Indonesian Journal of Electrical Engineering and Computer Science
Vol. 6, No. 2, May 2017, pp. 338 ~ 348
DOI: 10.11591/ijeecs.v6.i2.pp338-348

Harmonic Load Mitigation Using the Optimal Double Tuned Passive Filter Technique

Muhammad Murtadha Othman*, W Muhammad Faizol bin W Mustapha, Amirul Asyraf Mohd Kamaruzaman, Aainaa Mohd Arriffin, Ismail Musirin, Nur Ashida Salim, Zulkiffli Abdul Hamid, Nofri Yenita Dahlan
Faculty of Electrical Engineering, Universiti Teknologi MARA Malaysia, 40450 Shah Alam, Selangor, Malaysia
*Corresponding author, e-mail: mamat505my@yahoo.com

Abstract

Harmonic is one of the power quality disturbances customarily imminent in an unbalanced electrical system. Harmonic represents as the multiple integral of fundamental frequency of voltage and current inflicting towards the shifting in system frequency causing to a disruptive operation of electrical devices. This paper investigates on the performance of passive filter intrinsically by utilizing the inductor and capacitor electrical components to mitigate harmonic problem emanating from an unbalanced electrical system. In particular, explication in this paper will focus on the optimal parameters specification for the double tuned passive filter that used to overcome the phenomenon of harmonic issue. The two case studies constituting with different number of harmonic orders injected in a system were introduced to distinguish effectiveness of double tuned passive filter in solving the aforesaid problems. The parameters configuration of the passive filter are automatically tuned by the MATLAB® software to reduce the total harmonic distortion incurred in a system designed under the Simulink® software.

***Keywords**: Optimal parameters specification of double tuned passive filter, total harmonic distortion, power quality*

1. Introduction

There is a growing awareness among the users and utility regarding with the increasing number of nonlinear loads installed in a system inflicting towards the power quality predicament is such a way that the voltage and current waveforms are distorted from its fundamental frequency. This is due to the fact that the switching effect of semiconductor devices available in an electrical apparatus such as the personal computer can be defined as a nonlinear load rendering to the total harmonic distortion and hence deteriorating the sinusoidal current and voltage waveforms from its fundamental frequency in an electrical system [1, 2].

Subsequently, there should be an ongoing research study searching for the best and novel approach inhibits the harmonic which may elicit towards the occurrence of resonance as it is dangerous and adversely affect the efficacy of an electrical system operation [2, 3]. Hence, both of the characteristics should be identified in advance to prevent from power quality issues such as the harmonic that able to exert power losses in an electrical system as well as the short lifespan of an equipment, and also the resonance that has the ability to instigate problems related to the overcurrent and overvoltage in an electrical system [4]. There are many studies have been carried out on the harmonic mitigation technique using different types of filter. The filter is customarily installed at the point of common coupling to mitigate the harmonics attributed by the nonlinear load such as the adjustable speed drive (ASD) [5].

In-depth discussion on the analysis and optimal parameters specification of double tuned passive filter will be divulged in this paper. The double tuned passive filter constructed with the optimal passive components specification of capacitor and inductor is having the advantage of cancelling the harmonic at two different frequency.

Received January 7, 2017; Revised March 15, 2017; Accepted April 1, 2017

2. Research Method

2.1. Several Configurations of Double Tuned Passive Filter

Figure 1 and Figure 2 show the abridge type and damped-type of double tuned passive filter, respectively. In Figure 2, the double tuned passive filter is composed with several types of damped circuit. The basic concept of double tuned passive filter is consisting of series resonant frequency (ωs) and parallel resonant frequency (ωp) attributed by the combination of capacitors and inductors connected in series and parallel with the purpose to mitigate the harmonic distortion at two different frequencies, respectively [6, 7]. The abridge type of double tuned passive filter delineated in Figure 1 will be investigated comprehensively in turn to identify its effectiveness in mitigating the harmonic at two difference frequencies. In contrast with the damped type of double tuned passive filter, the resistor can be neglected in order to simplify intricate expression of impedance, Z and this can be referred to as the abridge type of double tuned passive filter [8]. Nevertheless, both types of double tuned passive filter acquiring relatively similar performance in mitigating the harmonic at two different frequencies.

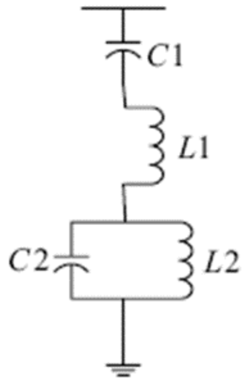


Figure 1. Abridge type of double tuned passive filter.

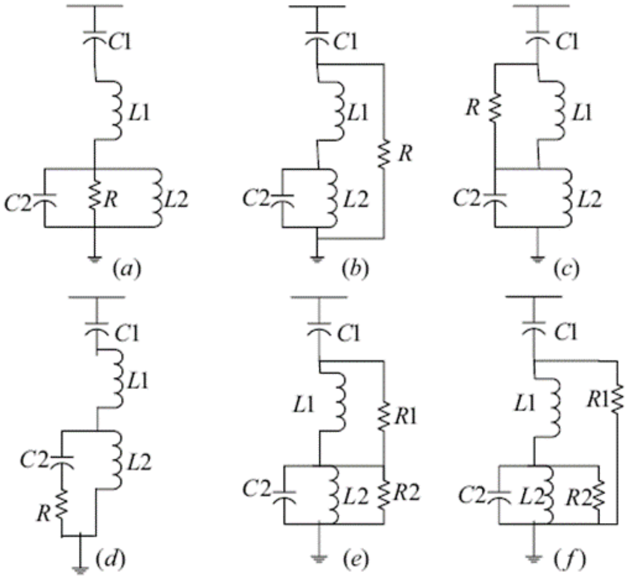


Figure 2. Different configurations of damped type of double tuned passive filter.

2.2. Abridge Type of Double Tuned Passive Filter

The abridge type of double tuned passive filter is comprising with the combination of series resonance circuit (L_1, C_1) and parallel resonance circuit (L_2, C_2) as shown in Figure 1. Hence, for this type of circuit, the calculation of impedance can be divided into two sections which are the series resonant circuit and parallel resonant circuit. Initially, Equation (1) is used to calculate the series impedance circuit by ignoring the dielectric losses in capacitor and also ignoring the resistance in reactor.

$$Z_s\omega = j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \tag{1}$$

where, $\omega = 2\pi f$ is the angular frequency in radian. By referring to Equation (1), the series resonance frequency can be calculated as,

$$Z(\omega_s) = 0 \quad \Rightarrow \quad \omega_s = \frac{1}{\sqrt{L_1 C_1}} \tag{2}$$

In conjunction with the series impedance circuit, $Z_s(\omega)$ will be capacitive when $\omega < \omega_s$ or either it can be inductive when $\omega>\omega_s$. This characteristic can be observed in Figure 3(a).

The parallel impedance circuit can be computed by using Equation (3).

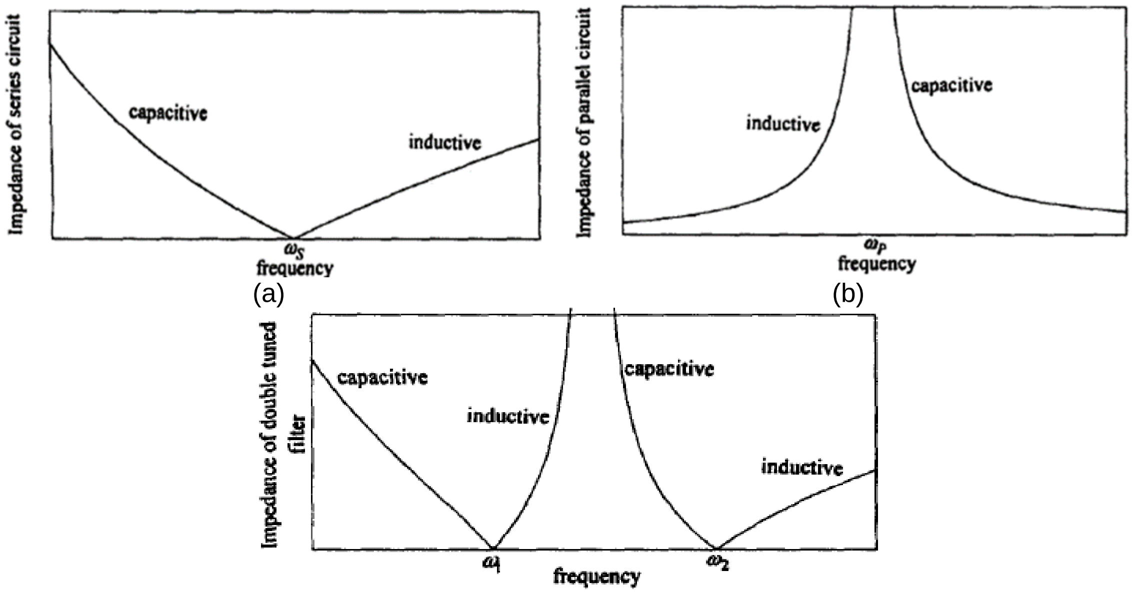
$$Z_p\omega = \left(\frac{1}{j\omega L_2} + j\omega C_2\right)^{-1} \tag{3}$$

Simultaneously, further derivation of Equation (3) is yielding to the parallel resonance frequency given in Equation (4).

$$Z(\omega_p) = 0 \;\; \Rightarrow \;\; \omega_p = \frac{1}{\sqrt{L_2 C_2}} \tag{4}$$

It is noteworthy that the parallel impedance circuit, Z_p, is either will be inductive when $\omega<\omega_p$ or capacitive when $\omega>\omega_p$. The aforesaid characteristic of the parallel impedance circuit is show in Figure 3(b).

The total impedance is calculated by the amalgamation of series and parallel impedance circuit. The total impedance is equal to zero only when the tuned frequency is at the first order (ω_1) and also at the second order (ω_2). This type of circuit has the tendency to filter out the harmonic simultaneously at two different frequencies and also able to provide the reactive power or capacitive to the system as shown in Figure 3(c).



(a) (b)

(c)

Figure 3. Abridge type of double tuned passive filter characteristics. (a) Series impedance circuit; (b) Parallel impedance circuit; (c) Total impedance of the filter

The filter will suppress the harmonic current due to the total impedance is zero at both tuned frequencies order of ω_1 and ω_2. This implies that it is important to determine the tuned frequencies beforehand so that the harmonic distortion could be eliminated at both frequencies. The formulation of tuned frequency can be derived which begins with,

$$\begin{aligned} Z(\omega) &= Z_s(\omega) + Z_p(\omega) \\ &= j\left(\omega L_1 - \frac{1}{\omega C_1}\right) - j\left(\omega C_2 - \frac{1}{\omega L_2}\right) \end{aligned} \tag{5}$$

Then, Equation (5) can be rewritten as,

$$\omega^4 L_1 L_2 C_1 C_2 - \omega^2 (L_2 C_1 + L_1 C_1 + L_2 C_2) + 1 = 0 \tag{6}$$

By referring to Vida’s theory, the relationship between root and coefficients in Equation (6) can be calculated by,

$$\omega_1 . \omega_2 = \frac{1}{\sqrt{L_1 C_1}} . \frac{1}{\sqrt{L_2 C_2}} = \omega_s . \omega_p \tag{7}$$

Since, the filter impedance is infinite at the parallel frequency (ω_p), the harmonic current at this point is easily to be amplified. To prevent from this happen in the circuit, more attention should be given when doing the designing. Parallel resonance frequency should be select properly and also taking account on the network characteristics in designing procedure to avoid form the harmonic current from being amplified.

The series resonant frequency (ω_s) can be calculated by using Eq. (7) based on the known parameters ω_1, ω_2 and ω_p. By substituting Equation (2) and Equation (4) in Equation (6), this may yield to Equation (8).

$$\frac{\omega^4}{{\omega_s}^2 . {\omega_p}^2} - \omega^2 \left(\frac{C_1}{C_2} . \frac{1}{{\omega_p}^2} + \frac{1}{{\omega_s}^2} + \frac{1}{{\omega_p}^2} \right) + 1 = 0 \tag{8}$$

The parameters C_1 and C_2 can be obtained from the Equation (8) by replacing ω with ω_1. Wherein, ω_1 is the roots characteristic for Equation (8). From this substitution, it leads to the following equation for C_1 and C_2.

$$\frac{C_1}{C_2} = \frac{{\omega_1}^2 + {\omega_2}^2 - {\omega_p}^2}{{\omega_s}^2} - 1 \tag{9}$$

Parameters L_1 and L_2 can be calculate from Equation (2) and Equation (4) by taking into consideration Equation (7). The expression of the L_1 and L_2 is written in Equation (10).

$$L_1 = \left(\frac{\omega_p}{\omega_1 . \omega_2} \right)^2 . \frac{1}{C_1} \tag{10}$$

and,

$$L_2 = \frac{1}{{\omega_p}^2} . \frac{1}{C_2} = \frac{1}{{\omega_p}^2 . C_1} \left(\frac{{\omega_1}^2 + {\omega_2}^2 - {\omega_p}^2}{{\omega_s}^2} - 1 \right) \tag{11}$$

Double tuned passive filter has the advantage of providing the required reactive power besides of bypassing the harmonic current. The reactive power generated by the double tuned passive filter can be calculated by using Equation (12).

$$Q = \frac{V^2}{Z(\omega_o)} \tag{12}$$

where, V^2 is the network fundamental rated ac voltage, ω_o is the fundamental frequency of the network in radian and $Z(\omega_o)$ represents as the filter impedance at the fundamental frequency. In relation with Equation (5), the filter impedance at the fundamental frequency, $Z(\omega_o)$ can be written as in Equation (13).

$$\begin{aligned} Z(\omega_o) &= Z_s(\omega_o) + Z_p(\omega_o) \\ &= j\left(\omega_o L_1 - \frac{1}{\omega_o C_1} \right) + j\left(\omega_o C_2 - \frac{1}{\omega_o L_2} \right) \end{aligned} \tag{13}$$

By substituting Equation (13) in Equation (12), the parameter C_1 can be obtained by using Equation (14).

$$C_1 = [\omega_o \left(\frac{\omega_p}{\omega_1\omega_2}\right)^2 - \frac{1}{\omega_o} + \frac{\omega_o\left({\omega_1}^2 + {\omega_2}^2 - {\omega_p}^2\right){\omega_p}^2 - {\omega_1}^2.{\omega_2}^2}{{\omega_1}^2.{\omega_2}^2\left({\omega_p}^2 - {\omega_o}^2\right)}]\frac{Q}{V^2} \quad (14)$$

By referring to Equation (9), Equation (10), Equation (11) and Equation (14), the parameters L_1, L_2, C_1 and C_2 for the double tuned passive filter can be optimally calculated based on the known voltage, V and demanded reactive power, Q. On top of that, the tuned frequencies (ω_1, ω_2) and parallel resonance frequency (ω_p) also need to be determined earlier before the optimal parameters of double tuned passive filter are calculated. During the operation of the filter, the changing of negative polarity indicates that a reactive power is being supplied to the load.

2.3. Unbalanced Electrical System Design with Optimal Double Tuned Passive Filter

Figure 4 is the flowchart for the algorithm used to design the optimal parameters specification of abridge type of double tuned passive filter that is installed in an unbalanced electrical system connected between the wye-connected load and the source of three phase 415 V, 50 Hz.

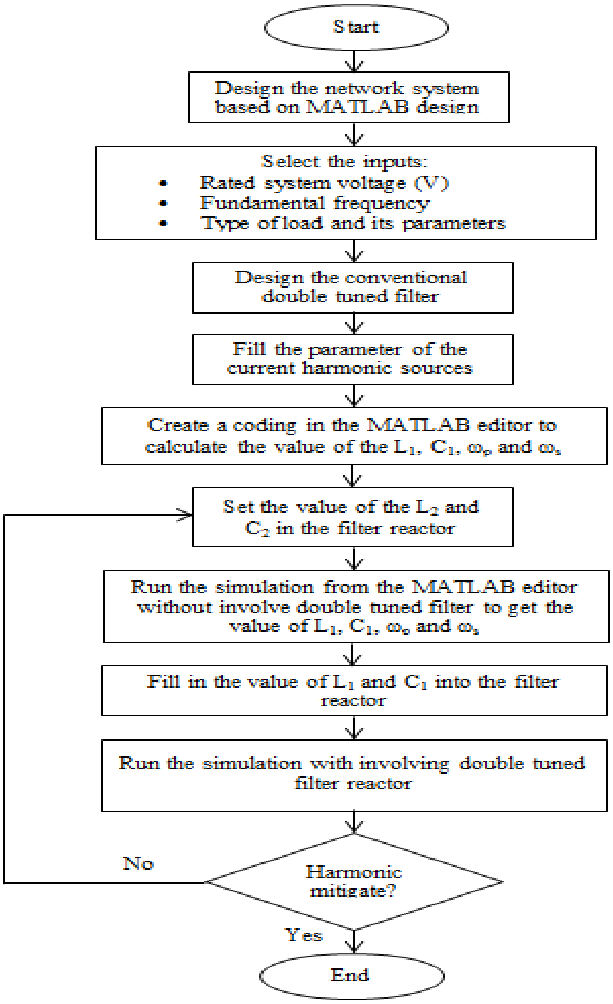


Figure 4. Flowchart of harmonic mitigation using the optimal parameters specification of double tuned passive filter

During the initial process of the algorithm, the L_2 and C_2 values of double tuned passive filter are assumed regarding to the level of harmonic distortion created by the harmonic current sources. This is followed with the double tuned passive filter parameters of L_1, C_1, ω_p and ω_s

calculated in the MATLAB® software. The calculated values of L_1 and C_1 are then transferred to the double tuned passive filter circuit designed in the Simulink® software. Simultaneously, execute the power flow solution of the unbalanced electrical distribution system so that harmonic distortion could be mitigated by the double tuned passive filter taking into account the specified parameters of L_1, L_2, C_1, C_2, ω_p and ω_s. This process is repeated until the optimal parameters specification of double tuned passive filter is attained and significantly improvises in mitigating the harmonic distortion.

3. Results and Discussion

Figure 5 elucidates on the unbalanced electrical system injected with the harmonic current sources at the wye-connected load and the optimal parameters specification of double tuned passive filter connected adjacent to the source. The unbalanced electrical system was designed in the Simulink® software. Table 1 represent specifications of the supply connected to the unbalanced electrical system depicted in Figure 5. The power factor is specified based on the desired amount of load connected at the receiving end whilst ensuring power losses reduction by means of effective operation in the unbalanced electrical system. Every phase of load is composed with the resistor and inductor representing as the electrical components of a motor injected with the harmonic current sources resemblance for the Adjustable Speed Drive (ASD), fluorescent and others. In particular, the harmonic current source is injected to the unbalanced electrical system depending on the percentage of fundamental voltage magnitude and phase angle specified at the fundamental until the 15th harmonic orders [4].

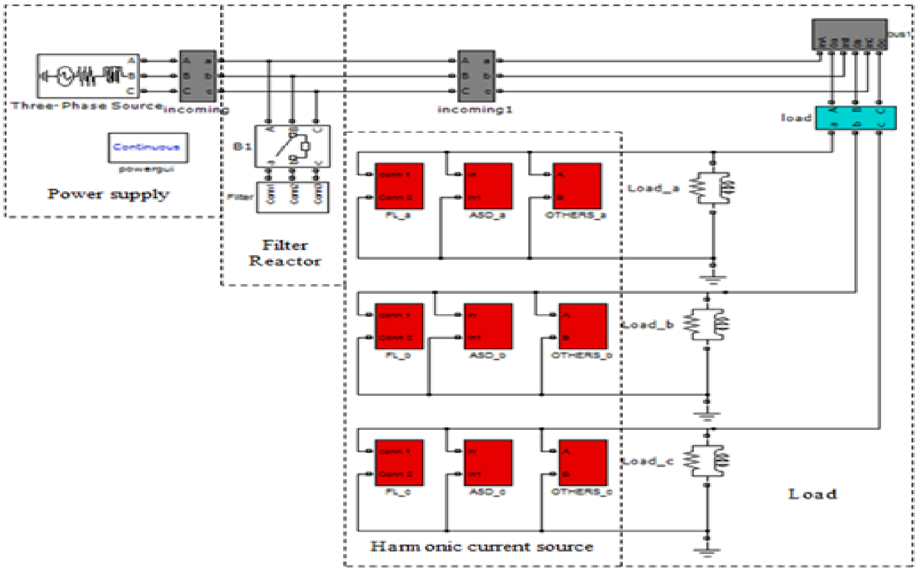


Figure 5. Unbalanced electrical system designed in the MATLAB® software

Table 1. Power supply parameters specification

Parameter	Value
Voltage Source, AC (V)	415
Frequency (Hz)	50
Desired power factor	0.97

Figure 6 shows a design of double tuned passive filter connected at every phase of unbalanced electrical system.

Robustness of the double tuned passive filter used to mitigate the harmonic distortion emerged in the system is investigated based on the two case studies. Case 1 is entailed with the investigation of double tuned passive filter used to mitigate the harmonic distortion specified at the fundamental until the 15th order wherein it is injected by the harmonic current sources at every phase of wye-connected load. Case 2 expounded with further investigation on the performance of double tuned passive filter that has the capability to mitigate the harmonic distortion specified only at the 3rd and 5th order.

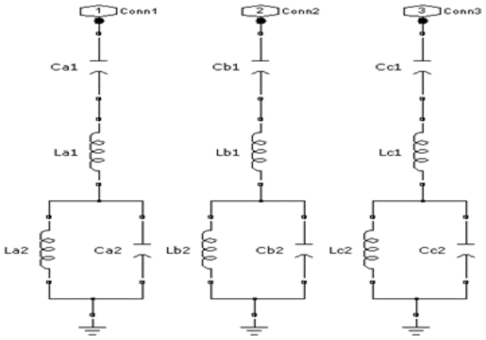


Figure 6. Every phase of double tuned passive filter

3.1. Case 1: Mitigation of Harmonic Distortion Specified from the Fundamental until the 15th Order

Figure 7 evinces on the current and voltage waveforms imminent in the unbalanced electrical system without the installation of double tuned passive filter. It is undoubtedly true that the waveforms distortion is upheaval by the effect of harmonic current source injected at every phase of wye-connected load. The harmonic spectrum for the voltage and current waveform distortion at phase A of an unbalanced electrical system can be observed in Figure 8 and Figure 9, respectively. The waveforms distortion arises due to a large spectrum from the 3rd until 9th harmonic orders. The implementation of double tuned passive filter will mitigate the two largest harmonics specified at the 3rd and 5th order that is dangerous to the system due to its adverse impact towards significant distortion of both waveforms. The optimal parameters of double tuned passive filter obtained from the proposed procedure is tabulated in Table 2.

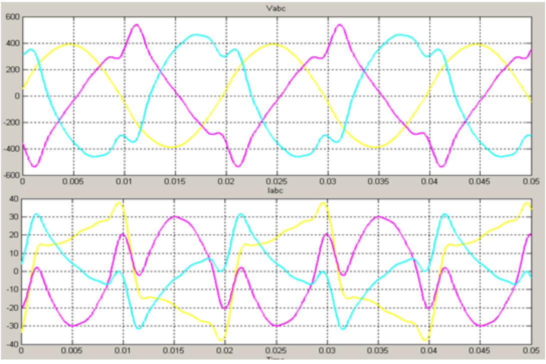


Figure 7. Current and voltage waveforms with harmonic from fundamental until the 15th order

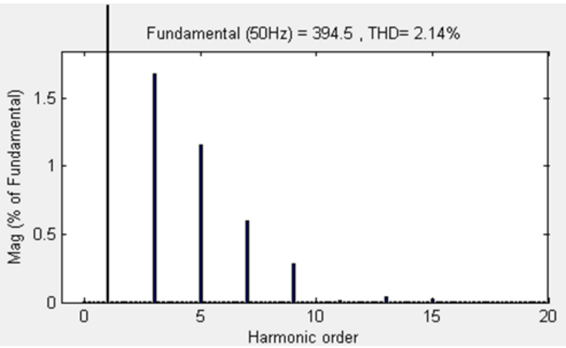


Figure 8. Harmonic spectrum for the voltage at phase A from fundamental until the 15th order

The percentage of harmonic distortion specified at the 3rd and 5th order is severely affecting every phase of the system that can be observed in Table 3. By referring to the 3rd and 5th harmonic orders, a large percentage of total harmonic order (THD) occurred at phase B and phase C of the system that requires mitigation of both harmonic orders reliant to the effective operation of double tuned passive filter.

The operation of double tuned passive filter is dexterous enough to suppress the harmonic hence mitigating both of the voltage and current waveforms distortion and this can be observed in Figure 10. As a result, reduction of THD percentage for every phase can be observed with the counteraction performed by the double tuned passive filter as elucidated in Table 4. The reduction of THD percentage is originated from the abatement of harmonic spectrum at the 3rd and 5th orders. Its significant implication can be observed via smooth cycle of both waveforms that can be seen in Figure 10 in contrast with the waveforms depicted in Figure 7. Nevertheless, there is still a slight distortion in both waveforms since the harmonics are not fully suppressed by the double tuned passive filter.

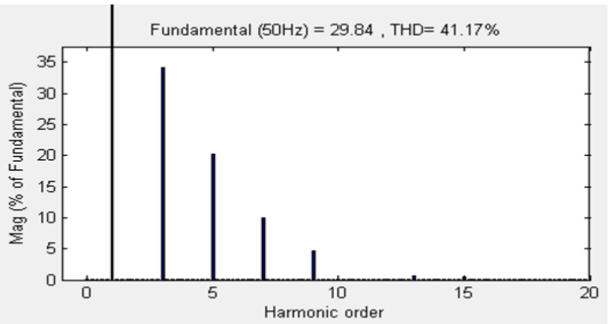


Figure 9. Harmonic spectrum for the current at phase A from fundamental until the 15th order

Table 2. Optimal Parameters of Double Tuned Passive Filter for Harmonic Distortion Mitigation at the 3rd And 5th Orders

Phase	L_1 (mH)	L_2 (mH)	C_1 (μH)	C_2 (μH)
A	1222	5.02	7.02	10.59
B	142		60.46	
C	500.8		17.14	

Table 3. Percentage of Harmonic Distortion without Improvisation from the Double Tuned Passive Filter

Phase	Harmonic order	Harmonic Percentage (%)		THD (%)	
		Voltage	Current	Voltage	Current
A	3	1.68	34.11	2.14	41.17
	5	1.16	20.25		
B	3	14.90	43.34	20.35	52.02
	5	11.77	25.32		
C	3	11.30	42.77	15.57	54.22
	5	9.07	28.75		

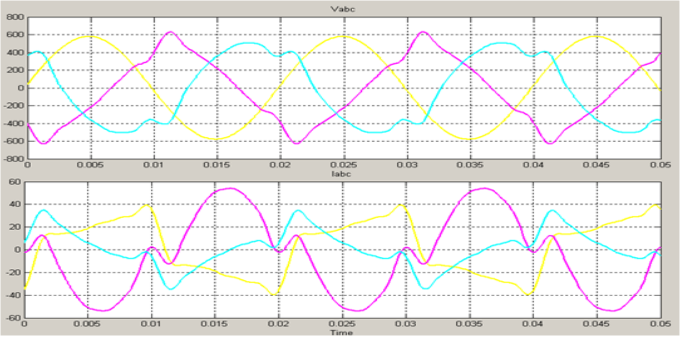


Figure 10. Current and voltage waveforms with improvisation from the double tuned passive filter

Table 4. Percentage of Harmonic Distortion with Improvisation from the Double Tuned Passive Filter

Phase	Harmonic order	Harmonic Percentage (%)		THD (%)	
		Voltage	Current	Voltage	Current
A	3	0.26	33.18	0.28	40.01
	5	0.10	19.66		
B	3	11.01	24.25	15.24	29.15
	5	8.93	14.24		
C	3	10.52	37.27	14.52	47.28
	5	8.48	25.11		

3.2. Case *2:* Mitigation of Harmonic Distortion Specified at the 3rd and 5thOrder

This case study has been undertaken by changing the current source so that harmonic specified at the 3rd and 5th orders is injected in every phase of load and flows to the unbalanced electrical system. This signifies that the number of harmonic order has been reduced without changing the type of harmonic sources. By reducing the number of harmonic order, Table 5 elucidates on the reduction of THD for each phase of voltage and current in contrast with the THD for case 1 shown in Table 3, and this is subject to without the implementation of the double tuned passive filter. The two harmonic orders that adversely distort the voltage and current waveforms at every phase is depicted in Figure 11 and this can be dangerous to the operation of unbalanced electrical system.

Table 6 divulges on the optimal parameters specified for the double tuned passive filter responsible to mitigate the 3rd and 5th harmonic orders. It is proven that the optimal parameters specified for the double tuned passive filter will reduce the harmonic distortion imminent in the current and voltage waveforms as clarified in Figure 12. Withal with Table 7 again showing that the voltage and current at every phase is having lower percentage of THD in contrast with the THD in Table 5 that is before the implementation of double tuned passive filter. Lower percentage of THD will ensure a safe operation of unbalanced electrical system.

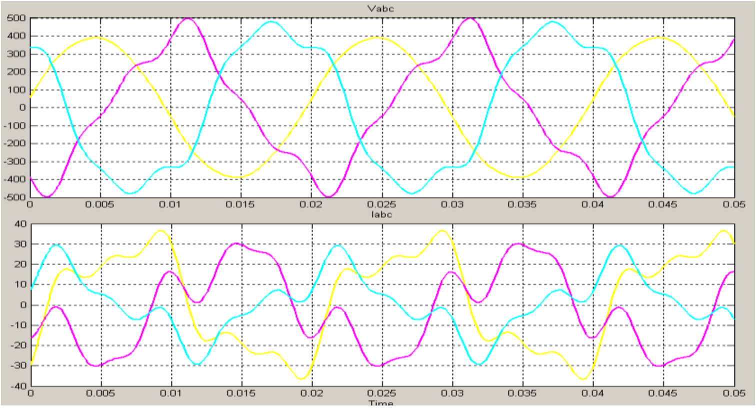


Figure 11. Current and voltage waveforms with the 3rd and 5th harmonic orders

Table 5. Percentage of Harmonic Distortion without Improvisation from the Double Tuned Passive Filter

Phase	Harmonic order	Harmonic Percentage (%)		THD (%)	
		Voltage	Current	Voltage	Current
A	3	1.67	33.97	2.02	39.42
	5	1.15	20.00		
B	3	14.87	43.17	18.89	49.89
	5	11.66	25.01		
C	3	11.28	42.62	14.42	51.24
	5	8.99	28.44		

Table 6. Optimal Parameters of Double Tuned Passive Filter for Harmonic Distortion Mitigation at The 3rd And 5th Orders

Phase	L_1 (mH)	L_2 (mH)	C_1 (μH)	C_2 (μH)
A	54.8	40.02	6.8	30.59
B	6.0		62.16	
C	22.3		16.74	

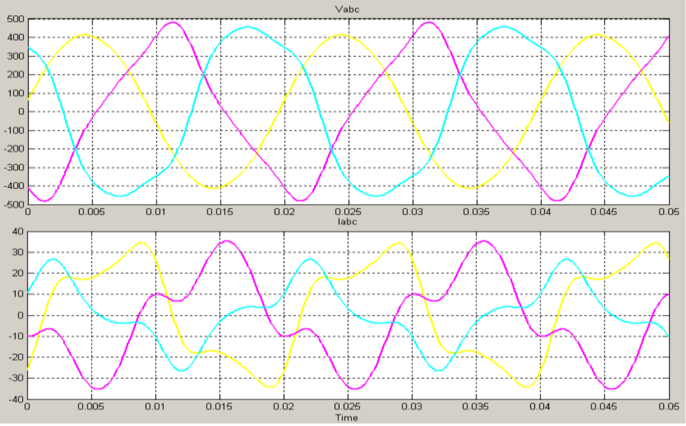


Figure 12. Current and voltage waveforms with improvisation from the double tuned passive filter

Table 7. Percentage of Harmonic Distortion with Improvisation from the Double Tuned Passive Filter

Phase	Harmonic order	Harmonic Percentage (%)		THD (%)	
		Voltage	Current	Voltage	Current
A	3	1.53	33.24	1.61	33.98
	5	0.51	7.05		
B	3	14.23	37.54	14.62	37.80
	5	3.36	4.43		
C	3	11.09	41.15	11.57	41.97
	5	3.30	8.25		

4. Conclusion

Significant implication of double tuned passive filter towards improvising the harmonic distortion for the two case studies has been expounded in this paper. The proposed technique has been introduced to determine the optimal parameters of double tuned passive filter to overcome the two cases of harmonic distortion specified from the fundamental until 15th order and also for the 3rd and 5th orders. It has the advantage of utilizing the sequentially process which eventually arrive to the optimal parameters of passive filter based on the tuned frequencies. Compendium of the results have shown the double tuned passive filter significantly suppress the two harmonic orders in case 1 yielding to the THD that is lower than the THD rendered from case 2. This is due to the fact that the proposed double tuned passive filter is designed particularly to suppress the two largest harmonic orders whilst the remaining harmonic orders not in the filtering range are ubiquitous in the waveforms causing case 2 to have a large THD compared to the THD obtained from case 1.

Acknowledgement

This research project is undertaken under the auspices of research grant FRGS/2/2014/TK03/UITM/02/1, RAGS/1/2014/TK03/UITM//6, 600-RMI/DANA 5/3/LESTARI (77/2015) and 600-IRMI/DANA/5/3/BESTARI(0001/2016) conferred by the Ministry of Higher Education (MOHE), Malaysia and the Institute of Research Management & Innovation (IRMI), Universiti Teknologi MARA, Malaysia.

References

[1] AF Zobaa, SHEA Aleem. A new approach for harmonic distortion minimization in power systems supplying nonlinear loads. *IEEE Transactions on Industrial informatics*. 2014; 10(2): 1401-1412.

[2] RM Patil, MS Nagaraj, PS Venkataramu. Harmonic problems in the switching devices with respect to electrical power quality point of view. *International Journal of Science, Technology & Management*. 2015; 4(3): 17-34.

[3] M Kesler, MC Kisacikoglu, LM Tolbert. Vehicle-to-grid reactive power operation using plug-in electric vehicle bidirectional offboard charger. *IEEE Transactions on Industrial Electronics*. 2014; 61(12): 6778-6784.

[4] A Bonner, T Grebe, E Gunther, L Hopkins, MB Marz, J Mahseredjian, NW Miller, TH Ortmeyer, V Rajagopalan, SJ Ranade, PF Ribeiro, BR Shperling, TR Sims, W Xu. Modeling and simulation of the propagation of harmonics in electric power networks. part II: sample system and examples. *IEEE Transactions on Power Delivery*. 1996; 11(1): 466-474.

[5] HA Kazem. Harmonic mitigation techniques applied to power distribution networks. *Advances in power electronics*. 2013: 1-10.

[6] RS Burton, N Christl, A Coutu, D Crisford, R Dass, NH Jendal, T Kuwabara, M Lahtinen, NM Macleod, JD Mijnlieff, G Moreau, A Nyman, K Papp, CAO Peixoto, J Price, W Richter, NL Shore. Guide to the specification and design evaluation of AC Filters for HVDC systems. *CIGRE Working Group*. 1999.

[7] HJ Lee, TS Nam, GT Son, JW Park, YH Chung, UH Lee, ST Baek, K Hur. Damped- tuned filter design for HVDC system. *The Korean Institute of Electrical Engineers*. 2012; 61(9): 1232-1241.

[8] Y Mingtao, C Jianye, W Weian, W Zanji. A double tuned filter based on controllable reactor. *IEEE, International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM* 2006. 2006: 1232-1235.

Appendix

Table 8. Harmonic current sources with respect to the phase angle and percentage of fundamental voltage [4]

	Harmonic current source type					
	ASD		Fluorescent		Others	
Harmonic Order	Mag. (%)	Phase (^{o})	Mag. (%)	Phase (^{o})	Mag. (%)	Phase (^{o})
1	100	-1.45	100	-107	100	105.5
3	84.6	-8.34	19.2	76	3.6	-44.4
5	68.3	-14.23	10.7	10	3.2	139.4
7	47.8	-20.13	2.1	37	-	-
9	27.7	-29.02	1.4	31	-	-
11	0.2	-27.91	0.9	36	-	-
13	6.1	158.2	0.6	47	-	-
15	4.2	122.3	0.5	20	-	-