AUT Journal of Electrical Engineering

AUT J. Elec. Eng., 49(1)(2017)3-10
DOI: 10.22060/eej.2016.811

Harmonic Elimination of 25 kV AC Electric Railways Utilizing a New Hybrid Filter Structure

S. Yousefi, M. M. Hosseini Biyouki, A. Zaboli, H. Askarian Abyaneh*, S. H. Hosseinian

Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran

ABSTRACT: Thyristor rectifiers are widely used in electric railways in order to control the speed. As a consequence of their usage in addition to substantial input lead current, an enormous amount of harmonics is injected into the grid. To avoid such harmonics as well as reactive power compensation, reactive power hybrid filters consisting of active and passive filters are utilized. Regarding different passive and active filters connection in a hybrid filter, various configurations of hybrid filters are possible. Each of these configurations has different functionality in harmonic elimination and reactive power compensation. Since electric railway has a non-linear and variable nature, a novel hybrid filter structure is designed that compensates reactive power and eliminates harmonics to attain desired harmonic level regarding the conventional allowable harmonics level standards. The designed filter model is simulated in MATLAB/SIMULINK and then applied to a harmonic model of an electric railway. Since electric railways are single phase loads, specific three-phase to two-phase transformers are required to feed the load. To attain such purpose, an adaptive transformer is utilized in this paper. The proposed model has properly overcome the deficiencies of active and passive filters as well as demonstrating an appropriate performance in the reduction of total harmonic distortion (THD).

Review History:

Received: 28 January 2015
Revised: 13 October 2016
Accepted: 25 October 2016
Available Online: 30 October 2016

Keywords:

Harmonics elimination
Hybrid filters
Non-linear loads
Reactive power compensation

1- Introduction

Development of modern populated cities makes public transportation an inevitable matter. Among all the transportation vehicles, electric railways having advantages such as high-speed transportation, safety, environmental sustainability and production of no pollution have been developed increasingly. Containing thyristor rectifiers used for controlling speed in electric railways, they have a non-linear characteristic which leads to current harmonic distortion (CHD). Considering system impedance, such CHD leads to harmonic voltage distortion (VHD). From electric grid viewpoint, the electric railway is a non-linear variable load and is considered as one of the most unfavorable loads [1,2]. In addition to high reactive power consumption, electric railway injects an enormous amount of harmonic current which is almost equal to 2-3 times of allowable system harmonic level [3]. Harmonics induce plenty of troubles such as excess loss in system, unsuitable function of control systems and improper trips of relays. In order to compensate reactive power and eliminate harmonics, a proper filter must be applied. There are three kinds of filters: passive, active and hybrid filter which is a combination of active and passive filters. Each of passive and active filters has its own pros and cons. However, hybrid filters have advantages of both active and passive filters and on the other hand, few disadvantages in comparison to these two filters. Hybrid filters have different structures with regard to their connections. Each of these structures has its own advantages. In this paper, in order to eliminate harmonics and compensate reactive power, a novel structure of the hybrid filter is introduced which has several advantages in comparison to latter structures. The introduced structure is simulated in MATLAB/SIMULINK and is applied to a harmonic electric railway model. The rest of this paper is outlined as follows: section 2 presents passive filter, active and hybrid filter structures and their advantages and disadvantages. The proposed hybrid filter structure is presented in section 3. Section 4 describes the control method of the active filter used in the proposed model. Simulation results are proposed in section 5. Finally, conclusions are presented in section 6.

Corresponding author; Email: askarian@aut.ac.ir

2- Passive, Active And Hybrid Filters

2- 1- Passive Filters

Structure of passive filters is simple consisting of elements such as inductor, capacitor and resistance. This filter was first utilized in 1940 to eliminate harmonics. Passive filters are categorized as resonant and damper types. In resonant type, inductor and capacitor are connected in a way that resonant frequency $F_r = \frac{1}{2\pi\sqrt{LC}}$ has almost no impedance. In fact, at this frequency short circuit occurs [4]. The damper type has a low impedance for a span of harmonic frequency. Resonant passive filters are used to eliminate fundamental harmonics, such as 5th and 7th order harmonics and damper filters are utilized to eliminate higher order harmonics. Passive filters are also used to correct system power factor and supply network reactive power. In fact, the most important parameter of a passive filter is the amount of injected reactive power to the network in fundamental frequency [5]. Although designing a passive filter is inexpensive, it may cause some problems. One of the problems is the change in its parameters caused by heat or lifetime which gradually leads to a change in filter functionality. Possibility of resonance, need of design for each harmonics frequency, deficiency due to random change in amplitude and dependency of filtering characteristic on system impedance are some other disadvantages of passive filters [1].

2- 2- Active Filters

As a result of power electronics development and passive filters problems, active filters were introduced in 1970s [6]. These filters have inverters and are considered as power electronic equipment which leads to higher cost. Active filters advantages are eliminating numerous harmonics at a time and avoiding resonance with system. Since these filters are in direct connection with the grid, their electronic equipment should tolerate high power which leads to high cost considered as one of the most important disadvantages of active filters [7]. Active filters are mainly used in situations in which passive filters are not able to operate due to resonance. Active filters play the role of current source which injects a current with the same amplitude and opposite direction to the network. Figure 1 demonstrates active filter performance. Active filters consist of different components, including the inverter which is a current source or voltage source. Voltage inverter is mostly preferred due to smaller size especially in DC capacitor, less cost and more efficiency in comparison to current inverter [8]. Figure 2 illustrates a voltage inverter. This filter is capable of performing different functions in electrical system besides harmonics control such as:

- Harmonic isolation between feeder and load or between subscribers and damping resonance between load and source,
- Line voltage regulation or voltage deviation prevention,
- Flicker compensation,
- Reactive power compensation,
- Unbalance or negative sequence compensation [5].

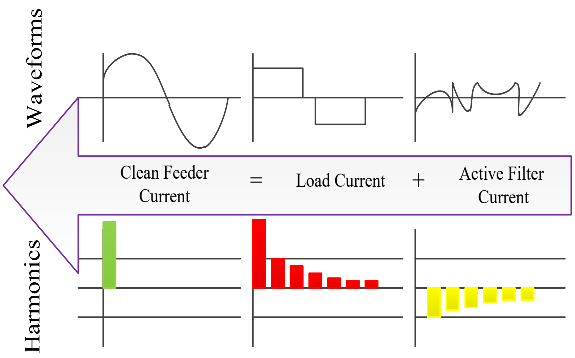

Fig. 1. Active filter performance [1].

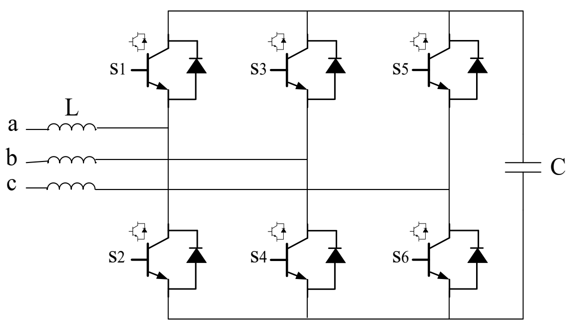

Fig. 2. Voltage inverter [7].

2- 3- Hybrid Filters

Passive filter functionality is highly dependent on system impedance. On the other hand, in order to eliminate each harmonic component, a passive filter is required. Also, in the case of random changes in amplitude and phase of a harmonic component, this filter would no longer be effective. Furthermore,, active filters have many advantages, such as avoiding resonance with network impedance, no need to be designed for each harmonic and compensating several harmonics simultaneously, compensating flicker, compensating reactive power and compensating voltage unbalance. However, since their switches rated power are proportional to the grid power, high power switches must be used which increases the cost of such filters. In comparison to passive filters, active filters are very costly. Therefore, in order to benefit from both passive and active filters advantages and to use an economical filter, hybrid filters have become very common. Hybrid filters are made of active and passive filters connected to each other. In this way, each of active and passive filters covers deficiencies of the other one. As a consequence, harmonics characteristics of passive filter increase and nominal power of active filter decreases. The main reason for applying hybrid filters is however to reduce the nominal power of active filter. In this way, nominal voltage and a nominal current of active filter decrease and filter cost which was the most crucial problem decrease as well. This has caused a diversity of structures for hybrid filters [5]. Regarding different passive and active filters connection in a hybrid filter, various configurations of hybrid filters are possible. Each of these configurations has a different functionality in harmonic elimination and reactive power compensation [2].

2- 3- 1- Parallel Connection of Passive and Active Filters and Load

Schematic of this configuration is demonstrated in Figure 3. Passive filter is tuned to eliminate desirable harmonics which are usually fundamental harmonics and active filters inject the required harmonic current for compensation to the grid. In this configuration, active filter acts like a current source. Active filter is controlled in such a way that it acts like an infinite impedance at the main frequency and shows a low resistance at the harmonic frequency. The functionality of the parallel filter causes the effectiveness of this configuration in asymmetric current compensation.

2- 3- 2- Series Connection of Passive and Active Filters Through Coupling Transformer and Parallelizing Hybrid Filter with Load

This configuration leads to the improvement of passive filter characteristics. On the other hand, as the power of active filter is reduced, its cost is decreased as well. As the active filter is installed at the passive filters terminals, the compensation characteristics and the flexibility of the filter are improved. Schematic of this configuration is shown in Figure 4. In this structure, passive filter is tuned on 5th and 7th harmonic and is connected through coupling transformer to the series active filter. The function of active filter is like current-controlled voltage source which causes injection of compensating current to the grid. In order to supply dynamically the required reactive power of the load, a thyristor-controlled passive filter is put in parallel with the main passive filter which is demonstrated in Figure 5.

2- 3- 3- Parallel Connection of Passive Filter and Series Connection of Active Filter with Load

In this configuration, active filter is in series with the load through coupling transformer, and the passive filter is in parallel with the load. Schematic of this configuration is demonstrated in Figure 6. Active filter power is about 3-5% of load nominal power. The active filter acts like an isolator between the load and the source. The functionality of this configuration is dependent on the source impedance. Higher source impedance to filter impedance ratio at the tuned frequency leads to a better filtering. On the other hand, the greatness of the source impedance results in voltage drop which does not allow the source impedance to be higher than a threshold. The active filter in this configuration does not directly compensate the harmonic current. The active filter conducts the harmonic current to the passive filter. Therefore, using a high-pass filter leads to a better performance than the configuration in Figure 6. In the configuration shown in Figure 7, active filter's rated power and the cost of passive filter are low which results in being more economical than the other introduced configuration. Isolation between the load and the source through the active filter is crucial because in this way the passive filter can be tuned exactly to the harmonic frequency. Control of the active filter in this configuration is important and the adopted control procedure must be able to make the active filter act as an isolator between the source and the load in any working condition. The Synchronous Reference Frame (SRF)

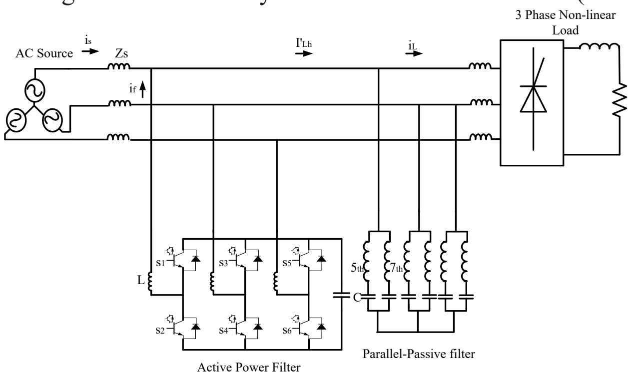

Fig. 3. Parallel connection of passive and active filter and load.

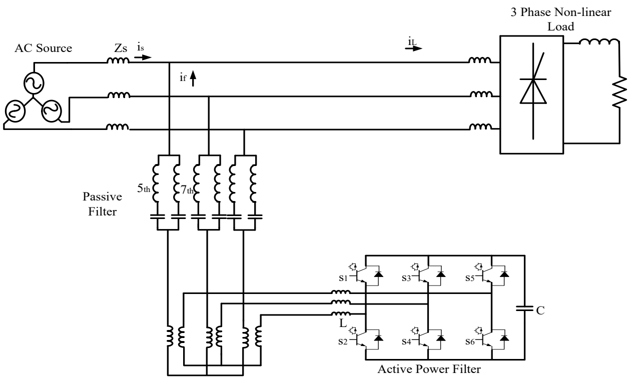

Fig. 4. Series connection of passive and active filters through coupling transformer and parallelizing hybrid filter with load.

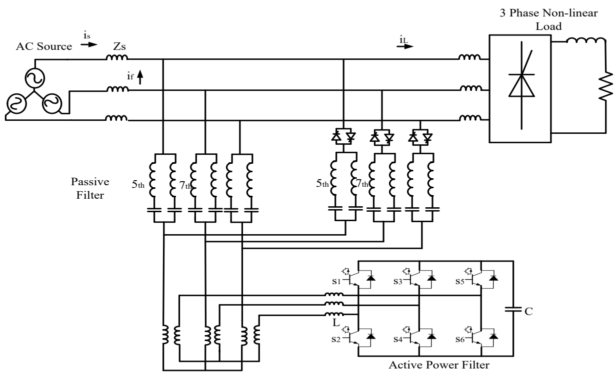

Fig. 5. Series connection of passive and active filters through coupling transformer and parallelizing hybrid filter with load and the thyristor-controlled passive filter.

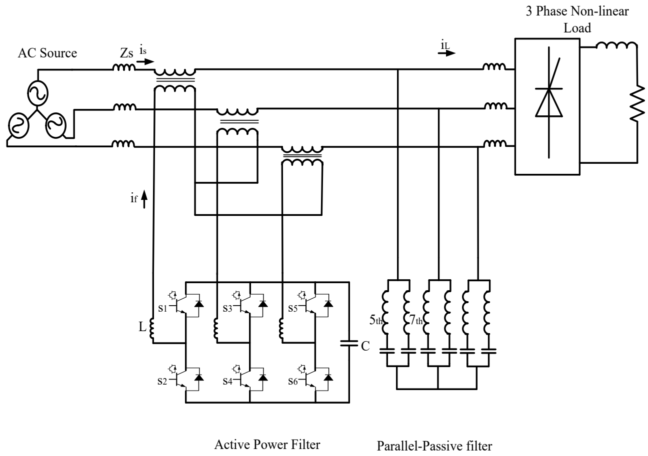

Fig. 6. Parallel connection of passive filter and series connection of active filter with the load.

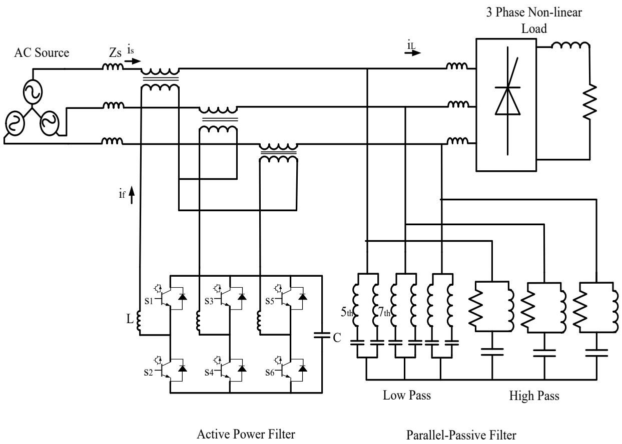

Fig. 7. Parallel connection of resonant and high-pass passive filter and a series connection of active filter with the load.

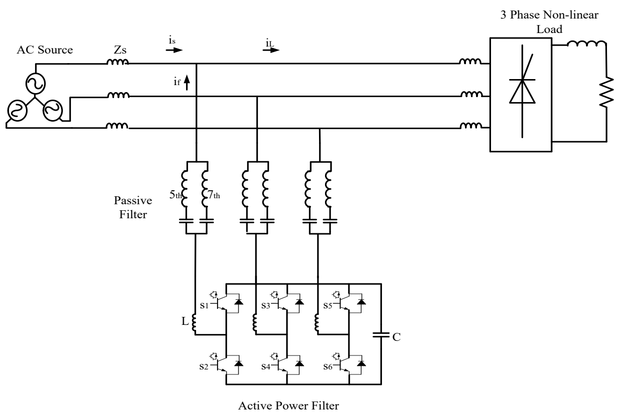

Fig. 8. Series connection of passive and active filters and parallel with the load.

control method can effectively provide the required isolator [2].

2- 3- 4- Series Connection of Passive and Active Filters and Parallel with Load

In this configuration, passive and active filters are in series and are parallel with the load. If a problem arises in the active filter, it can be omitted from this structure and the passive filter can eliminate the tuned harmonics. Schematic of this configuration is shown in Figure 8.

3- The Proposed Structure

The best structure for a hybrid filter is the one in which nominal power of the active part is low and the efficiency of compensating harmonics and improving power quality is at the best level. Normally, in hybrid filter designing, passive part is to compensate low order harmonics (5th and 7th) with larger amplitudes and active part is to compensate higher order harmonics with lower amplitudes. Electric railway not only injects a large amount of harmonics current to the network but also consumes high reactive power. Therefore, the proposed structure should be able to supply required reactive power. Since electric railways are single phase loads, specific three-phase to two-phase transformers are required to feed the load [1]. In this structure, the adaptive transformer is utilized. Figure 9 illustrates a model of electric railway feeding system. Figure 10 shows the single phase equivalent circuit of AC electric railway. In this figure, railway consumption power consists of active and reactive parts. Active power as a function of distance is illustrated in Figure 11. Figure 12 illustrates input reactive power as a function of time. As can be seen, the consumption of reactive power at the beginning of the train movement is high and at the other spans of time becomes less or even negative. Since the purpose is to eliminate harmonics and supply reactive power, special attention should be paid to the railway start moment. The proposed model supplies reactive power of railway at beginning and eliminate harmonics. Schematic of the proposed structure is shown in Figure 13. In this structure, passive filter consists of two parts: passive filter and controlled passive filter with thyristor parallel to passive filter which supplies required reactive power for railway movement start point. The active filter in this structure is designed three-phase and by means of Scott transformer is in series with two passive filters. Traction substation in this structure has asymmetrical star-delta connection. Due to this way of connection to the power grid, the active power part is low because of the high voltage loss in the passive filter. On the other hand, controlled passive filters supply required reactive power for the movement.

4- Control Of Active Filter

The control of the active filter is generating reference signals to inject current and voltage with the aim of compensating harmonics in the network. These signals are applied to the inverter to compensate harmonics. Compensation occurs by means of modulation. The reference signal can be extracted in frequency or time domains. Extraction of the reference signal in the frequency domain has some problems such as more complex calculation. Therefore, extraction in time domain is more applicable and has been used in this paper. Reference signal extraction method should not be affected by voltage or current unbalance and must require less calculation. As electric railway is a single phase, it causes voltage unbalance. Among all control methods, instantaneous reactive power theory (p-q theory) has the ability to compensate in a situation of load current and source voltage unbalance. Also, it requires low calculation in addition to its proper performance [11-15]. This theory has been introduced by H. Akagi in 1983 [11]. The block diagram of this theory is shown in Figure 14. For modulation of the active part inverter, a hysteresis control

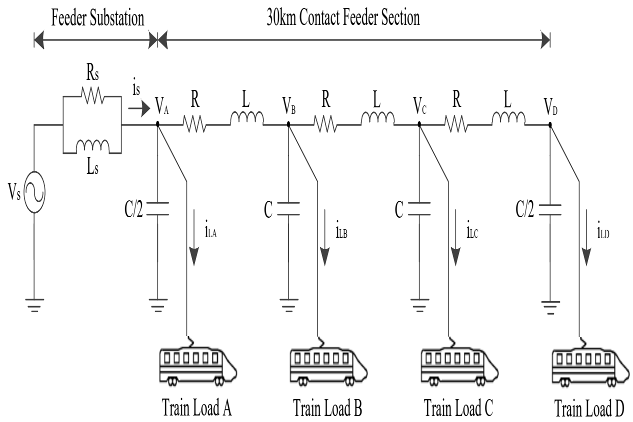

Fig. 9. Model of 25 kV Ac electric railway [9].

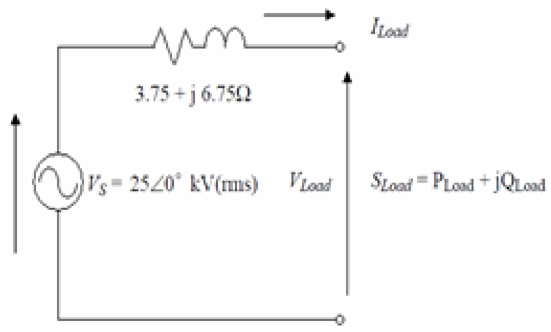

Fig. 10. Single phase equivalent circuit of railway and electrification system [9].

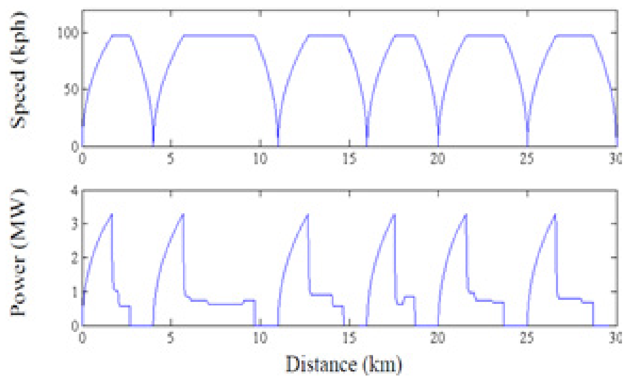

Fig. 11. Speed and active power as a function of distance [10].

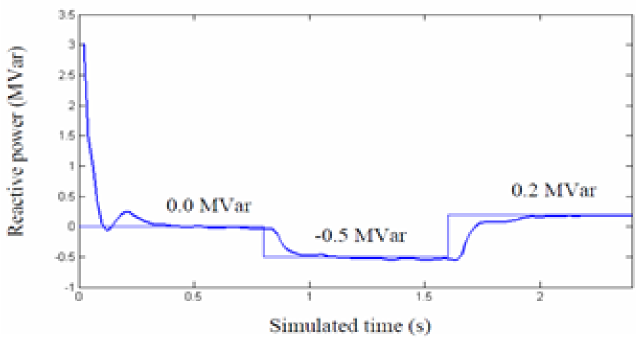

Fig. 12. Reactive power as a function of time [10].

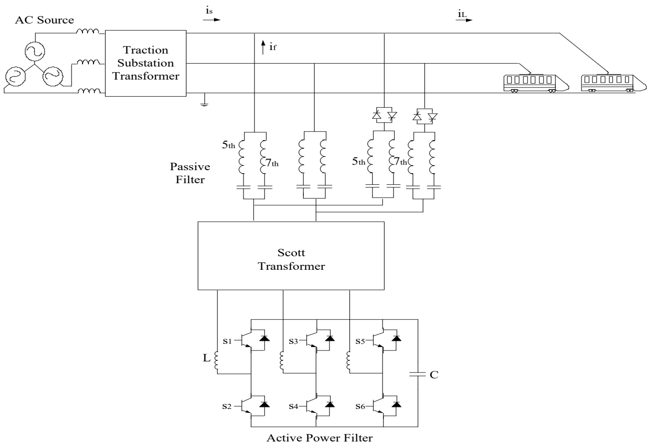

Fig. 13. The proposed model.

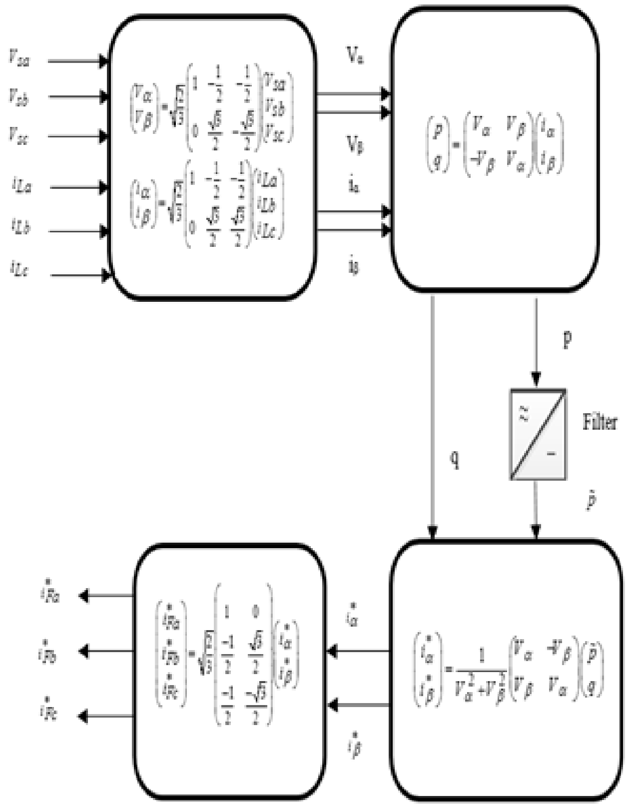

Fig. 14. Block diagram of (p-q) theory.

Table 1. Simulated Passive Filter Parameters

	R (Ω)	L (mH)	C (μF)
5th	337	1.2	0.1
7th	172	1.2	0.1
Z_{System}=0.03 pu (inductive)			

Table 2. Comparison between Harmonic Values Before and After Applying the Hybrid Filter

Phase	THD (Before filtering)	THD (After filtering)
A	33.72	1.35
B	30.52	1.20
C	29.89	1.30

pulse-width method is applied [16].

5- Simulation Results

In order to evaluate the capability of the designed model for eliminating harmonics and compensating reactive power, the designed model is applied to a harmonic model of electric railway and simulated in MATLAB/SIMULINK. The simulated railway is a 25 kV, 4 MVA, 50 Hz urban electric railway which its harmonic model is equivalent to a single phase rectifier SCR and has 90-degree angle which feeds a load of L=120 mH and R=100Ω[17] for each railway. Passive filter controlled by thyristor has been removed from the circuit after 0.1 seconds. The simulated passive filter parameters are presented in Table 1. Phase A current before and after applying the hybrid filter is illustrated in Figure 15. Phase B current before and after applying the hybrid filter is also shown in Figure 16. Phase C current before and after applying the hybrid filter is also presented in Figure 17. Phase A FFT Analysis and corresponding THD is illustrated in Figure 18. Phase B FFT Analysis and corresponding THD is shown in Figure 19. Phase C FFT Analysis and corresponding THD is presented in Figure 20. Comparison between THD values before and after applying the hybrid filter is proposed in Table 2. As can be seen, THD of all phases have decreased below the allowed level of 1.5 % which demonstrates the effectiveness of the proposed hybrid filter.

6- Conclusion

The designed model not only is able to eliminate harmonics but also compensates required reactive power at the start of railway movement. In the presented model, passive filter disadvantages have been covered by active filter capabilities and active power is so low which leads to a low cost of the active filter. The proposed model has properly solved the problems of active and passive filters as well as demonstrating an appropriate performance in the reduction of THD.

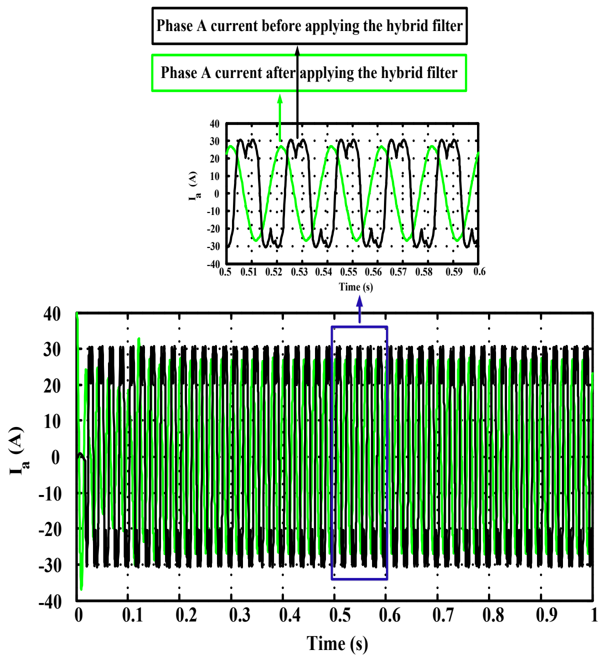

Fig. 15. Phase A current before (black line) and after (green line) applying the hybrid filter.

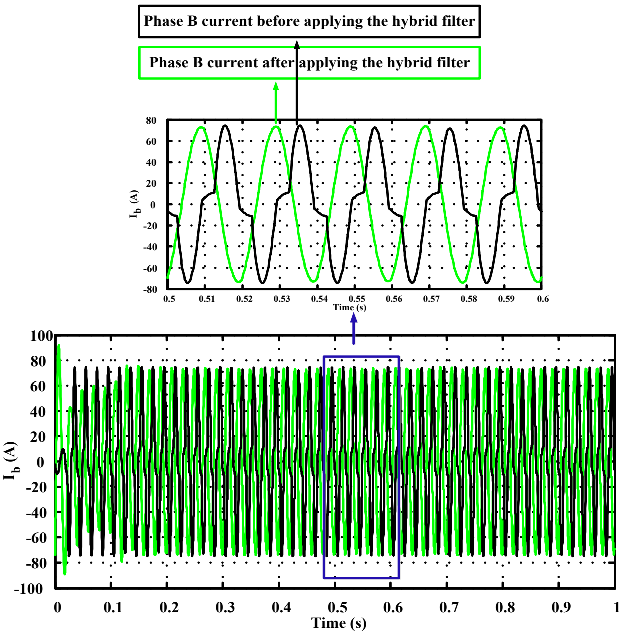

Fig. 16. Phase B current before (black line) and after (green line) applying the hybrid filter.

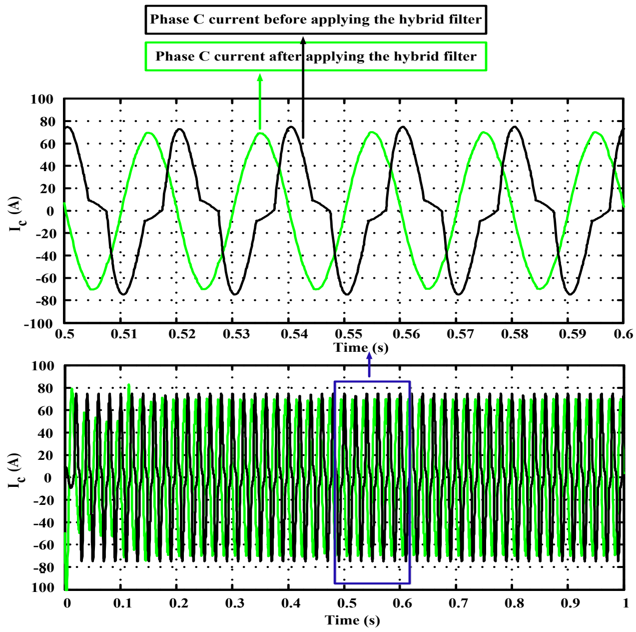

Fig. 17. Phase C current before (black line) and after (green line) applying the hybrid filter.

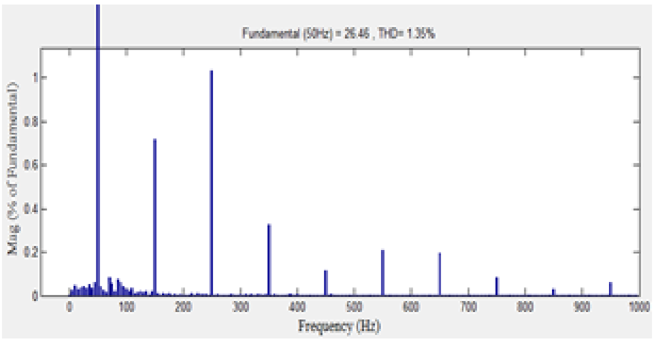

Fig. 18. Phase A FFT Analysis and corresponding THD.

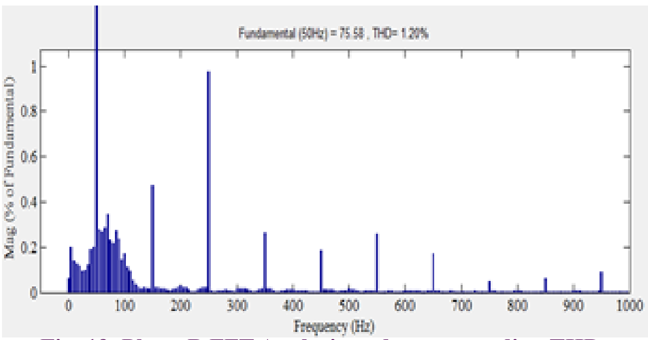

Fig. 19. Phase B FFT Analysis and corresponding THD.

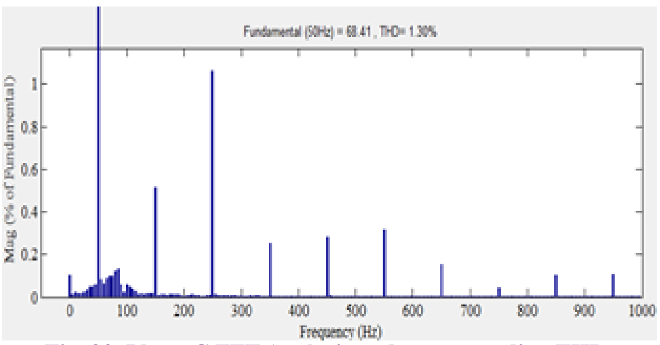

Fig. 20. Phase C FFT Analysis and corresponding THD.

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S. Yousefi, M. M. Hosseini Biyouki, A. Zaboli, H. Askarian Abyaneh, S. H. Hosseinian," Harmonic Elimination of 25 kV AC Electric Railways Utilizing a New Hybrid Filter Structure", *AUT J. Elec. Eng.*, 49(1)(2017)3-10.

DOI: 10.22060/eej.2016.811