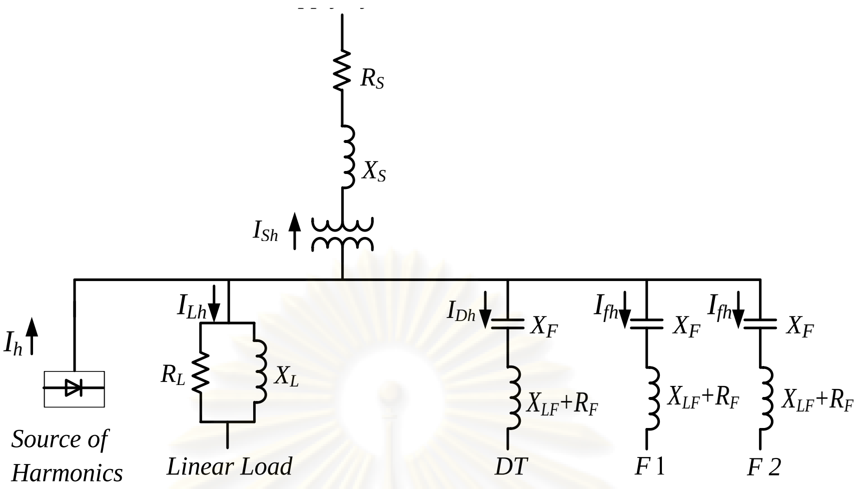


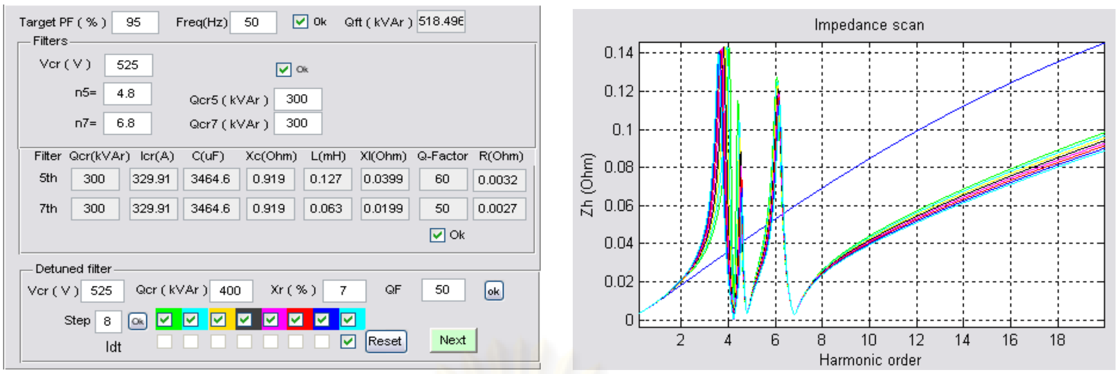
Figure 5.31 Single-line diagram of case study 12

Table 5.49 The input parameters for case study 12

System	500 MVA_{SC}	22 kV	X/R 10	
Transformer	1000 kVA	22 kV/400 V	%Z = 6	P_k = 19.8 kW
LV Bus	400 V			
Non-Linear Load	500 kW	PF = 80 %		
Linear Load	650 kW	PF = 75 %		
Detuned filter	400 kVAr / 525 V	Q-Factor 50, $\%X_L$ (5.6 & 7)		
5th tuned filter	260 kVAr / 525 V	Q-Factor 50, Tuning point 4.8		
7th tuned filter	260 kVAr / 525 V	Q-Factor 50, Tuning point 6.8		

Case study 12 is case study 0 with detuned filters, 5th and 7th tuned filter. Which it's analyzing 2 conditions: first condition detuned filter (50kVAr / 525V, $\%X_L$=5.6, 8 step), 5th tuned filter (260kVAr / 525V, n=4.8), 7th tuned filter (260kVAr / 525V, n=6.8). Second condition detuned filter (50kVAr / 525V, $\%X_L$= 7, 8 step), 5th tuned filter (260kVAr / 525V, n=4.8), 7th tuned filter (260kVAr / 525V, n=6.8).

5.2.14.1 Results of case study 12 for detuned filter 5.6% X_L



Target PF (%) 95 Freq(Hz) 50 ☑ Ok Qft (kVAr) 518.496

Filters

Vcr (V) 525 ☑ Ok

n5= 4.8 Qcr5 (kVAr) 300

n7= 6.8 Qcr7 (kVAr) 300

Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	300	329.91	3464.6	0.919	0.127	0.0399	60	0.0032
7th	300	329.91	3464.6	0.919	0.063	0.0199	50	0.0027

☑ Ok

Detuned filter

Vcr (V) 525 Qcr (kVAr) 400 Xr (%) 7 QF 50

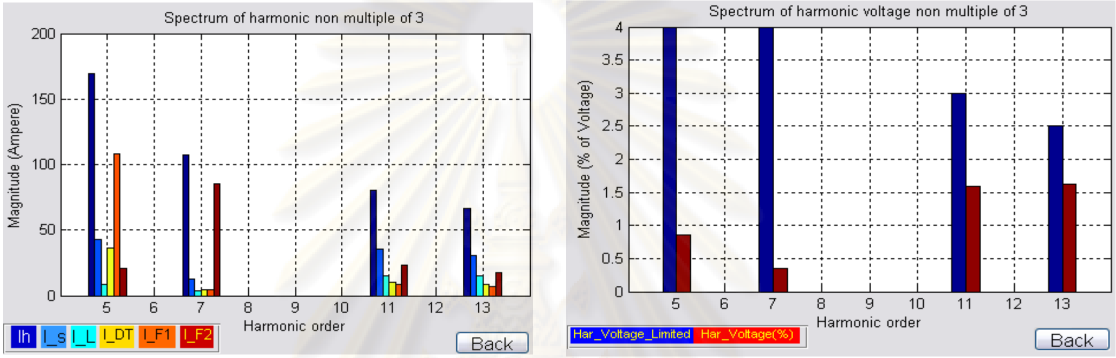
Step 8

☑ ☑ ☑ ☑ ☑ ☑ ☑ ☑

Idt ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☑

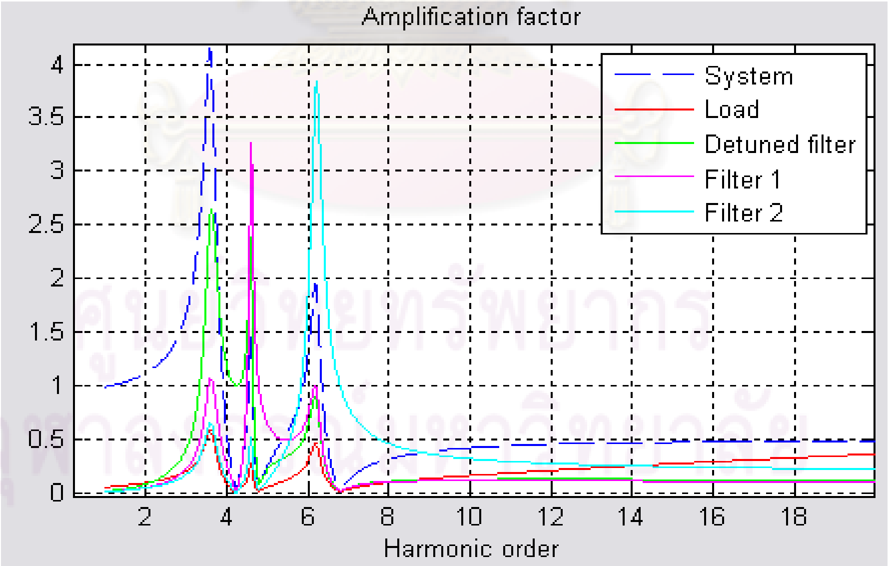
(a) Passive filter design (detuned filter, 5^{th}, 7^{th})

(b) Impedance scan for case study 12



(c) Spectra of harmonic currents for case study 12

(d) Spectra of harmonic voltages for case study 12



(e) Harmonic current amplification in system, load, detuned and tuned filters

Figure 5.32 Results of case study 12

Table 5.50 **The results of calculation for case study 12 (detuned filter 5.6%X_L)**

Step	V_{CR} (V)	Q (kVAr)			Low Voltage Side										
					PF	DT					$I_{5th\ filter}$				
		DT	5th filter	7th filter		Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)
1	525	50	260	260	0.901	6.01	44.78	0.81	0.89	13.55	133.78	264.12	0.92	0.99	58.75
2	525	100	260	260	0.91	11.68	89.52	0.81	0.89	13.16	129.68	262.07	0.92	0.99	56.95
3	525	150	260	260	0.919	17.04	134.22	0.81	0.89	12.80	125.83	260.18	0.91	0.98	55.25
4	525	200	260	260	0.928	22.11	178.89	0.81	0.89	12.45	122.18	258.44	0.90	0.97	53.65
5	525	250	260	260	0.936	26.91	223.52	0.81	0.89	12.13	118.75	256.83	0.90	0.97	52.14
6	525	300	260	260	0.945	31.47	268.13	0.81	0.89	11.82	115.49	255.34	0.89	0.96	50.71
7	525	350	260	260	0.952	35.81	312.71	0.81	0.89	11.53	112.41	253.96	0.89	0.96	49.36
8	525	400	260	260	0.959	39.94	357.27	0.81	0.89	11.25	109.48	252.68	0.88	0.96	48.08

Table 5.50 The results of calculation for case study 12 (detuned filter 5.6%X_L) (continues)

Step	Low Voltage Side													
	$I_{7th\ filter}$					I_S			I_L			THD_V (%)		
	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
1	99.17	243.75	0.85	0.92	44.54	85.34	1844.2	4.63	41.52	1203.5	3.45	4.42	5	88.4
2	98.32	243.40	0.85	0.92	44.16	83.53	1825.4	4.58	40.85	1203.5	3.40	4.35	5	87.0
3	97.49	243.07	0.85	0.92	43.78	81.80	1807.4	4.53	40.21	1203.5	3.34	4.28	5	85.6
4	96.69	242.75	0.85	0.92	43.43	80.15	1790.3	4.48	39.58	1203.5	3.29	4.21	5	84.2
5	95.92	242.44	0.85	0.92	43.08	78.58	1774.2	4.43	38.97	1203.4	3.24	4.15	5	83.0
6	95.16	242.15	0.85	0.92	42.74	77.07	1759.1	4.39	38.39	1203.4	3.19	4.08	5	81.6
7	94.43	241.86	0.85	0.92	42.41	75.63	1745.0	4.34	37.82	1203.4	3.14	4.02	5	80.4
8	93.71	241.58	0.84	0.92	42.09	74.25	1731.9	4.29	37.26	1203.4	4.29	3.96	5	79.2

5.2.14.2 Results of case study 12 for detuned filter 7% X_L

Table 5.51 The results of calculation for case study 12 (detuned filter 7%X_L)

Step	V_{CR} (V)	Q (kVAr)			Low Voltage Side										
					PF	DT					$I_{5th\ filter}$				
		DT	5^{th} filter	7^{th} filter		Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)
1	525	50	260	260	0.901	3.51	45.18	0.82	0.90	7.79	135.77	265.13	0.93	1.0	59.62
2	525	100	260	260	0.911	6.91	90.36	0.82	0.90	7.67	133.49	263.97	0.92	0.99	58.62
3	525	150	260	260	0.92	10.20	135.53	0.82	0.90	7.55	131.27	262.86	0.92	0.99	57.64
4	525	200	260	260	0.929	13.40	180.69	0.82	0.90	7.43	129.13	261.79	0.92	0.99	56.70
5	525	250	260	260	0.937	16.50	225.84	0.82	0.90	7.32	127.05	260.77	0.91	0.98	55.79
6	525	300	260	260	0.945	19.50	270.99	0.82	0.90	7.22	125.04	259.80	0.91	0.98	54.91
7	525	350	260	260	0.953	22.42	316.13	0.82	0.90	7.11	123.09	258.87	0.91	0.98	54.05
8	525	400	260	260	0.96	25.26	361.26	0.82	0.90	7.01	121.19	257.97	0.90	0.97	53.22

Table 5.51 The results of calculation for case study 12 (detuned filter 7%X_L) (continues)

Step	Low Voltage Side													
	$I_{7th\ filter}$					I_S			I_L			THD_V (%)		
	Ihrms (A)	Irms (A)	Irms/Icr	I_L/I_{CR}	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Ihrms (A)	Irms (A)	THD (%)	Results	PL (ERG5/4)	(%) of PL
1	99.44	243.86	0.85	0.92	44.66	86.01	1844.0	4.67	41.68	1203.5	3.47	4.43	5	88.6
2	98.84	243.61	0.85	0.92	44.39	84.80	1824.9	4.65	41.17	12.03	3.42	4.38	5	87.6
3	98.25	243.38	0.85	0.92	44.13	83.63	1806.7	4.63	40.67	1203.5	3.38	4.33	5	86.6
4	97.68	243.14	0.85	0.92	43.87	82.49	1789.4	4.61	40.18	1203.5	3.34	4.27	5	85.4
5	97.11	242.92	0.85	0.92	43.61	81.38	1773.2	4.59	39.70	1203.5	3.30	4.22	5	84.4
6	96.55	242.70	0.85	0.92	43.36	80.30	1757.9	4.57	39.24	1203.5	3.26	4.17	5	83.4
7	96.01	242.48	0.85	0.92	43.12	79.24	1743.7	4.55	38.78	1203.4	3.22	4.13	5	82.6
8	95.47	242.27	0.85	0.92	42.88	78.22	1730.6	4.52	38.33	1203.4	3.19	4.08	5	81.6

The results of calculation case study 12, when using detuned filters together with 5th and 7th tuned filters in two conditions are illustrated in table 5.50 and 5.51. It is noticed that detuned filters, 5th, 7th tuned filters can be operated safely; the THD_V values at low voltage bus 400 V of two conditions are within planning level and can improve power factor to target value.

Table 5.52 The design parameters of detuned filters, 5th and 7th tuned filters

Detuned filter							5th tuned filter						7th tuned filter					
Capacitor			Reactor				Capacitor			Reactor			Capacitor			Reactor		
Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	$\%X_L$	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
8x50	525	55	5.6	0.981	58.9	84.47	260	525	285.9	0.1465	286.1	432.7	260	525	285.9	0.073	264.6	432.1
8x50	525	55	7.0	1.24	52.07	84.47	260	525	285.9	0.1465	286.1	432.7	260	525	285.9	0.073	264.6	432.1

5.2.15 Comparison of impedance scan

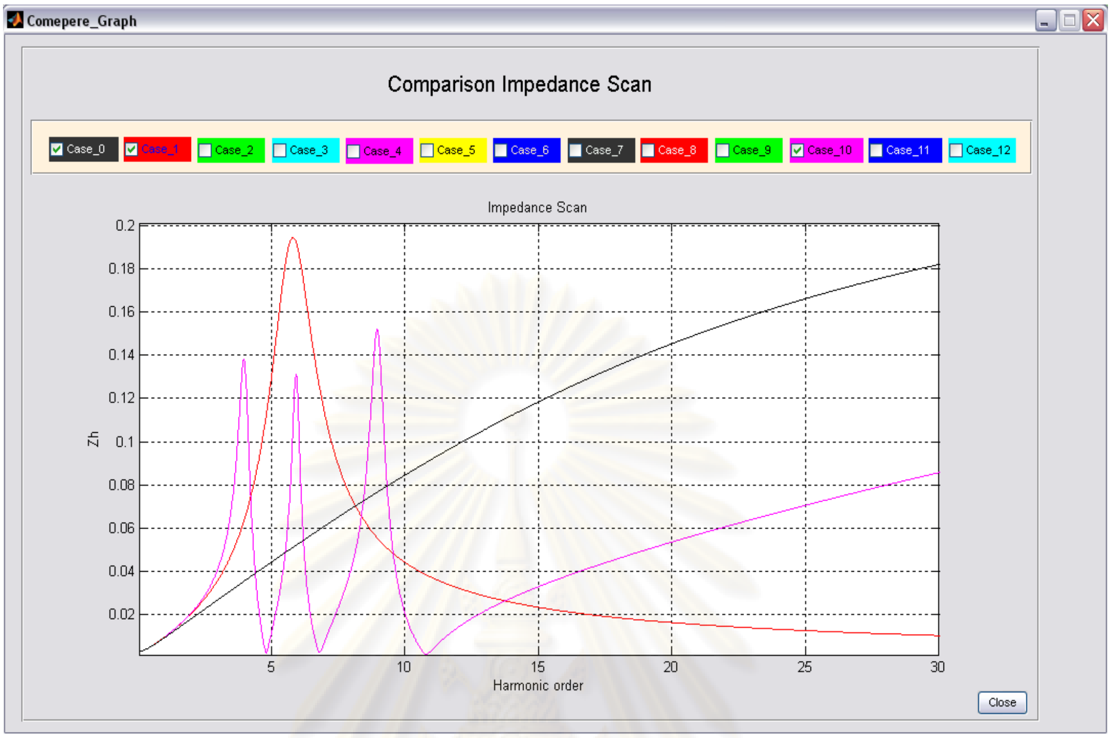


Figure 5.33 Page for impedance scan comparison

Results from case study 0 can be used as a reference case where there are linear and nonlinear loads in the system. When a capacitor is installed in the system as in case study 1, a parallel resonance can occur. For case study 2 to 12, filter(s) are added to the system in order to lower harmonic levels. The user can vary parameters of harmonic filters in order to check the effectiveness of harmonic filters based on the design steps. Figure 5.32 shows results of impedance scan of case studies 0, 1 and 10. By comparing these system characteristic results, a proper filter design can be achieved.

5.2.16 Capacitor deterioration for case study 10 (case study 0 with 5th, 7th and 11th tuned filters)

Table 5.53 The input parameters for case study 10

System	Transformer	LV Bus	Non-Linear Load	Linear Load	5th tuned filter	7th tuned filter	11th tuned filter
500 MVA_{SC} 22 kV X/R 10	1000 kVA 22 kV/400 V %Z = 6 P_k = 19.8 kW	400 V	500 kW PF = 80 %	650 kW PF = 75 %	40 % (370 kVAr) V_{cr} 525 V Q-Factor 60	30 % (280 kVAr) V_{cr} 525 V Q-Factor 50	30 % (280 kVAr) V_{cr} 525 V Q-Factor 50

Table 5.54 The design parameters of 5th, 7th and 11th tuned filters

5th tuned filter						7th tuned filter						11th tuned filter					
Capacitor			Reactor			Capacitor			Reactor			Capacitor			Reactor		
Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
370	525	406.9	0.103	389.9	615.8	280	525	307.9	0.068	282	455.6	280	525	307.9	0.027	277	449.6

5.2.16.1 The results for 5th tuned filter only

Table 5.55 The results for deterioration of the capacitor in 5th tuned filter

5th Filter									
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I rms (A)	I cr (A)	I rms/Icr (%)	L (mH)	C (uF)	hr
0	324.1	157.6	7.1	360.5	406.9	88.6	0.103	1424.3	4.8
2	317.3	159.7	7.3	355.4	398.8	89.1	0.103	1395.8	4.9
4	310.6	161.9	7.4	350.4	390.6	89.7	0.103	1367.4	4.9
6	303.8	164.2	7.5	345.5	382.5	90.3	0.103	1338.9	5
8	297.1	166.7	7.7	340.8	374.3	91	0.103	1310.4	5
10	290.4	169.2	7.9	336.2	366.2	91.8	0.103	1281.9	5.1
12	283.6	171.8	8	331.8	358.1	92.7	0.103	1253.4	5.1
14	276.9	174.6	8.2	327.6	349.9	93.6	0.103	1224.9	5.2
16	270.3	177.4	8.5	323.5	341.8	94.7	0.103	1196.4	5.2
18	263.6	180.4	8.7	319.6	333.7	95.8	0.103	1168.0	5.3
20	256.9	183.4	9	315.9	325.5	97	0.103	1139.5	5.4

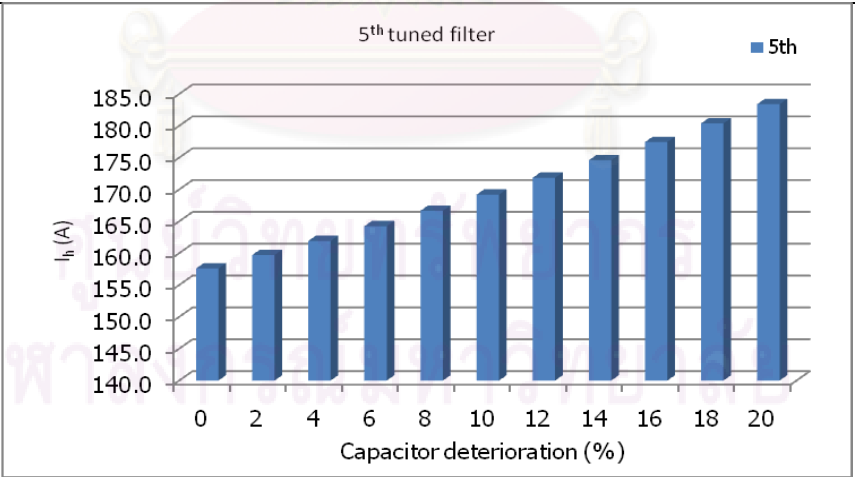


Figure 5.34 5th harmonic currents in 5th order tuned filter

When the capacitor deteriorates from 0-20% for 5th tuned filter, it make 5th harmonic current flow through 5th tuned filter increasingly as shown in table 5.55 and illustrated in figure 5.33. These results indicate that the 5th harmonic current has change in the range of 157.6 – 183.4A and for the tuning point also change from 4.8 – 5.37 and 5th tuned filter is still operated safely because I_{rms} / I_{cr} value is less than 100%.

5.2.16.2 The results for deterioration 7th tuned filter only

Table 5.56 The results for deterioration of the capacitor in 7th tuned filter

7th Filter									
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I rms (A)	I cr (A)	I rms/Icr (%)	L (mH)	C (uF)	hr
0	239.8	22.5	96.3	259.7	307.9	84.4	0.0678	1077.9	6.8
2	312.6	21.5	99.3	328.9	301.8	109	0.0678	1056.3	6.9
4	306	20.4	102.7	323.7	295.6	109.5	0.0678	1034.8	6.9
6	299.5	19.5	106.3	318.7	289.4	110.1	0.0678	1013.2	7.0
8	292.9	18.6	110.4	313.9	283.3	110.8	0.0678	991.6	7.1
10	286.4	17.7	115	309.4	277.1	111.6	0.0678	970.1	7.2
12	279.8	16.9	120.1	305.3	271	112.7	0.0678	948.5	7.3
14	273.3	16.1	125.9	301.7	264.8	113.9	0.0678	927	7.3
16	266.8	15.4	132.5	298.6	258.7	115.4	0.0678	905.4	7.4
18	260.3	14.6	140	296.2	252.5	117.3	0.0678	883.9	7.5
20	253.8	14	148.5	294.7	246.3	119.6	0.0678	862.3	7.6

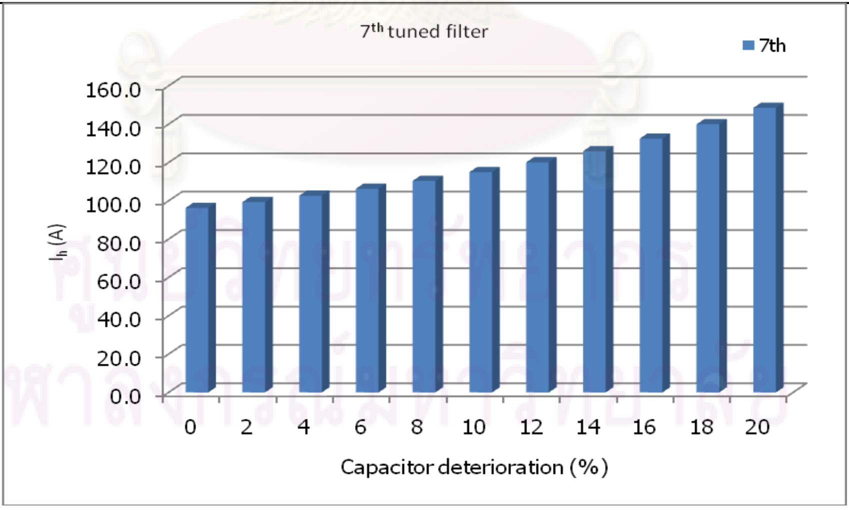


Figure 5.35 7th harmonic currents in 7th order tuned filter

When the capacitor deteriorates from 0-20% for 7th tuned filter, it make 7th harmonic current flow through 7th tuned filter increasingly as shown in table 5.56 and illustrated in figure 5.34. These results indicate that the 7th harmonic current has change in the range of 96.3 – 148.5A and for the tuning point also change from 6.8 – 7.6 and 7th tuned filter is still operated safely because I_{rms} / I_{cr} values is less than 130%.

5.2.16.3 The results for 11th tuned filter only

Table 5.57 The results for deterioration of the capacitor in 11th tuned filter

11th Filter										
Det (%)	I 1 (A)	I 5 A)	I 7 (A)	I11 (A)	I rms (A)	I cr (A)	I rms/Icr (%)	L (mH)	C (uF)	hr
0	236.6	76.6	8.4	12.4	249.6	307.9	81.1	0.0269	1077.9	10.8
2	231.9	66.1	8.7	12.4	242	301.8	80.2	0.0269	1056.3	10.9
4	227.1	57.7	9	12.5	235.3	295.6	79.6	0.0269	1034.8	11
6	222.3	51	9.4	12.6	229.1	289.4	79.2	0.0269	1013.2	11.1
8	217.6	45.5	9.7	12.7	223.3	283.3	78.8	0.0269	991.6	11.3
10	212.8	40.8	10.2	12.8	217.8	277.1	78.6	0.0269	970.1	11.4
12	208	36.9	10.6	12.9	212.4	271	78.4	0.0269	948.5	11.5
14	203.3	33.5	11.2	13	207.3	264.8	78.3	0.0269	927	11.7
16	198.5	30.6	11.9	13.1	202.2	258.7	78.2	0.0269	905.4	11.8
18	193.7	28	12.7	13.2	197.2	252.5	78.1	0.0269	883.9	11.9
20	189	25.7	13.6	13.3	192.3	246.3	78	0.0269	862.3	12.1

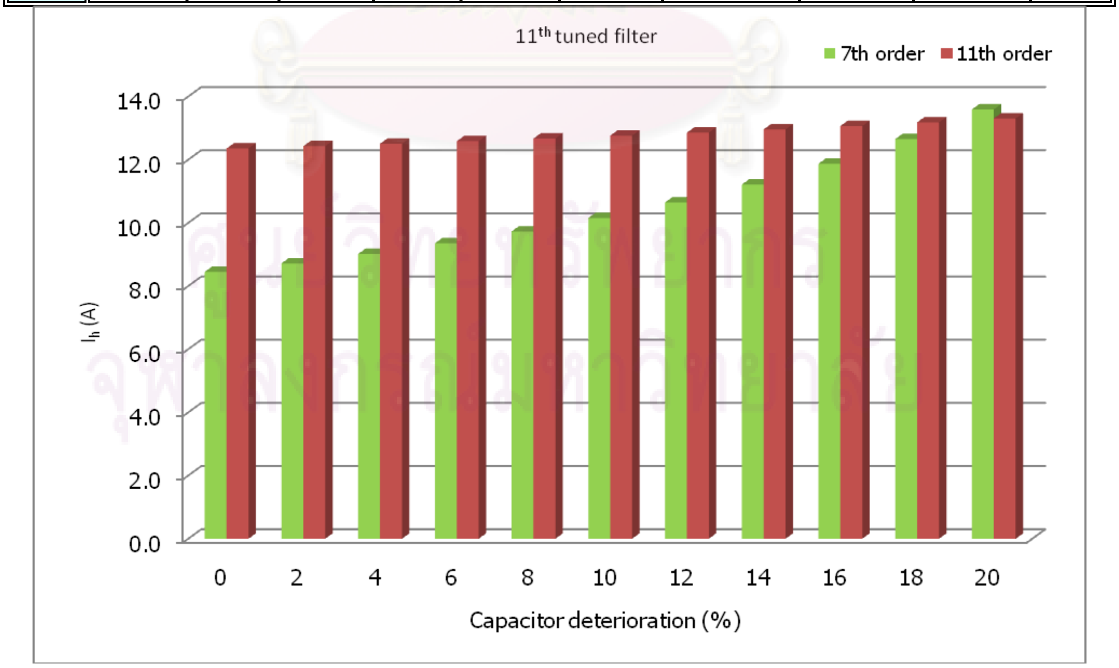


Figure 5.36 7th and 11th harmonic currents in 11th order tuned filter

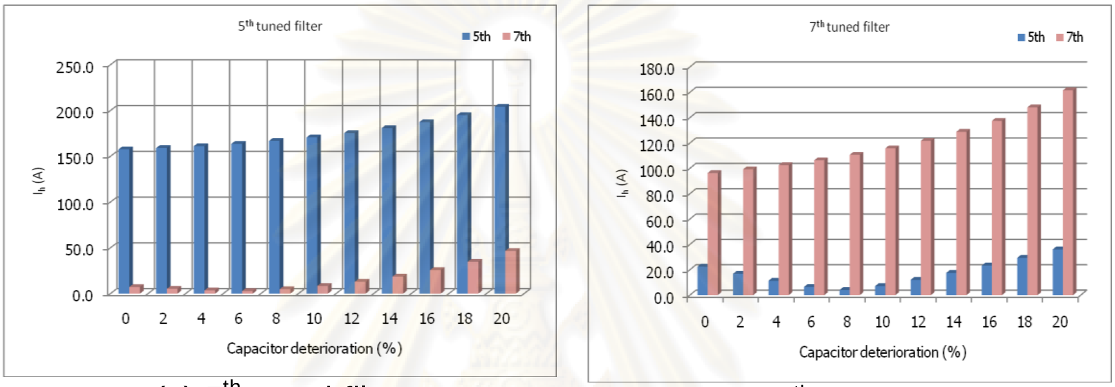
When the capacitor deteriorates from 0-20% for 11th tuned filter, it make 7th, 11th harmonic current flow through 11th tuned filter increasingly as shown in table 5.57 and illustrated in figure 5.35. These results indicate that the 7th harmonic current has change in the range of 8.4 – 13.6A, 11th harmonic current 12.4 – 13.3A and for the tuning point also change from 10.8 – 12.1 and 11th tuned filter is still operated safely because Irms / Icr value are less than 130%.

5.2.16.4 The results for deterioration of the capacitor in 5th and 7th tuned filters.

Table 5.58 The results for deterioration of the capacitor in 5th and 7th tuned filter

5th Filter										
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I 11 (A)	I rms (A)	I cr (A)	I rms/Icr (%)	L (mH)	C (uF)	hr
0	324.1	157.6	7.1	1.0	360.5	406.9	88.6	0.103	1424.3	4.8
2	317.3	159.0	5.3	1.0	355.1	398.8	89.0	0.103	1395.8	4.9
4	310.6	161.0	3.4	1.0	349.9	390.6	89.6	0.103	1367.4	4.9
6	303.8	163.6	2.8	1.0	345.2	382.5	90.2	0.103	1338.9	5.0
8	297.1	166.8	4.8	1.0	340.8	374.3	91.0	0.103	1310.4	5.0
10	290.4	170.6	8.3	1.0	337.0	366.2	92.0	0.103	1281.9	5.1
12	283.6	175.3	12.9	1.0	333.8	358.1	93.2	0.103	1253.4	5.1
14	276.9	180.8	18.6	1.0	331.4	349.9	94.7	0.103	1224.9	5.2
16	270.3	187.3	25.7	1.0	329.9	341.8	96.5	0.103	1196.4	5.2
18	263.6	195.0	34.8	1.0	329.8	333.7	98.9	0.103	1168.0	5.3
20	256.9	204.1	46.6	1.0	331.5	325.5	101.8	0.103	1139.5	5.4
7th Filter										
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I 11 (A)	I rms (A)	I cr (A)	I rms/Icr (%)	L (mH)	C (uF)	hr
0	239.8	22.5	96.3	2.0	259.7	307.9	84.4	0.0687	1077.9	6.8
2	234.9	16.8	99.3	2.0	255.9	301.8	84.8	0.0678	1056.3	6.9
4	230.0	11.4	102.6	2.0	252.4	295.6	85.4	0.0687	1034.8	6.9
6	225.1	6.5	106.4	2.1	249.4	289.4	86.2	0.0678	1013.2	7.0

8	220.2	4.0	110.7	2.1	246.9	283.3	87.1	0.0687	991.6	7.1
10	215.3	7.1	115.8	2.1	245.0	277.1	88.4	0.0678	970.1	7.2
12	210.5	12.1	121.7	2.2	243.8	271.0	90.0	0.0687	948.5	7.3
14	205.6	17.5	128.8	2.2	243.6	264.8	92.0	0.0678	927.0	7.3
16	200.7	23.3	137.5	2.2	244.8	258.7	94.6	0.0687	905.4	7.4
18	195.8	29.5	148.1	2.3	247.7	252.5	98.1	0.0687	883.9	7.5
20	191.0	36.1	161.6	2.3	253.1	246.3	102.8	0.0678	862.3	7.6



(a) 5th tuned filter (b) 7th tuned filter

Figure 5.37 Spectra of harmonic currents for (capacitor deteriorate in 5th and 7th tuned filters)

When capacitors deteriorates from 0 – 20% for 5th and 7th tuned filter at the same rate, results can be summarized as follows.

In the 5th tuned filter; 5th and 7th harmonic current flow through 5th tuned filter increasingly as shown in table 5.58 and illustrated in figure 5.36.a. these results indicate that 5th harmonic current change in the range of 157.6 - 204.1A and 7th harmonic current 7.1 – 46.6 A and for the tuning point 4.8 – 5.4.

In the 7th tuned filter; 7th harmonic current flow through 7th tuned filter increasingly, as shown in table 5.58 and illustrated in figure 5.35.b. these results indicate that 7th harmonic current change in the range of 96.3 – 161.6 A and for the tuning point 6.8 – 7.6.

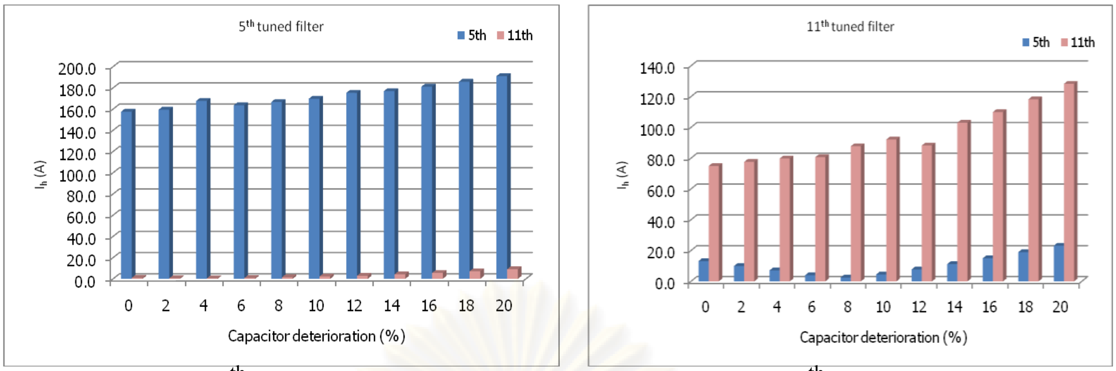
From the result of calculation in table 5.58, both 5th, 7th tuned filter still operating safely.

5.2.16.5 Results for deterioration of capacitor in 5th and 11th tuned filters.

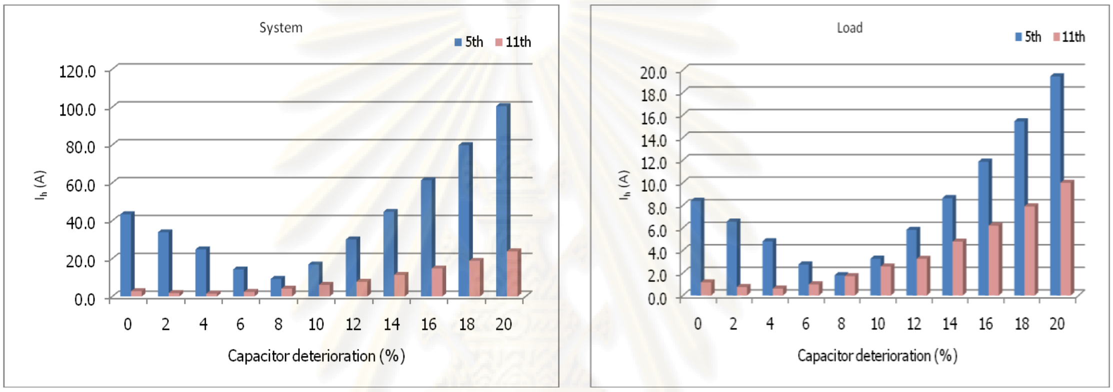
Table 5.59 The results for deterioration of the capacitor in 5th and 11th tuned filter

5th Filter										
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I 11 (A)	I rms (A)	I cr (A)	Irms/Icr (%)	L (mH)	C (uF)	hr
0	324.1	157.6	7.1	1.0	360.5	406.9	88.6	0.103	1424.3	4.8
2	317.3	159.5	7.2	0.6	355.3	398.8	89.1	0.103	1395.8	4.9
4	310.6	167.7	7.4	0.5	353.1	390.6	90.4	0.103	1367.4	4.9
6	303.8	163.6	8.2	0.8	345.2	382.5	90.3	0.103	1338.9	5.0
8	297.1	166.7	7.6	1.5	340.8	374.3	91.0	0.103	1310.4	5.0
10	290.4	169.7	7.7	2.2	336.5	366.2	91.9	0.103	1281.9	5.1
12	283.6	175.3	9.5	2.9	333.7	358.1	93.2	0.103	1253.4	5.1
14	276.9	176.9	8.1	4.2	328.8	349.9	94.0	0.103	1224.9	5.2
16	270.3	181.1	8.3	5.5	325.6	341.8	95.3	0.103	1196.4	5.2
18	263.6	185.9	8.5	7.1	322.8	333.7	96.7	0.103	1168.0	5.3
20	256.9	191.1	8.8	9.1	320.5	325.5	98.5	0.103	1139.5	5.4
11th Filter										
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I 11 (A)	I rms (A)	I cr (A)	Irms/Icr	L (mH)	C (uF)	hr
0	236.6	13.2	10.5	75.0	259.7	307.9	84.4	0.0269	1077.9	10.8
2	231.9	10.0	10.1	77.6	259.2	301.8	85.9	0.0269	1056.3	10.9
4	227.1	7.2	9.7	79.8	258.9	295.6	87.6	0.0269	1034.8	11.0
6	222.3	4.0	10.2	80.7	261.9	289.4	90.5	0.0269	1013.2	11.1
8	217.6	2.5	9.0	87.8	258.2	283.3	91.1	0.0269	991.6	11.3
10	212.8	4.5	8.6	92.2	258.1	277.1	93.2	0.0269	970.1	11.4
12	208.0	7.8	9.9	88.3	265.7	271.0	98.1	0.0269	948.5	11.5
14	203.3	11.2	7.9	103.1	258.8	264.8	97.7	0.0269	927.0	11.7
16	198.5	15.0	7.6	110.0	259.6	258.7	100.4	0.0269	905.4	11.8
18	193.7	19.0	7.3	118.3	261.0	252.5	103.4	0.0269	883.9	11.9

20	189.0	23.2	7.0	128.3	262.9	246.3	106.7	0.0269	862.3	12.1



(a) 5th tuned filter **(b)** 11th tuned filter



(c) System **(d)** Load

Figure 5.38 Spectra of harmonic currents for (capacitor deteriorate in 5th and 7th tuned filters)

When capacitors deteriorates from 0 – 20% for 5th and 11th tuned filter at the same rate, results can be summarized as follows.

In the 5th tuned filter, the result of calculation as shown in table 5.59 and illustrated in figure 5.37.a. these results indicate that 5th tuned filter can be operated safely.

In the 11th tuned filter; 11th harmonic current flow through 11th tuned filter increasingly, as shown in table 5.59 and illustrated in figure 5.37.b. these results indicate that 11th harmonic current change in the range of 75.0 – 128.3 A and for the tuning point 10.8 – 12.1. The ratio I_{rms} / I_{cr} begin higher than 100%, when capacitors are deteriorated more than 16% but 11th tuned filter still operates safely because the ratio of I_{rms} / I_{Cr} is less than 130%.

5.2.16.6 The results for deterioration of the capacitor in 5th, 7th and 11th tuned filters.

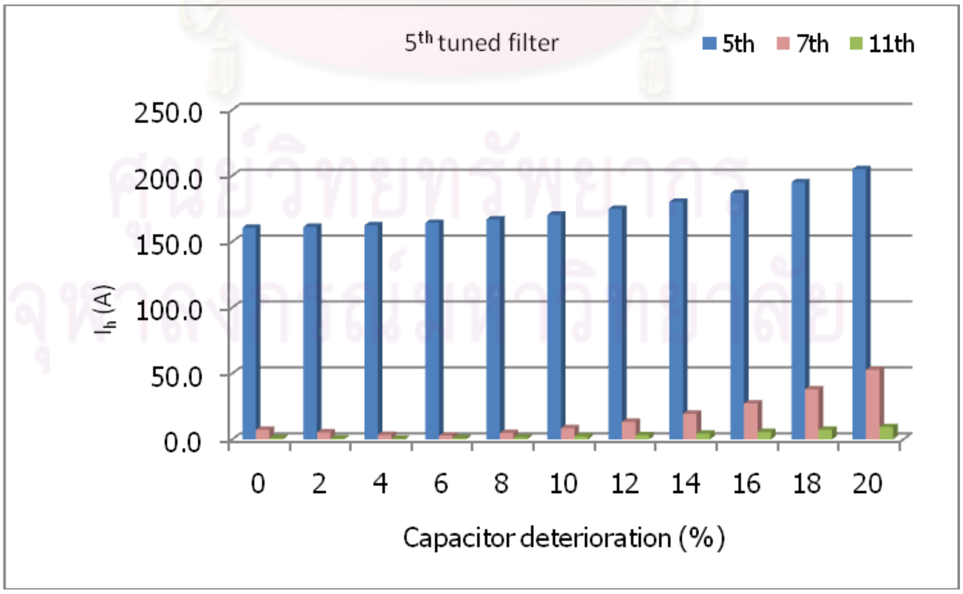
Table 5.60 The results of calculation for deterioration of the capacitor in 5th, 7th and 11th tuned filter

5th Filter										
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I 11 (A)	I rms (A)	I cr (A)	Irms/Icr (%)	L (mH)	C (uF)	hr
0	324.1	157.6	7.1	1.0	360.5	406.9	88.6	0.103	1424.3	4.8
2	317.3	158.8	5.2	0.6	355.0	398.8	89.0	0.103	1395.8	4.9
4	310.6	160.7	3.4	0.5	349.8	390.6	89.5	0.103	1367.4	4.9
6	303.8	163.4	2.8	0.9	345.0	382.5	90.2	0.103	1338.9	5.0
8	297.1	166.8	4.8	1.5	340.8	374.3	91.0	0.103	1310.4	5.0
10	290.4	171.2	8.5	2.3	337.2	366.2	92.1	0.103	1281.9	5.1
12	283.6	176.6	13.3	3.2	334.5	358.1	93.4	0.103	1253.4	5.1
14	276.9	183.3	19.4	4.3	332.8	349.9	95.1	0.103	1224.9	5.2
16	270.3	191.4	27.6	5.6	332.5	341.8	97.3	0.103	1196.4	5.2
18	263.6	201.4	38.6	7.3	334.1	333.7	100.1	0.103	1168.0	5.3
20	256.9	213.7	54.1	9.4	338.7	325.5	104.1	0.103	1139.5	5.4
7th Filter										
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I 11 (A)	I rms (A)	I cr (A)	Irms/Icr (%)	L (mH)	C (uF)	hr
0	239.8	22.5	96.3	2.0	259.7	307.9	84.4	0.0678	1077.9	6.8
2	234.9	16.8	99.1	1.3	255.8	301.8	84.8	0.0678	1056.3	6.9
4	230.0	11.3	102.4	1.1	252.3	295.6	85.4	0.0678	1034.8	6.9
6	225.1	6.5	106.4	1.8	249.4	289.4	86.2	0.0678	1013.2	7.0
8	220.2	4.0	111.4	3.1	247.2	283.3	87.3	0.0678	991.6	7.1
10	215.3	7.1	117.5	4.7	245.8	277.1	88.7	0.0678	970.1	7.2
12	210.5	12.1	125.2	6.7	245.6	271.0	90.6	0.0678	948.5	7.3
14	205.6	17.7	135.0	9.1	247.0	264.8	93.3	0.0678	927.0	7.3

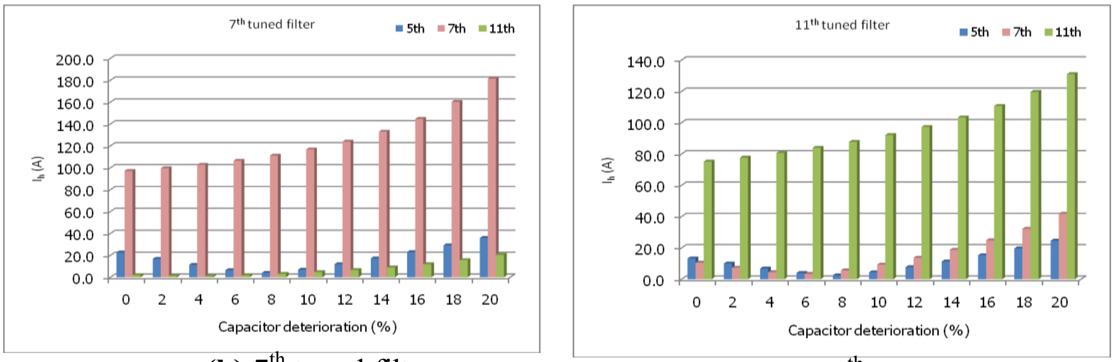
16	200.7	23.8	147.7	12.1	250.9	258.7	97.0	0.0678	905.4	7.4
18	195.8	30.4	164.5	15.9	258.3	252.5	102.3	0.0678	883.9	7.5
20	191.0	37.8	187.7	20.8	271.5	246.3	110.2	0.0678	862.3	7.6

11th Filter

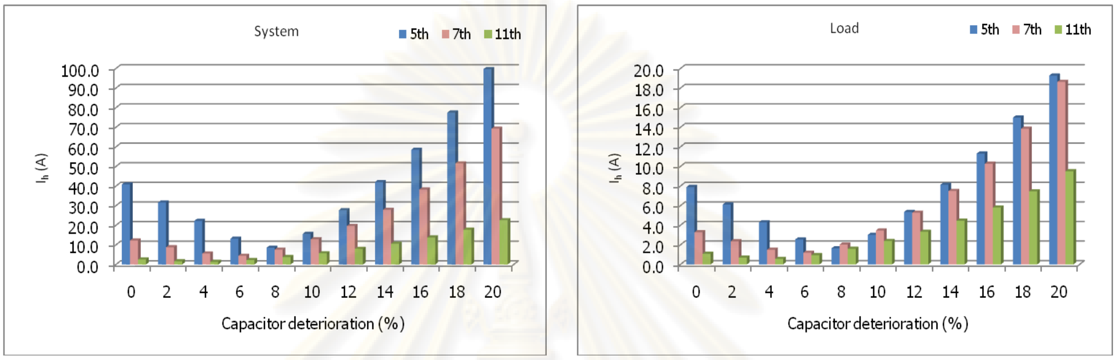
Det (%)	I 1 (A)	I 5 (A)	I 7 (A)	I 11 (A)	I rms (A)	I cr (A)	Irms/Icr (%)	L (mH)	C (uF)	hr
0	236.6	13.2	10.5	75.0	254.3	307.9	82.6	0.0269	1077.9	10.8
2	231.9	10.0	7.3	77.6	251.2	301.8	83.2	0.0269	1056.3	10.9
4	227.1	6.9	4.5	80.6	247.7	295.6	83.8	0.0269	1034.8	11.0
6	222.3	4.0	3.5	84.0	244.6	289.4	84.5	0.0269	1013.2	11.1
8	217.6	2.5	5.7	88.0	241.9	283.3	85.4	0.0269	991.6	11.3
10	212.8	4.5	9.4	92.5	239.7	277.1	86.5	0.0269	970.1	11.4
12	208.0	7.8	13.9	97.8	238.2	271.0	87.9	0.0269	948.5	11.5
14	203.3	11.6	19.1	104.2	237.5	264.8	89.7	0.0269	927.0	11.7
16	198.5	15.9	25.4	111.8	238.1	258.7	92.1	0.0269	905.4	11.8
18	193.7	20.6	33.2	121.3	240.4	252.5	95.2	0.0269	883.9	11.9
20	189.0	25.9	43.3	133.1	245.4	246.3	99.6	0.0269	862.3	12.1



(a) 5th tuned filter



(b) 7th tuned filter **(c)** 11th tuned filter



(d) System **(e)** Load

Figure 5.39 Spectra of harmonic currents for (capacitor deteriorated in 5th, 7th and 11th tuned filters)

When capacitors deteriorates from 0 – 20% for 5th, 7th and 11th tuned filter at the same rate, results can be summarized as follows.

In the 5th tuned filter; 5th harmonic current flow through 5th tuned filter increasingly, as shown in table 5.60 and illustrated in figure 5.38.a. these results indicate that 5th harmonic current change in the range of 157.6 – 213.7A and for the tuning point 4.8 – 5.4. The ratio I_{rms} / I_{cr} begin higher than 100%, when capacitors are deteriorated more than 18% but 5th tuned filter still operates safely because the ratio of I_{rms} / I_{Cr} is less than 130%.

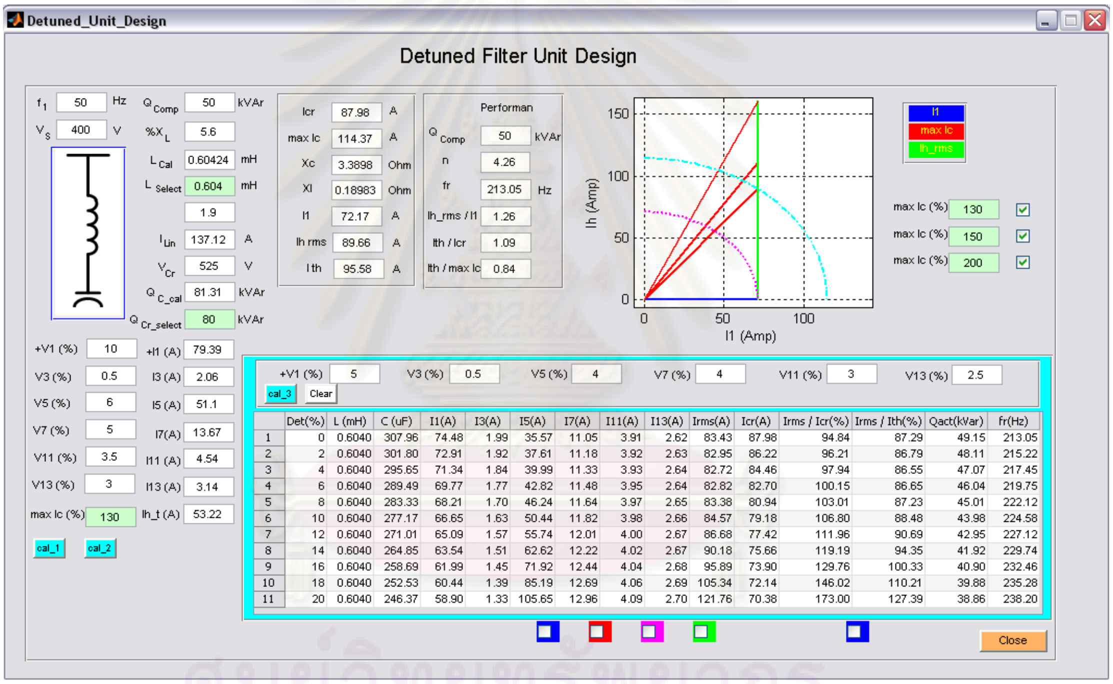
In the 7th tuned filter, 7th harmonic current flow through 7th tuned filter increasingly, as shown in table 5.60 and illustrated in figure 5.38.b. these results indicate that 7th harmonic current change in the range of 96.3 – 187.7A and for the tuning point 6.8 – 7.6. The ratio I_{rms} / I_{cr} begin higher than 100%, when capacitors are deteriorated more than 18% and 7th tuned filter still operates safely because the ratio of I_{rms} / I_{Cr} is less than 130%.

In the 11th tuned filter, 11th harmonic current flow through 11th tuned filter increasingly, as shown in table 5.60 and illustrated in figure 5.38.c. these results indicate that 11th harmonic current change in the range of 75.0 – 133.1A and for the tuning point 10.8 – 12.1. The ratios I_{rms} / I_{cr} are less than 100% so it can operate safely.

5.3 Detuned harmonic filter unit design

Table 5.61 The input parameters for detuned filter unit design

Rated voltage	Frequency	$Q_{COMPENSATE}$	Percent X_L	$K * I_1$	V_{CR}	Max I_C(%)
400 V	50 Hz	50 kVAr	5.6, 7 (%)	1.9	525 V	130 (%)
	+V1 (%)	V3 (%)	V5 (%)	V7 (%)	V11(%)	V13 (%)
Design limits	10	0.5	6	5	3.5	3
Operation	5	0.5	4	5	3	2.5



f_1 50 Hz

V_S 400 V

Q_{Comp} 50 kVAr

$\%X_L$ 5.6

L_{Cal} 0.60424 mH

L_{Select} 0.604 mH

1.9

I_{Lin} 137.12 A

V_{Cr} 525 V

Q_{C_cal} 81.31 kVAr

Q_{Cr_select} 80 kVAr

+V1 (%) 10

V3 (%) 0.5

V5 (%) 6

V7 (%) 5

V11 (%) 3.5

V13 (%) 3

max Ic (%) 130

+I1 (A) 79.39

I3 (A) 2.06

I5 (A) 51.1

I7(A) 13.67

I11 (A) 4.54

I13 (A) 3.14

Ih_t (A) 53.22

Icr 87.98 A

max Ic 114.37 A

Xc 3.3898 Ohm

Xl 0.18983 Ohm

I1 72.17 A

Ih rms 89.66 A

I th 95.58 A

Performan

Q_{Comp} 50 kVAr

n 4.26

fr 213.05 Hz

Ih_rms / I1 1.26

Ith / Icr 1.09

Ith / max Ic 0.84

max Ic (%) 130 ☑

max Ic (%) 150 ☑

max Ic (%) 200 ☑

+V1 (%) 5

V3 (%) 0.5

V5 (%) 4

V7 (%) 4

V11 (%) 3

V13 (%) 2.5

	Det(%)	L (mH)	C (uF)	I1(A)	I3(A)	I5(A)	I7(A)	I11(A)	I13(A)	Irms(A)	Icr(A)	Irms / Icr(%)	Irms / Ith(%)	Qact(kVar)	fr(Hz)
1	0	0.6040	307.96	74.48	1.99	35.57	11.05	3.91	2.62	83.43	87.98	94.84	87.29	49.15	213.05
2	2	0.6040	301.80	72.91	1.92	37.61	11.18	3.92	2.63	82.95	86.22	96.21	86.79	48.11	215.22
3	4	0.6040	295.65	71.34	1.84	39.99	11.33	3.93	2.64	82.72	84.46	97.94	86.55	47.07	217.45
4	6	0.6040	289.49	69.77	1.77	42.82	11.48	3.95	2.64	82.82	82.70	100.15	86.65	46.04	219.75
5	8	0.6040	283.33	68.21	1.70	46.24	11.64	3.97	2.65	83.38	80.94	103.01	87.23	45.01	222.12
6	10	0.6040	277.17	66.65	1.63	50.44	11.82	3.98	2.66	84.57	79.18	106.80	88.48	43.98	224.58
7	12	0.6040	271.01	65.09	1.57	55.74	12.01	4.00	2.67	86.68	77.42	111.96	90.69	42.95	227.12
8	14	0.6040	264.85	63.54	1.51	62.62	12.22	4.02	2.67	90.18	75.66	119.19	94.35	41.92	229.74
9	16	0.6040	258.69	61.99	1.45	71.92	12.44	4.04	2.68	95.89	73.90	129.76	100.33	40.90	232.46
10	18	0.6040	252.53	60.44	1.39	85.19	12.69	4.06	2.69	105.34	72.14	146.02	110.21	39.88	235.28
11	20	0.6040	246.37	58.90	1.33	105.65	12.96	4.09	2.70	121.76	70.38	173.00	127.39	38.86	238.20

Figure 5.40 Main for detuned filter unit design

5.3.1 Detuned filter unit design for 5.6%X_L

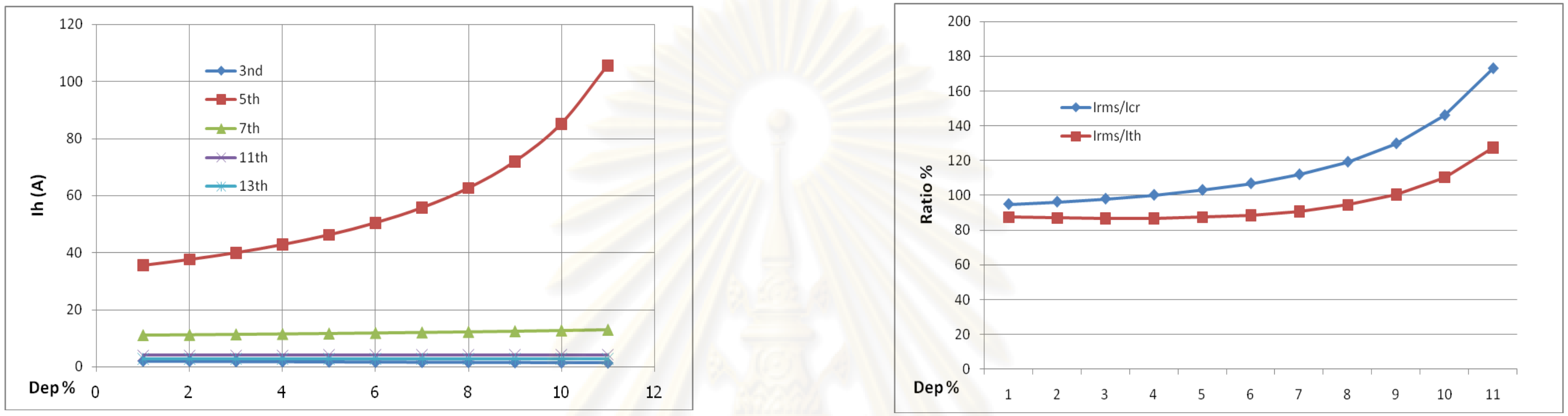
Table 5.62 The component rating of detuned filter unit

Detuned filter unit						
Capacitor			Reactor			
Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	$\%X_L$	L (mH)	I_{th} (A)	I_{Lin} (A)
80	525	87.98	5.6	0.604	95.58	137.12

5.3.1.1 Detuned filter unit design for capacitor deteriorate from 0 – 20 %

Table 5.63 The results of calculation

Detuned Filter Unit Design														
Det (%)	L (mH)	C (uF)	I1 (A)	I3 (A)	I5 (A)	I7 (A)	I11 (A)	I13 (A)	I_{rms} (A)	Icr (A)	I_{rms}/I_{cr} (%)	I_{rms}/I_{th} (%)	Q_{act} (kVAr)	fr (Hz)
0	0.604	307.96	74.48	1.99	35.57	11.05	3.91	2.62	83.43	87.98	94.84	87.29	49.15	213.05
2	0.604	301.8	72.91	1.92	37.61	11.18	3.92	2.63	82.95	86.22	96.21	86.79	48.11	215.22
4	0.604	295.65	71.34	1.84	39.99	11.33	3.93	2.64	82.72	84.46	97.94	86.55	47.07	217.45
6	0.604	289.49	69.77	1.77	42.82	11.48	3.95	2.64	82.82	82.7	100.15	86.65	46.04	219.75
8	0.604	283.33	68.21	1.7	46.24	11.64	3.97	2.65	83.38	80.94	103.01	87.23	45.01	222.12
10	0.604	277.17	66.65	1.63	50.44	11.82	3.98	2.66	84.57	79.18	106.8	88.48	43.98	224.58
12	0.604	271.01	65.09	1.57	55.74	12.01	4	2.67	86.68	77.42	111.96	90.69	42.95	227.12
14	0.604	264.85	63.54	1.51	62.62	12.22	4.02	2.67	90.18	75.66	119.19	94.35	41.92	229.74
16	0.604	258.69	61.99	1.45	71.92	12.44	4.04	2.68	95.89	73.9	129.76	100.33	40.9	232.46
18	0.604	252.53	60.44	1.39	85.19	12.69	4.06	2.69	105.34	72.14	146.02	110.21	39.88	235.28
20	0.604	246.37	58.9	1.33	105.65	12.96	4.09	2.7	121.76	70.38	173	127.39	38.86	238.2



(a) Graph of Harmonic current for (capacitor deteriorate from 0 – 20 %)

(b) Graph of I_{rms}/I_{cr} and I_{rms}/I_{th} for (capacitor deteriorate from 0 – 20 %)

Figure 5.41 Graph of detuned filter unit design for capacitor deteriorate from 0 – 20 %

5.3.2 Detuned filter unit design for 7%X_L

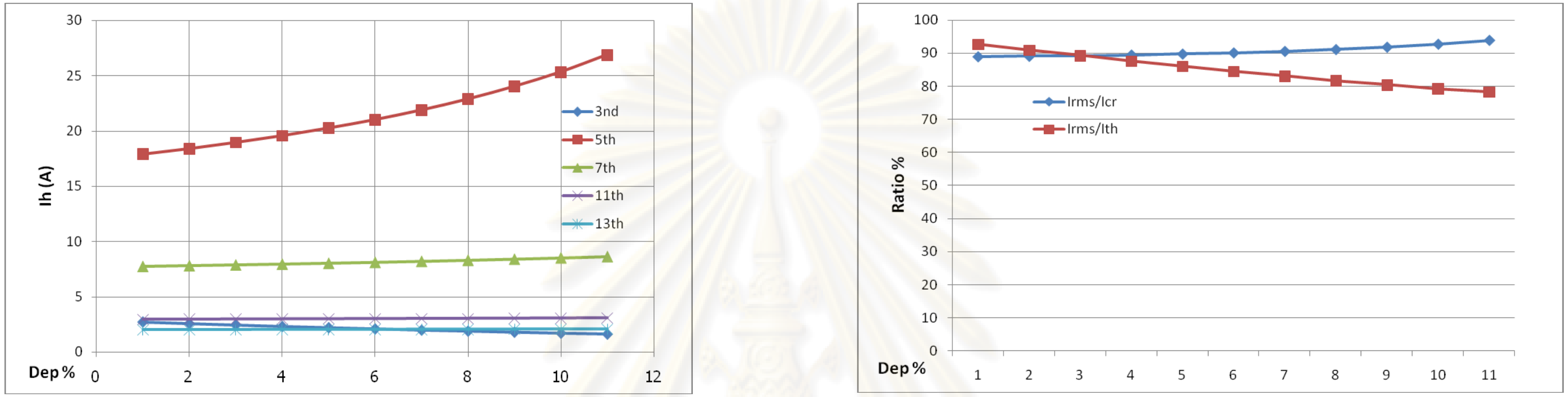
Table 5.64 The rating component of detuned filter unit

Detuned filter unit						
Capacitor			Reactor			
Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	%X_L	L (mH)	I_{th} (A)	I_{Lin} (A)
80	525	87.98	7	0.767	84.51	137.12

5.3.2.1 Detuned filter unit design for capacitor deteriorate from 0 – 20 %

Table 5.65 The results of calculation

Detuned Filter Unit Design														
Det (%)	L (mH)	C (uF)	I1 (A)	I3 (A)	I5 (A)	I7 (A)	I11 (A)	I13 (A)	I_{rms} (A)	Icr (A)	I_{rms}/I_{cr} (%)	I_{rms}/I_{th} (%)	Q_{act} (kVAr)	fr (Hz)
0	0.767	307.96	75.67	2.71	17.91	7.73	2.96	2.01	78.28	87.98	88.98	92.63	49.93	189.07
2	0.767	301.8	74.05	2.57	18.41	7.8	2.97	2.02	76.83	86.22	89.11	90.91	48.86	190.98
4	0.767	295.65	72.43	2.44	18.97	7.87	2.98	2.02	75.41	84.46	89.29	89.23	47.79	192.96
6	0.767	289.49	70.81	2.31	19.58	7.94	2.99	2.03	74.02	82.7	89.51	87.59	46.73	195.01
8	0.767	283.33	69.2	2.2	20.27	8.02	3	2.03	72.68	80.94	89.79	86	45.66	197.11
10	0.767	277.17	67.6	2.09	21.03	8.1	3.01	2.03	71.38	79.18	90.15	84.46	44.6	199.29
12	0.767	271.01	66	1.98	21.9	8.19	3.02	2.04	70.14	77.42	90.6	83	43.55	201.54
14	0.767	264.85	64.4	1.89	22.89	8.29	3.03	2.04	68.97	75.66	91.16	81.61	42.49	203.87
16	0.767	258.69	62.81	1.79	24.03	8.39	3.04	2.05	67.89	73.9	91.87	80.34	41.44	206.29
18	0.767	252.53	61.22	1.7	25.34	8.5	3.05	2.06	66.93	72.14	92.77	79.2	40.4	208.79
20	0.767	246.37	59.64	1.62	26.89	8.62	3.07	2.06	66.11	70.38	93.94	78.23	39.35	211.38



(a) Graph of Harmonic current for capacitor deteriorate from 0 – 20 %

(b) Graph of I_{rms}/I_{cr} and I_{rms}/I_{th} for capacitor deteriorate from 0 – 20 %

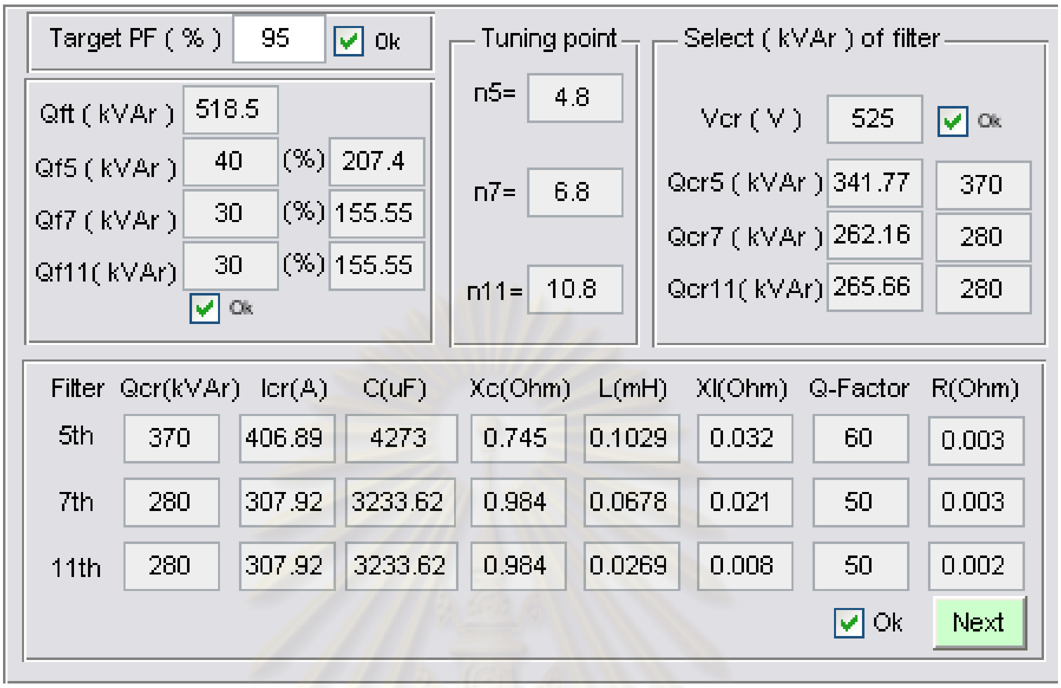
Figure 5.42 Graph of detuned filter unit design for capacitor deteriorate from 0 – 20 %

The objective of detuned filter unit design is to determine components rating of detuned filter units that will be used with the system that has a high harmonic current. The components of detuned filter units consist of: Capacitor (reactive power rating Q_{cr}: kVAr, voltage rating V_{cr}:V, current rating I_{cr}:A), Reactor(inductance L:mH, thermal current rating I_{th}:A, maximum current that still causes the value of the L change less than 5% I_{Lin}:A).

With 5.6%X_L, the result of calculation has the components rating of detuned filter units as shown in table 5.64. To test decreased of the capacitor from 0-20%, the results shown in table 5.64. From the results the I_{rms} / I_{cr} =103% with 8% decreased of capacitor and I_{rms} / I_{cr} =173% when decreasing with 20%. The ratio of rms current and thermal current rating (I_{rms} / I_{th}) is more than 100% and I_{rms} / I_{th} =127.39% when decreased capacitor 20%. And from the results was illustrated in figure 5. 40.

With 7%X_L, the result of calculation has the components rating of detuned filter units as shown in table 5.65. When to test the operating of detuned filter unit by decreasing of the capacitor from 0-20%, detuned filter unit can operate safety as shown in table 5.63 and illustrated in figure 5.41.

5.4 Tuned harmonic filter design



Target PF (%) 95 ☑ Ok

Qft (kVAr) 518.5

Qf5 (kVAr)	40	(%)	207.4
Qf7 (kVAr)	30	(%)	155.55
Qf11(kVAr)	30	(%)	155.55

☑ Ok

Tuning point

n5= 4.8

n7= 6.8

n11= 10.8

Select (kVAr) of filter

Vcr (V) 525 ☑ Ok

Qcr5 (kVAr)	341.77	370
Qcr7 (kVAr)	262.16	280
Qcr11(kVAr)	265.66	280

Filter	Qcr(kVAr)	Icr(A)	C(uF)	Xc(Ohm)	L(mH)	Xl(Ohm)	Q-Factor	R(Ohm)
5th	370	406.89	4273	0.745	0.1029	0.032	60	0.003
7th	280	307.92	3233.62	0.984	0.0678	0.021	50	0.003
11th	280	307.92	3233.62	0.984	0.0269	0.008	50	0.002

☑ Ok

Figure 5.43 Main display for tuned filter design

Harmonic filter can be designed using following 12 steps as shown in chapter 2, page 23 (Tuned filter design).

After parameters of filter are determined, harmonic flows of harmonic currents between system component and harmonic filter are required. Figure 5.42 shown the design page of harmonic filter in the developed program.

For case studies 3-6 and 7-12, harmonic filters have to be designed as previously explained before the harmonic flows can be simulated.

- For example in case study 10 consist of case study 0 with 5^{th}, 7th and 11^{th} tuned filters. Which it's analyzing 2 conditions: first condition 5^{th} tuned filter (310kVAr / 525V, n=4.8), 7^{th} tuned filter (310kVAr / 525V, n=6.8) and 11th tuned filter (310kVAr / 525V, n=10.8). Second condition 5^{th} tuned filter (370kVAr / 525V, n=6.8), 7^{th} tuned filter (280kVAr / 525V, n=6.8) and 11^{th} tuned filter (280kVAr / 525V, n=10.8).

The results of calculation for case study 10 is show in table 5.66 and the design parameters of tuned filters as show in table 5.67.

Table 5.66 The results of calculation for tuned filter design

h	I_h (A)	Z_h ohm)	V_h (%)	I_S (A)	I_L (A)	I_{F1} (A)	I_{F2}(A)	I_{F3} (A)
1	902.11	0.0098	100	1731.7	1202.8	324.08	239.79	236.63
5	169.03	0.0121	0.8827	43.36	8.39	157.59	22.53	13.18
7	107.3	0.008	0.3704	13.01	3.50	7.13	96.34	10.49
11	80.72	0.0035	0.1237	2.77	1.16	0.99	1.97	74.97
13	66.47	0.0218	0.6271	11.87	5.89	3.99	7.20	42.55
17	48.43	0.042	0.8799	12.74	8.26	4.01	6.68	23.74
19	39.88	0.0499	0.8616	11.16	8.09	3.46	5.64	18.34
23	31.34	0.0641	0.8693	9.30	8.16	2.82	4.49	13.27
$I_{h\ total}$	239.15	0	0	51.83	21.08	157.96	99.83	94.84
I_{rms}	933.27	0	0	1732.5	1203	360.52	259.74	254.93
I_{rms} / I_{cr}	0	0	0	0	0	0.89	0.84	0.83
THD (%)	26.51	0	2.24	2.99	1.75	48.74	41.63	40.08
I_{th}	0	0	0	0	0	389.92	282.03	277.04
I_{th} / I_{cr}	0	0	0	0	0	0.96	0.92	0.9
I_{lin}	0	0	0	0	0	615.75	455.6	449.6

Table 5.67 The design parameters of tuned filters

Tuned filter 5th (%)	Tuned filter 7th (%)	Tuned filter 11th (%)	5th tuned filter						7th tuned filter						11th tuned filter					
			Capacitor			Reactor			Capacitor			Reactor			Capacitor			Reactor		
			Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)	Q_{cr} (kVA)	V_{cr} (V)	I_{cr} (A)	L (mH)	I_{th} (A)	I_{Lin} (A)
33%	33%	33%	310	525	340.91	0.123	338.73	515.90	310	525	340.91	0.0612	310.18	504.42	310	525	340.91	0.0243	304.19	497.78
40%	30%	30%	370	525	406.90	0.103	389.92	615.75	280	525	307.92	0.0678	282.03	455.60	280	525	307.92	0.0269	277.04	449.60

CHAPTER VI

CONCLUSION

6.1 Conclusion

The harmonic analysis program can be used as a tool for power quality teaching and studying. The developed program consists of waveform synthesis, harmonic responses and harmonic filter design. With a help of graphic user interface (GUI) of MATLAB program, non-experienced and experienced users can utilize user-friendly feature and perform various sensitivity studies in order to understand harmonic analysis.

In analyzing case studies in part 2, the reference case consists of non-linear load connected and the power factor (PF) of the system is low. The solution was analysed by using capacitors to increase the power factor and using only detuned filters, tuned filter or a combination of them. For solving the problem, harmonic current flow through each component is analyzed and the total harmonic distortion voltage at low voltage bus (400 V) is compared with the planning level.

The results from analyzing case studies can be summarized as follows: when using only capacitors or combine with detuned filter, the harmonic current amplifier occurs and may cause the capacitor failure, this is because I_{rms} is greater than $1.3I_{Cr}$ and total harmonic distortion voltage at low voltage bus (400 V) is higher than the planning level. Using only detuned filters, it can solve the problem from harmonic current and operating safely but total harmonic distortion voltage value at low voltage bus is still higher than the planning level. Using only tuned filter (only 5th, 7th or 11th order tuned filter), it can solve the problem if choosing tuned filter with suitable harmonic current. If the system has high harmonic currents, combination of tuned filters is suggested but with suitable tuning frequencies and proper rating kVAR of each orders of tuned filter.

6.2 Future work

Recommendations for the future researcher who is interested to further develop this program are:

1. The objective of developing this program is for power quality teaching and studying. Therefore, this program uses the simple system models, but in

practice harmonic models could be very complicated. More advanced harmonic models can be used to improve the output accuracy.

2. In this program, phase angles of harmonic currents are not considered because there is only one harmonic source. Multiple harmonic sources can be included in the future with the help of phaser calculation.

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