

THE IMPACT OF ELECTRICAL TRACTION DRIVES ON POWER SYSTEM

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ELECTRICAL ENGINEERING

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**THE IMPACT OF ELECTRICAL TRACTION DRIVES ON
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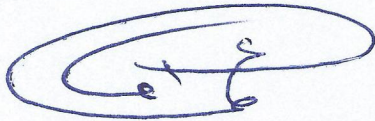
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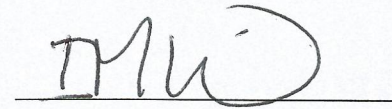
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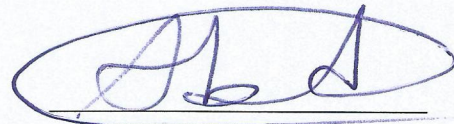
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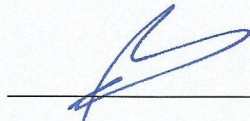
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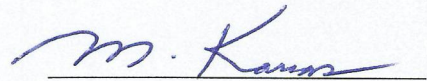
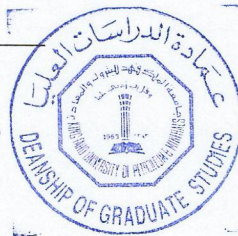
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Dedicated to my parents

To my brother and my sisters

To my under graduate Teacher Elmubarak Shamoog

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LIST OF ABBREVIATIONS

THD	:	Total Harmonic Distortion
Pf	:	Power Factor
NSCs	:	Negative Sequence Components
PSCs	:	Positive Sequence Components
OCS	:	Overhead Catenary System
ASDs	:	Adjustable Speed Drives
PQ	:	Power Quality
PCC	:	Point of Common Coupling
APF	:	Active Power Filter
BLDC	:	Brushless DC motor
SEC	:	Saudi Electricity Company

ABSTRACT

Full Name : AMMAR MISHAL ABDELRASOOL ELAGAB
Thesis Title : The Impact of Electrical Traction Drives on Power System
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Modern societies and cities require fast and reliable transportations system. Electric tractions and trains are now the predominant mass transportation throughout the world. Recently Riyadh City has embarked on the construction of the first metro in the kingdom, while electric train will soon operate between Madinah and Makkah. However, the wide application and usage of electrical traction system present utilities with planning and operation challenges.

Electric railways impose several power quality problems to the utility grid such as: generated large negative sequence components (NSCs) and undesirable harmonic, cause system voltage and current unbalances. All these issues have become more and more significant.

This research is an attempt to quantify and assess the impact of electrical traction on the power quality and thereby, suggesting some solutions. MATLAB\Simulink is used to solve a dynamic model of the traction system. The model includes all components and control accessories. The model has considered the different dynamic modes which are: acceleration mode, cruising mode and deceleration mode. Two different loading conditions are considered to assess the impact of electrical traction system on power system. In order to validate the obtained results, real power system data of Riyadh metro system is

considered. The results show that, the electric traction has affected the power system negatively, high amount of harmonics are injected into the power system. The individual and total harmonic distortion have exceeded the IEEE standard limits adversely. The power factor (Pf) is decreased and thereby, large amount of reactive power and current are absorbed from the utility side. This is manifested during the acceleration and deceleration stages of the train movement. Whereas, few of harmonics appeared when the traction moves with constant speed. A corrective action is taken by designing an active filter to improve power system quality. A PI controller is used to control filter performance. The filter is tested at different locations in the power system. The individual and total harmonic distortion (THD) in the voltage and current wave are reduced significantly, the Pf has improved and thereby, the total reactive power consumption and the absorbed current from the utility side have been reduced as well.

ملخص الرسالة

الاسم الكامل: عمار مشعل عبدالرسول العجب

عنوان الرسالة: أثر محركات القطارات الكهربائية علي نظام القدرة

التخصص: الهندسة الكهربائية

تاريخ الدرجة العلمية: ديسمبر 2017

إن المجتمعات والمدن الحديثة والمتطورة تتطلب نظام مواصلات سريع وموثوق به. وتعتبر القطارات الكهربائية الآن أكثر وسائل النقل الجماعي تطوراً في العالم. وقد شرعت مدينة الرياض مؤخراً في إنشاء أول قطار كهربائي -مترو انفاق- في المملكة العربية السعودية، بينما سيعمل قطار كهربائي آخر قريباً بين المدينة ومكة. ولذلك، فإن التطبيق الواسع واستخدام القطارات الكهربائية وتغذيتها من الشبكة القومية يعتبر تحدياً كبيراً لمهندسي التشغيل ويتطلب التخطيط المسبق والمحكم لاستيعاب هذا النوع من الأحمال.

ورغم الفوائد الكبيرة للقطارات الكهربائية، إلا أنها تعتبر سبباً مباشراً في ظهور العديد من الآثار السالبة بالشبكة الكهربائية العامة وإلحاق الضرر بها. هذه الاضرار تتمثل في حقن الشبكة الكهربائية بكميات كبيرة من التوافقيات غير المرغوب فيها، بالإضافة الي التأثير السالب علي جهد الشبكة. كل هذه الآثار وغيرها اصبحت موضع اهتمام وجديرة بأن توضع لها الحلول التي تحد منها.

هذا البحث هو محاولة لتحديد وتقييم تأثير القطار الكهربائي على نظام القدرة وإقتراح بعض الحلول التي من شأنها أن تقلل من تلك الآثار. تم استخدام برنامج الماتلاب لإنشاء نموذج ديناميكي للقطار الكهربائي. تضمن النموذج جميع المكونات الأساسية والملحقات الأخرى اللازمة للتحكم فيه. وتم الأخذ في الاعتبار الثلاث مراحل الديناميكية والتي تبدأ بمرحلة تسارع القطار، ثم بعد ذلك تأتي مرحلة سير القطار بسرعة ثابتة وذلك بعد وصوله للسرعة القصوي المصمم للسير بها، وأخيراً تأتي مرحلة تقليل السرعة أو الكبح حتي الوقوف تماماً. تم دراسة اثر القطار الكهربائي علي الشبكة في هذه المراحل الثلاث كل علي حده وذلك في حالة حملة لعدد كبير من الركاب وفي حالة تحميله بعدد قليل منهم لتقييم أثر القطار على نظام القدرة. ومن أجل التحقق من صحة النتائج التي تم الحصول عليها. فقد تم توصيل القطار مع نظام القدرة المغذي لمترو الرياض. وأظهرت النتائج أن، القطار الكهربائي يؤثر سلبياً على نظام

القدرة، فقد ظهر عدد كبير من التوافقيات في جانب القطار وفي جانب الشبكة العامة المغذية. أدى ذلك إلى التأثير سلباً على الشبكة وذلك بتقليل معامل القدرة ومن ثم، سحب كمية كبيرة من القدرة الرد فعلية. هذه الآثار تظهر بصورة واضحة في مرحلتي التسارع والكبح. بينما تقل في حالة سير القطار بسرعة ثابتة. تم تصميم مرشح قدرة فعال لتقليل التوافقيات المتولدة وتحسين معامل القدرة وبالتالي تحسين جودة النظام. تم استخدام المتحكم التكاملي الطردي للتحكم في عمل المرشح بالصورة المثلى. تم توصيل المرشح في مواقع مختلفة لتحديد مدى فاعليته وإختيار الموقع الأمثل له. و بعد ربط المرشح في جانب الحمل فقد قلت التوافقيات المتولدة بشكل كبير في موجتي الجهد والتيار علي حد سواء في جميع النقاط علي الشبكة، كما تم تحسين معامل القدرة وبالتالي انخفضت كمية القدرة الرد فعلية والتيار المسحوبين من الشبكة بواسطة القطار.

CHAPTER 1

INTRODUCTION

1.1 Background

Electric transportation acquired and maintained strong presence in modern transportation societies. It is the preferred option due to the high performance, low maintenance cost, and lack of greenhouse-gas emissions [1]. Historically, the train system started in the central Europe cities and it has developed faster and faster since 18th and 19th centuries. It becomes the most effective means of transport. The steam engine played a very significant role of developing the railways systems. However, the real revolution of the railways has begun in the 20th century with the electrification systems. An electric locomotive is faster than the diesel locomotive but it requires a lot of infrastructure and investments in order to electrify the railways. The last decade of the 20th century and the first decade of the 21st century were marked by large increases in high speed trains due to the revolution of electric locomotive technology. There is a large diversity of electric traction systems over the world. Traction systems are designed to be consistent with their railways, location and technology [2].

There are two types of electric tractions: AC and DC tractions. Usually, high speed electric trains are fed by AC power supply, while underground trains are operated with DC supply [2]. The DC supply is obtained by rectifying the AC current, which is obtained from a

public utility. This AC power is transferred through the transmission lines to the traction system location. Generally, the DC traction system is used for short distances where the AC system is used for the long distances. In the past, in order to maintain a constant voltage level throughout the railway track, substations were located every three or four kilometers. However, nowadays the voltage is transmitted at high values and then stepped down to low rating such as 25 kV or others voltage levels. Substations could thus be laid every 20 kilometers [3]. The electrified railway systems are different from one system to another. This variation can occur between countries or sometimes within the country itself. Sometimes trains must transfer from one electric system to another. This is achieved by changing locomotives at the stations. These stations include overhead lines that could be transferred from one voltage level to another. The train arrives with one locomotive and leaves with a different one. These switching stations include compact and sophisticated units [4].

An important part of the electric traction system is the power supply system. The electrified railways systems need a sustainable power supply. It could be either DC or AC. For the AC systems, the electrical power always delivered by using an overhead line, whereas in the DC systems, the power could be delivered through an overhead line or underground cable by using an extra third rail laid near the running rails [5-7]. The basic components of any electric railway system are:

1. The electric return. The return circuit is provided through the railway whether in AC or DC traction system.
2. Catenary. The main function of the catenary is to provide the current to the electric traction. It has to be held in tension horizontally.

3. Pantograph. It is used as a medium between the overhead line -or the third rail- and between the transmitters of the power. It enables the motor to be connected to the catenary.
4. Third Rail. It is used when the power is provided at the ground level. It is laid beside the running railway in order to supply the traction by the required amount of current.

Figure 1.1 displays the basic electrical parts of the electric train.

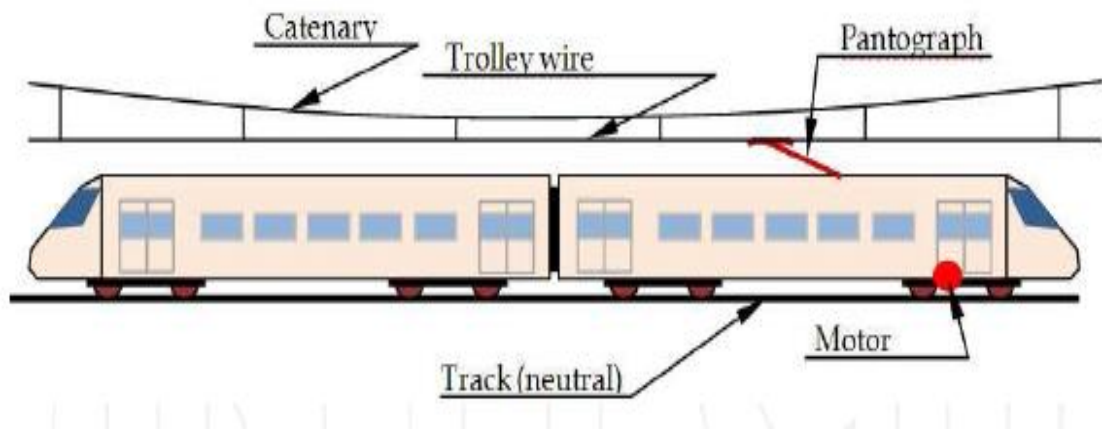


Figure 1.1. The main components of an electrical traction

1.2 The impact of electrical traction drives on power system

Electric traction systems are useful and play an important role in the people's life. However, they may have a negative impact on the power system. They may cause problems in the public utility grid. Such as: injecting a large Negative Sequence Components (NSCs), generating undesirable harmonics, reducing the power factor (Pf), causing additional system losses, causing malfunction of protection relays and measuring instruments, and overheating the rotating machine [8],[9]. The situation is aggravated further if DC series motors are used in the electric locomotives. Series DC motors draw large amount of current

at starting. This is magnified when several locomotives run from the same section of the overhead system at the same time [10]. In addition, the electric traction is a dynamic load as it moves with different speed and changes its position continuously. The power demands for the electric train varies with the time and it is influenced by the operating conditions, such as accelerating, running with constant speed, and breaking when it becomes close to the station. It is also a function of the railroad profile due to ascent and descent grades, curvature radius and rolling resistance, as well as, the weight of the traction [11-14].

Moreover, the train travels with different speeds in every section in order to maintain within the railways tracks. Thus, the supply current are varying continuously with the time [15]. The most common power quality issues in power system due to the electric traction can be classified as follows:

1.2.1 System Imbalance

The unbalanced voltage is the main problem caused by the AC traction system. This is because most of the AC tractions are single-phase loads. A 3-phase power system is connected to the primary side of the step down transformer. The secondary side is either two phases or single phase system. When the secondary side is two-phase system, both two phases must be kept isolated from each other along the line, in this case, the neutral sections must be used at the joint points between different feeders for this purpose. The transformer can balance the current on the two phases if the load was balance. However, in most cases the traction load is unbalance due to the difference of the operation conditions of the locomotives such as the speed, number of passengers and number of locomotives on each side of the substation. Thus, the Negative Sequence Components (NSCs) are produced may

be as much as the Positive Sequence Components (PSCs) [16]. Unbalanced voltage and current are unavoidable, even, in the 3-phase AC traction system. The load that associated with each single-phase circuit does not compensate each other, due to the variable demands in the transport system and the railroad line profile. Moreover, the use of uncontrolled rectification to feed the traction load contributes to the total unbalance seen in the supply. This unbalance occurs due to the injection of current harmonics into the main three-phase system [17]. This unbalanced voltage has a large negative impact on the power system and on the other components connected to it. This impact has different forms such as: reducing the net torque of rotating machines, vibration, overheating the transformers, interference and overlapping with adjacent communication systems, raising electric and magnetic field [3], [15], [18].

1.2.2 Harmonics

Harmonics generation in the power system is one of the major problems caused by the electric traction. The harmonics are produced mainly due to the nonlinear nature of the traction loads. It is also due to the use of the converters which are connected with the substations transformer in order to rectify and control the applied voltage on the motors [19]. In addition, harmonics are produced due to arcing between the overhead catenary system (OCS) and pantograph collector. The level of harmonics increases with the increasing of the train speed. Also, harmonics might increase due to the friction at the contact point between the pantograph collector and OCS [20], [21].

The harmonics may cause repeated start or the locking of the protection relays. This happens because it contains NSCs or composite voltage components. This will lead to increase windings dissipation, eddy currents and hysteresis losses, cause vibration and

noise [8]. The long-term vibration would cause metal fatigue, which might lead at the end to damage the rotating parts in the system. Furthermore, Harmonic currents also overheat system components and produce additional transmission losses and the voltage drops on circuit impedance. Harmonics may also trigger resonance of system inductors and capacitors. This may present a threat to the power grid [3], [15], [16]. Detailed analysis and special consideration of harmonics in electric traction system are thus warranted.

1.2.3 Voltage Fluctuation

Electric traction is considered as a dynamic load. The size of the load varies with the time due to different operation conditions. It starts with low speed. Then, it accelerates gradually until reaches to the normal speed. It maintains moving with constant speed, eventually. It starts decelerating when it becomes close to the station. During this journey, the energy consumption varies continuously with the time according to the train operation condition, between absorption at the acceleration mode and regeneration when it starts breaking. This will lead to voltage fluctuations. This fluctuation has a negative effect on the voltage profile of the utility grid side at the high voltage side of the transformer [17-19].

1.2.4 Reactive Power Consumption

Due to the nonlinearity nature of the electric traction load, large amount of reactive power is consumed and dissipated in particular in the AC traction systems. This is because they are equipped with induction motors. In addition to that, modern adjustable speed drives (ASDs) absorb a considerable level of reactive power[25], [26]. Moreover, the existence of asymmetrical load in the three phase network causes excessive reactive power consumption [19].

1.3 Research Motivation

Nowadays, Electric metro-transit systems are ever more important for solving traffic problems in cities and supporting environmentally sustainable policies concerning urban mobility worldwide; due to their high performance, low maintenance cost, and lack of greenhouse-gas emissions.

Recently, Riyadh City has embarked on the construction of the first metro in the kingdom, while electric train will operate between Madinah and Makkah soon. However, the wide application and usage of electrical traction system presents Saudi utilities with planning and operation challenges. The AC and DC traction systems can generate disturbances to the power system quality. Electric railways impose several power quality problems to the utility grid.

The impact of this type of unfamiliar loads on the power system should be subjected for an extensive study and analysis. Thereby, precautions and corrective actions must be taken to reduce and avoid these problems.

Many researchers have addressed the issue of the impact of electric traction on power system. However, most of these researches were a measuring based researches. Few of them have used a simulation software to study this issue. The purpose of this thesis, is to design a model of an electric train with full dynamic system to give more realistic and accurate results.

1.4 Thesis Objectives

The general objective of this research is to study the impact of electric traction on power system through modeling and simulation. The specific objectives from this research are as follows:

1. Conduct and document an extensive literature survey on the subject of electrical traction and its impact on power system.
2. Develop a model for the dynamic load of an electric traction including all components and control accessories. The model must take into consideration accelerating time, cruising time and deceleration time.
3. Simulate and study the operation of the electric traction by using the developed model on a power network under different operating conditions of light and heavy load.
4. Suggest mitigating equipment.
5. Test the model with real system data.

1.5 Thesis Outlines

The contents of this thesis are distributed over seven chapters. Chapter one, is dedicated for giving an overview about the different aspects of the impact of electric traction drives on power system. Chapter two, includes literatures survey about the impact of traction system on power system, it discusses some cases for traction systems that have a great impact on power systems over the world. Then, a comparison between the work that has been done in the literature and this work is described. Chapter three, describes in details

the model that has been developed in MATLAB/SIMULINK. Also, it describes the mathematical model and the general relationships that have been used to model the electrical and mechanical part of the dynamic system. Chapter four, deals with results of the proposed model of the traction system in different loading conditions. It discusses in details the output simulation results that obtained from integrating the proposed traction model with a power system. After that, a corrective action has suggested in chapter five by designing an active power filter, the optimal position of the filter is determined after testing different location of the filter in the power system. In order to validate the proposed model of the train system, a real data of Riyadh metro is adopted as case study and the simulation results with a suggested corrective action have presented in Chapter six. Finally, chapter seven contains the conclusions and some recommendations for the future work.

CHAPTER 2

LITERATURE REVIEW

The major problems caused by the electric traction are the voltage unbalance and generation of undesirable harmonics. These problems represent big challenge to the utility grid, as they affect the whole power system. Voltage unbalance occurs because the traction system usually connected between two lines. The harmonics are produced due to the rectifier circuits, and the nonlinear nature of the traction load as well. Even though, harmonics are produced at the load side, they propagate into the grid side [27].

Many technical papers have discussed the impact of electric traction drives on power system [19–22]. The majority of these papers discussed this issue based on a real data that is measured at the traction substations. The data has been recorded at different conditions in order to understand the traction behavior with different operation conditions [23–27]. Few authors have developed their own software to build an electric traction model [16], [35]–[37], the authors then validated the results by comparing them with the measurement data. Some of these studies will be discussed in the following section.

2.1 Power Quality Disturbances in the Supply System of Rome Subway

Rome metro-transit system in Rome has total length of 40 km of railway line. It is provided by a special electric power system owned by the company, which is responsible about the operating of the whole transit system.

The traction system consists of two railway lines fed from 1500 V DC through AC/DC 4.0 MW rated converters. The power supply system is supplied from five distinct connections to the public network from 20 KV. The total power demand is 20 MW. The three phase AC/DC converters are used to meet this large demand by connecting it in parallel along the railway. These converters are generating large amount of harmonics. In addition, the traction is a dynamic load and acts as a non-linear load due to continuous load variation with the time. This will affect voltage waveform of the power system and might cause detrimental impacts at the (PCC) [38].

In References [39-42] the Italian electrified railway system is described in details. There are two distinct lines, which supply the metro-transit system of Rome city. The trains are supplied from a contact line at 1.5 KV. The electric power system is fed by the local Electric Utility of Rome city at 20 KV in five distinct service entrances.

Figure 2.1 shows the general scheme of the power supply for Rome metro system.

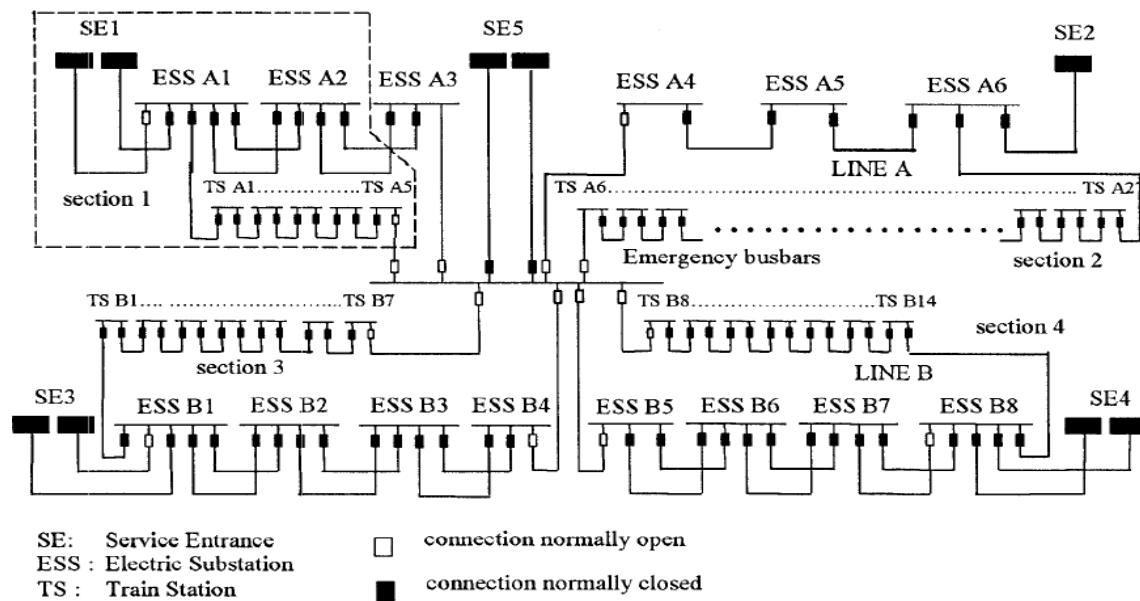


Figure 2.1. Schematic of the electric power system at 20 kV supplying metro-transit system in Rome [40]

For the reliability purposes, each service entrance is provided by double cables. The total system includes four sections: two for line A, and two for line B as shown in Fig 2.1 Each service entrance (SE), during regular operation, supplies a section through a radially distribution system. The distribution system supplies the AC/DC converters at the entrance service (ES) points. Each (ES) is connected with two twelve-pulse full diode bridge converters (1.5 KV, 4.0 MW). This system is analyzed in order to determine the harmonic penetration level to the utility grid adding the new line which is Line (A) [42].

The study has shown that, a sever distortion on the voltage waveform of the utility side has occurred. The overvoltage phenomenon, due to the switching operations for the maintenance purpose, is less frequent than the overvoltage that happened due the switching of the breakers that control the converters operation. This is due to the switching of the converters occurs daily according to the operating condition of the train [39]. Moreover, harmonics levels also have exceeded the allowed level. The DC electrified metro-transit systems are seen by the completely electric system as very large polluting loads.

Publication [43] proposed filter scheme to eliminate the harmonics that flow to the high voltage side of the traction substation. The author aims to apply this filter design to Italian high speed railways. The filter could be located on the locomotive itself or at the substation. Because of the different type of locomotives running simultaneously on the same traction section the most effective place for the harmonic filter location is the 20 kV side of the substation. For this model a passive filter has been adopted. The use of LC filter in traction substation increases the power factor to a high value and reduces the tuned frequency harmonics to a low value.

2.2 The Impact of 25 KV Electrified Railway system on the Power Quality in India

Indian railways have been adopting 25 KV single phase to be the AC voltage level for feeding the electric traction system. This voltage is provided by the utility source, which is a three-phase power supply system. This supply feeds a large single-phase load. This causes a severe distortion in the voltage waveform as well as generating large amount of harmonics. When the train changes its situation during its movement from driving to the braking mode, a large amount of harmonics will be produced and affect the quality of the power system supply. Furthermore, the traction transformers are exposed for repeated re-switching. Large inrush current will flow when contact of circuit breaker turns on at zero crossover instant [15].

The traction substations are located at 30-40 km from each other. The substations take the power from any two phases of the utility transmission line. The high voltage side is 220/166/132/110 KV which is stepped down to 25 KV. The pantograph is used to feed the locomotive. The locomotive contains traction transformer, which is supplied by 25 KV and then stepped down to 1000 V [44]. There are two secondary sides of the transformer. The output voltage is determined according to the position of the transformer tap changer. Each coil at the secondary side feeds an uncontrolled rectifier. The rectifier then feeds the traction motors through the smoothing reactors. The locomotive consists of six DC series motors. Each three motors are connected in parallel and are fed by diode based rectifier block. By changing the on-load tap changer and by changing the DC motor field, the speed of the locomotive can be controlled [45].

A power analyzer has been used to analyze the above described system. Voltage and current waves are measured at the traction substations (110/25 kV). The data is taken continuously at the feeder of the substation. It is observed that, there was a slight variation in the readings day by day depending on the load pattern. The voltage harmonics are also measured for which the total harmonic distortion comes to 2%. This is within the IEEE standard limit as shown in Tables (A.1 to A.4) in the Appendix. The average THD for the measurement period comes to 34%, which is above the limit of IEEE standard for current limit. The peak current was 409 A and peak THD was 99.9%. The peak value of the 3rd harmonic was 110% and average value comes to 30%. Prominences of 3rd and 17th harmonic frequencies were present. In addition, a lesser amount of 7th and 15th harmonic frequencies are present. Based on the IEEE standard limits the THD and individual harmonics of the load current have exceed the IEEE standard for current harmonics. The presence of these harmonics created problems in the locomotive and the traction substation equipment. A filter scheme has designed to reduce these harmonics [34].

Recently Indian railways began using three phase induction motors, due to the low cost of maintenance compared to the DC motors. The converter-inverter combination has been used to feed the AC motors from a single-phase AC voltage. In this type of traction, the inverter is used to control the speed by using the pulse width modulation (PWM). The single phase AC voltage is converted into three phase AC voltage by a converter-inverter combination, so as to feed the AC traction motors [46].

The traction system can be integrated with the power system supply through a single-phase transformer with V/V connection. Usually, there are two traction transformers; one of them is working in the normal operation, while the second one is a standby for emergency cases.

In most cases, the train operates in three typical situations, starting by accelerating then, running with constant speed and decelerating mode [44].

The regenerative power during breaking mode of the traction is discussed in [46]. The generated power due to decelerating or traction breaking could be fed back to the power system through the catenary system. A three-phase locomotive is considered with three-phase induction motors. The power is supplied through a single-phase transformer. Then, it is rectified into DC. An inverter is used to get a 3-phase AC current to feed the traction's motors [46].

The 5th, 7th and 11th harmonics were the dominants and according to that, the THD of the voltage and current was 14.2% and 39.3% respectively, these values were over the maximum level the IEEE standard distortion limits. Therefore, a filter scheme has been used In [9] to reduce the amount of the system harmonics. The most effective location for these filters was the primary side of traction substation (25 KV side) [9]. This is because different types of locomotives are running at the same time on the same section of the traction.

2.3 Power Quality Problems Caused by the Electric Traction systems in China

China is the largest country in the world in terms of the population. The Chinese developed a transport system that meets the challenges of population and vast areas of the country. They adopted the metro-transit system to be the main transport system. Recently electrified railway has developed rapidly [47].

In China, the traction system is composed of AC-DC and AC-DC-AC configuration which is causing a lot of problems in the electric network [33]. The major problem of the DC traction is producing harmonics. The harmonics are injected to the utility grid with adverse effects. The traction is fed from a single-phase power supply system with rated voltage about 25 KV. This causes severe unbalance in the 3-phase power system [48].

Voltage fluctuation is one of problems that represents a challenge for the utility in China. This wide application and usage of electrical traction system presents utilities with planning and operation challenges. The utilities adopted many methods to decrease the effect of electric traction on the power quality such as using transformers with Scott connection and Static VAR Compensator (SVC) to reduce the harmonics and thereby power factor (Pf) can be improved.

The authors in Ref.[32], discussed the impact of a high speed railway (HSR) with speed of 350 km/h on the utility grid. To analyze the effect of electric traction on utility voltage wave, the adopted model called CRH2C [32]. This model uses rectifier and inverter. Both of them have been design with diode base. The authors in Ref.[32] have presented three suggestions to mitigate power quality problems. The first suggestion is to use thyristor based static VAR compensation device (SVC). The second method to reduce the negative effect of traction on the utility grid, is to use static synchronous compensator. The static synchronous compensator is better than SVC in terms of adaptability, high speed of response, wide range of load operation, efficiency and low harmonic content. The third suggestion is to use active filters to absorb generated harmonics before transferring to high voltage side of the transformer.

A typical Chinese model of High Speed Rail (HSR) connected to a power supply system, is presented in Ref. [30]. In this model, the efficiency of AC-DC-AC transformation determines the amount of absorbed current from the power supply system, when the traction needs to speed down, it transfers to the braking mode, and in that case, the traction motors will act as generators, while the converters work as inverters. Most of the frequent methods that are used to present the traction load have represented the traction load by an equivalent admittance. This is called constant impedance model or by an equivalent impedance which is called constant current model. However, these models are not valid to represent a dynamic activity of a system, which is the actual situation for the electric traction during its journey. Furthermore, the parameters of the system are vulnerable and can be affected by the other tractions connected to the same power supply [30].

PSCAD/EMTDC simulation software, has been adopted in Ref. [48] to simulate another Chinese electric traction model. This model consists of three DC motors connected with three half-controlled bridge rectifier circuits. This type of rectifier enables different levels of output voltage by controlling the firing angle of the thyristors, the DC traction's motors have been represented by their back e.m.f connected in series with their armature resistance.

In Ref. [47], another Chinese model has been developed. In this model, the authors have adopted a real time simulation in large-scale power grid by using Advanced Digital Power system Simulator (ADPSS). It gives more accurate results than the previous studies. Authors in Ref [47] mentioned that, some dynamic conditions such as the slope of the road and the friction force have not considered. Autotransformer has been used to step-down

the voltage from 25 KV to 1.5 KV. The secondary side of the transformer connected with a thyristor based converter circuit in order to rectify the current from AC to DC.

From all previous literatures, it has been clearly seen that, most of studies have depended on a measurements and recorded data rather than using model-based simulation for assessing Power Quality (PQ) problems. Of course, the outcome results from field test are more accurate than the results that come from model-based simulation and reflect the real PQ issues and actual physical situation. However, model-based simulation is useful for the prediction process; it gives an overview about prospective conditions in future by assuming unrealistic cases. Furthermore, model-based simulation is effective in system planning and enables the utility to take the required precautions for expected abnormal conditions.

Most of the simulation models for the traction systems have not considered all the expected conditions of the train. These conditions are the acceleration, cruising and deceleration modes. They have discussed the power quality issues related to the power electronics elements. They also discussed the voltage unbalance problem, which caused by the single-phase traction motors. Nevertheless, they have neglected the most important part, which the dynamic features of the traction system. This is essential part and has sever negative impact on the power system quality.

Also, the power quality problems of traction load have been studied [34–38]. Such as establishing the load models, analyzing the measured data and proposing methods to improve power quality. Ref. [7] proposed a novel single-phase hybrid active power filter to deal with the power quality problems in the electrical railway system, which could improve the pf. Then, compensate high-capacity reactive power as well as suppressing the

harmonic. However, the filter was relatively sophisticated and is not enough real-time. According to the actual condition of Guyuan Powe grid [8], the influence and damage of electric iron loads was analyzed which pointed out the harmonic was treated from its source. Based on the actual load structure of traction power supply system, a novel load model consisted of an induction motor in parallel with a traction motor and constant impedance model, was introduced [9], which had a simple and useful structure and could meet the requirements of the power grid digital simulation. Combined with the traction load's simulation model, the information of power quality monitoring data is deeply mined in this research, a quantitative analysis of the impact of electric railway operating on the grid voltage fluctuation is conducted.

It is very clear that, most of the researches have been done based on measurement, few papers have simulated the electric traction system using software. Even, for those papers which have discussed the modelling of the traction systems. Most of them have not considered the different dynamic modes of the train which are: acceleration, cruising and deceleration modes [54–62].

Also, all the authors used the conventional AC or DC motor to develop a model for an electrical train.

In this research a Brushless DC (BLDC) motor will be used to design a model for the dynamic load of an electric traction including all components and control accessories. The model will take into consideration accelerating time, cruising time and deceleration time. Then, it will be connected to a utility grid to study its impact on the power system. BLDC motors are used in Riyadh metro system as well.

CHAPTER 3

TRACTION SYSTEM MODELLING

3.1 Introduction

In this research, SIMULINK/MATLAB software is used to model the dynamic load of an electric train including all components and control accessories. The model has taken into consideration all the stages for a real electrical train movement which are accelerating, cruising and decelerating modes.

The developed model is used to study the impact of electric traction on power system under different loading conditions.

This chapter will describe the components of the model and the mathematical equations that are considered for developing the traction system.

3.2 Problem Formulation

The purpose of this research is to develop a dynamic model of an electric traction with all possible controlling accessories. The traction model will be integrated with a power system network. Different loading conditions will be applied on the traction system to identify whether the loading condition has an impact on the power system or not. Since the electric traction is a nonlinear load, many issues are expected to be presented, such as the harmonics, unbalance voltage and the voltage fluctuation.

After evaluating and determining these problems, corrective action will be suggested to mitigate and release these problems.

3.3 Research Methodology

Firstly, from the literature survey, it has been found that, most of researches that have conducted to study the impact of electric traction system on power system depended on a analyzing some data that obtained by measuring the voltage, current and power at different time in a day during the operating period of the train.

In this thesis, MATLAB/Simulink is used to design a model for a traction system. The main idea of the model depends on the dynamic equations that control the movement of traction system. At the beginning, the train accelerates. Then, it moves with constant speed. Finally, it decelerates until reaching zero speed.

3.3.1 SYSTEM APPROACH

Generally, the high-voltage network of a power system without the traction load system is clean from any distortions

Connecting a traction load always causes the power system to become distorted with high amount of harmonics. Therefore, the primary considerations of the proposed systematic approach are as follows:

1. Three-phase real and reactive powers and power factor (Pf), must be considered and calculated to assess the total consumption of power that will be absorbed by the traction load.

2. Traction loads usually connected to the high-voltage side of a public power system which contains many other loads (PCC).
3. There are several transformer connection schemes commonly used in electrical train substations, in this research, delta to delta connection is used.
4. Substation loads of a traction system are normally unknown, especially during the planning stage. In this study, two conditions of the load have been assumed which are the heavy load and light load conditions. For the heavy load case, the train will operate with its full load capacity whereas, in the light load condition, the train will be loaded with a few number of passengers.
5. The short circuit MVA, ratings of the transformers are obtained from the Italy model [39-42].
6. Electrical traction substations can be represented in either simplified or detailed models. Single schemes of traction substation are considered for this study.

3.3.2 Components of traction system

The ratings of the model component affect the accuracy of the simulation results significantly. Hence, it is necessary to model all network elements carefully to have an accurate results about the impact of the electric train on power system.

A brief discussion of each component is presented here.

- 1- Point of Common Coupling (PCC). The PCC is important. There are typical three-phase bus system models obtained from Italy mode [39-42]. The system consists of three phase bus system, 110 KV bus represents the PCC, 11 KV bus and 1.06 KV bus. The traction will be connected at 1.06 KV bus.

- 2- Transformers. For a separate solution method, distinct implementation of the transformer model should be applied. In this research, a real data of the equivalent circuits of transformers are directly implemented in MATLAB/Simulink model, the delta-delta connection is considered in the model. Delta-delta connection is effective to trap the triple harmonics from the system.
- 3- Traction load system. Traction load is represented by connecting 12 brushless DC motor (BLDC), these motors are connected at the dedicated bus (1.06 KV).
- 4- The Converter system. A 3-phase IGBT based converter is used to rectify the AC current into DC. The output voltage of this converter will be stepped up through a DC/DC converter to be compatible with the rating of the BLDC motors that represent the traction load.

After developing the traction system, it will be integrated to a power supply system to study the impact of such kinds of loads on the power systems. Then, real case study will be considered to have more realistic overview about such kinds of systems.

For the case study, same model of the traction system will be used with real data of the power supply system.

Figure 3.1 describes the system approach that is adopted to study the impact of electric traction on power system.

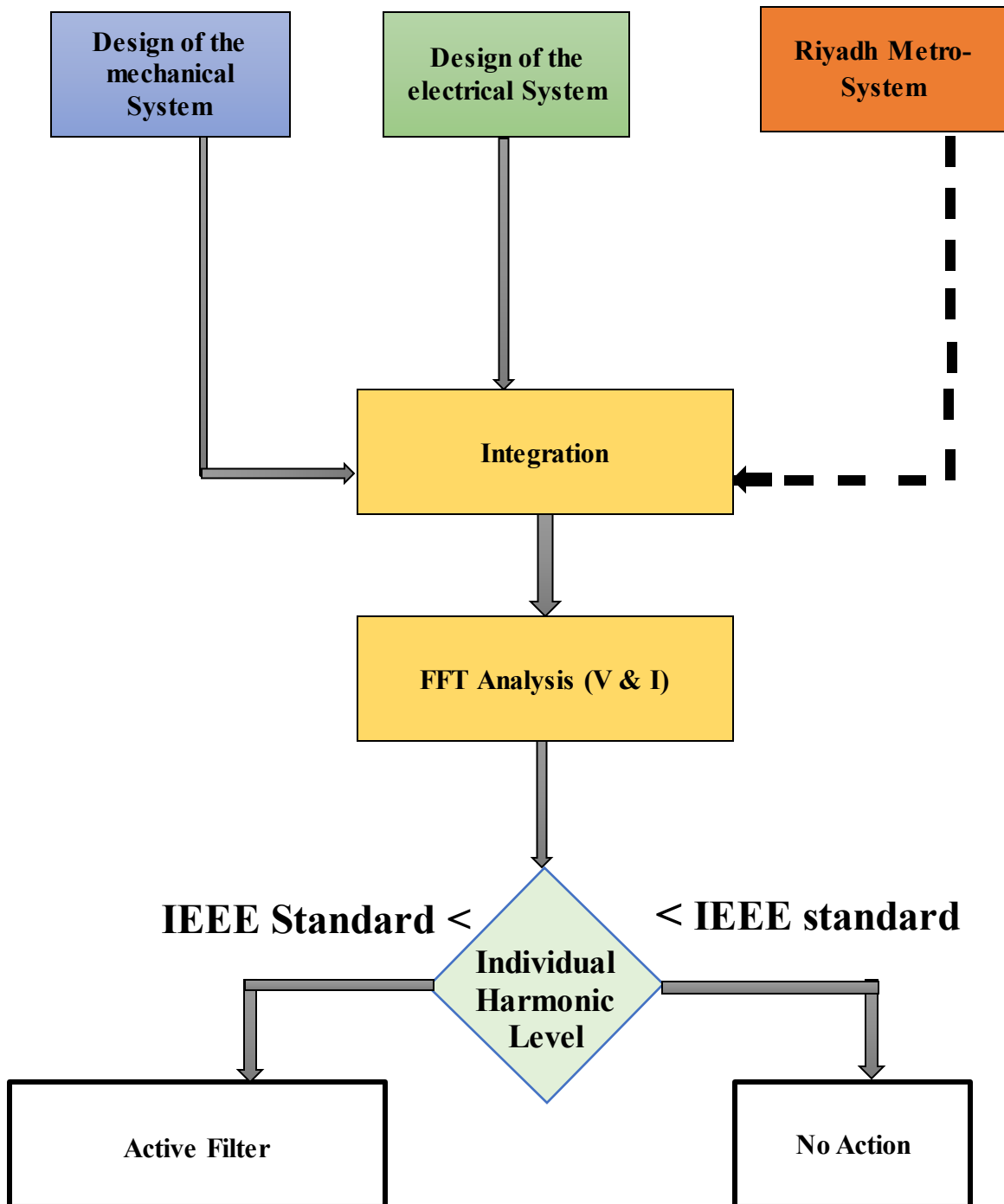


Figure 3.1. Flow chart of the system approach of studying the traction impact on the power system

3.3.3 Mathematical Model

The traction system is built based on electrical and mechanical equations. These equations describe the model that will be used to analyze the output voltage and current. Whereas, the mechanical equations describes the dynamic model of the traction system.

The voltage and current will be analyzed based on the equations (3.1 to 3.3) as follows:

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{r.m.s} \quad (3.1)$$

$$THD_v = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \dots + V_n^2}}{V_1} \quad (3.2)$$

$$THD_i = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \dots + I_n^2}}{I_1} \quad (3.3)$$

Where

$i = 1, 2, 3, \dots, N$.

V_{dc} The converter output DC voltage

$V_{r.m.s}$ The r.m.s line to line voltage of the power supply

THD_v The total harmonic distortion of the voltage wave

THD_i The total harmonic distortion of the current wave

The Planetary Gear block represents a set of carrier, ring, planet, and sun gear wheels. A planetary gear set is constructed from planet-planet and ring-planet gears. The ring and sun coronate with a fixed gear ratio and in opposite directions with respect to the carrier. To model the planet's rotational inertia, Inertia block has been connected to a planet connector port.

The Planetary Gear block imposes two kinematic and two geometric constraints on the three connected axes and the fourth, internal wheel (planet) as it is described in equations (3.4) and (3.5).

$$r_c \omega_c = r_s \omega_s + r_p \omega_p, r_c = r_s + r_p \quad (3.4)$$

$$r_R \omega_R = r_c \omega_c + r_p \omega_p, r_R = r_c + r_p \quad (3.5)$$

Where

r_c The teeth number of carrier gear

r_R The teeth number of ring gear

r_s The teeth number of sun gear

r_p The teeth number of planet gear

ω_c The speed of carrier gear

ω_R The speed of ring gear

ω_s The speed of sun gear

ω_p The speed of planet gear

In terms of the ring-to-sun gear ratio $g_{RS} = \frac{r_R}{r_s}$ the key effective kinematic constraint is given by equation (3.6).

$$(1 + g_{RS})\omega_c = \omega_s + g_{RS} \cdot \omega_R \quad (3.6)$$

The four degrees of freedom are reduced to two independent degrees of freedom.

The gear ratio is also the ratio of the number of teeth on each gear and the ratio of the torques in each axis. The equations ((3.7) to (3.15)) describe the dynamic of the electrical train.

$$g_{RS} = \frac{N_R}{N_S} = \frac{T_R}{T_S}. \quad (3.7)$$

Where

g_{RS} The gear ratio

N_R The speed of the ring gear

N_S The speed of the sun gear

T_R The torque of the ring gear

T_S The torque of the sun gear

$$J_R \dot{\omega}_w = G_r T_m - T_L \quad (3.8)$$

Where

J_R Rotary inertia moment around wheel axis

$\dot{\omega}_w$ Driving wheel angular acceleration

T_m Mechanical gear ratio

T_L Mechanical input torque

Load torque

$$M\dot{V}_T = \frac{T_L}{r} - F_{ext} \quad (3.9)$$

Where

M Translational body mass per one axle

$\dot{V}_T$ Longitudinal traction acceleration

F_{ext} Radius of a gearbox

External running resistance force

$$v_s = r\dot{\omega}_w - v_b \quad (3.10)$$

Where

v_s Slip speed

$\dot{\omega}_w$ Driving angular acceleration

V_T Longitudinal traction speed

$$\mu = \frac{T_L}{W_r} \quad (3.11)$$

Where

μ Friction factor

$$J_R = \frac{1}{4} M_R r^2 \quad (3.12)$$

Where

M_R Equivalent translational inertia

$$J = M r^2 \quad (3.13)$$

Where

M Translational body mass

$$a = \frac{1}{J_R} \left\{ G_r T_m - \left(1 + \frac{J_R}{J} \right) T_L + \frac{J_R}{J} r F_{ext} \right\} \quad (3.14)$$

The speed at any time is given by equation (3.15)

$$V_T(t) = V_0 + a * T \quad (3.15)$$

Where

V_T Traction Speed in km/h.

V_0 Initial speed which is equal zero in the acceleration mode and has a same in the cruising and the deceleration mode in km/h.

a Acceleration rate in km/h which has appositive value in the accelerating mode and has a negative value in the deceleration mode, whereas equal zero in the cruising mode

T Time in hour

The traction system is designed and analyzed based on equations ((3.4) to (3.15)). These equations are represented in MATLAB/Simulink. Then, the traction model is connected to three phase power supply through two units of a three phase step down transformer and DC/DC converter. The equations ((3.1) to (3.3)) will be used to analyze the voltage and current waveforms.

An accelerator signal has been used to control the time of the train movement starting with acceleration mode, cruising mode, and deceleration mode.

3.4 SIMULINK/MATLAB Model

The MATLAB/Simulink model consists of four main parts as shown in Figure 3.2. Each part has been represented by a separate block. Each block has a subsystem. Each block is discussed in details.

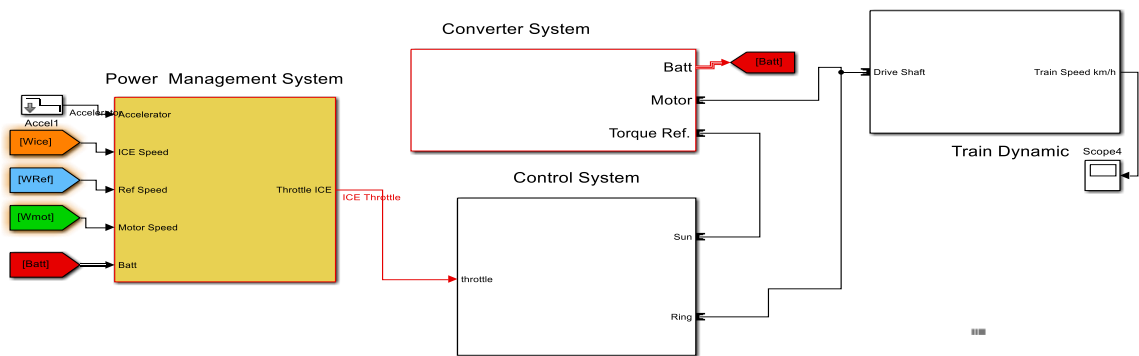


Figure 3.2. Simulink model of the electrical traction system

3.4.1 Power management system

The power management system includes two parts: the power supply and the battery systems. Figure 3.3 shows the power management system. It is designed of a compact components to coordinate the power flow between the source, the traction load and the battery system. This can be achieved by specifying the maximum and minimum values for the power that will be stored in the batteries. Also, a specific amount of torque and speed are determined to the point that the battery will start charge and discharge.

The relationship between the traction speed and the torque is controlled by determining the maximum speed and torque of the train. Then according to these values, a torque limitation block, which is shown in Fig 3.3, will coordinate and maintain the torque value consistent with the speed values according to the operating condition.

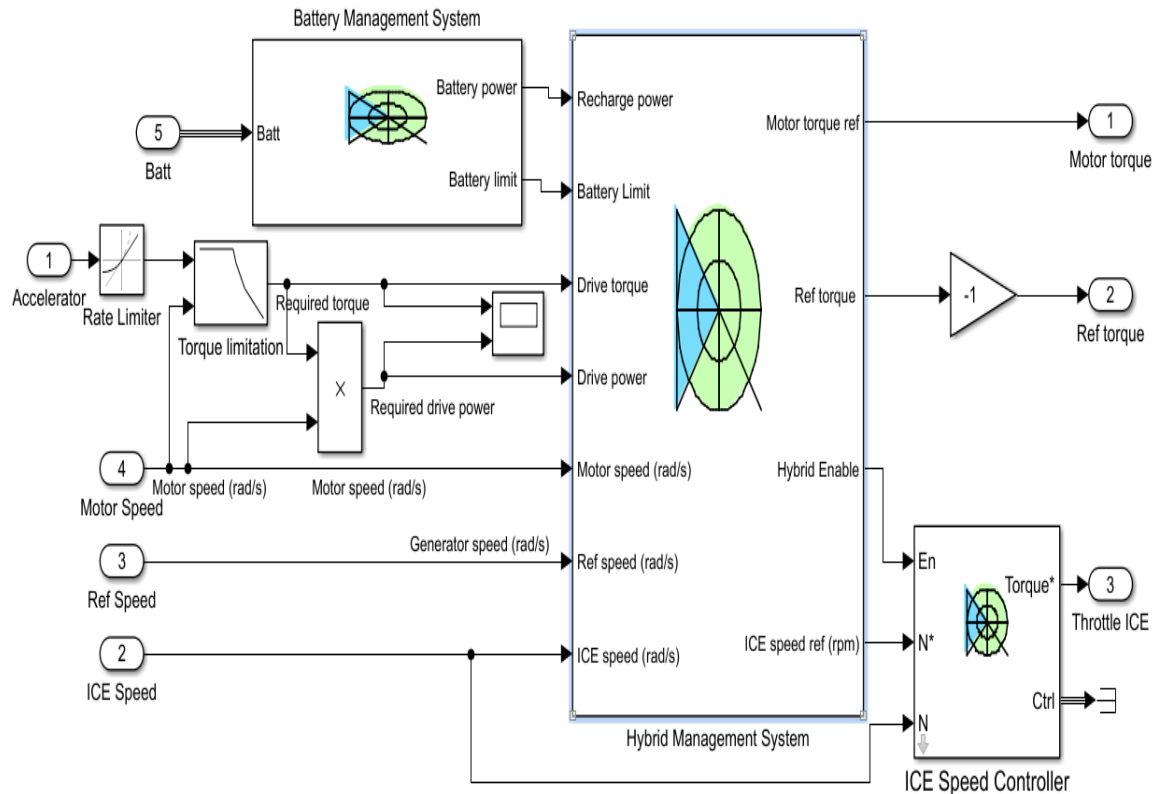


Figure 3.3. Power management system

The power supply system is a three-phase voltage source with rated voltage of 110 KV (r.m.s), line-line, 60 Hz, the short circuit MVA has been obtained from Ref. [40].

The power supply source is connected as star with ground. There are two step-down transformers are used in this model. Both of them have a delta-delta connection.

The first transformer is stepping down the voltage from 110 KV to 11 KV whereas the second one is reducing the voltage from 11 KV to 1.06 KV.

The battery system is designed to store the regenerative power that produced when the traction in the braking mode. The basic idea for the operation of the battery system is to work only in the braking mode by storing the excessive power that might be generated.

3.4.2 Train Dynamic

The train dynamic block is the most complicated part in this model. It represents the dynamic of the traction movement, starting by acceleration mode, then it moves with constant speed and then it is decelerating until stop totally.

3.4.3 AC/DC Converter System

A 3-phase, 12-pulse, IGBT based multi-level converter has been used to convert the AC current in to DC current to feed the traction system. Using a 3-phase converter has enabled us to overcome the unbalance problem which is appeared in case of using a single phase converter. Figure 3.5 shows the converter Module in MATLAB.

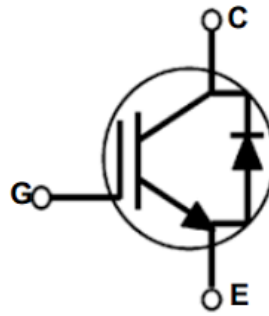


Figure 3.5. IGBT-based converter

Since a 12-pulse multi-level converter is used in this study, the generated harmonics are expected to be in this sequence:

$$h_i = 12q \pm 1 \quad (3.16)$$

Where

$$q = 1, 2, 3, 4, \dots$$

From equation (3.16), the generated harmonics will be 11, 13, 23, 25.....etc.

Also, DC/DC converter is connected to the output of the 12-pulse converter in order to increase the voltage level to be compatible with the rated voltage of the BLDC motor.

3.4.4 Control System

The control system is designed to control the power flow between the utility grid and the traction system. The control system is divided into two main blocks:

The first block which is shown in Figure 3.6 coordinates the torque of the traction with its speed; this is accomplished by connecting a speed governor. The train runs at a variable speed that can be controlled with a Simulink throttle signal. The throttle signal directly controls the output torque that the motor generates and indirectly controls the speed at which the traction runs. If the traction speed exceeded the maximum speed that has already specified, the motor does not generate any torque and vice versa. If the speed decreases below the rated speed that has already specified, the motor will generate more torque. The block accepts the throttle signal through a Simulink in port. This signal specifies the motor torque as a fraction of the maximum torque possible in a steady state at a fixed motor speed and should lie between 0 and 1.

To prevent engine's power and torque from becoming negative, the block imposes an upper limit on the maximum traction speed itself.

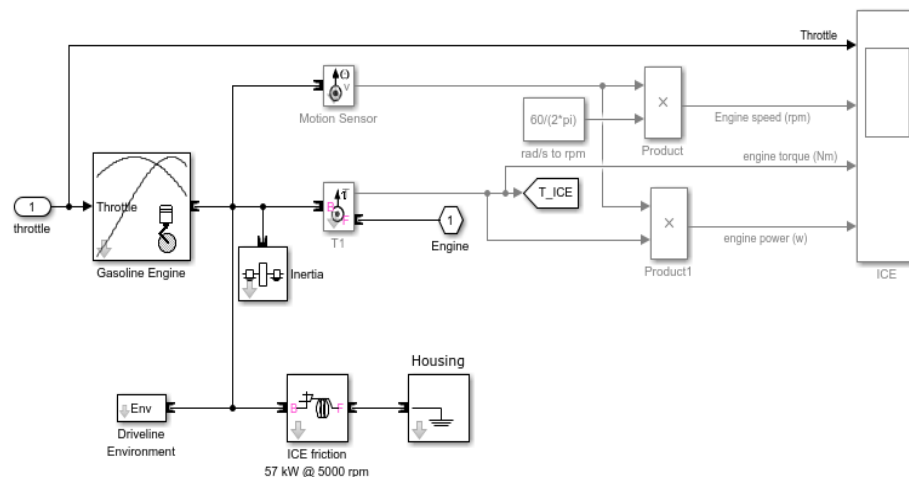


Figure 3.6. Torque-speed coordinator system

The second block is controlling the dynamic of the traction through a group of gears as shown in Figure 3.7.

The Planetary Gear block represents a set of carrier, ring, planet, and sun gear wheels. A planetary gear set has been constructed from planet-planet and ring-planet gears. The ring and sun co rotate with a fixed gear ratio and in opposite directions with respect to the carrier.

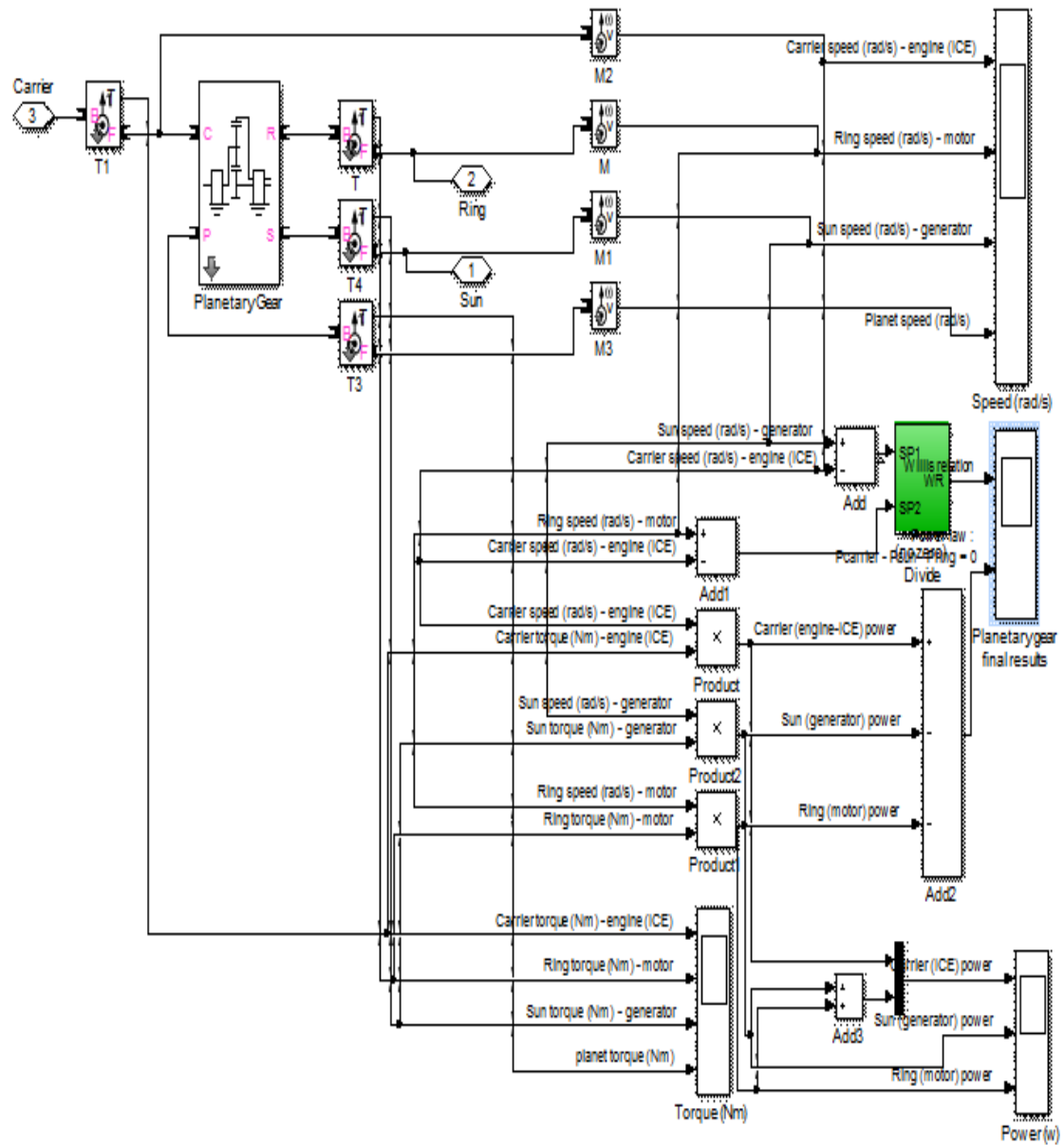


Figure 3.7. Control of the dynamic system

CHAPTER 4

SIMULATION RESULTS

This research is conducted to study the impact of electric traction drives on power system.

In this chapter, after developing a model for the electric traction system in MATLAB/Simulink. The traction is connected to a power supply system to assess the impact of the traction on this power system

In order to identify whether the loading condition has an impact on the power system, two different cases of loading condition of the train are considered in this research.

Firstly, the train has been operating with few numbers of passengers. This represents the light load condition. Then, the train is loaded with its full capacity which is representing the heavy load condition.

In both cases, the train moves with similar speed. Therefore, the loading condition affects the power that the train requires to maintain moving with the same speed.

The traction system is fed from the utility grid side through two step down transformers. Both transformers are connected delta to delta to avoid zero phase sequence components that might be generated in the system. The output of the second transformers is connected to a multi-level IGBT based rectifier, the traction is connected to this rectifier through a DC/DC converter.

Figure 4.1 shows a single line diagram of the proposed model of the traction system connected to 110 KV bus system.

The power supply system is represented by 110 KV bus, two transformers are used to step down the voltage from 110 KV to 11 KV then, from 11 KV to 1.06 KV. The two transformers are connected delta to delta. DC/DC converter is used to increase the rectifier output DC voltage to be compatible with the rated voltage of the BLDC motor.

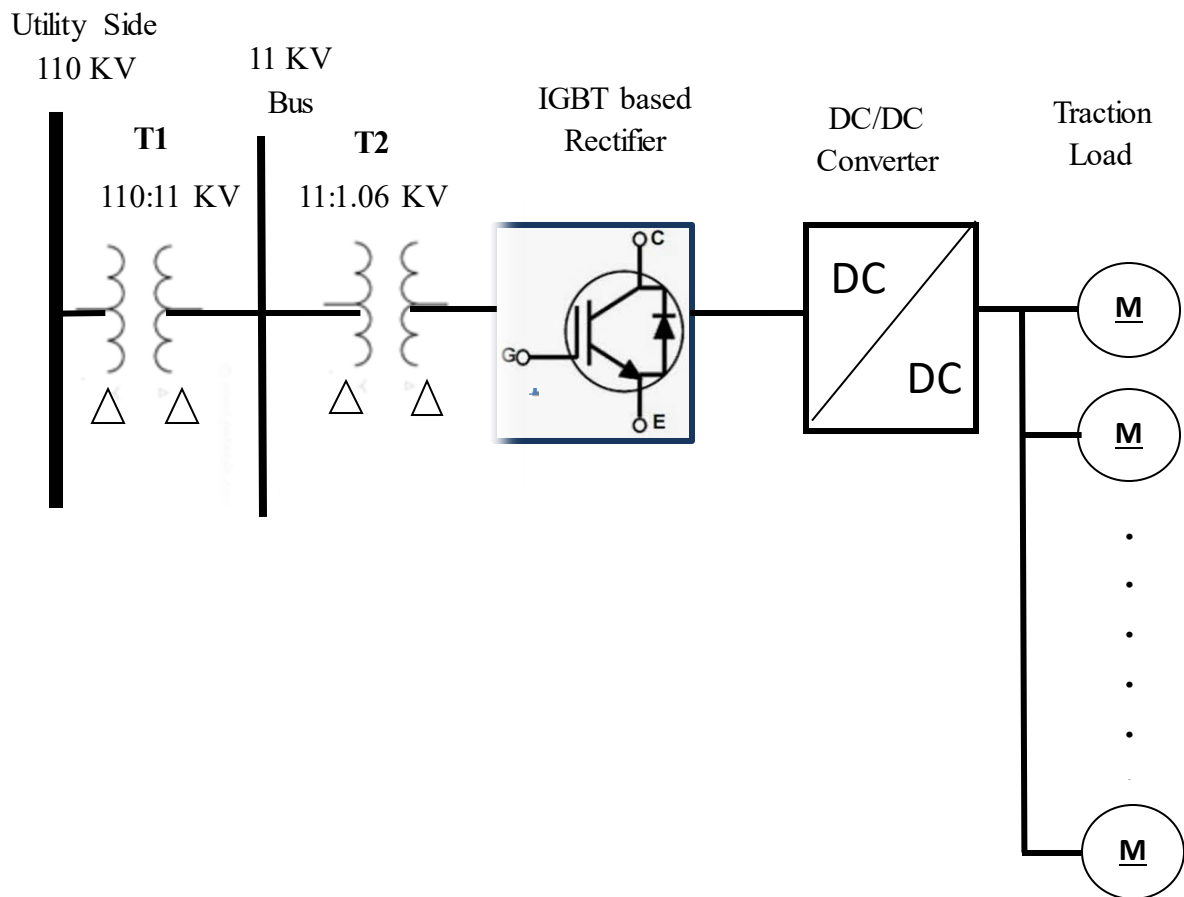


Figure 4.1. Single line diagram of the traction system connected to 110 KV substation

4.1 Light Load Case

In this case, the train launches the journey with few number of passengers. The voltage and current are measured at the utility grid side at 110 KV, 11 KV and at the AC side of the traction load which is 1.06 KV side.

The ratings of the proposed system components are shown in Table 4.1.

Table 4. 1. The ratings of Traction system components

Component	Rated voltage (KV)	Q (MVAR)	S (MVA)	P (MW)	Current (A)
Transformer (1)	110/11	-	100	-	-
Transformer (2)	11/1.06	-	100	-	-
IGBT based Rectifier system	1.06	-	-	-	68000
DC/DC Converter system	1.43/11	-	-	75	I/P 50000 O/P 6555
BLDC motor	11	-	-	72	-

The total period of the journey is 10 minutes. The train starts accelerating with constant rate, this stage takes 2 minutes. Then, the train continues moving with invariable speed

which is called cruising mode. This stages takes about 6 minutes. In the last stage which is taking 2 minutes, the train decreases its speed gradually until reaches zero.

4.1.1 Analysis of the light load case

The speed of the train varies with the time. Figure 4.2 shows the train speed in km/h against the time in seconds.

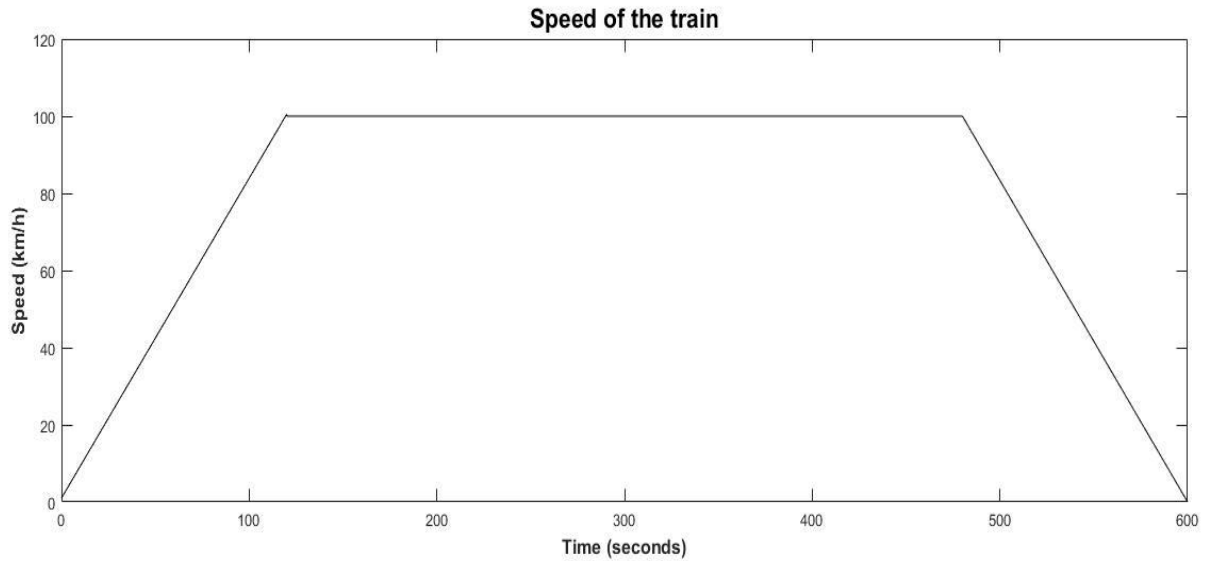


Figure 4.2. Traction speed in km/h versus the Time in Seconds

For the DC side, the output voltage of the secondary side of the transformer (11/1.06) KV is connected to a 12 pulse, 3-phase, IGBT based AC/DC converter. The output voltage of this converter is connected to a DC/DC converter in order to increase the DC voltage to be compatible with the rating of the traction load.

The traction load is represented by 12 brushless DC (BLDC) motors connected in parallel. The rated voltage for these motors is 11 KV DC, with power ratings of 6 MW for each

motor at full load. Thus, the total power rating of the traction system at the full load is 72 MW.

Figure 4.3 shows the converter output DC voltage, it is very clear that, the DC voltage has a constant value which is 1430 V. This value remains constant along the whole journey.

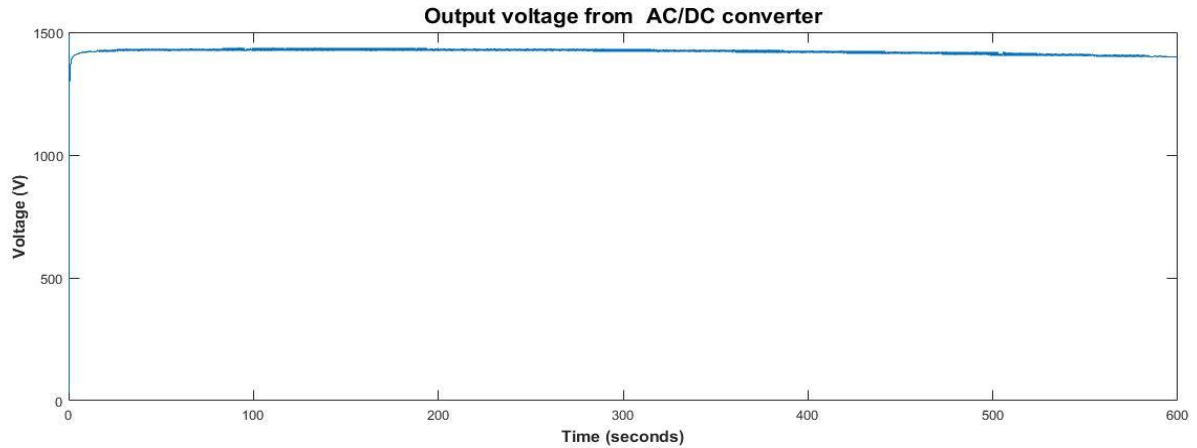


Figure 4.3. Output DC voltage from the IGBT based rectifier when the traction is lightly loaded

The output DC voltage of the rectifier is amplified from 1430 V to 11 KV to be compatible with the rating of the BLDC motors. This is accomplished by using DC/DC converter. Figure 4.4 shows the converter output DC voltage.

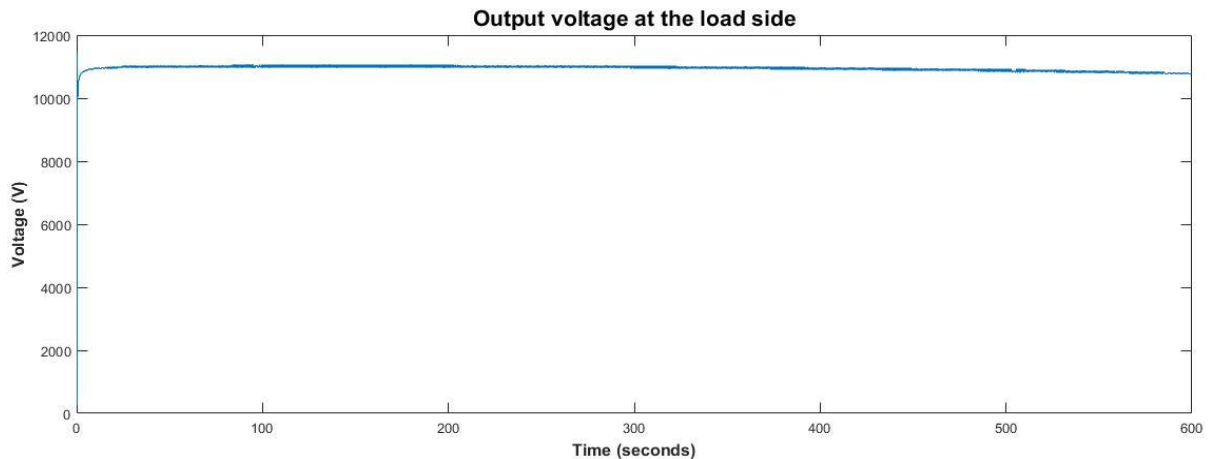


Figure 4.4. Applied DC voltage on the traction in the light load case

The total DC current absorbed by the traction increases with the speed. The current starts from zero. Then, it increases as the speed increased, when the traction moves with a constant speed the current remains constant. Finally, it declines when the train starts decelerating.

For the light load case, the BLDC motors are working by 50% of their full load values. Therefore, the total current that absorbed from the power supply is approximately equal half of the full load current.

Figures 4.5 shows the total DC current that absorbed by the traction load.

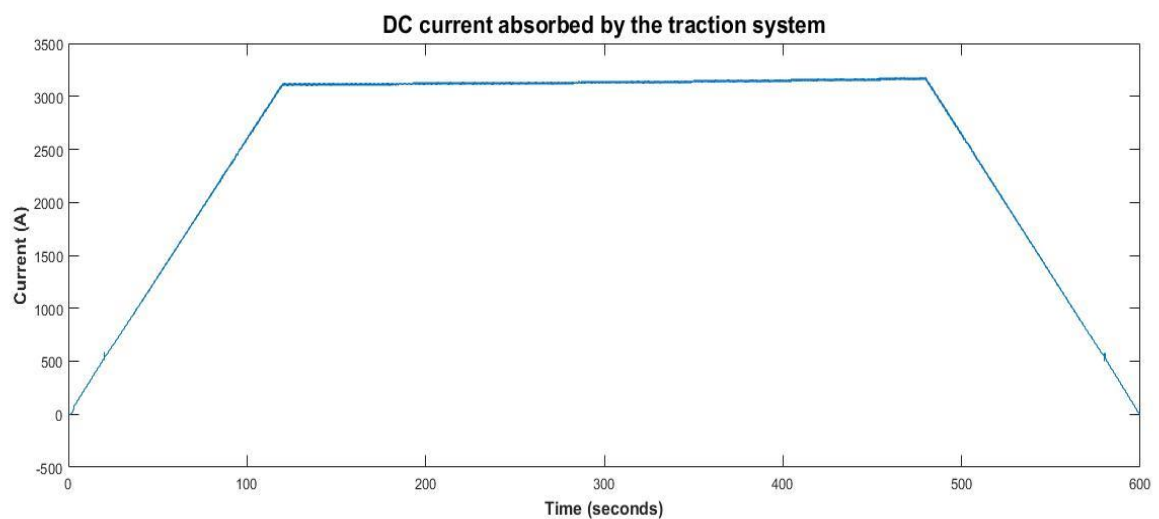


Figure 4.5. DC current absorbed by each BLDC motor in the light load case

Figures 4.5 shows that, at the beginning, the speed of the train increases gradually, in this mode, the absorbed current by the traction increases as the speed increased. After two minutes, the train continues moving with constant speed. In this stage the current will have a constant value. Finally, the train starts decelerating until reach zero speed, the current in this mode decreases accordingly.

4.1.2 FFT Analysis

In order to assess the impact of the electric traction drives on power quality, in particular at the point of common coupling (PCC), FFT is used to analyze voltage and current waves at different locations in the system. The analysis considered a three different dynamic modes of the electric traction which are: the acceleration, cruising and deceleration modes.

Before analyzing the voltage and current waves. The IEEE standard distortion limits are determined. The short circuit MVA values at 110 KV, 11 KV and 1.06 KV buses are obtained from [40]. The short circuit current can be calculated using equation (4.1)

$$I_{s/c}(KA) = \frac{MVA_{s/c}}{\sqrt{3} * V (KV)} \quad (4.1)$$

Where

$MVA_{s/c}$ Short circuit MVA at the specific bus in MVA

V Line-line voltage at the specific bus in KV

The fundamental frequency is 60 HZ in all cases.

The load current at the PCC when the traction is lightly loaded is measured. It was about 266 A, according to this value, the maximum limit of the THD in the voltage and current

waveforms at 110 KV, 11 KV and 1.06 KV sides can be determined according to the IEEE standard distortion limits.

According to the ratio between $I_{s/c}$ and I_L IEEE standard distortion limits can be specified,

Harmonic distortion limits increase for the higher values of the short circuit level with light load and vice versa.

Table 4.2 shows the short circuit data, load current and the according values of the IEEE 519 standard distortion limits.

Table 4.2. Short circuit data and the distortion limits for the light load case according to the IEEE standard 519

Voltage Level	MVA s/c	$I_{s/c}$ (KA)	I_L (A)	$I_{s/c}/I_L$	IEEE Standard limit
110 KV	6955	36.5	266	137.2	7.5%
11 KV	4000	210	2660	78.9	12.0%
1.06 KV	2750	1500	27603	54.3	12.0%

Firstly, FFT has used to analyze voltage and current waveforms at 110 KV side which is representing the PCC in this case. These waves are analyzed based on the dynamic operation mode of the train, the total interval is divided into three periods, accelerating, cruising and decelerating period. A snap shot of the current wave when the traction accelerates is shown in Figure 4.6.

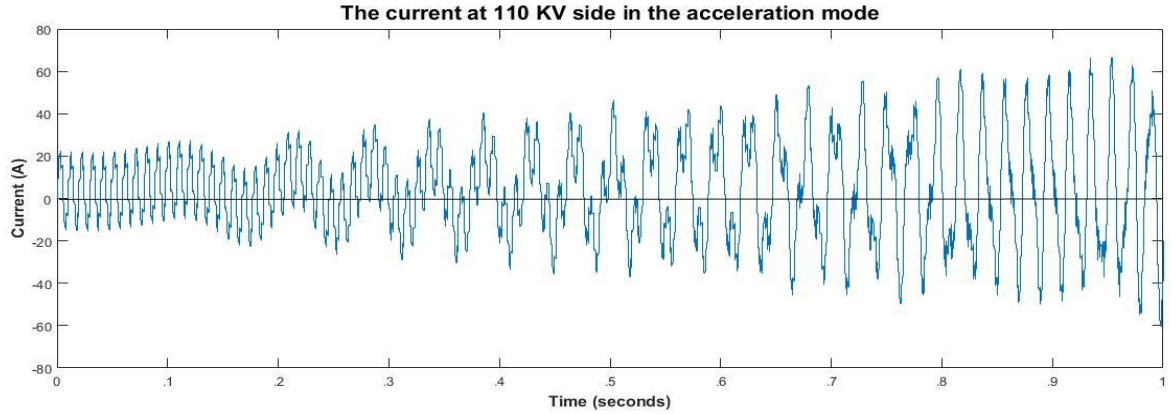


Figure 4.6. Small section of the current wave at 110 KV side when the traction is lightly loaded

The THD of the voltage and current waves can be calculated from equations (3.2) and 3.3.

In this case the THD values are obtained from the FFT analysis directly.

Figure 4.7 shows the harmonic spectrum and the Total harmonic distortion (THD) of the current waveform at 110 KV side, when the traction operates in the acceleration mode.

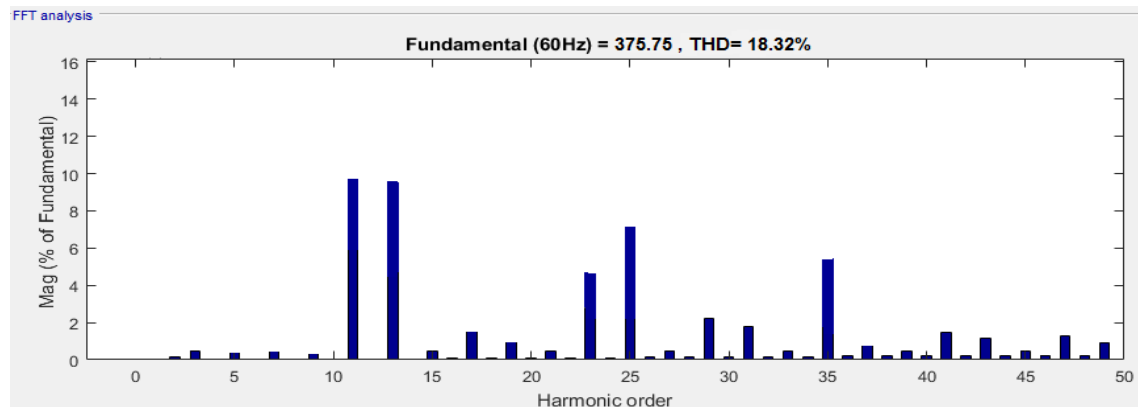


Figure 4.7. Harmonic spectrum and THD index of the current wave at 110 KV side in the acceleration mode when the traction is lightly loaded

$$\text{THD} = 18.32\%$$

Figure 4.7, shows that, the dominant harmonics in the current waveform at 110 KV side are the 11th and 13th orders. These harmonics, are almost representing 10% of the fundamental harmonic, which is very high ratio. They have exceeded the IEEE standard distortion limits as shown in Tables (A.1 to A.4) in the Appendix.

When speed of the traction reaches 100 km/h, it starts moving with constant speed. In this mode, the traction absorbs constant current from the utility side. Figure 4.8 shows a snapshot of the current waveform at 110 KV side when the traction in the cruising mode

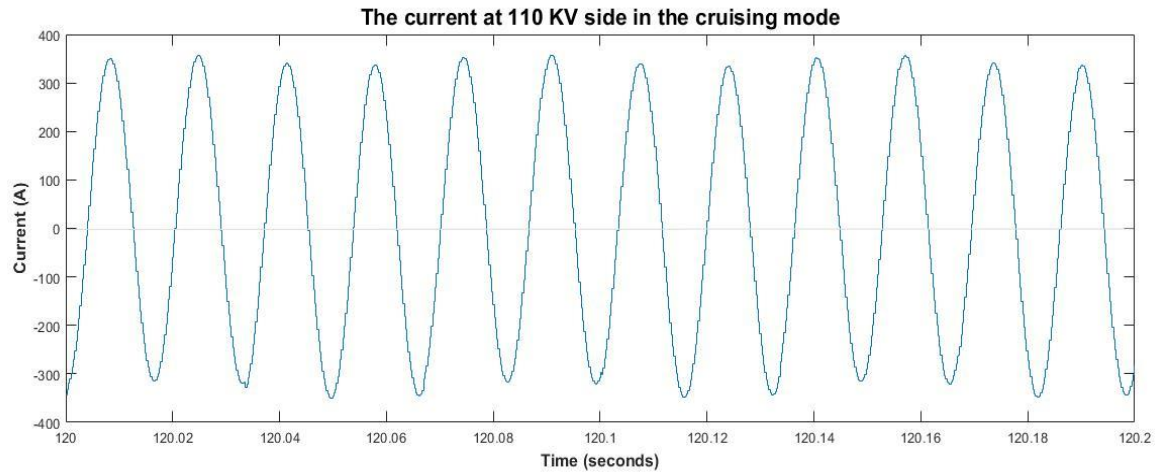


Figure 4.8. The current wave at 110 KV side when the traction in the cruising mode when the traction is lightly loaded

The harmonics spectrum and THD index of the current wave at 110 KV side when the traction is operating in the cruising mode is shown in Figure 4.9.

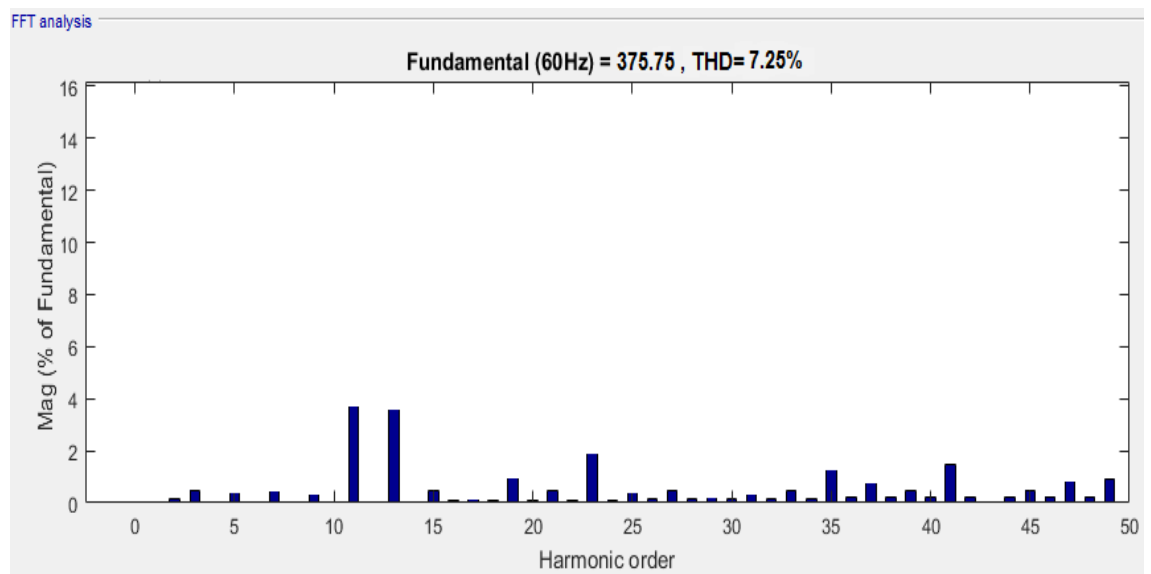


Figure 4.9. Harmonic spectrum and THD index of the current wave at 110 KV side in the cruising mode when the traction is lightly loaded

$$\text{THD} = 7.25\%$$

In the cruising mode, the generation of harmonics is low compared to the harmonics that generated in the acceleration mode. Since the THD in this case is less than 7.5%, it is within the IEEE standard distortion limits.

After 8 minutes from the starting, the train starts decreasing its speed gradually. When the traction decelerates, the current that absorbed from the source decreases accordingly. Figure 4.10 shows snap shot of the current at 110 KV side when the train operates in the deceleration mode.

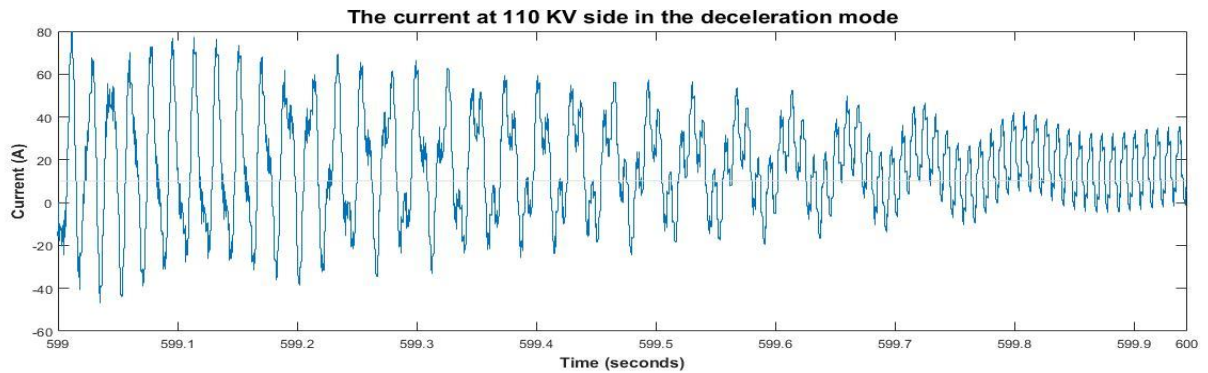


Figure 4.10. The voltage wave at 110 KV in the deceleration mode when the traction is lightly loaded

Figure 4.11 shows the harmonic spectrum and THD index of the current waveform in the deceleration mode.

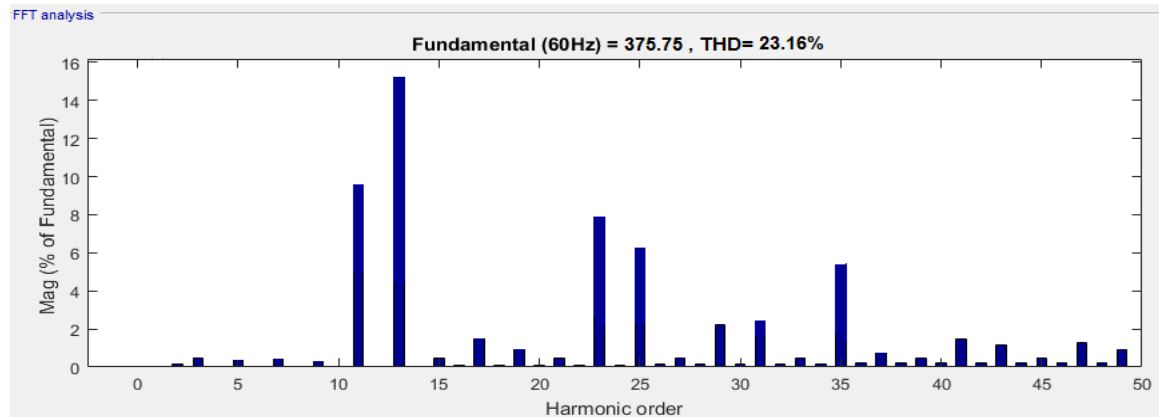


Figure 4.11. Harmonic spectrum and THD index of the current wave at 110 KV side when the traction is deceleration with light load

$$\text{THD} = 23.16\%$$

In the deceleration mode, the THD in the current wave is very high compared to the THD in the acceleration and cruising modes, the 13th harmonic is the dominant one in this case, it is almost about 16% of the fundamental harmonic.

Generally, large amount of harmonics is injected into the PCC during the acceleration and deceleration modes whereas, few of them are injected when the train is moving with constant speed.

Figures 4.12, shows the full current wave at 110 KV side during the full travelling period.

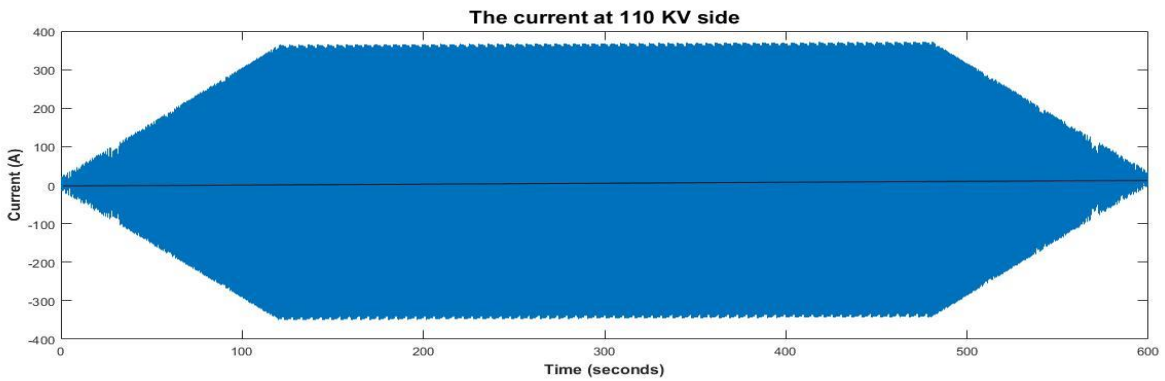


Figure 4. 12. The current wave at 110 KV side when the traction is lightly loaded

The harmonic spectrum and the THD index for the current waveform over the total period at 110 KV side is shown in Figure 4.13.

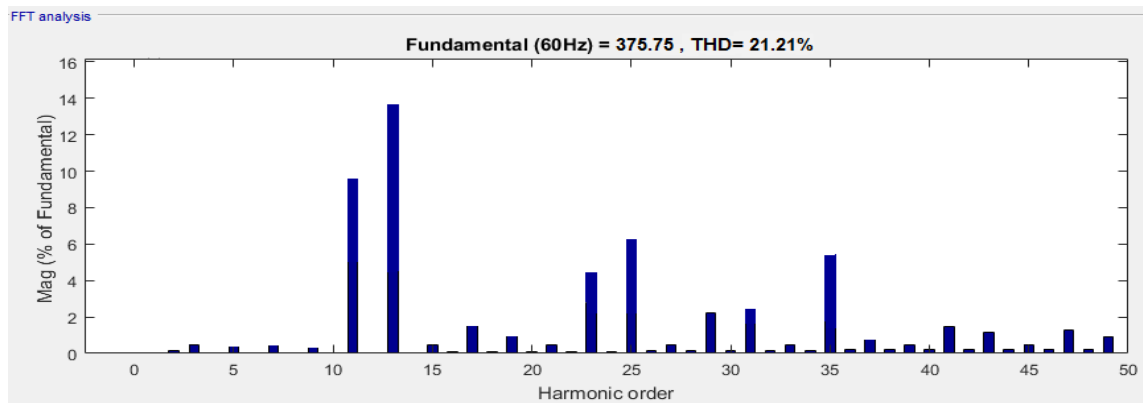


Figure 4.13. Harmonic Spectrum and THD index of the current wave at 110 KV side when the traction is lightly loaded

$$\text{THD} = 21.21\%$$

Figure 4.13 shows that, the dominant harmonics is the 13th order, it is almost 15% of the fundamental harmonics. The THD is 21.21% which is very high compared to the IEEE standard limits.

The harmonic spectrum and the THD index of the current wave at 11 KV and 1.06 KV sides are shown in Figures 4.14 and 4.15 respectively.

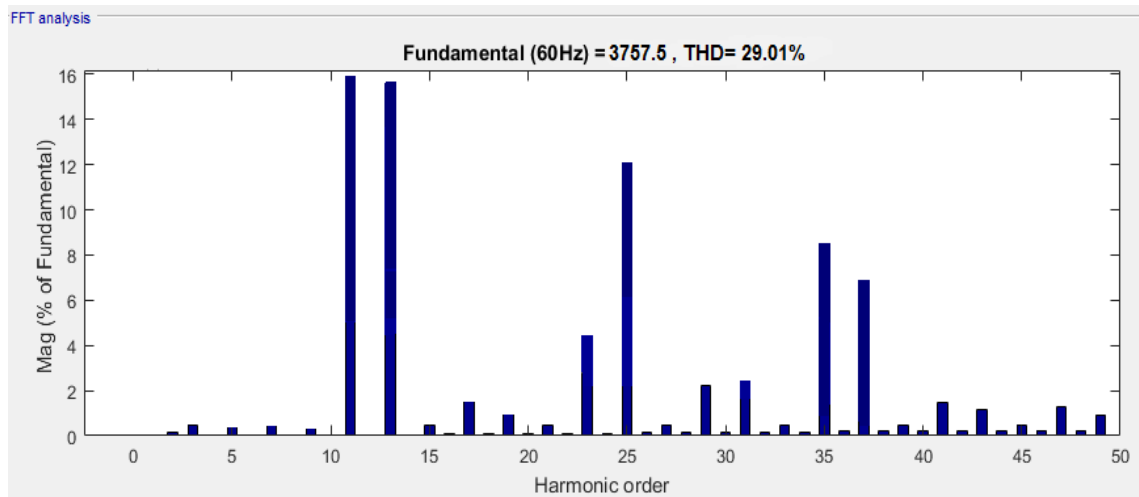


Figure 4.14. Harmonic Spectrum and THD index of the current wave at 11 KV side when the traction is lightly loaded

$$\text{THD} = 29.01\%$$

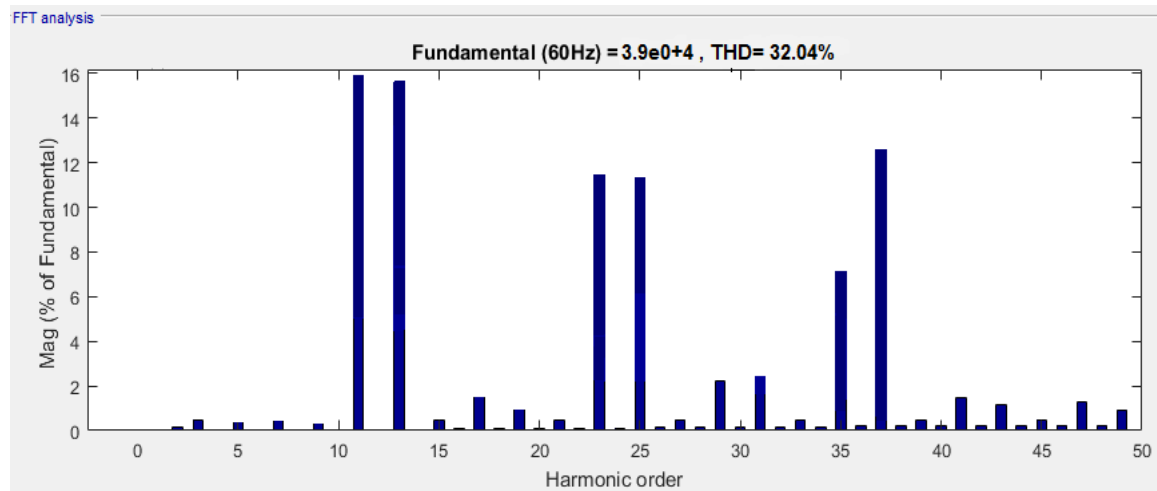


Figure 4.15. Harmonic Spectrum and THD index of the current wave at 1.06 KV side when the traction is lightly loaded

$$\text{THD} = 32.04\%$$

From Figures 4.13, 4.14 and 4.15, large amount of harmonics is generated at 110 KV bus, 11 KV bus and 1.06 KV bus due to the dynamic and nonlinearity nature of the traction load. These harmonics, are generated at the traction load side, then, they propagate through the transformers to the PCC. Thus, the total harmonic distortion (THD) has the highest value at the nearest point to the traction load, then, THD decreases and reaches the lowest value at the PCC. Because the PCC is far away from the harmonic source which is the traction load. A snap shot of the voltage wave in the acceleration mode at PCC is shown in Figure 4.16.

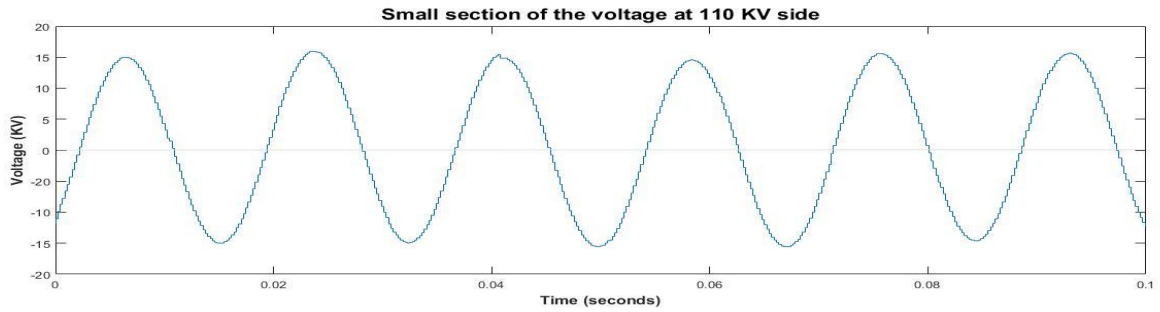


Figure 4.16. Small section of the voltage at 110 KV side when the traction is lightly loaded

The voltage wave at 110 KV side is analyzed with the FFT. The harmonic spectrum and the THD index of the voltage waveform in the acceleration mode is shown in Figure 4.17.

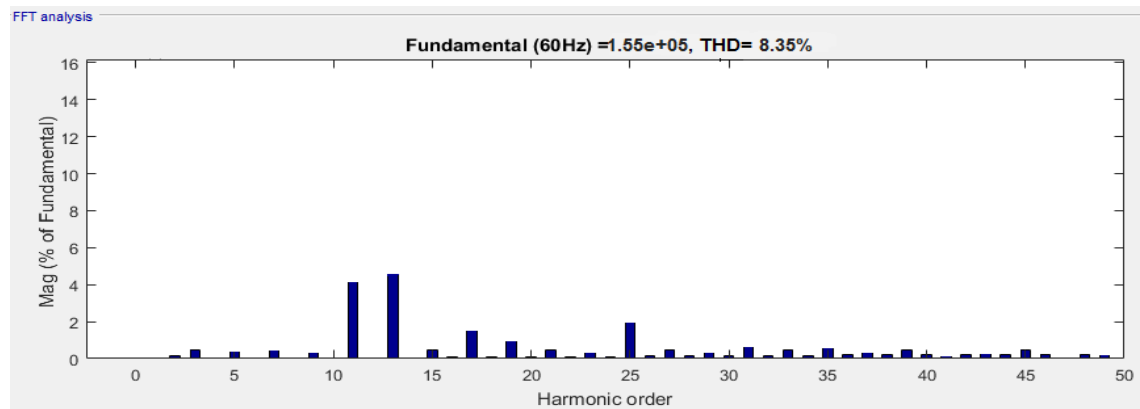


Figure 4.17. Harmonic spectrum and THD index of the voltage wave at 110 KV side when the traction is accelerating with light load

$$\text{THD} = 8.35\%$$

The harmonic spectrum and THD of the voltage wave at 110 KV side in the cruising mode and deceleration mode are shown in Figures, 4.18 and 4.19 respectively.

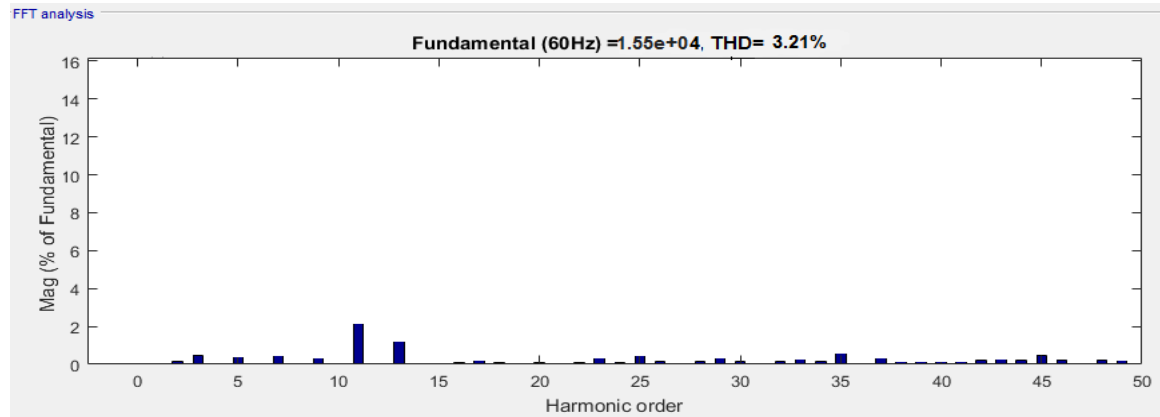


Figure 4.18. Harmonic spectrum and THD index of the voltage wave at 110 KV side when the traction in the cruising mode with light load

$$\text{THD} = 3.21\%$$

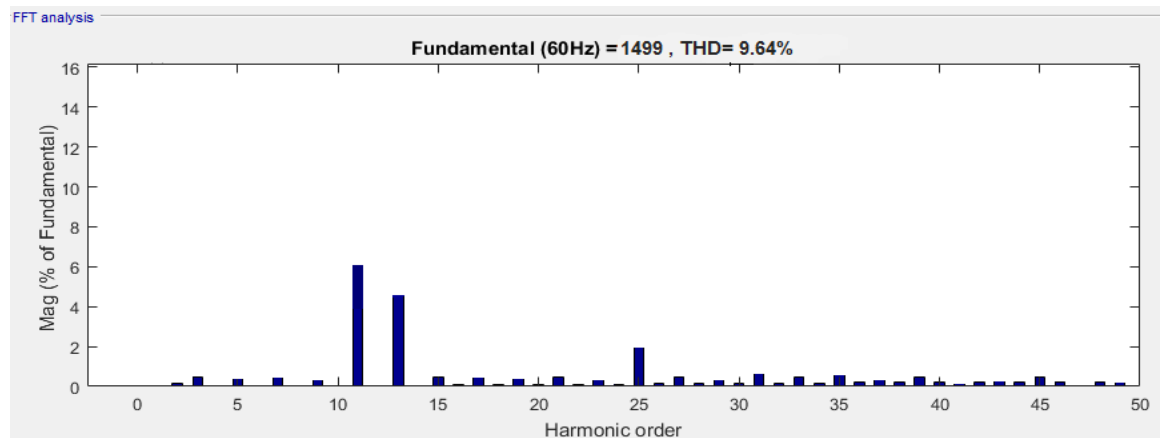


Figure 4.19. Harmonic spectrum and THD index of the voltage wave at 110 KV side when the traction is deceleration with light load

$$\text{THD} = 9.64\%$$

Figures 4.17, 4.18 and 4.19 show that, the THD index in the cruising mode is relatively low compared with the THD index in the other modes. The THD index has a high value when the traction operates in the acceleration and deceleration mode. It is almost equal three times the THD value when the train is moving with constant speed.

The dominant harmonics in the three modes are the 11th and 13th harmonics order, they represent around 8% and 9.64% in the acceleration and deceleration modes respectively, whereas, they are less than 4 % in the cruising mode which is a low value compared to the other two modes.

Figures 4.20, 4.21 and 4.22, show the harmonic spectrum and the THD index of the voltage wave over the full period at 110 KV side, 11 KV side and 1.06 KV side respectively,

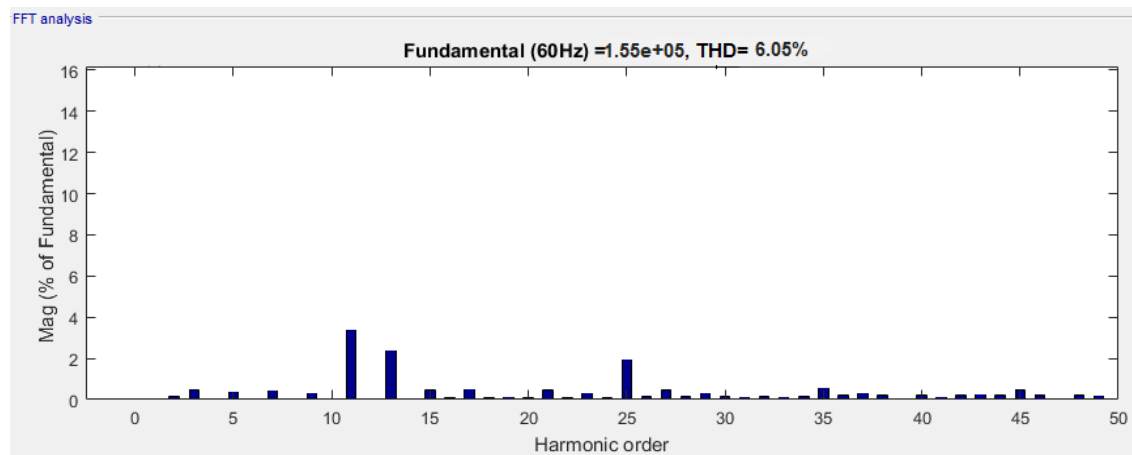


Figure 4.20. Harmonic Spectrum and THD index of the voltage wave at 110 KV side when the traction is lightly loaded

$$\text{THD} = 6.05\%$$

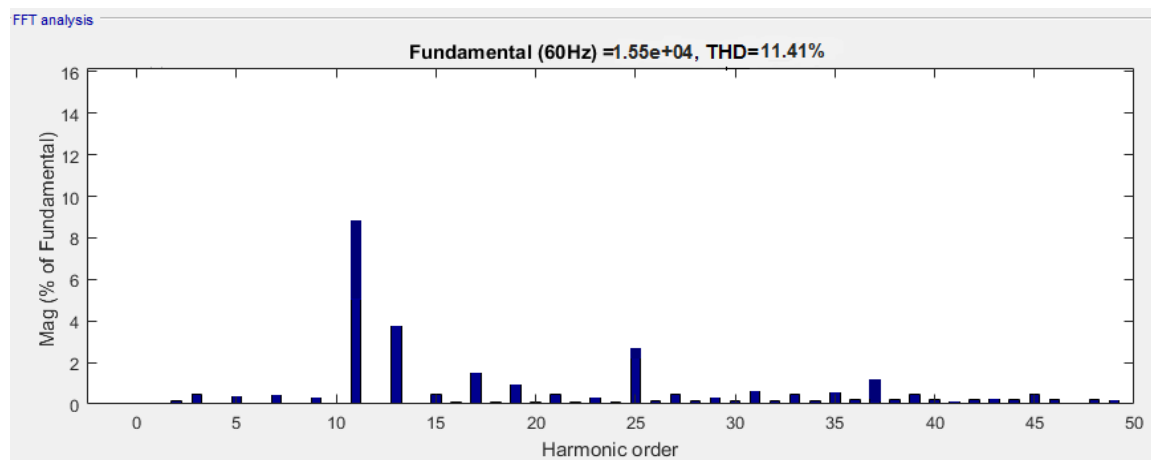


Figure 4.21. Harmonic Spectrum and THD index of the voltage wave at 11 KV side when the traction is lightly loaded

$$\text{THD} = 11.41\%$$

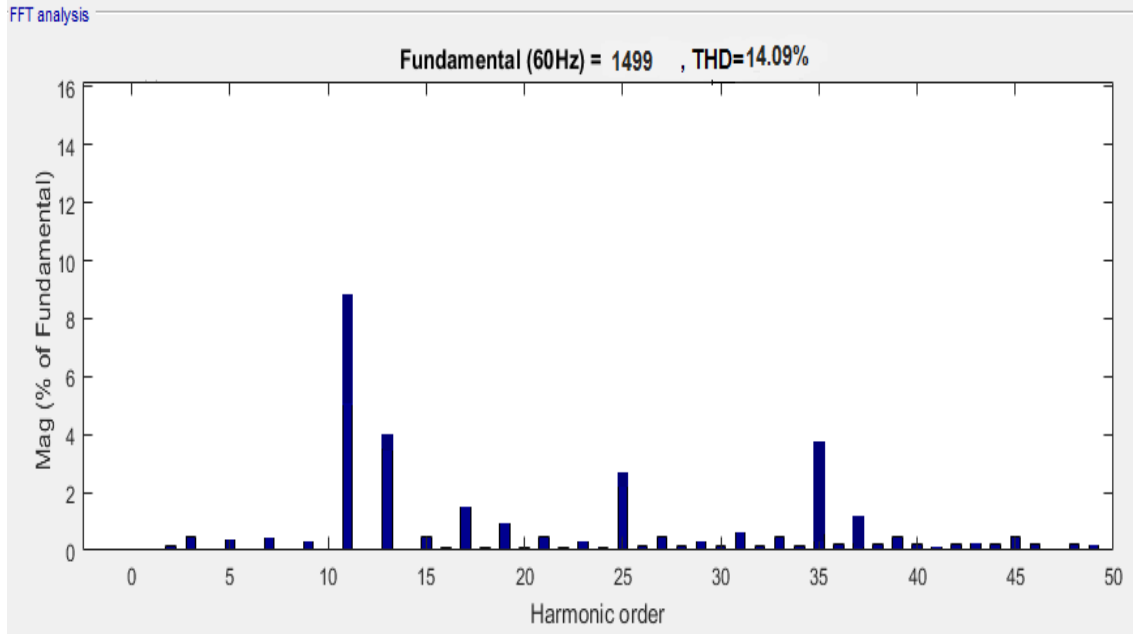


Figure 4.22. Harmonic Spectrum and THD index of the voltage wave at 1.06 KV when the traction is lightly loaded

$$\text{THD} = 14.09\%$$

From Figures 4.20, 4.21 and 4.22, it is clear that, the voltage wave at 1.06 KV and 11 KV sides are highly affected compared with the voltage wave at 110 KV side. The THD at 1.06 KV side is very close to the THD at 11 KV side, they are almost twice the THD at 110 KV side. This is because the traction system is connected at 1.06 KV side through the DC//DC converter. Thus, high amount of harmonics is generated at the load side, then, it propagates through the transformers for the other buses.

Tables 4.3 and 4.4 show the THD index in the voltage and current waves over the full period respectively at 110 KV, 11 KV, and 1.06 KV sides. The THD at all buses has exceeded the IEEE standard limits adversely.

Table 4.3. THD index in the voltage wave at the different buses when the traction is lightly loaded

Voltage Level	THD_v (% of Fundamental)	IEEE Standard Limit
110 KV	6.05	2.5%
11 KV	11.41	5.0%
1.06 KV	14.09	5.0%

Table 4.3 shows that, the THD index in the current waves at 11 KV and 1.06 KV buses are twice the THD index at 110 KV bus.

Table 4.4. THD index in the current wave at the different buses when the traction is lightly loaded

Voltage Level	THD_i (% of Fundamental)	IEEE Standard Limit
110 KV	21.21	7.5%
11 KV	29.01	12.0%
1.06 KV	32.04	12.0%

THD in the voltage wave at 110 KV side in the acceleration, cruising and the deceleration modes, when the train operates with light load are shown in Table 4.5.

Table 4.5. THD index in the voltage wave at the PCC (110 KV side) in the three dynamic modes of the train with light load

Dynamic mode	THD_v (% of Fundamental)	THD_i (% of Fundamental)
Acceleration	8.35	18.32
Cruising	3.21	7.25
Deceleration	9.64	23.16
IEEE standard Limit	2.5%	7.50%

High amount of harmonics are injected to the PCC when the traction operates in the acceleration and deceleration modes. This effect disappeared when the train moves with constant speed as shown in Table 4.5.

The consumption of the power depends on the dynamic of the traction system, i.e., when the traction accelerates the power consumption increases accordingly. Then, the power consumption remains constant during the cruising mode. Finally, the power decreases when the train decreases its speed up to reach zero. Figure 4.23 shows the consumption of the active power for the whole interval.

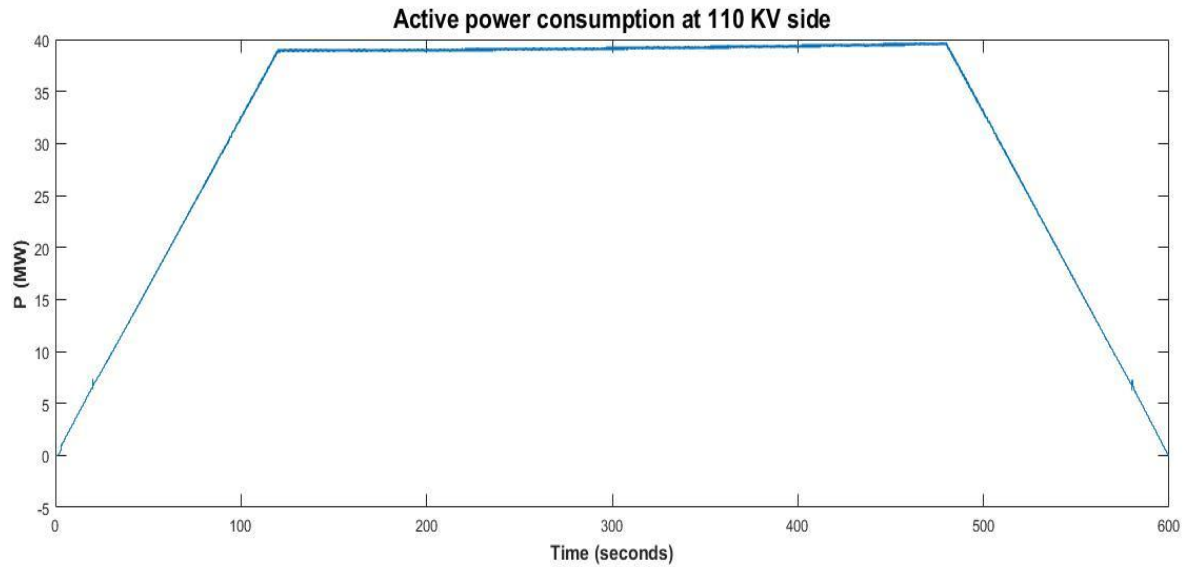


Figure 4.23. Active power consumed by the traction load measured at the PCC

Figure 4.24 shows that, the traction load absorbs high amount of reactive power, this happens due to the low value of power factor (Pf) which is 0.75. This will lead to absorb high amount of reactive power and thereby high amount of current.

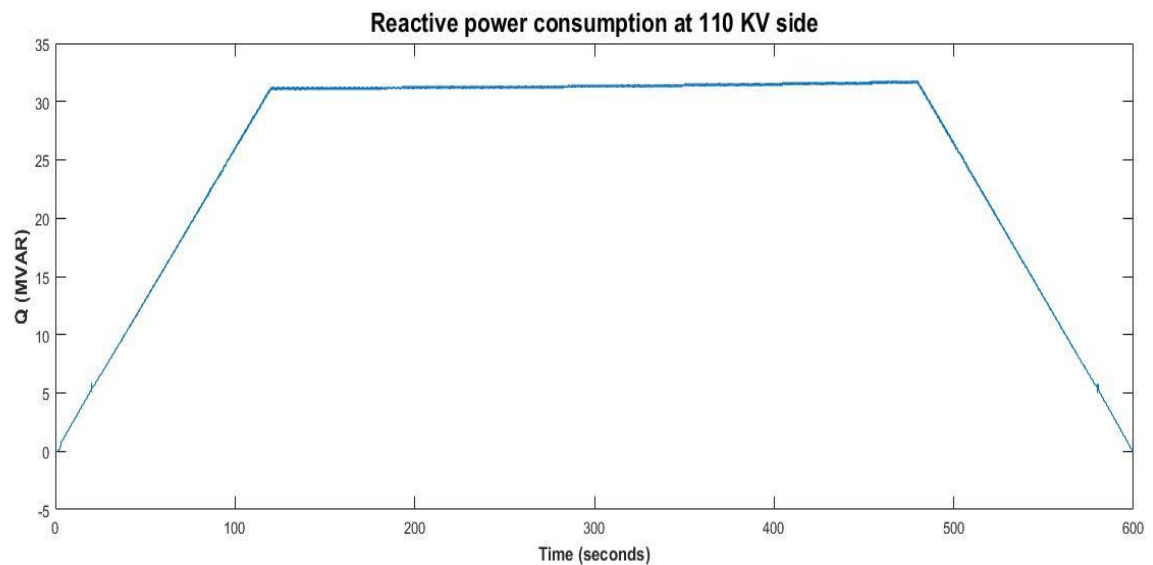


Figure 4.24. Reactive power absorbed by the traction load measured at the PCC

4.2 Heavy Load Case

In the heavy load condition, the train is assumed to carry large numbers of passengers, the train has the same dynamic of the light load case. At the beginning, it accelerates. Then it continues moving with constant speed. Finally, it slows down up to reach zero speed.

To evaluate the impact of the traction on the power quality, FFT has used to analyze the voltage and current waves at different locations in the power system

4.2.1 Analysis of the heavy load case

In the heavy load condition, the speed of the train increases gradually up to reach 100 km/h after 2 minutes of the starting. The train continues moving with this speed for 6 minutes. Finally, it decelerates up to reach zero speed within 2 minutes. Figure 4.25 shows the traction speed in the full period.

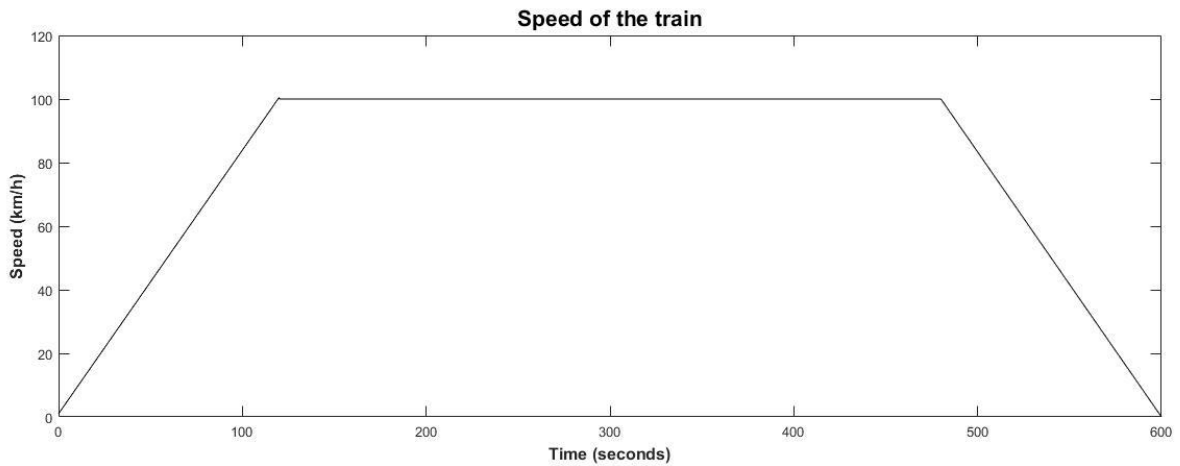


Figure 4.25. Traction speed in km/h versus the Time in Seconds

For the DC side, the output voltage of the AC/DC and DC/DC converters are similar to the output voltage in the previous case when the traction was lightly loaded.

Figures 4.26 and 4.27 show the output voltage from each of the (AC/DC) and (DC/DC) converters respectively.

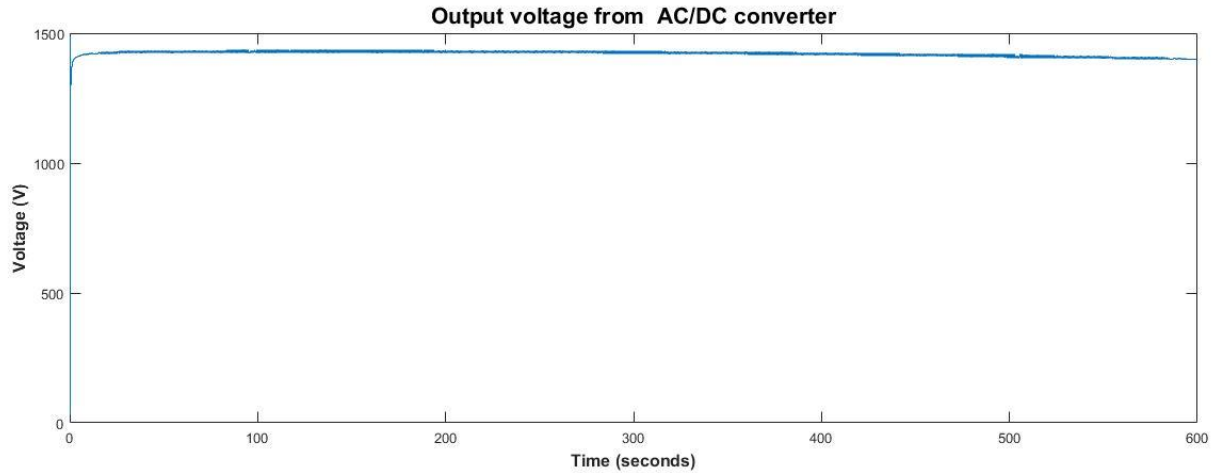


Figure 4.26. Output DC voltage from the rectifier circuit when the traction is heavily loaded

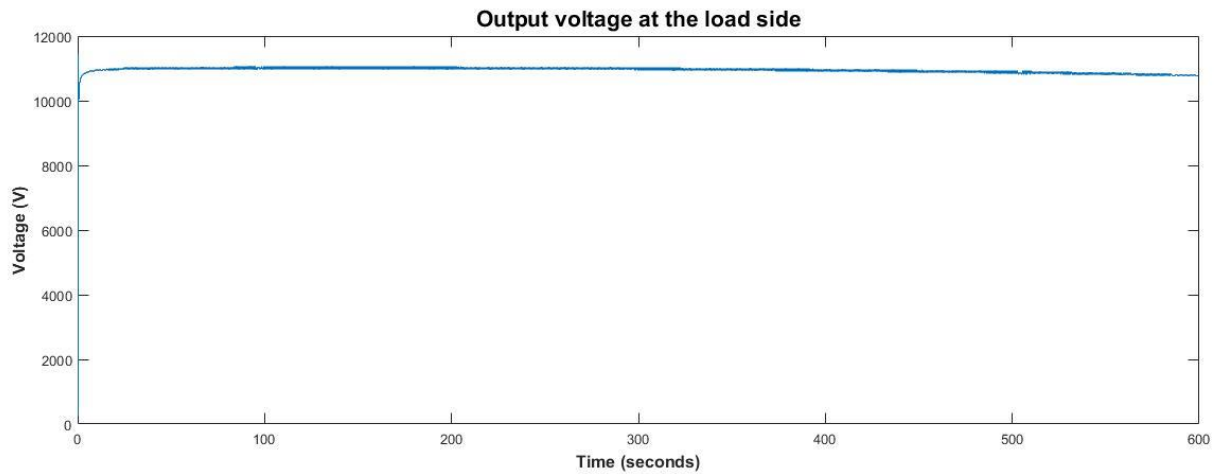


Figure 4.27. DC voltage applied on the traction load when the traction is heavily loaded

Figures 4.26 and 4.27 show that, the output DC voltage is not affected by the speed of the train. It remains constant along the whole period of the journey.

The traction system is represented by 12 BLDC motors connected together in parallel. The rating of each motor is 6 MW at the full load. Since the traction operates with its full

capacity in the heavy load condition. Therefore, the total power of the traction system is 72 MW. The absorbed DC current by the traction load when it is heavily loaded has the same trend of the current in the light load case. However, the absorbed current by the traction load in this case is very high compared to the light load case, approximately twice the current in the light load case. This is shown clearly in Figure 4.28.

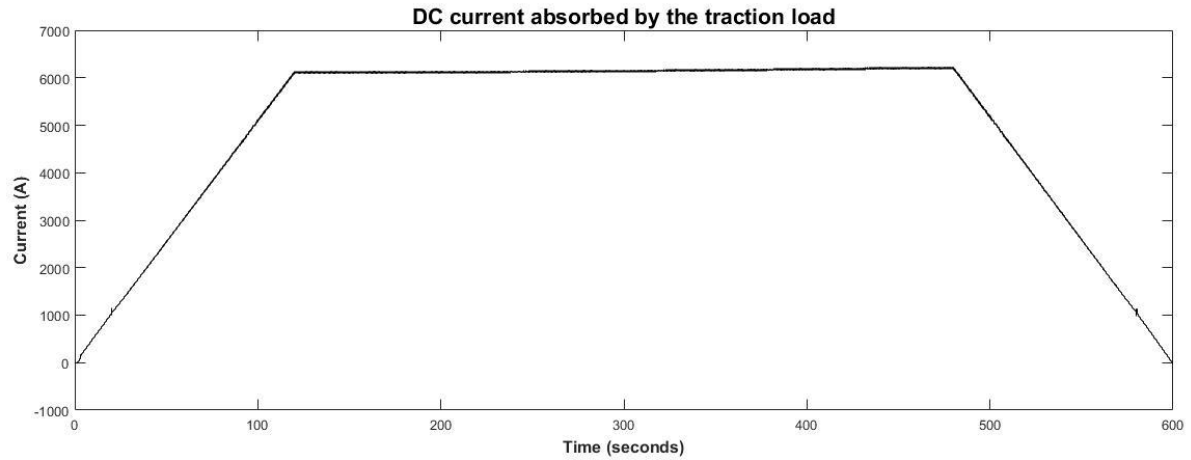


Figure 4.28. Total current absorbed from the utility grid at the heavy load case

4.2.2 FFT analysis

In order to study the impact of the traction on the power system, FFT has used to analyze the utility current wave at each operating dynamic mode separately.

The load current at 110 KV side when the traction is heavily loaded is measured. It is about 525 A, according to this value, the maximum limit of the THD in the voltage and current waveforms at 110 KV, 11 KV and 1.06 KV sides can be determined according to the IEEE standard distortion limits.

According to the ratio between $I_{s/c}$ and I_L IEEE distortion limit can be specified.

Table 4.6 shows the short circuit data, load current and the according values of the IEEE standard distortion limits when the traction is heavily loaded.

Table 4.6. Short circuit data and the distortion limits standards for the heavy load case according to the IEEE 519

Voltage Level	MVA s/c	$I_{s/c}$ (KA)	I_L (A)	$I_{s/c} / I_L$	IEEE Standard limit
110 KV	6955	36.5	525	69.5	6.0%
11 KV	4000	210	5250	40	8.0%
1.06 KV	2750	1500	54481	27.5	8.0%

Figure 4.29 shows a snap shot of the current wave at 110 KV side when the traction is operating in the acceleration mode with heavy load.

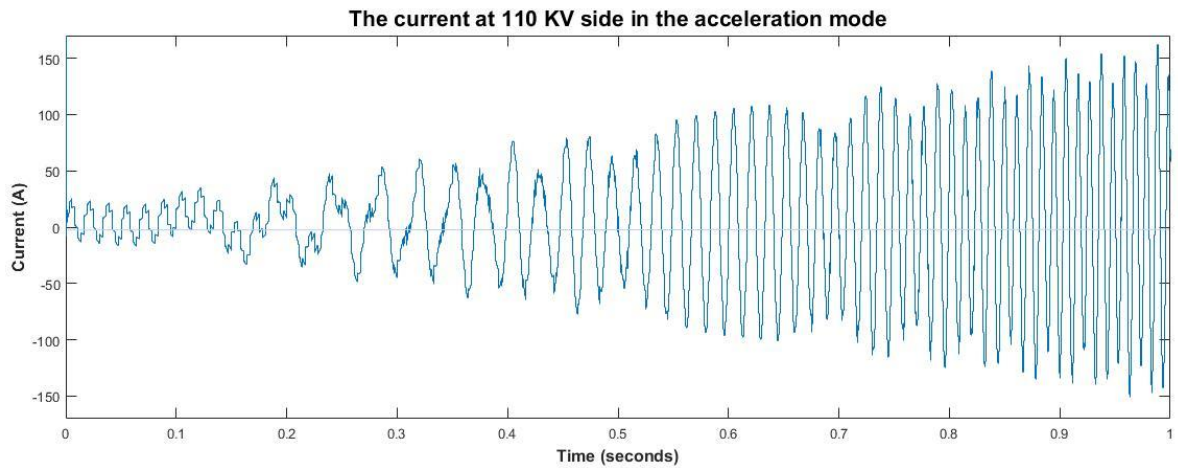


Figure 4.29. The current wave at 110 KV side when the traction is heavily loaded

Figure 4.30, shows the harmonic spectrum of the current wave at 110 KV side. The THD index of the current waveform is very high. The 11th harmonic is the dominant one around 14% of the fundamental harmonic, whereas, the remaining harmonics (13th, 23rd and 25th) are almost have the same value about 10 %.

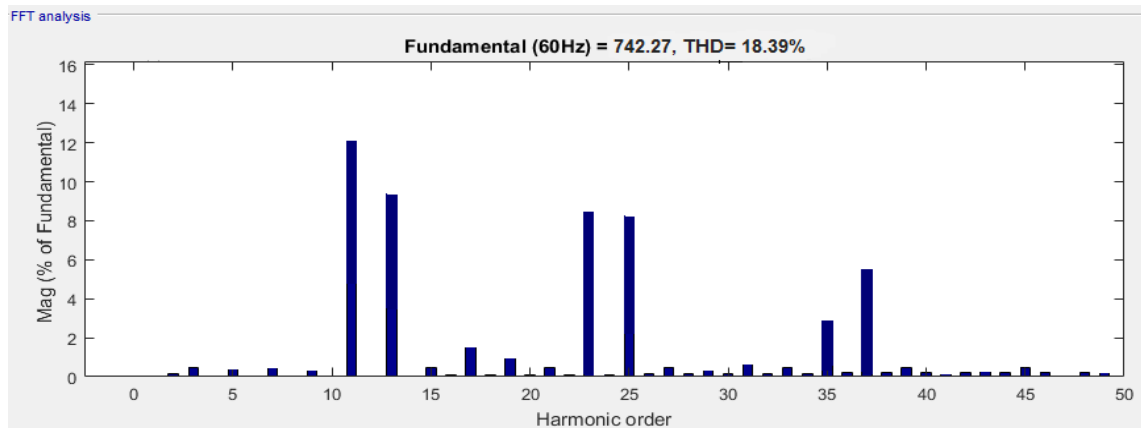


Figure 4.30. Harmonic spectrum and THD index of the current wave at 110 KV side when the traction is accelerating with heavy load

$$\text{THD} = 18.39\%$$

When the train reaches its maximum speed after 2 minutes from starting. It continues moving with constant speed. In this mode, the absorbed current from the utility grid is invariable.

Figure 4.31 shows a snap shot of the current at the PCC when the train in the cruising mode.

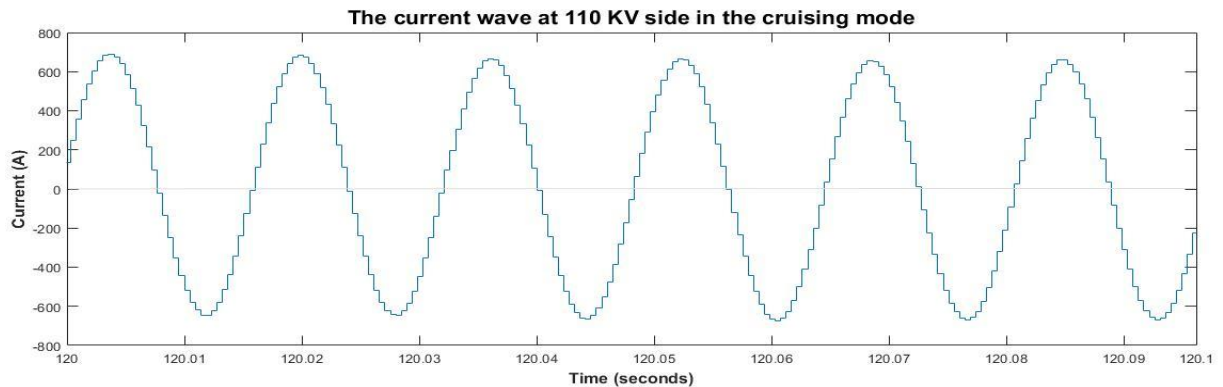


Figure 4.31. Small section of the current wave at 110 KV side in the cruising mode when the traction is heavily loaded

The harmonics spectrum and the THD index of the current in the cruising mode is shown in Figure 4.32.

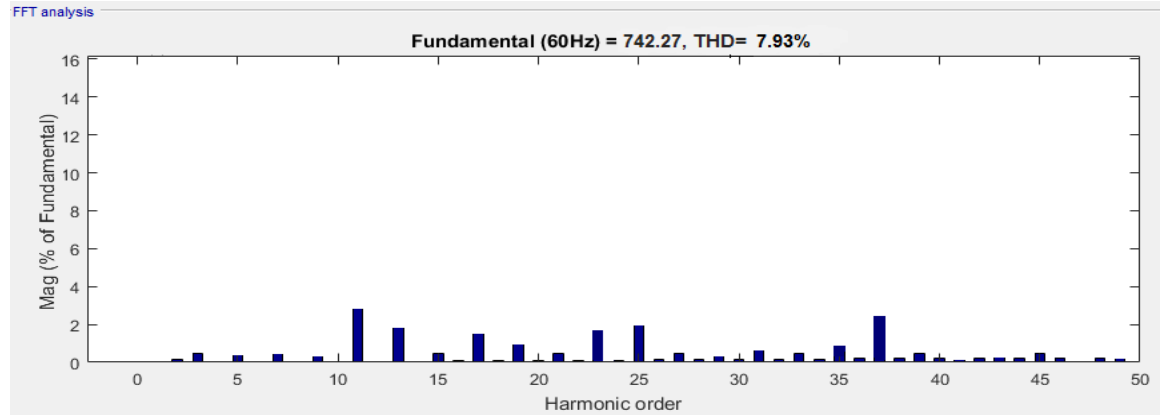


Figure 4.32. Harmonic spectrum and THD index of the current wave at 110 KV side when the train in the cruising mode with heavy load

$$\text{THD} = 7.93\%$$

Figure 4.32, shows that, when the harmonic spectrum of the current wave in the cruising mode, the THD is 7.93%. It is slightly higher than IEEE standards. The percentage of the individual harmonics distortion are slightly higher than IEEE standards as well.

After 8 minutes from starting, the traction starts decelerating its speed gradually. Thus, the current that absorbed from the utility will be reduced accordingly as shown in Figure 4.33

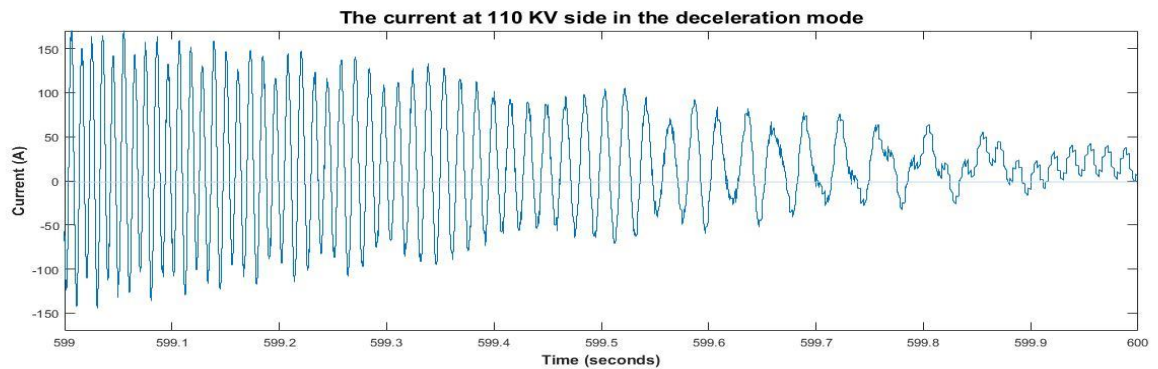


Figure 4.33. The current wave at 110 KV side in the deceleration mode when the traction is heavily loaded

The current wave in the deceleration mode has been analyzed. The harmonic spectrum and the THD index is shown in Figure 4.34

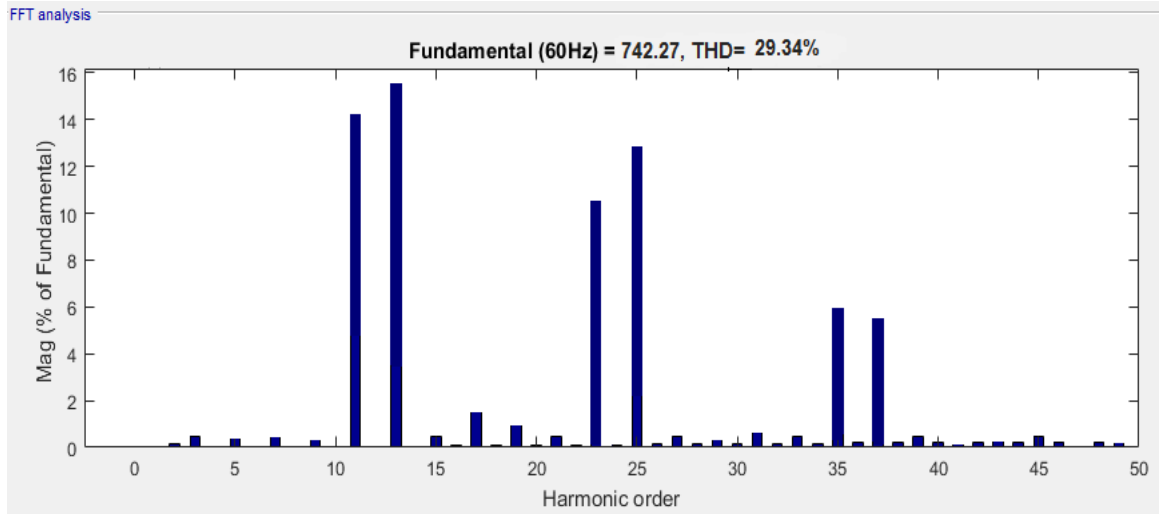


Figure 4.34. Harmonic spectrum and THD index of the current wave at PCC when the train is decelerating with heavy load

$$\text{THD} = 29.34\%$$

From Figures 4.30, 4.32 and 4.34, it can be concluded that, the THD in the current wave at the PCC is very high in the deceleration mode. It has a relatively low value when the train is moving with invariable speed, THD in the acceleration and deceleration mode are 18.39% and 29.34% respectively which are very much higher than the limits specified by IEEE standards, the percentage of the individual current harmonics 11th and 13th are also around 12% in the acceleration mode and around 16% in the deceleration mode which are also very much higher than the IEEE standards limits. These harmonics are less than 6.0% in the cruising mode.

Figure 4.35 shows the current wave over the full period at 110 KV which represents the PCC of the system

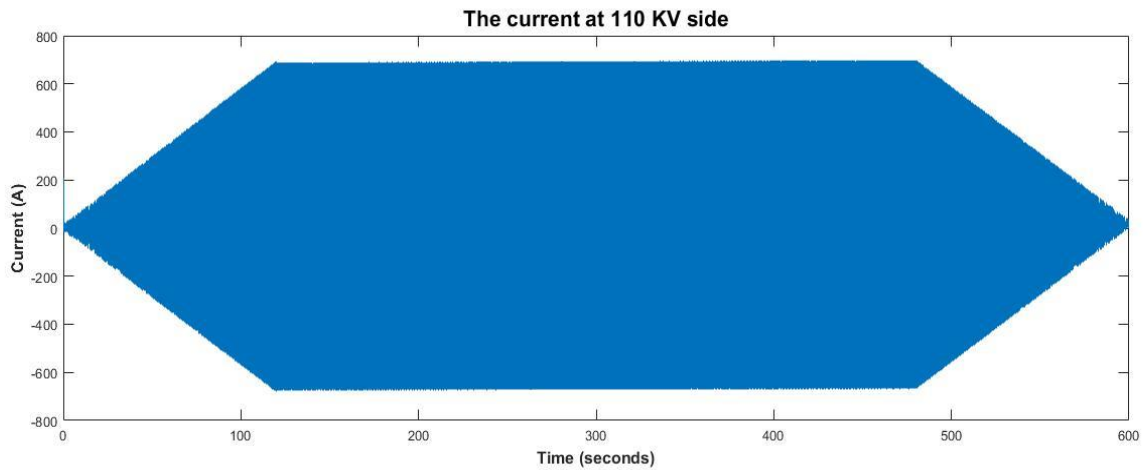


Figure 4.35. The current at 110 KV side when the traction is heavily loaded

The harmonic spectrum for this wave is shown in Figure 4.36, the THD is 21.35% which is much higher than IEEE standard limits.

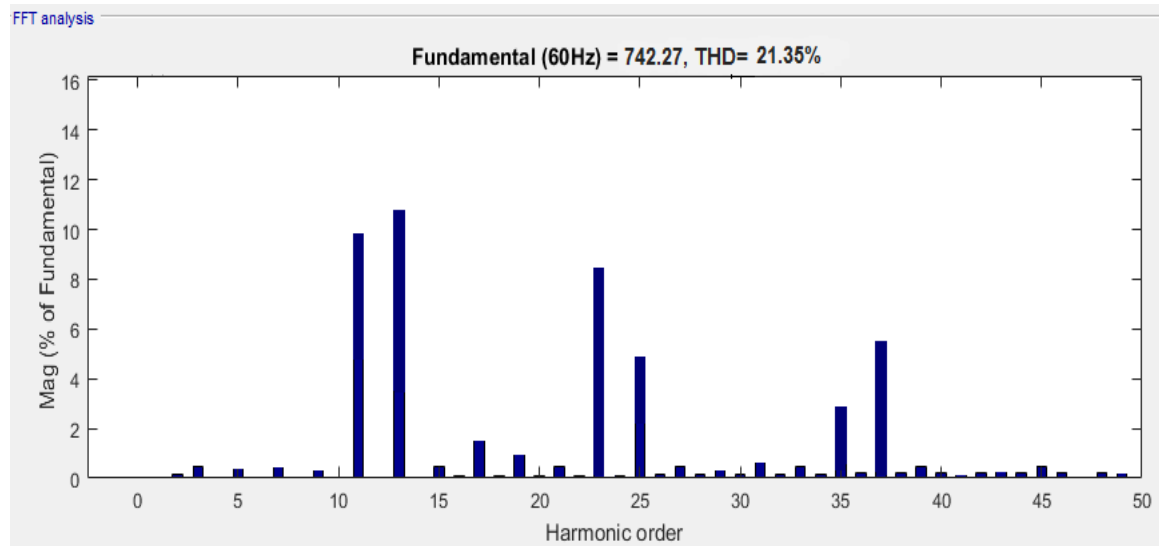


Figure 4.36. Harmonic spectrum and THD index of the current wave at 110 KV side when the traction is heavily loaded

$$\text{THD} = 21.35\%$$

The current wave at 11 KV side and the harmonic spectrum for this wave are shown in Figures 4.37 and 4.38 respectively.

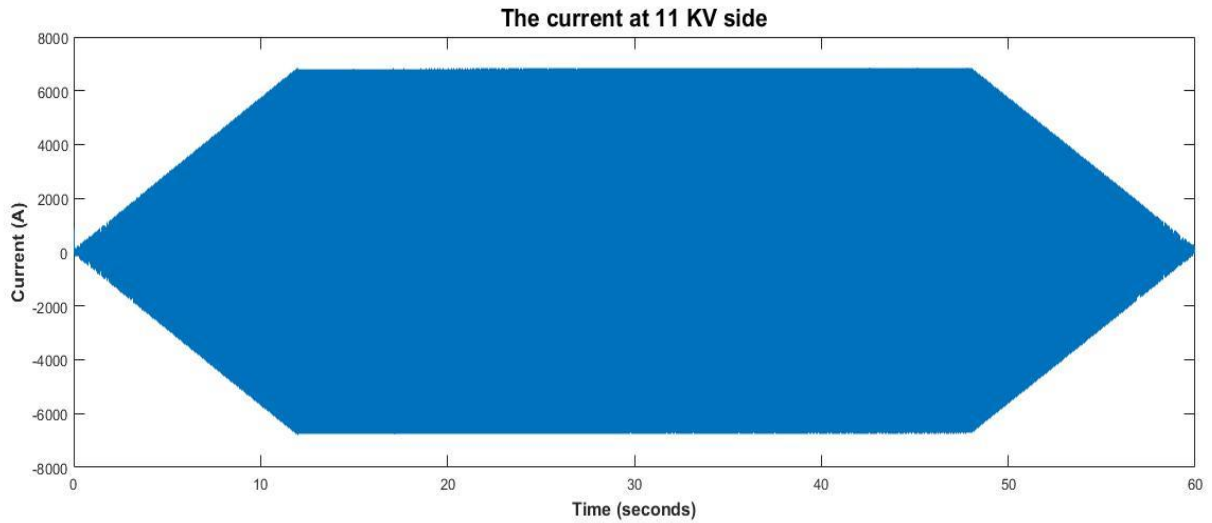


Figure 4.37. The current at 11 KV side when the traction is heavily loaded

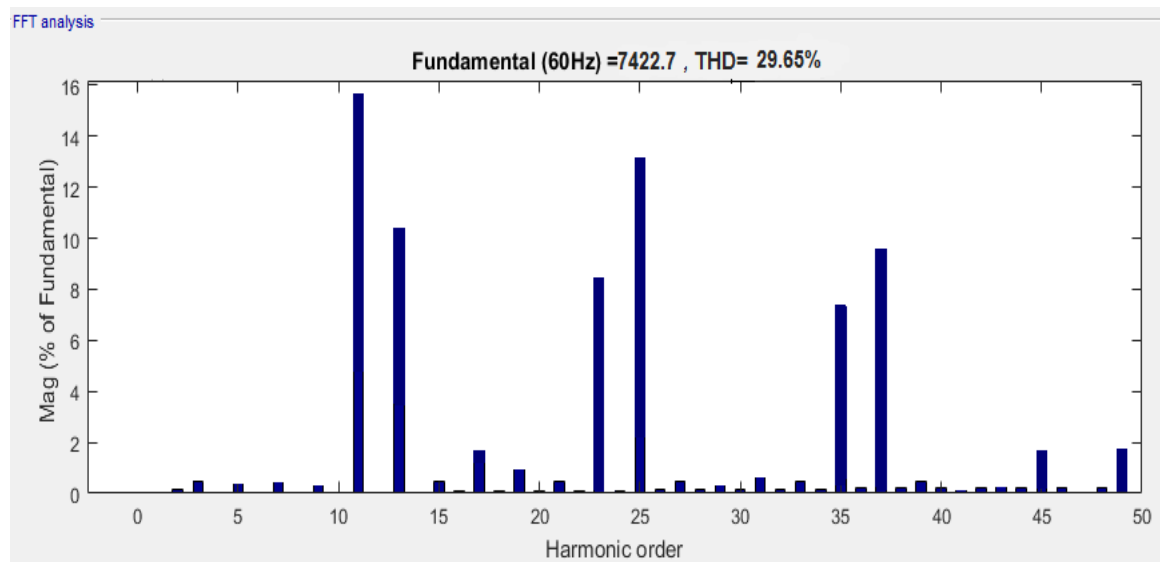


Figure 4.38. Harmonic spectrum and THD index of the current wave at 11 KV side when the traction is heavily loaded

$$\text{THD} = 29.65\%$$

From Figure 4.38, it is very clear that the 11th, 25th and 37th harmonics are the dominant, they are almost equal 16%, 14% and 10% of the fundamental harmonic respectively. The 13th, 23rd and 35th harmonics are around 10% of the fundamental harmonic.

Figure 4.39 shows the current at 1.06 KV side, the harmonic spectrum and the THD index is shown in Figure 4.40.

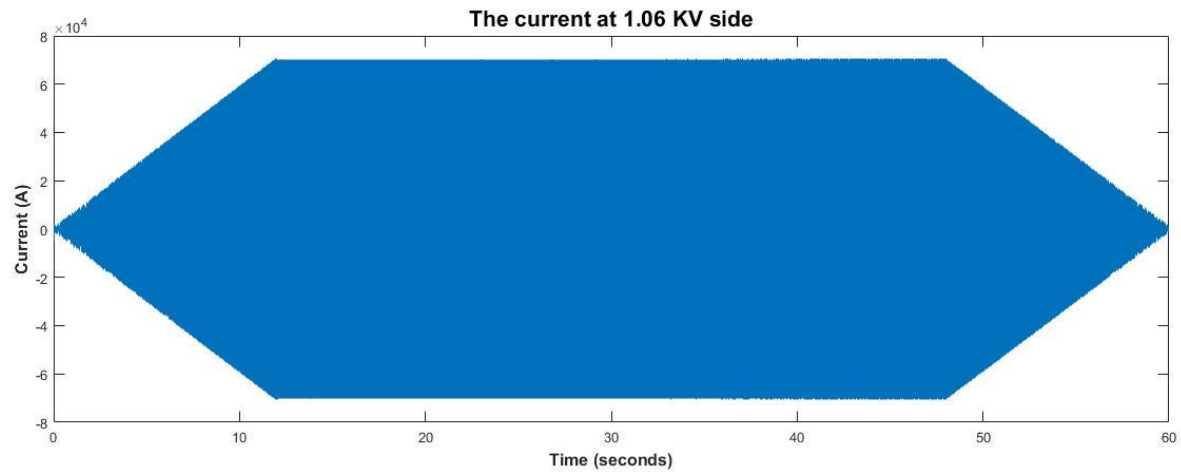


Figure 4.39. The current at 1.06 KV side when the traction is heavily loaded

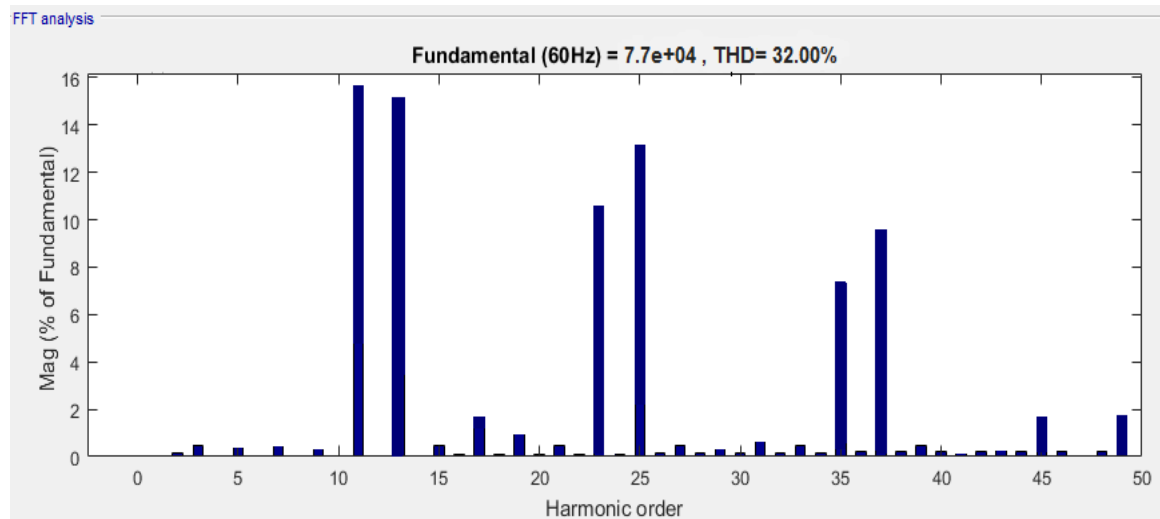


Figure 4.40. Harmonic spectrum and THD index of the current wave at 1.06 KV side when the traction is heavily loaded

$$\text{THD} = 32.00\%$$

From Figures 4.38 and 4.40 the current waveform at 1.06 KV side and 11 KV side is highly distorted compared with the current at the PCC in Figure 4.36. This occurs due to the high amount of harmonics that are transferred from the traction load side to 1.06 KV side and 11 KV side. The voltage waves at the PCC and at the other buses are analyzed at the different operating conditions to assess the impact of the traction dynamic on power system. A snap shot of the voltage wave when the traction is heavily loaded is shown in Figure 4.41.

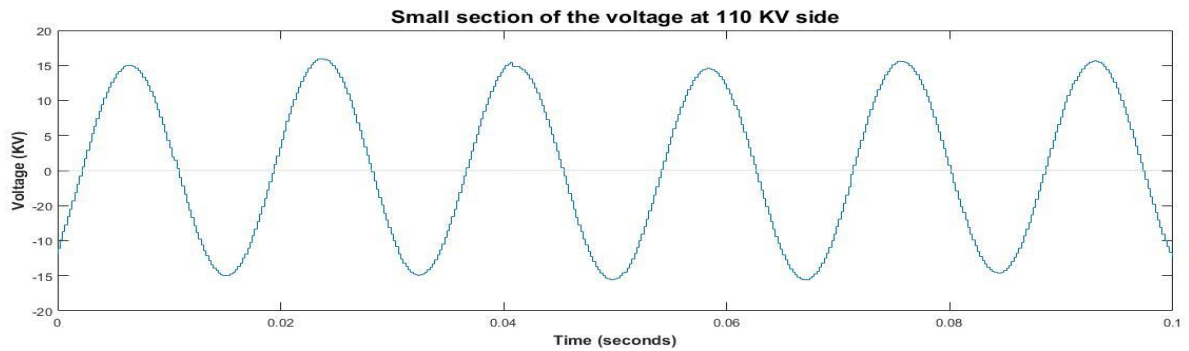


Figure 4.41. Small section of the voltage wave at 110 KV side when the traction is heavily loaded

Figures 4.42, 4.43 and 4.44. Show the harmonic spectrum and the THD index at the acceleration, cruising and deceleration modes respectively.

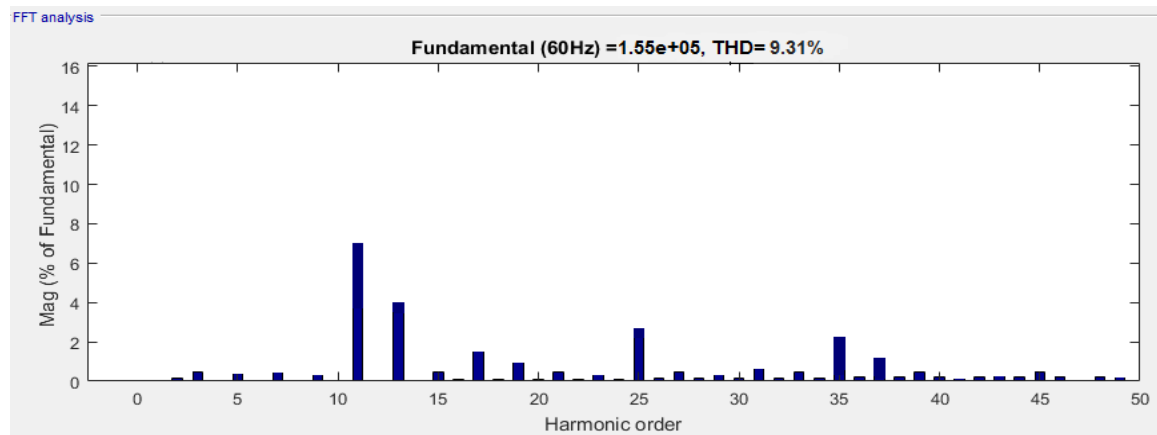


Figure 4.42. Harmonic spectrum and THD index of the voltage wave at 110 KV side when the traction is accelerating with heavy load

$$\text{THD} = 9.31\%$$

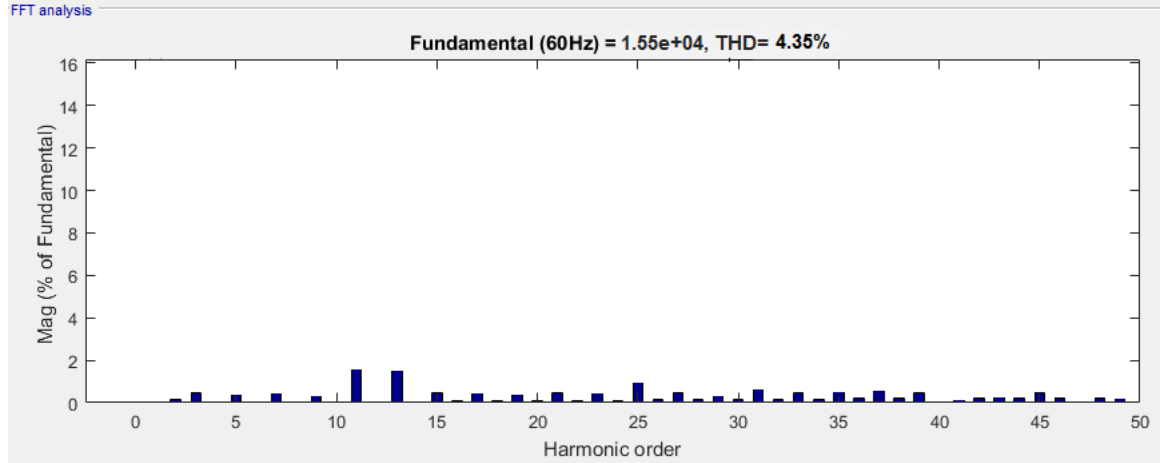


Figure 4.43. Harmonic spectrum and THD index of the voltage wave at 110 KV side when the traction in the cruising mode with heavy load

$$\text{THD} = 4.35\%$$

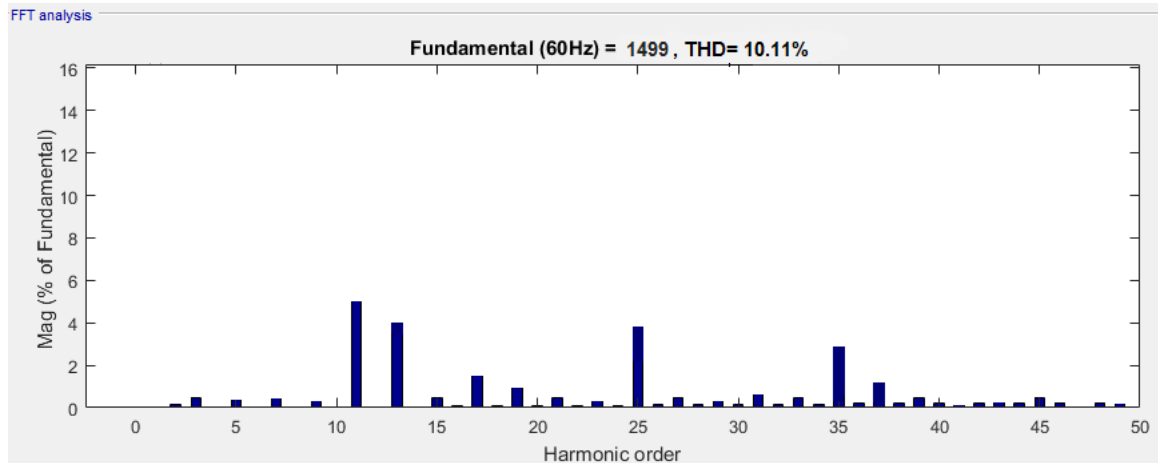


Figure 4.44. Harmonic spectrum and THD index of the voltage wave at 110 KV side when the train is decelerating with heavy load

$$\text{THD} = 10.11\%$$

From Figures 4.42, 4.43 and 4.44. It is observable that, THD in the voltage waveform at the PCC in the acceleration and the deceleration modes which are 9.31% and 10.11% are much higher than the IEEE standards 519 limits. Whereas, the THD in the cruising mode is 4.35% only, which is slightly higher than the maximum limits of the IEEE standards.

The voltage waveforms over the full period at 110 KV, 11 KV and at 1.06 KV are analyzed. The THD index is slightly higher than the THD at the light load case. Figures 4.45, 4.46 and 4.47 show the THD index and harmonic spectrum of the voltage waves at 110 KV, 11 KV and 1.06 KV sides respectively.

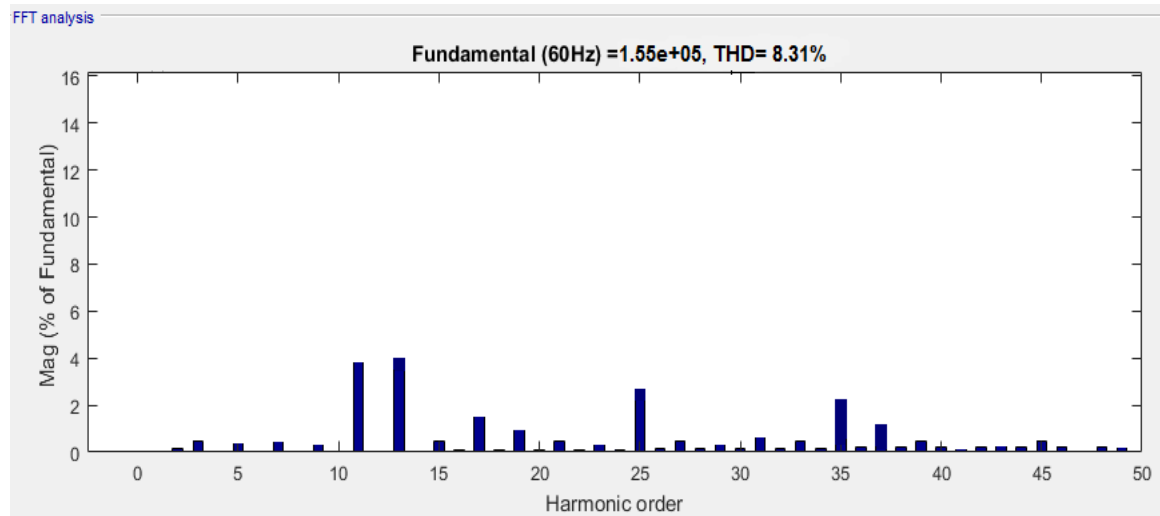


Figure 4.45. Harmonic Spectrum and THD index of the voltage wave at 110 KV side when the traction is heavily loaded

$$\text{THD} = 8.31\%$$

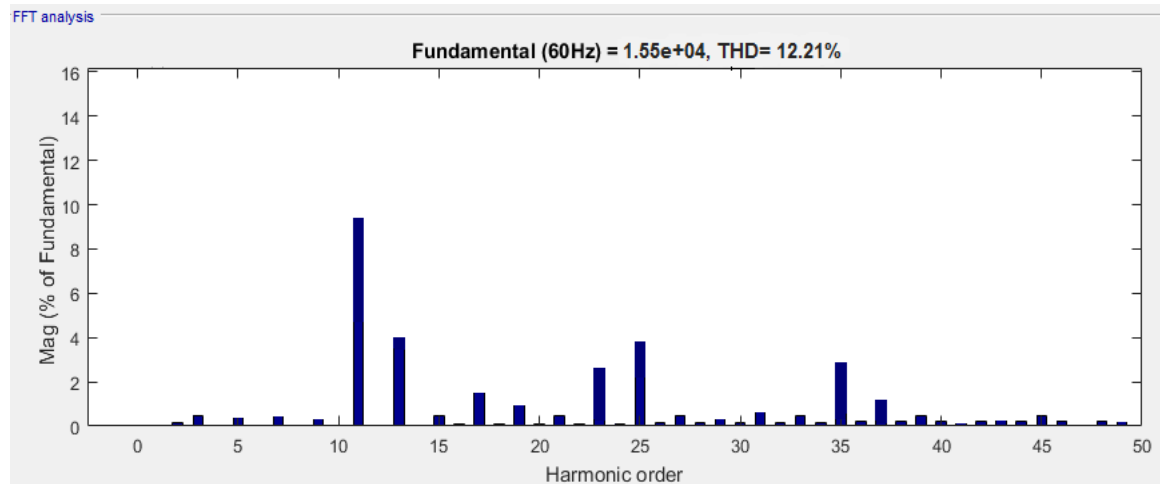


Figure 4.46. Harmonic Spectrum and THD index of the voltage wave at 11 KV side when the traction is heavily loaded

$$\text{THD} = 12.21\%$$

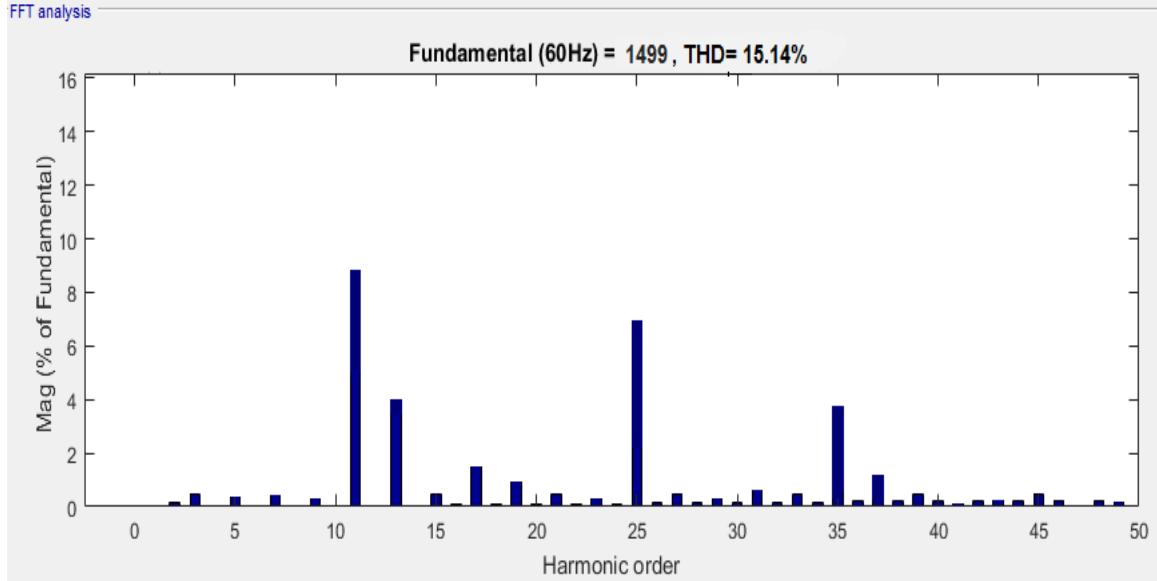


Figure 4.47. Harmonic Spectrum and THD index of the voltage wave at 1.06 KV when the traction is heavily loaded

$$\text{THD} = 15.14\%$$

From Figures 4.45, 46 and 4.47, it is very clear that, the voltage waves at the 11 KV bus and 1.06 KV bus are affected adversely by the harmonics that generated from the traction load. The THD at 1.06 KV side is almost twice the THD at 110 KV side.

Active power that consumed by the traction load is almost twice the power that consumed in the light load case.

The active power consumption has the same trend that in the light load case. It increases in the acceleration load and decreases in the deceleration mode, whereas, it remains constant in the cruising mode.

In the heavy load case, the Pf is very low approximately 0.7. Thus, the traction system absorbs large amount of current and reactive power (Q), which is almost equal to the active power (P).

Figures 4.48 and 4.49 show the active and reactive power that consumed by the traction system in the heavy load case.

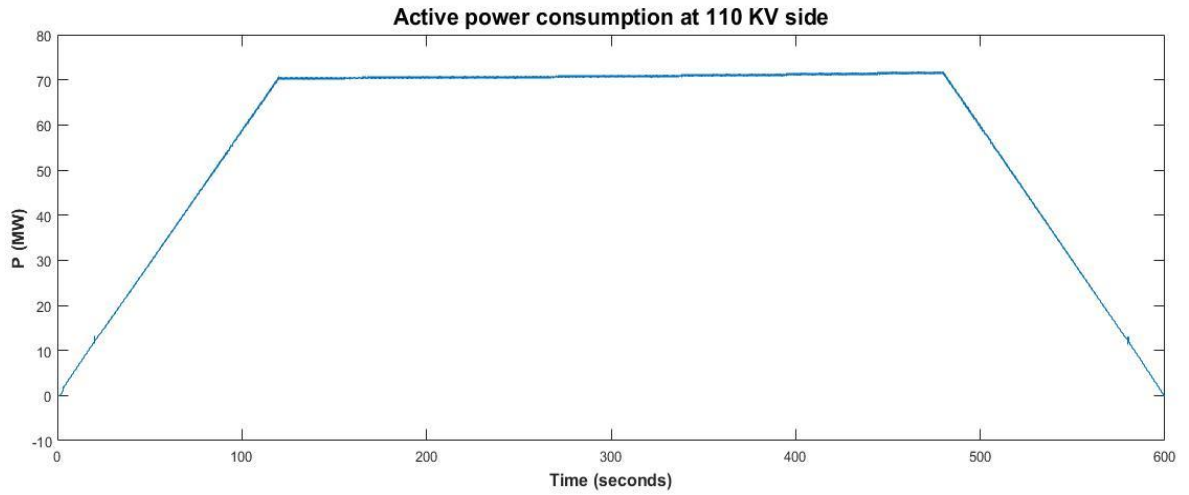


Figure 4.48. The reactive power consumed by the traction load measured at 110 KV side

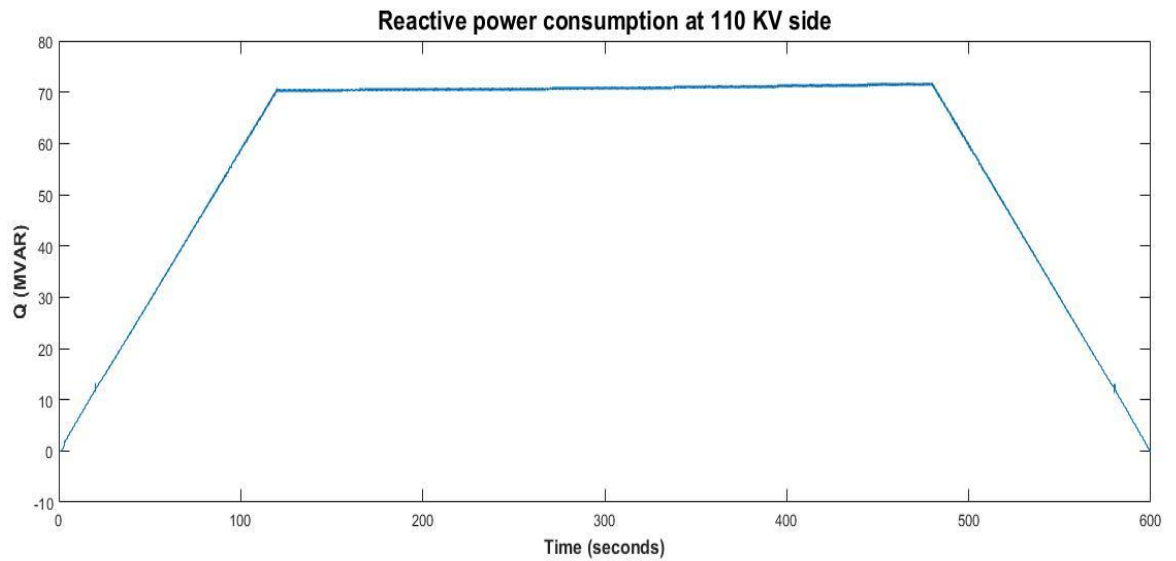


Figure 4.49. The reactive power consumed by the traction load measured at 110 KV side

The THD in the current and the voltage waves when the traction is heavily loaded at the three buses are shown in Table 4.7.

Table 4.7. THD index in the voltage waves at the different buses when the traction is heavily loaded

Voltage Level	THD_v (% of Fundamental)	IEEE Standard Limits
110 KV	8.31	2.5%
11 KV	12.21	5.0%
1.06 KV	15.14	5.0%

Table 4.8 shows the THD index in the voltage and current waves over the full period at 110 KV, 11 KV and 1.06 KV sides

Table 4.8. THD index in the current waves at the different buses when the traction is heavily loaded

Voltage Level	THD_i (% of Fundamental)	IEEE Standard Limit
110 KV	21.35	6.0%
11 KV	29.65	8.0%
1.06 KV	32.00	8.0%

Tables 4.7 and 4.8, show the voltage and current waves at the PCC and at the other buses. They are affected with high amount of harmonics, the THD values have exceeded the IEEE standard distortion limit. They reach up to 4 times the allowed limits of the IEEE standard.

THD in the voltage wave at 110 KV side in the acceleration, cruising and the deceleration modes, are shown in Table 4.9.

Table 4.9. THD index in the voltage wave at the PCC in the three dynamic modes of the train with heavy load

Dynamic mode	THD_v (% of Fundamental)	THD_i (% of Fundamental)
Acceleration	9.31	18.39
Cruising	4.35	7.93
Deceleration	10.11	29.34
IEEE standard Limit	2.5	6.0

Tables 4.7, 4.8 and 4.9 show that, the THD values in the voltage and current waves have violated the IEEE standard distortion limits adversely. Therefore, a corrective action must be taken to suppress these undesirable generated harmonics and to stop the penetration of these harmonics to the PCC. This will result in enhancing the quality of the power system. In Chapter 5, an active filter scheme will be discussed in details as a corrective action to enhance the power system quality.

CHAPTER 5

ACTIVE FILTER SCHEME

5.1 Overview

Generally, the purpose of connecting a filter with any power system, is to reduce the harmonics and providing this system with a reactive power and thereby, reducing the absorbed current and improve the power factor [62]. There are two types of the filter that can be used to absorb the undesirable harmonics from power system:

5.1.1 Passive Filter

Passive filter is designed based on passive elements like capacitor and inductor. The basic idea of this type of filters depends on the resonance principle. The tuning of the passive elements is adjusted to absorb a particular harmonic which will be compensated [63], [64].

5.1.2 Active Filter

This filter is more effective than the passive filter. The basic principle of this filter depends on extraction of a reference current which is to be supplied by the active filter in ant phase with the same magnitude of the harmonic current. The reference current is extracted by sensing the load current and source voltage and applying some control techniques like Constant power control technique, Sinusoidal current control technique, synchronous reference theory or Unit template control techniques [65-70].

In this study, sinusoidal current control technique is used to control the performance of the active filter scheme.

Connecting a traction system to a public utility grid has resulted a high amount of undesirable harmonics which are affecting the whole power system and all the other loads that are connected to this utility grid at the PCC.

The solution for this problem, can be accomplished by developing a parallel active or passive filter which can be tuned to a particular harmonic frequency. The usage of the passive L-C Filters has more disadvantages because of their large size, series and/or parallel resonance the impedance of source affects the filtering characteristics, filters are overload because of the high degree harmonic currents, and more filters are required for compensation because one filter can compensate only one particular frequency and this increases the cost of the filters [71-74].

This work is conducted in order to solve the power quality issues by designing a suitable active power filter. This filter eliminates current and voltage harmonics by improving the power factor, and cancel out the negative and zero sequence components. There are two types of active power filters shunt active filter and series active filter. In this research, a comprehensive study of a 3-phase Shunt active power filter (SAPFs) has been conducted, which compensates the current harmonics by injecting a currents with different magnitudes and at different frequencies which are equal but opposite in phase. The shunt active power filter has been created in MATLAB/Simulink environment and Simpower systems environment.

5.2 Active Power Filter Components

The active power filter (APF) system is developed in MATLAB/Simulink. It consists of a DC voltage source connected to an IGBT based converter. Figure 5.1 shows the filter model in MATLAB/Simulink.

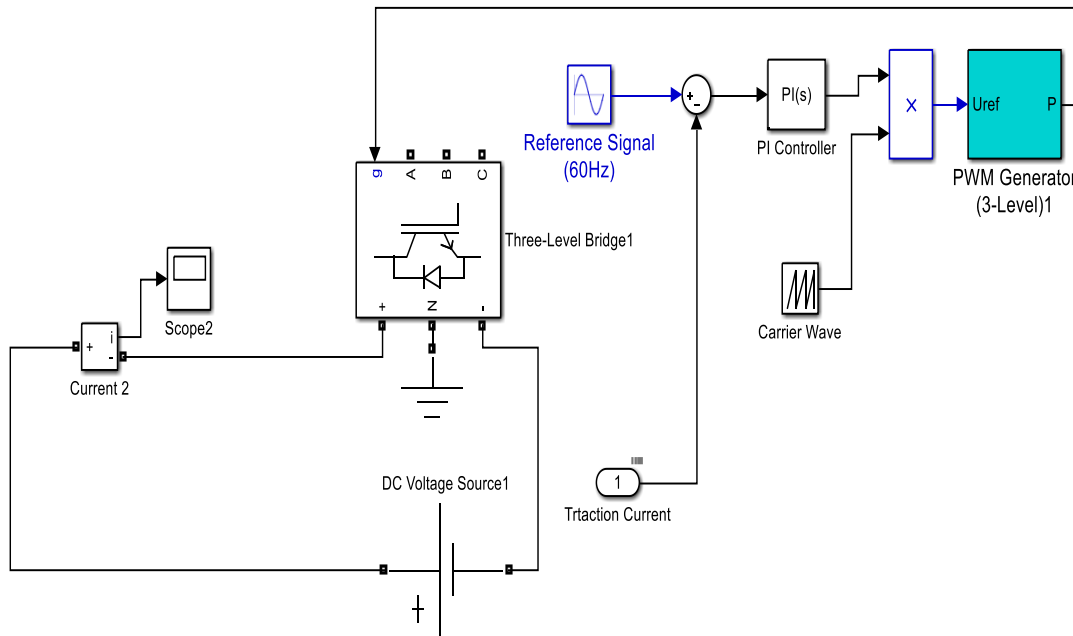


Figure 5.1. Active Filter model in MATLAB/Simulink

5.2.1 Voltage Source Inverter (VSI)

The voltage source inverter (VSI) block is a DC voltage source connected to a 3-phase, IGBT based inverter. VSI provides a three phase voltage source with constant amplitude of voltage and variable with the time. The frequency must be controlled by an external signal which is usually coming from a pulse width modulation (PWM) as shown in Figure 5.1.

5.2.2 Pulse Width Modulation (PWM)

The pulse width modulation is controlling the average value of the input DC voltage, it works as a switch (ON and OFF). PWM receives a signal from the PI controller according to that, it generates a signal that will be multiplied by a carrier wave with high frequency, then, the result signal directly will be connected to the IGBT based converter which is inverting the input DC voltage to a 3-phase AC voltage that will be injected in to the main power system in terms of harmonics with same magnitude of the undesirable harmonics but in an opposite direction. Thus, the undesirable harmonics will be cancelled.

5.2.3 Active Filter Parameters

The active filter parameters are selected based on the ratings of the power system components. The DC voltage is determined according to the location that the filter will be connected with. A Trigonometric carrier wave is used as an input to the PWM to control the output voltage of the DC source. The frequency of the carrier wave is 500 KHZ. This value is specified base on the voltage level. From the literature, the frequency of the carrier wave usually takes value between 300 to 700 KHZ when it connected to voltage above 10 KV [50].

The ratings of the voltage source and the VSI is shown in Table 5.1 below.

Table 5.1. Ratings of the active filter components

Component	Voltage (KV)	P (MW)	Current (A)
Voltage source	1.5	15	-
Inverter	1.5 (DC) / 1.06 (AC)	-	10000 (DC)

5.2.4 PI Controller

PI controller has been adopted to control the PWM operation. The output current of the inverter is determined according to a predetermined reference value. The main aim of this controller is to compare between the actual current that absorbed from the utility side with the reference value in the PI controller. 'P' is represented by proportion part and 'I' is represented by integral part. In proportional, part 'P' reduces the error whether, integral part 'I' reduces the offset. 'P' is a contingent in present error, whether, 'I' is contingent in past error. Therefore, active filter parameters can be set controlled to the desired value by using PI controller.

Base on the literature, the values of the PI controller parameters are specified by applying different values of them, after many trials the optimal values of K_p and K_i are found to be equal 4 and 1 respectively.

A sinusoidal wave with the same magnitude of the fundamental load current wave and with a frequency of the fundamental harmonic (60 HZ) is used as a reference signal. This signal will be compared with the actual current wave that absorbed from the utility side by the traction load. Then, according to the difference between them, an error signal will be generated. The generated error signal will be used as an input to the PWM after multiplied by a carrier wave which is a trigonometric wave with high frequency.

Figure 5.2 shows a flow chart of the filter operation.

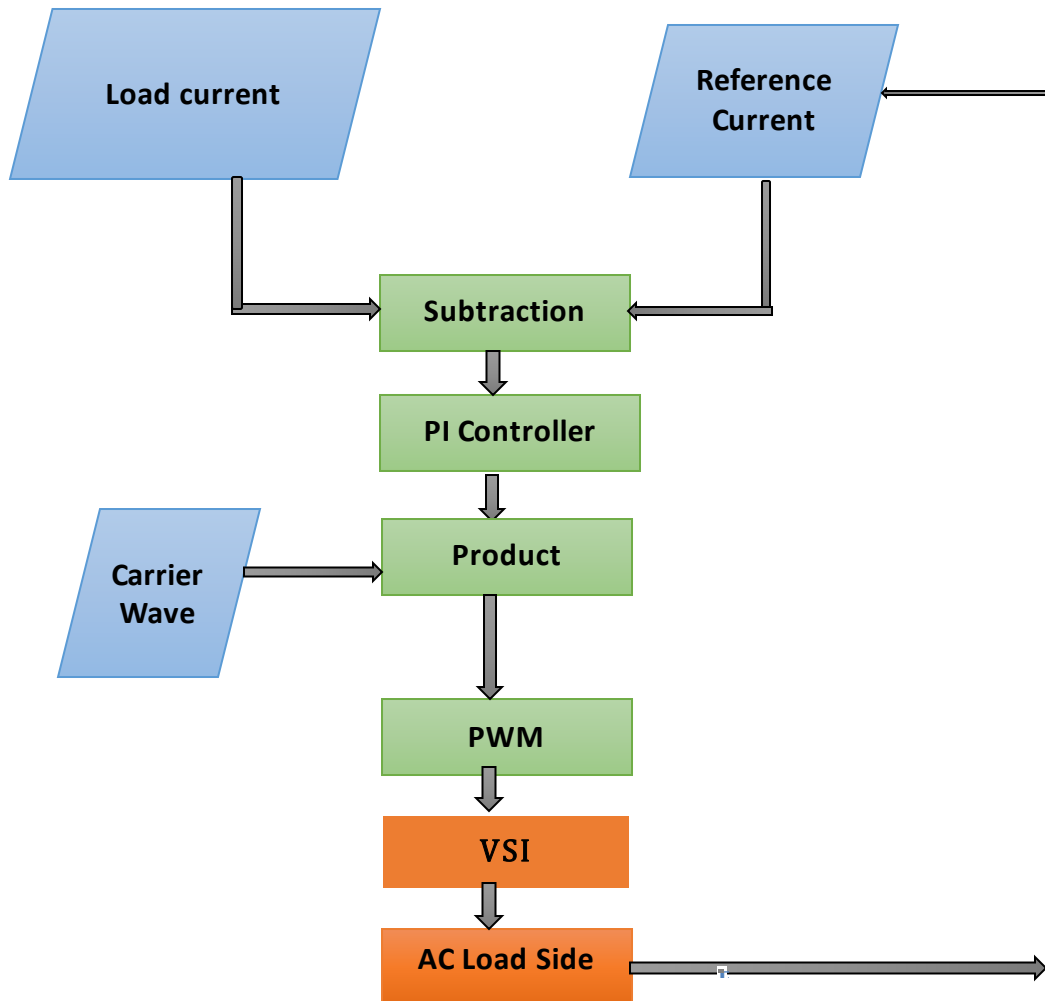


Figure 5.2. Flow chart of the filter principle operation

5.3 Simulation results

The active power filter is applied to the traction system designated in chapter four.

Since the heavy loading condition is the most common operating condition for the traction system. The APF scheme has connected to the traction system when it is heavily loaded.

This is the worst case of the operating condition. Since there are some load are connected

at 11 KV bus according to the Italy model that is adopted. The proposed filter scheme is connected at different locations on the power system to identify the suitable location and the most effective position for the filter.

The adopted model which has been described in chapter three, has some loads connected at the other buses. Therefore, two possible different locations for the APF are tested by connecting the filter in parallel with the power system at the load side (1.06 KV) and at the PCC (110 KV) side.

5.3.1 Active power filter connected at the load side

In this case, the filter scheme is connected at the nearest point for the load side which is 1.06 KV side.

Figure 5.3 shows a block diagram for the active filter when it is connected at 1.06 KV side.

The DC voltage source for the filter when it is connected at the load side is 11 KV.

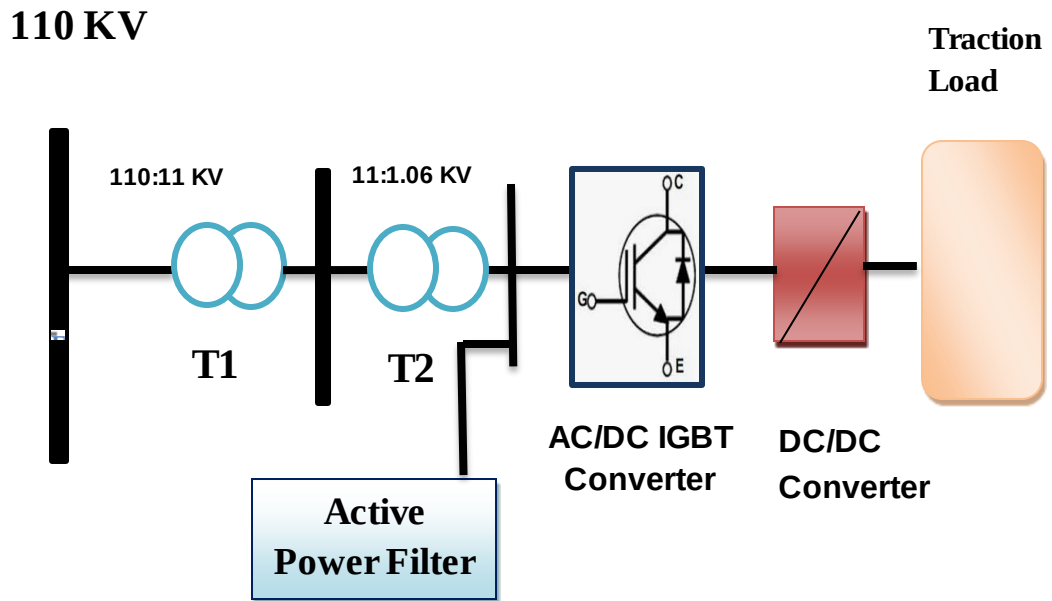


Figure 5.3. Block diagram of the traction system when the filter is connected at the load side

The block diagram in Figure 5.3 is simulated in MATLAB/Simulink. The voltage and current waves are measured and analyzed by using FFT to evaluate the performance of the filter when it is connected at the load side.

The voltage waves at the PCC are analyzed in the three dynamic modes after connecting the filter at the load side. The THD index has suppressed significantly at the: acceleration, cursing and deceleration modes as shown in Figures 5.4, 5.5 and 5.6 respectively.

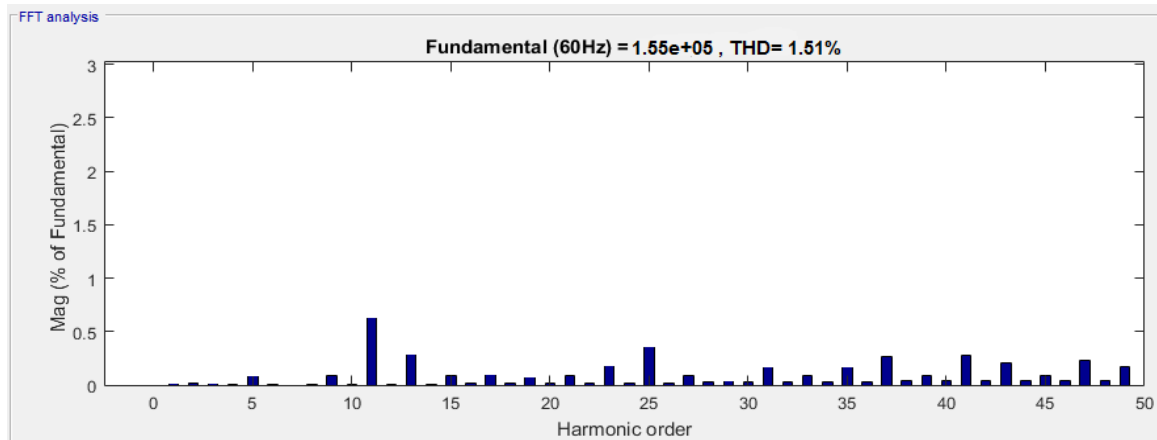


Figure 5.4. Harmonic spectrum and the THD index of the voltage wave at 110 KV side in the acceleration mode after connecting the Filter at the load side

$$\text{THD} = 1.51\%$$

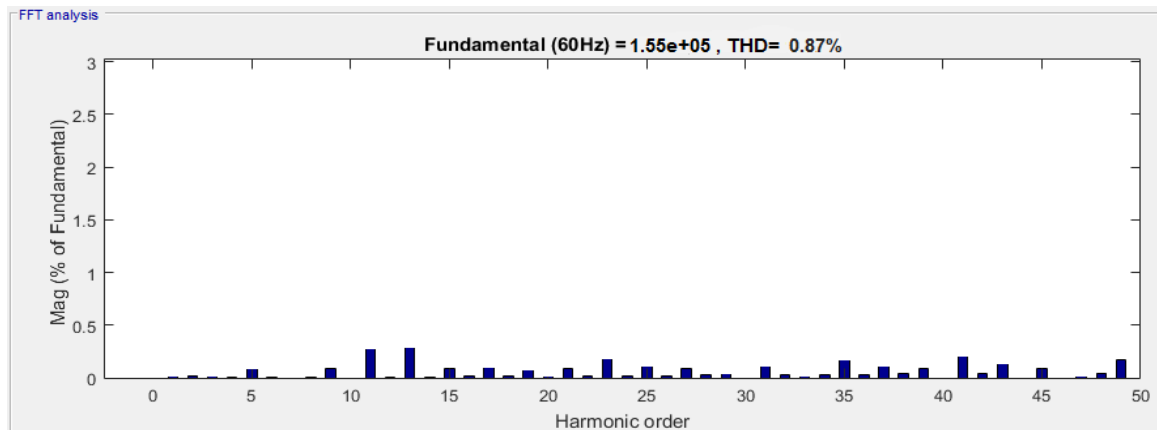


Figure 5.5. Harmonic spectrum and the THD index of the voltage wave at 110 KV side in the cruising mode after connecting the Filter at the load side

$$\text{THD} = 0.87\%$$

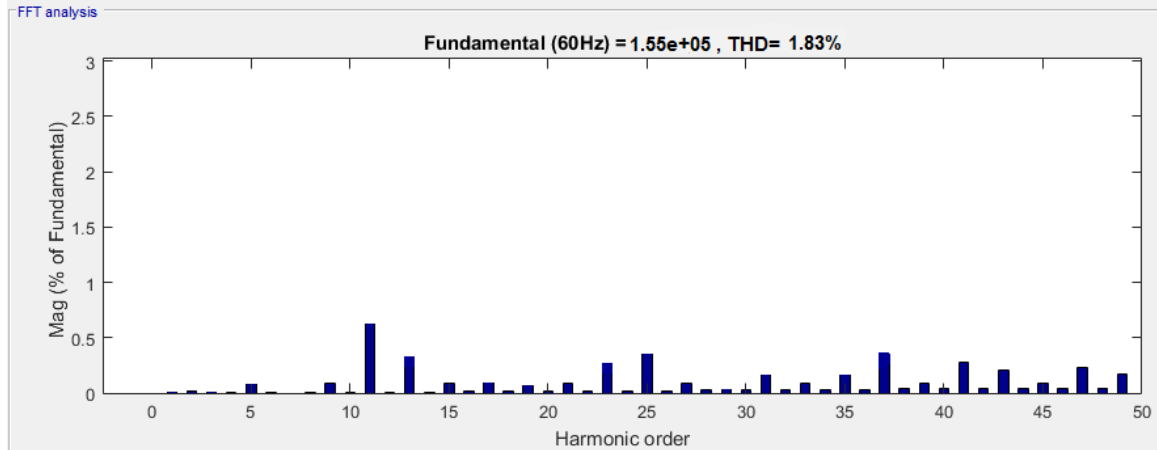


Figure 5.6. Harmonic spectrum and the THD index of the voltage wave at 110 KV side in the deceleration mode after connecting the Filter at the load side

$$\text{THD} = 1.83\%$$

Figures 5.4, 5.5 and 5.6 show that, all the individual harmonic distortions have reduced below 1.0% in the acceleration and deceleration modes and suppressed below 0.5% during the cruising mode. Thus, the THD has decreased accordingly.

For the full period, the voltage waves at the three buses are analyzed. Figures 5.7, 5.8 and 5.9 show the harmonic spectrum and THD index of the voltage wave at 110 KV side, 11 KV side and 1.06 KV side respectively after connecting the filter at the load side.

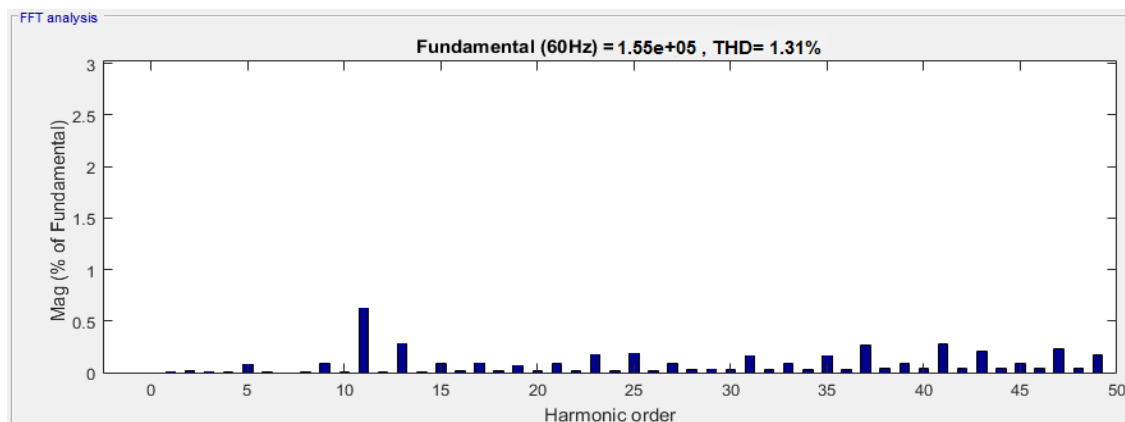


Figure 5.7. Harmonic spectrum and THD index of the full voltage wave at 110 KV side after connecting the Filter at the load side

$$\text{THD} = 1.31\%$$

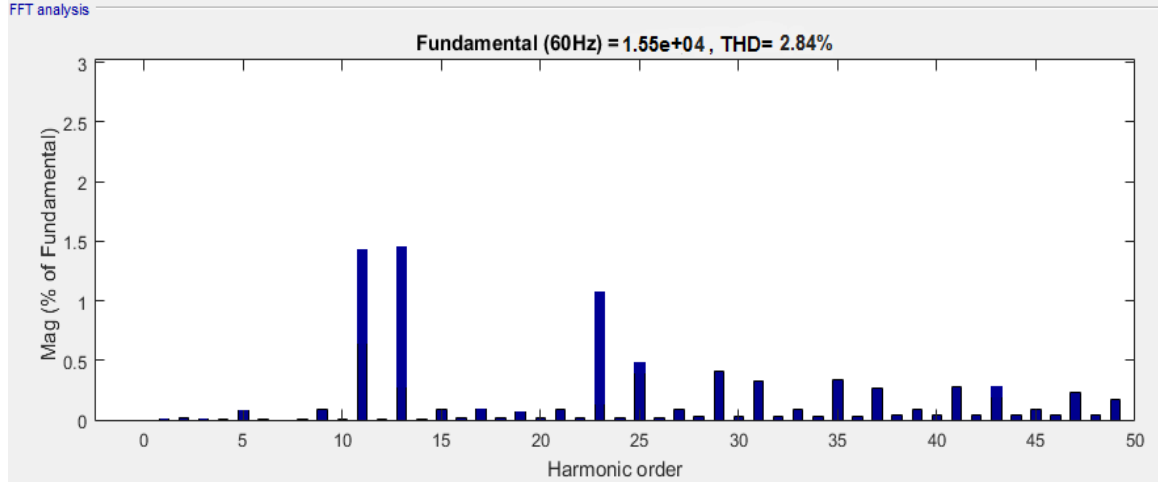


Figure 5.8. Harmonic spectrum and THD index of the full voltage wave at 11 KV side after connecting the Active Filter at the load side

THD 2.84

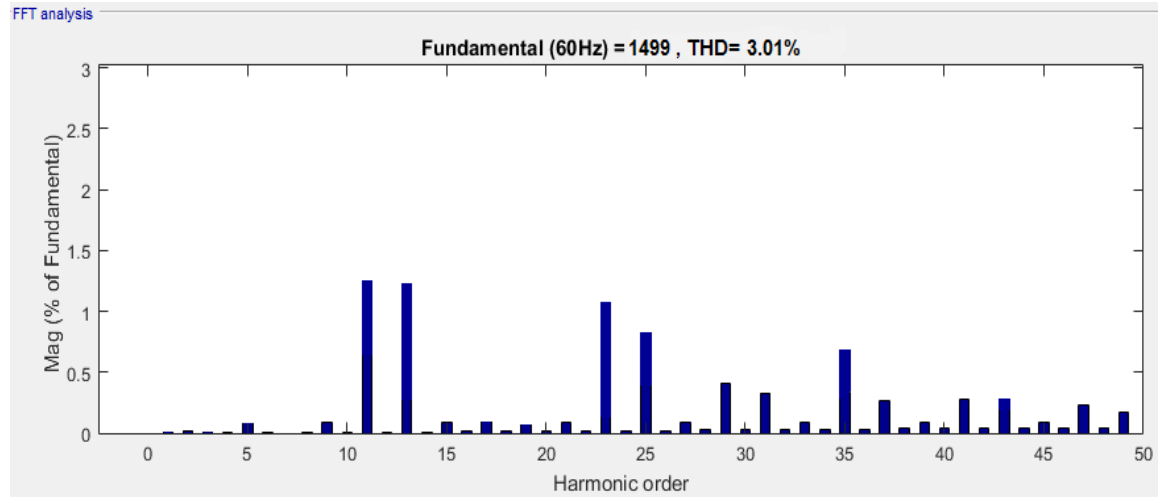


Figure 5.9. Harmonic spectrum and THD index of the full voltage wave at 1.06 KV side after connecting the Active Filter at the load side

THD 3.01%

From Figure 5.7, it is observable that, the THD index of the voltage wave has suppressed and decreased less than 2.5% which is below the IEEE standard distortion limits. Figures 5.8 and 5.9 show that, the THD has suppressed significantly less than 5%, the individual harmonics have decreased as well less than 1.5% which is below the IEEE standard distortion limits.

The current waves also have been subjected for the FFT analysis. The THD index and the harmonic spectrum of the current wave at the PCC in the acceleration, cruising and deceleration modes are shown in Figures 5.10, 5.11 and 5.12 respectively.

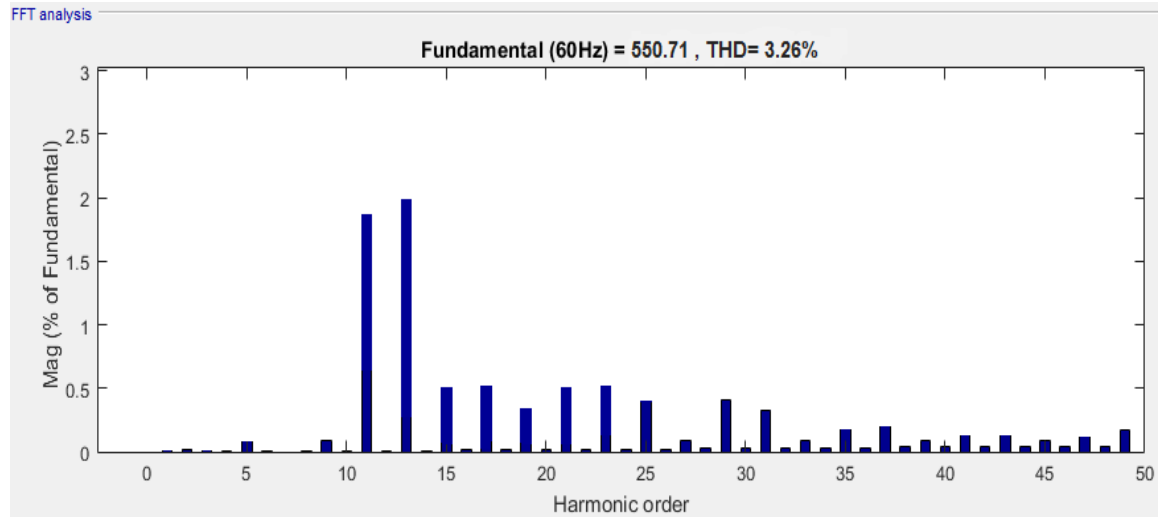


Figure 5.10. Harmonic spectrum and the THD index of the current wave at 110 KV side in the acceleration mode after connecting the Filter at the load side

$$\text{THD} = 3.26\%$$

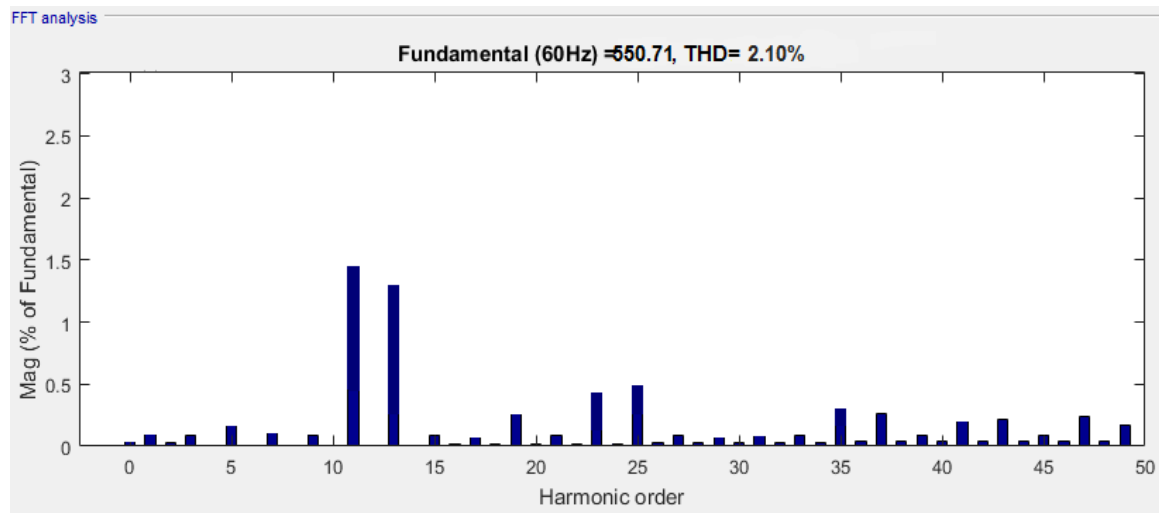


Figure 5.11. Harmonic spectrum and the THD index of the current wave at 110 KV side in the cruising mode after connecting the Filter at the load side

$$\text{THD} = 2.10\%$$

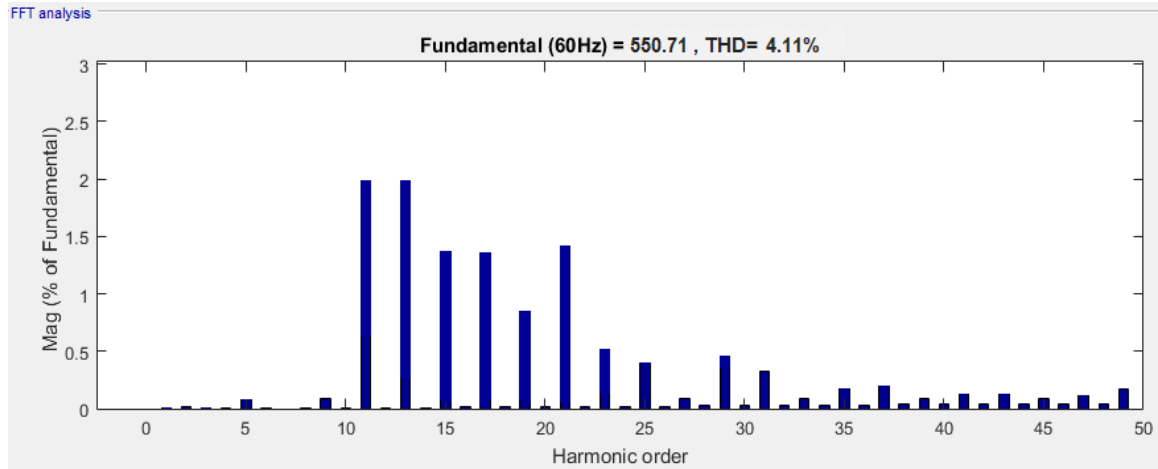


Figure 5.12. Harmonic spectrum and the THD index of the current wave at 110 KV side in the deceleration mode after connecting the Filter at the load side

$$\text{THD} = 4.11\%$$

Figures 5.10, 5.11 and 5.12 show that, the individual and total harmonic distortion in the current waves have reduced to be less than the maximum limits of the IEEE distortion limits.

Figures 5.13, 5.14 and 5.15 show the individual harmonic distortion and THD index in the current waves at 110 KV side, 11 KV side and 1.06 KV side respectively.

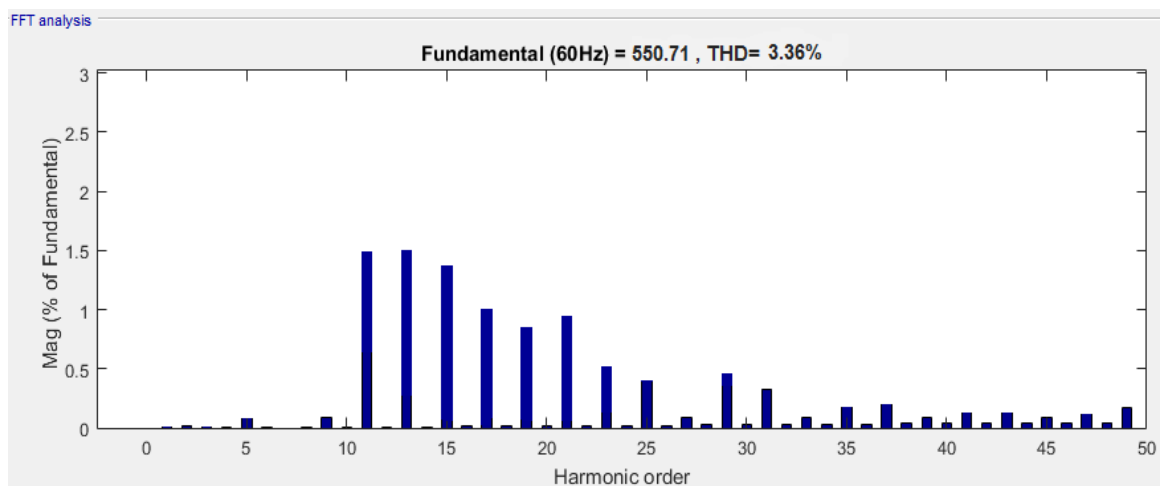


Figure 5.13. Harmonic spectrum and THD index of the current wave at 110 KV side after connecting the Active Filter at the load side

$$\text{THD} 3.36\%$$

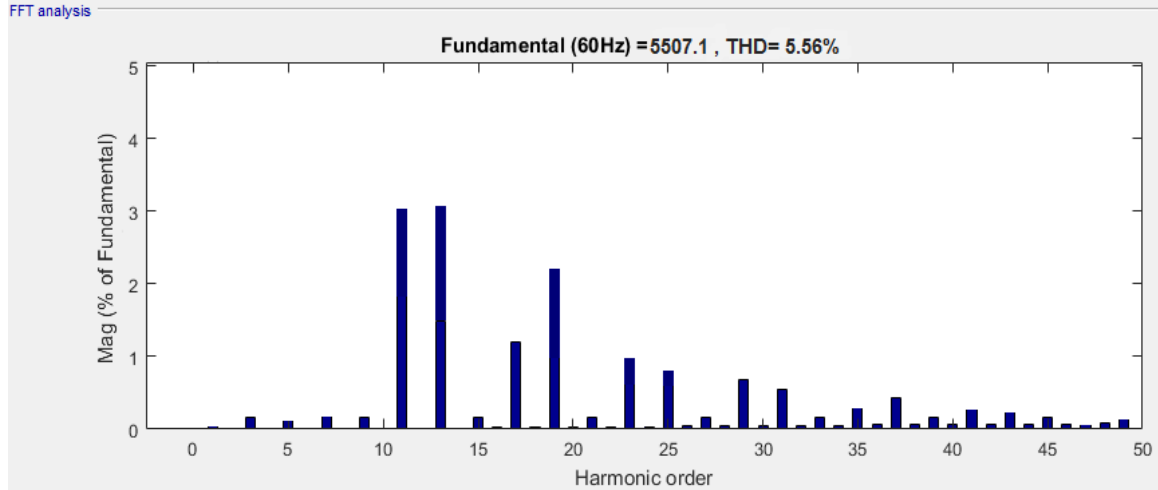


Figure 5.14. Harmonic spectrum and THD index of the current wave at 11 KV side after connecting the Active Filter at the load side

THD 5.56%

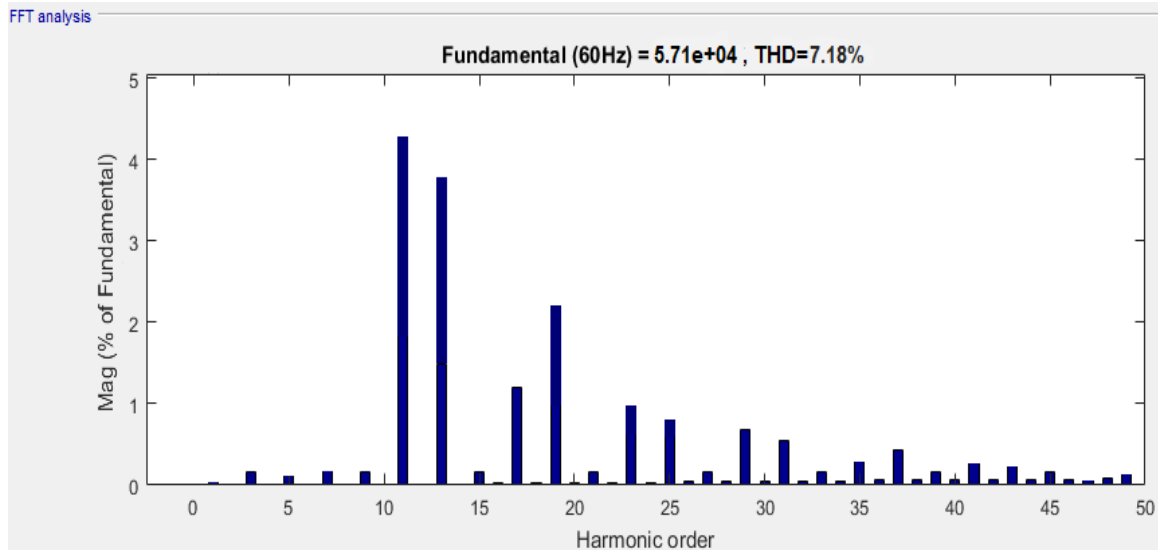


Figure 5.15. Harmonic spectrum and THD index of the current wave at 1.06 KV side after connecting the Active Filter at the load side

THD = 7.18%

From Figures 5.13, 5.14 and 5.15. The individual and total harmonic distortion (THD) in all buses has reduced significantly and suppressed lower the IEEE standard distortion limits. The highest reduction occurred in the current wave at the PCC.

THD in the voltage wave at 110 KV side in the acceleration mode, cruising mode and the deceleration mode, are shown in Table 5.2.

Table 5.2. THD index in the voltage wave at the PCC (110 KV side) in the three dynamic modes when the traction is heavily loaded

Dynamic mode	THD_v(% in the fundamental)		THD_i(% in the fundamental)	
	Before adding the filter	After adding the filter	Before adding the filter	After adding the filter
Acceleration	9.31	1.51	18.39	3.26
Cruising	4.35	0.87	7.93	2.10
Deceleration	10.11	1.83	29.34	4.11
Standard Limit (IEEE)	2.5%		7.5%	

From Table 5.2, it is clear that, the THD indexes in the voltage and current waves have decreased significantly and suppressed below the IEEE standard 519 distortion limits after connecting the filter at the load side.

Tables 5.3 and 5.4 show the THD indexes in the voltage and current waves at the three buses respectively. The THD ratios have reduced and become within the allowed limits according to the IEEE standards.

Table 5.3. THD index in the voltage wave at different buses when the traction is heavily loaded

Voltage Level	THD_v(% in the fundamental)		IEEE Standard Limit
	Before adding the filter	After adding the filter	
110 KV	8.31	1.31	2.5%
11 KV	12.21	2.84	5.0%
1.06 KV	15.14	3.01	5.0%

Table 5.4. THD index in the current waves at different buses when the traction is heavily loaded

Voltage Level	THD_i(% in the fundamental)		IEEE Standard Limit
	Before adding the filter	After adding the filter	
110 KV	21.33	3.36	7.5%
11 KV	29.65	5.65	12.0%
1.06 KV	32.0	7.18	12.0%

Figures 5.16 and 5.17 show the active and reactive power consumption after connecting the APF at the load side.

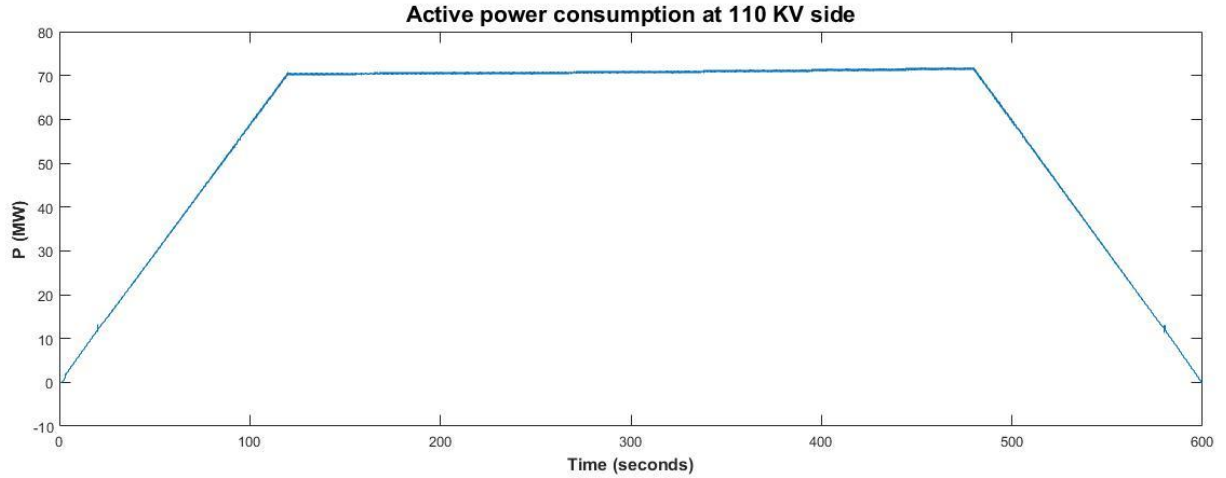


Figure 5.16. The active power consumed by the traction load after connecting the active filter at the load side

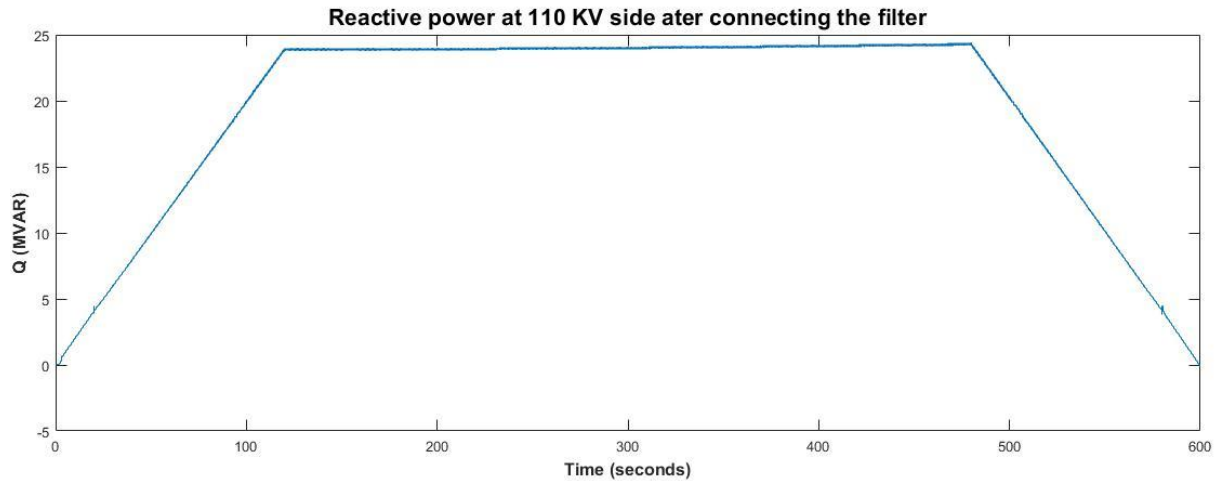


Figure 5.17. The reactive power absorbed from the utility grid after connecting the active filter at the load side

From Figures 5.16 and 5.17, the active power that consumed by the traction load has the same profile after connecting the filter. However, the reactive power has decreased significantly. It has reduced from 71 MVAR to 24.5 MW only. This means less amount of reactive power is needed after connecting the active filter. This has resulted in improving

Pf from 0.70 to 0.94. According to that, the total current absorbed by the traction system from the utility side has decreased significantly from 525 A to 390 A only.

5.3.2 Active power filter connected at the PCC

According to the model that has been adopted in this study, there are some loads connected at the 11 KV bus. Therefore, the filter scheme has been connected at the PCC (110 KV) side to see if there will be a major effect on the harmonic reduction at this bus. Figure 5.18 shows the block diagram of the (APF) connection

Due to the high power rating at the PCC, the rating of the DC source in this case is 110 KV which is relatively high compared to the case of connecting the filter at the load side.

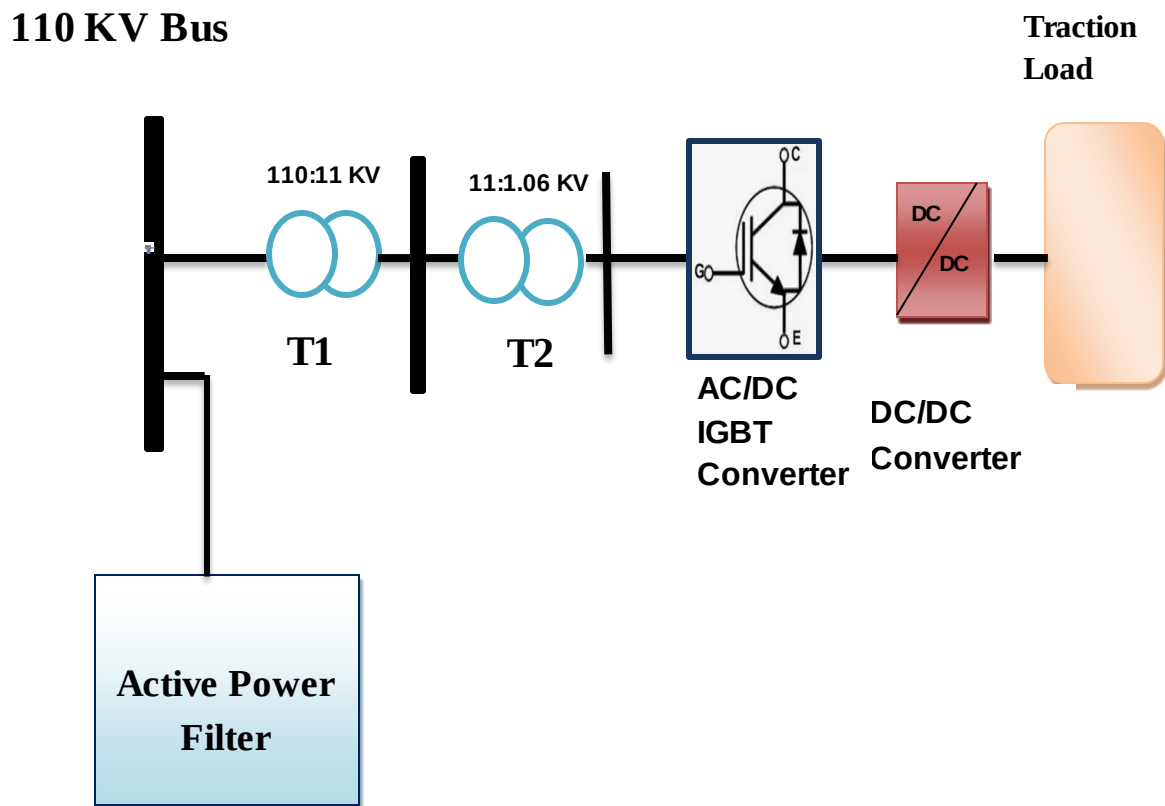


Figure 5.18. Block diagram of the traction system when the filter is connected at the 110 KV side

The block diagram in Figure 5.18 is simulated in MATLAB/Simulink. FFT results have plotted.

After connecting the active filter at the load side, the THD has decreased significantly in the voltage wave at 110 KV side when the traction operates in the acceleration, cruising and deceleration modes as shown in Figures 5.19, 5.20 and 5.21 respectively

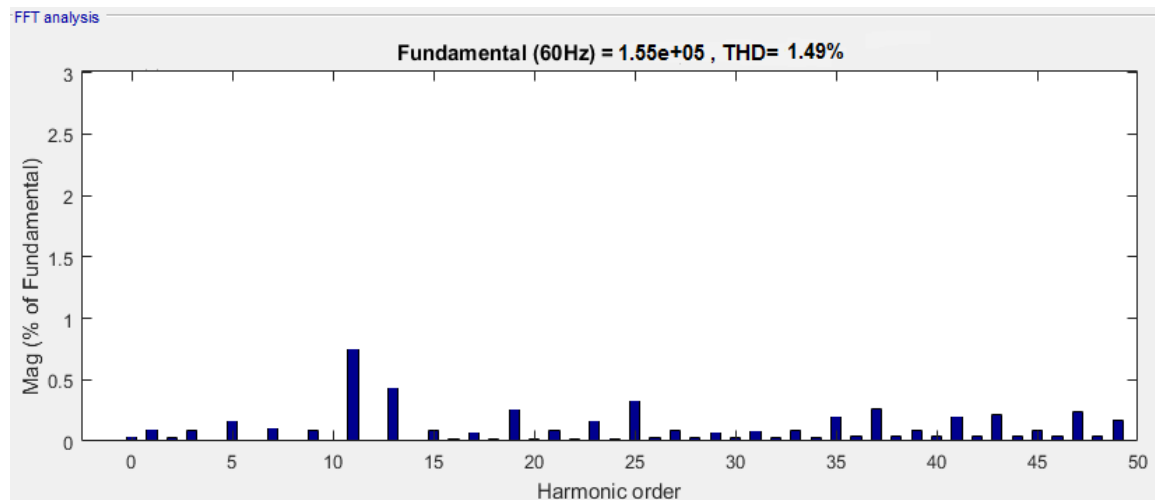


Figure 5.19. Harmonic spectrum and the THD index of the voltage wave at 110 KV side in the acceleration mode after connecting the Filter at 110 KV side

$$\text{THD} = 1.49\%$$

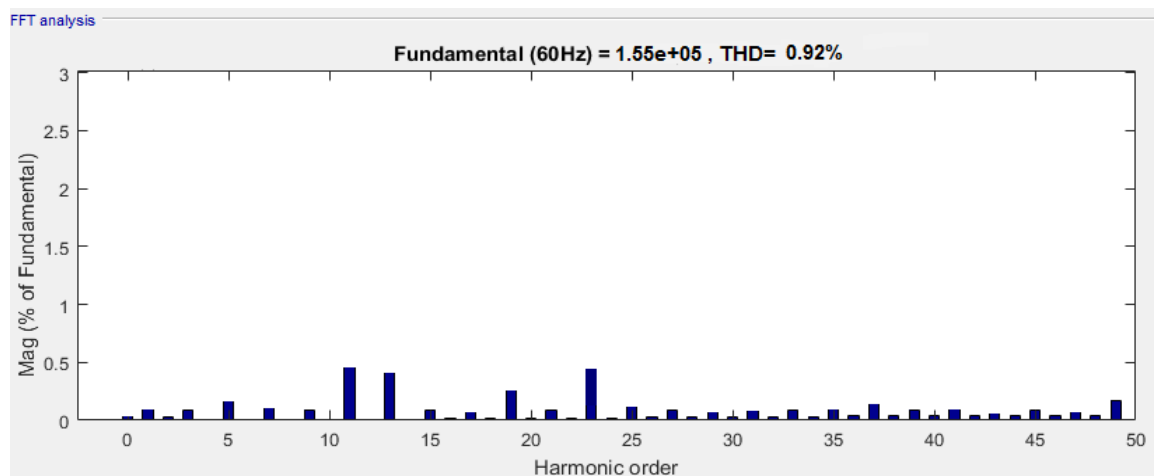


Figure 5.20. Harmonic spectrum and the THD index of the voltage wave at 110 KV side in the cruising mode after connecting the Filter at 110 KV side

$$\text{THD} = 0.92\%$$

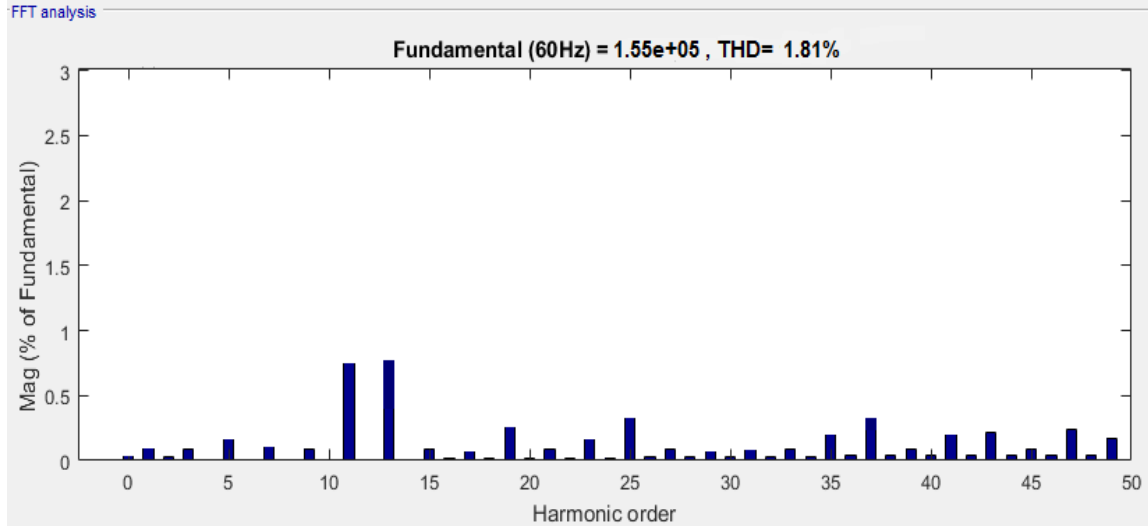


Figure 5.21. Harmonic spectrum and the THD index of the voltage wave at 110 KV side in the deceleration mode after connecting the Filter at 110 KV side

$$\text{THD} = 1.81\%$$

The individual and total harmonic distortion (THD) have reduced below IEEE standard distortion limits.

Figures 5.22, 5.23 and 5.24 show the THD in the waveform at 110 KV side, 11 KV side and 1.06 KV side respectively.

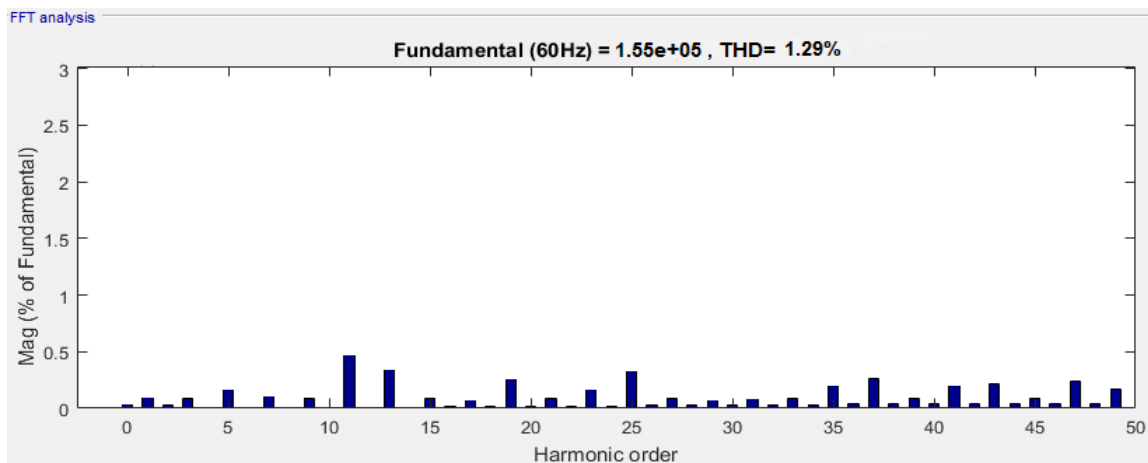


Figure 5.22. Harmonic spectrum and THD index of the voltage wave at 110 KV side after connecting the Filter at 110 KV side

$$\text{THD} = 1.29\%$$

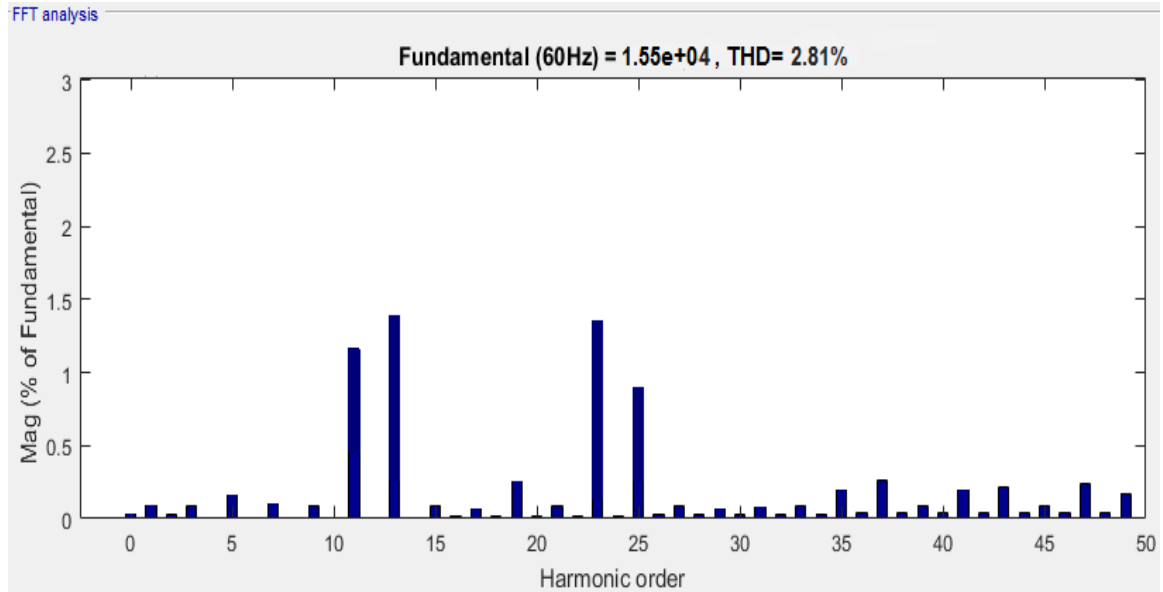


Figure 5.23. Harmonic spectrum and THD index of the voltage wave at 11 KV side after connecting the Filter at 110 KV side

$$\text{THD} = 2.81\%$$

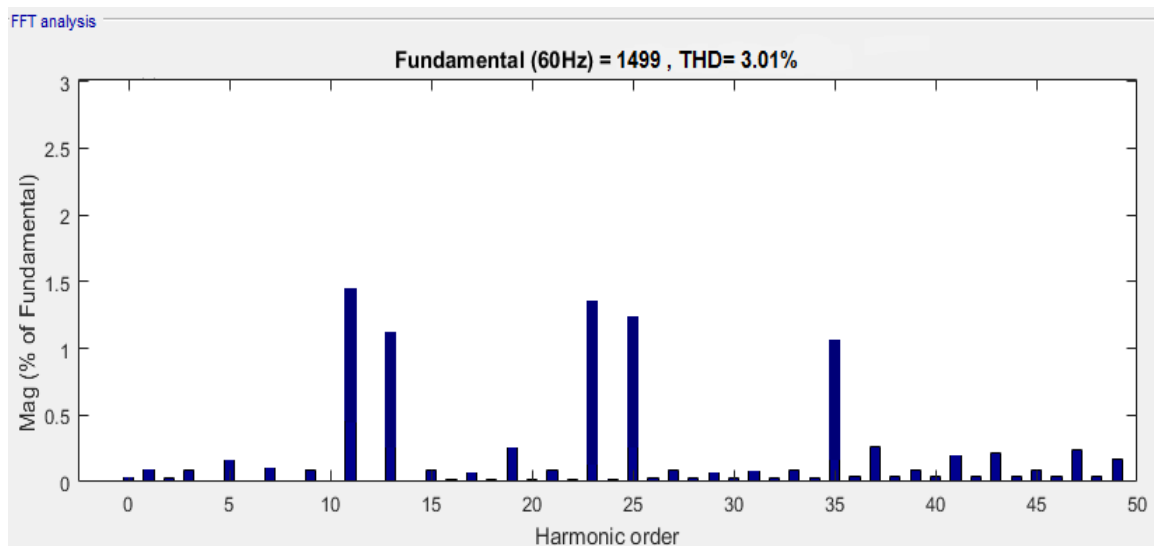


Figure 5.24. Harmonic spectrum and THD index of the voltage wave at 1.06 KV side after connecting the Filter at 110 KV side

$$\text{THD} = 3.01\%$$

The individual and total harmonic distortion (THD) have reduced significantly below the IEEE standards distortion limit. All the individual harmonics are less than the maximum limit of the IEEE standard. Tables (A.1 to A.4) in the Appendix.

The current waves also are subjected for the FFT analysis. The THD index and the harmonic spectrum of the current wave at the PCC in the acceleration, cruising and deceleration modes are shown in Figures 5.25, 5.26 and 5.27 and respectively.

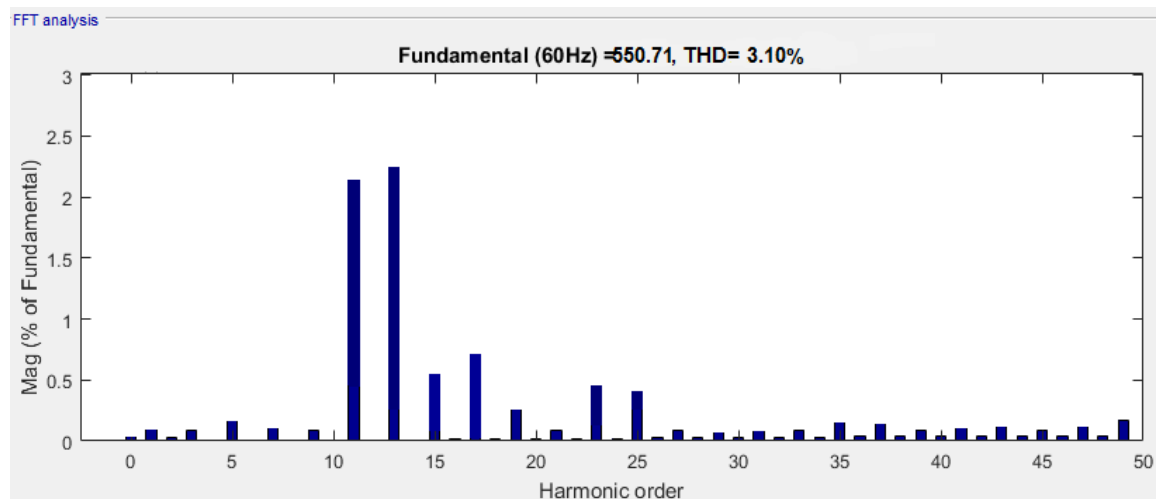


Figure 5.25. Harmonic spectrum and the THD index of the current wave at 110 KV side in the acceleration mode after connecting the Filter at 110 KV side

$$\text{THD} = 3.10\%$$

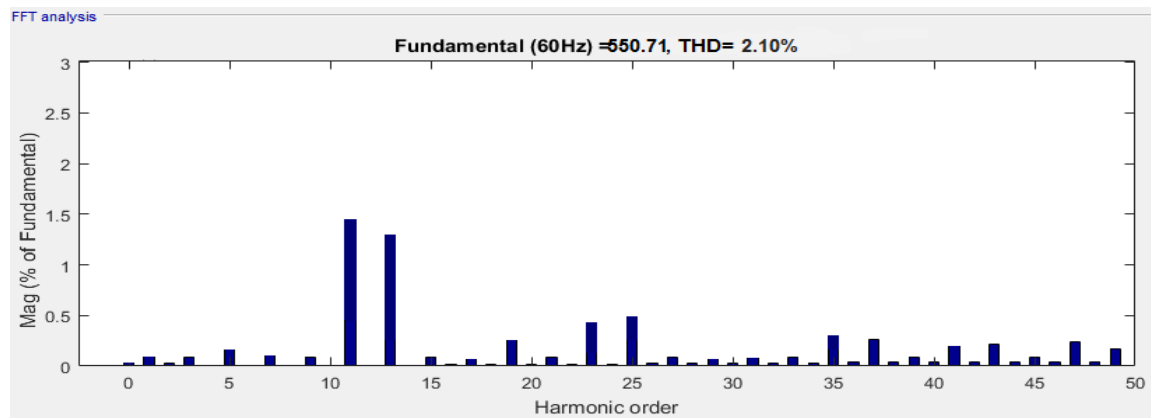


Figure 5.26. Harmonic spectrum and the THD index of the current wave at 110 KV side in the cruising mode after connecting the Filter at 110 KV side

$$\text{THD} = 2.10\%$$

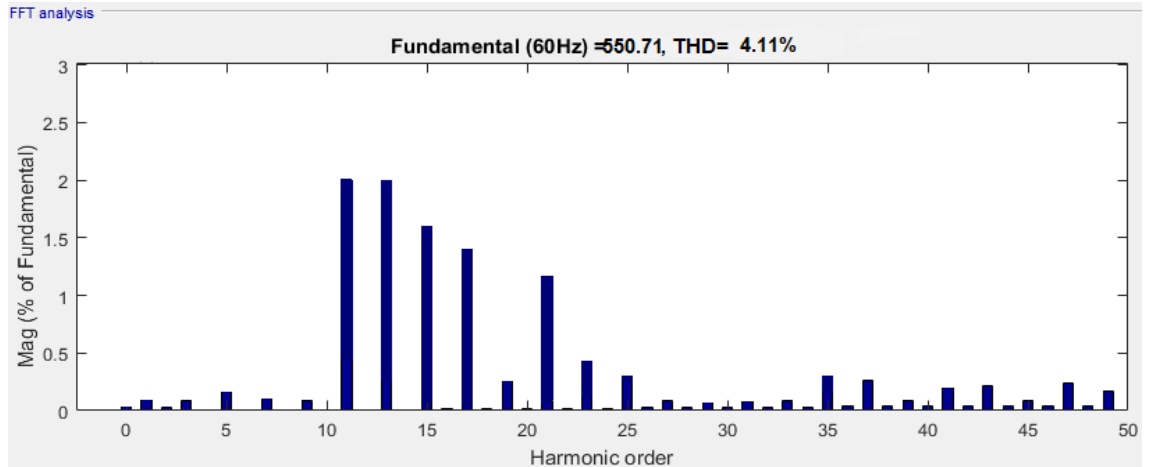


Figure 5.27. Harmonic spectrum and the THD index of the current wave at 110 KV side in the deceleration mode after connecting the Filter at 110 KV side

$$\text{THD} = 4.11\%$$

Figures 5.25, 5.26 and 5.27 show that the dominant harmonics still the 11th and 13th harmonic orders, but their values are below the maximum limits of the IEEE standards.

The individual harmonic distortion and THD index in the current at 110 KV side, 11 KV side and 1.06 KV side have decreased significantly after connecting the active filter at the PCC, this is shown in Figures 5.28, 5.29 and 5.30 respectively.

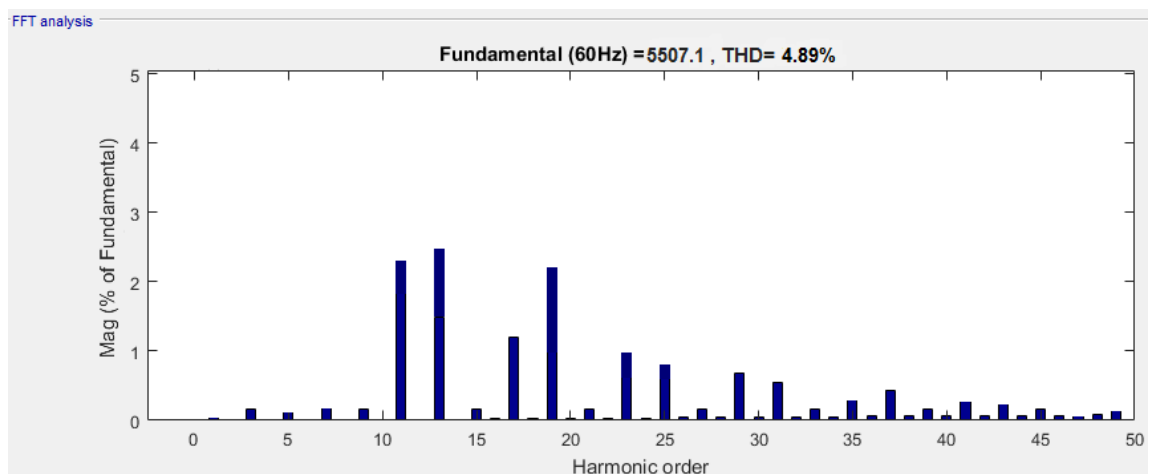


Figure 5.28. Harmonic spectrum and THD index of the current wave at 110 KV side after connecting the Active Filter at 110 KV side

$$\text{THD} 4.89\%$$

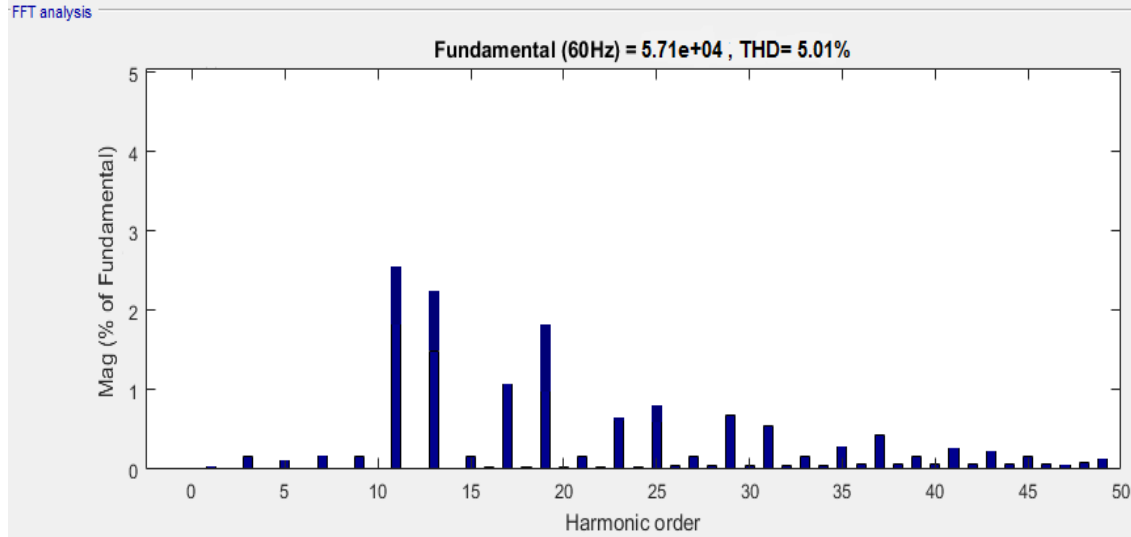


Figure 5.29. Harmonic spectrum and THD index of the current wave at 11 KV side after connecting the Active Filter at 110 KV side

THD 4. 5. 01%

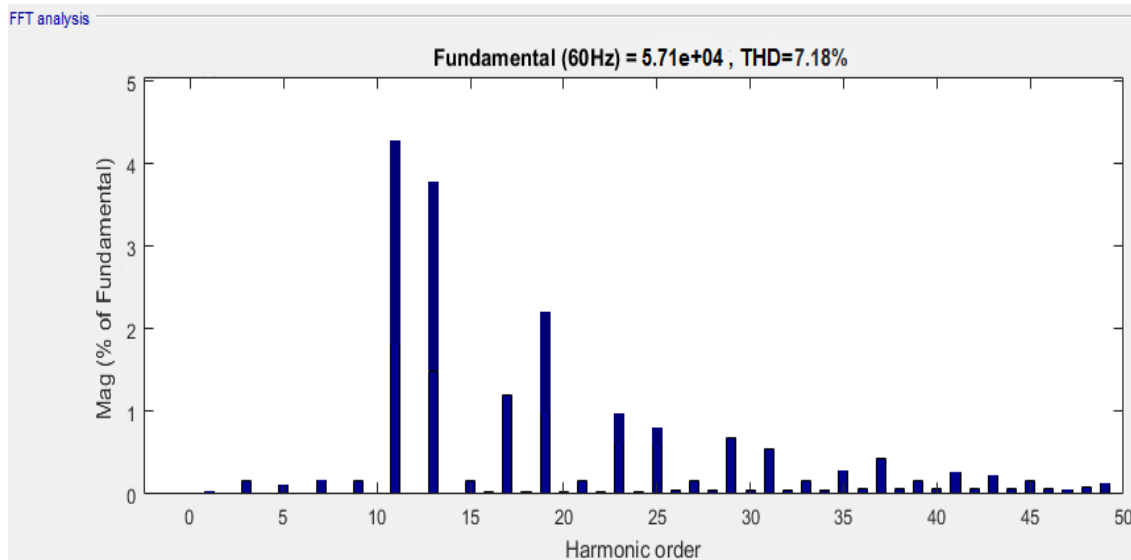


Figure 5.30. Harmonic spectrum and THD index of the current wave at 1.06 KV side after connecting the Active Filter at 110 KV side

THD 7. 18%

According to the previous results. connecting the active filter at 1.06 KV, the individual and total harmonic distortion (THD) have reduced and suppressed below the IEEE

standards 519 distortion limits, the total reactive power absorbed by the traction system has decreased as well and thereby, the Pf is improved from 0.7 to 0.94.

When the filter is connected at 110 KV side, the reduction of the individual and total harmonics is almost similar to that results when the filter is connected at the load side. Therefore, due to high power ratings that are needed for designing a filter at the PCC are much higher than the ratings of the filter at the load side, it is recommended to connect the active filter at the load side which will have the same performance of the filter when it connected at the PCC.

CHAPTER 6

RIYADH METRO SYSTEM

6.1 Riyadh Metro Model

Riyadh city metro is considered one of the most modern metros over the world. It will meet the demands of the growing population while reducing traffic congestion and improving air quality.

The metro includes the construction of an advanced center for the control and operation of the train traffic management and control, and monitor all elements of the system of stations, tracks, facilities and systems, and will provide the center with the latest operating control and monitoring systems [75]. Riyadh metro will also include technical specifications and high design, notably the use of automated rail system without driver.

The train will be fed by Saudi Electricity Company (SEC). The total power rating of the train is estimated to be 468 MW, through 4 main power substations, and 12 small substations. Riyadh metro is designed to move with maximum speed of 80 km/h, it is one of the fastest metros in the Middle East area [75].

In Chapter four, different loading conditions have applied on the developed electric traction system. The proposed model of the traction system has given a reasonable result. However, in order to validate the developed electric traction model and for having more realistic overview about the impact of electric traction drives on power system, a real data for Riyadh metro has been obtained from Saudi Electricity Company (SEC) [75].

SEC has provided us with some data of the electrical power system that the traction will be connected to. However, the electric traction system data has not provided. Thus, the proposed electric traction model that has been developed in chapter three will be used.

Riyadh metro will be tested with load condition which is the worst case. A corrective action will be suggested to improve the power quality of the systems if required.

6.1.1 Riyadh Model Descriptions

Figure 6.1 shows a block diagram of Riyadh metro system. It describes the power system that feed the metro system.

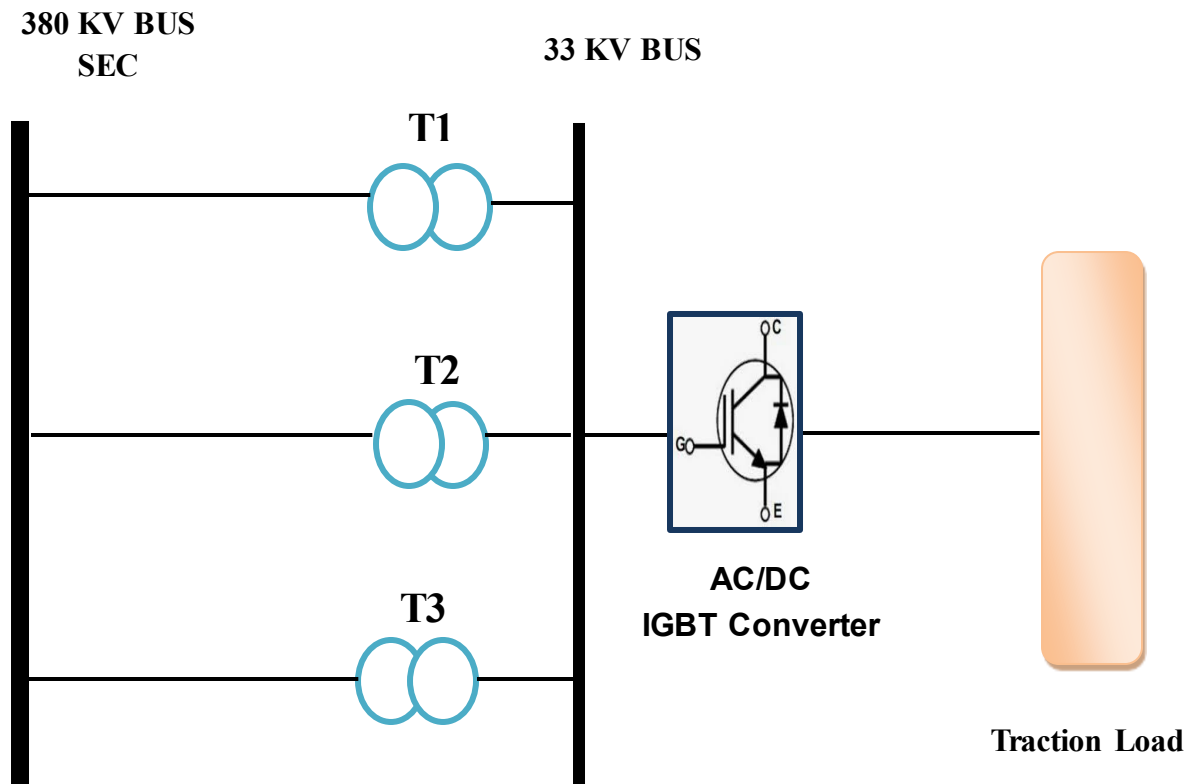


Figure 6.1 Block diagram of Riyadh metro system connected to a utility grid

The BLDC motors specification are shown in Table 6.1 below

Table 6.1. Ratings of Riyadh metro components

Component	Rated voltage (KV)	Q (MVAR)	S (MVA)	P (MW)	Current (A)
Transformer (1)	380/33	-	100	-	-
Transformer (2)					
Transformer (3)					
IGBT based Rectifier system	11	-	-	-	6550
BLDC motor	11	-	-	72	-

Riyadh metro is fed from 380 KV bus system through three feeders. Three special transformers will be used to step down the voltage from 380 KV to 33 KV. The rating of these transformer is 100 MVA for each one.

The short circuit data that provided is used to determine the allowed limits of total and individual harmonic distortions according to the IEEE standard 519 in Tables (A.1 to A.4) in the Appendix.

Figure 6.2 shows a single line diagram of the power system that supplies Riyadh metro system. The single line diagram has been obtained from SEC [75].

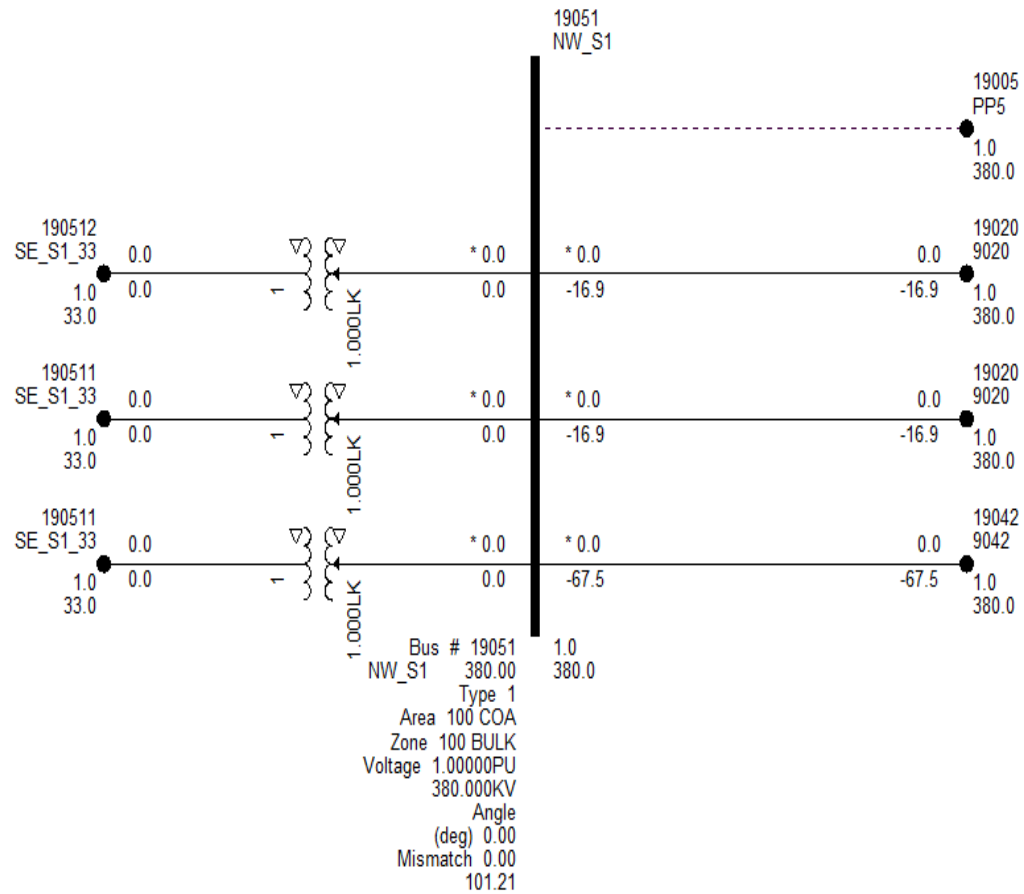


Figure 6.2. Single line diagram of Riyadh metro connected to the utility grid obtained from SEC [75]

Table 6.2 shows the data of 380 KV bus and 33 KV bus that have obtained from SEC [75].

Table 6.2. Riyadh metro power supply system data

Bus No	Bus Name	Voltage (kV)	3 phase SC		1 phase SC	
			(kA)	X/R	(kA)	X/R
9051	Metro - 380	380	43.6	23.9	42.9	12.9
90511	Metro - 33	33	20.7	54	20.7	49.8

Riyadh metro has been operating with heavy load to assess its impact on the utility side in the worst case. The total current load has been measured at 380 KV side, it was about 456 A.

Based on Table 6.2 and by using equation (4.1), IEEE standard distortion limits can be determined. Table 6.3 shows the IEEE distortion limits according to the load current.

Table 6.3. Short circuit data and the distortion limits for Riyadh metro system according to the IEEE 519

Voltage Level	$I_{s/c}$ KA)	I_L(A)	$I_{s/c}/I_L$	IEEE limit
380 KV	43.6	456	95	3.75%
33 KV	20.7	5250	3.96	5.0%

6.1.2 Simulation Results

The model of the power system is simulated in MATLAB/Simulink. Electric traction system that has already been developed in Chapter three is connected to this power system. The traction is operating with heavy load. Voltage and current waves are measured at 380 KV and 33 KV side and thereby subjected for FFT analysis to evaluate the impact of this train on the utility network that might be occur.

To study the impact of the traction system on the power system, simulation is divided in to three modes, acceleration mode, cruising mode and deceleration mode.

Figure 6.3 shows the traction speed over the three modes. In the first 2 minutes, the traction accelerates up to reach 80 km/h. Then, it moves with this speed for 6 minutes and in the last 2 minutes, it decelerates up to stop totally.

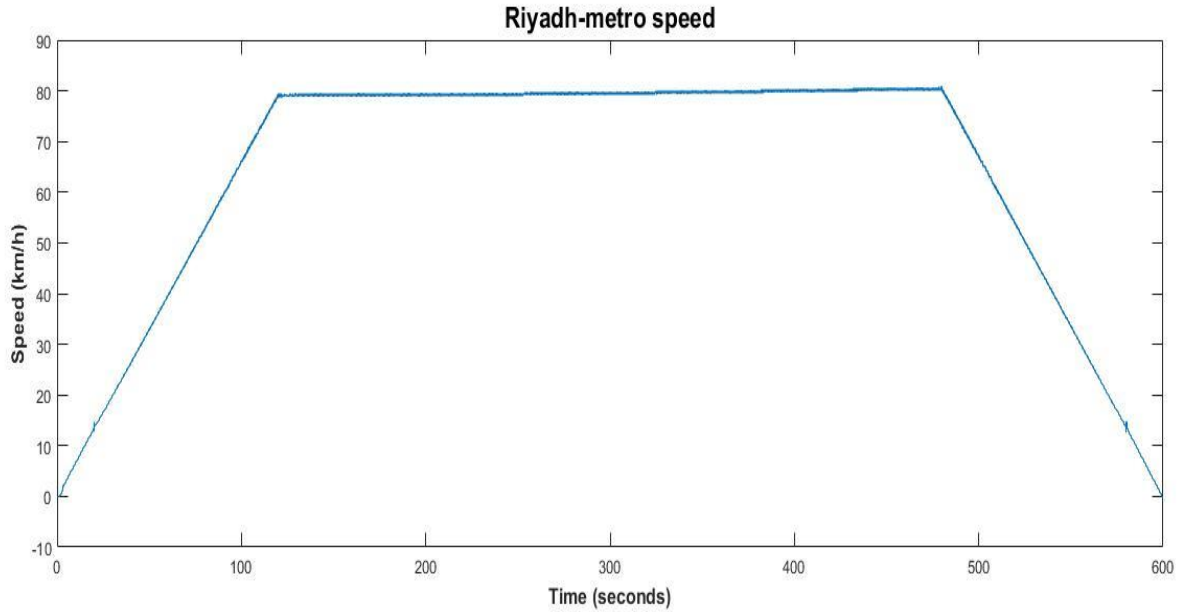


Figure 6.3. Electric traction speed in Km/h versus the time in seconds

In chapter five, the corrective action that has been taken presented a good result by suppressing the harmonic and improving negative sequence, which is verified by simulation. For Riyadh metro, same corrective action will be considered if there is a high distortion of harmonics or when the THD exceeded the maximum limits of the distortion according to IEEE standard. Tables (A.1 to A.4) in the Appendix.

Figure 6.4 shows a snap shot of the current wave at 380 KV side when the traction in the acceleration mode.

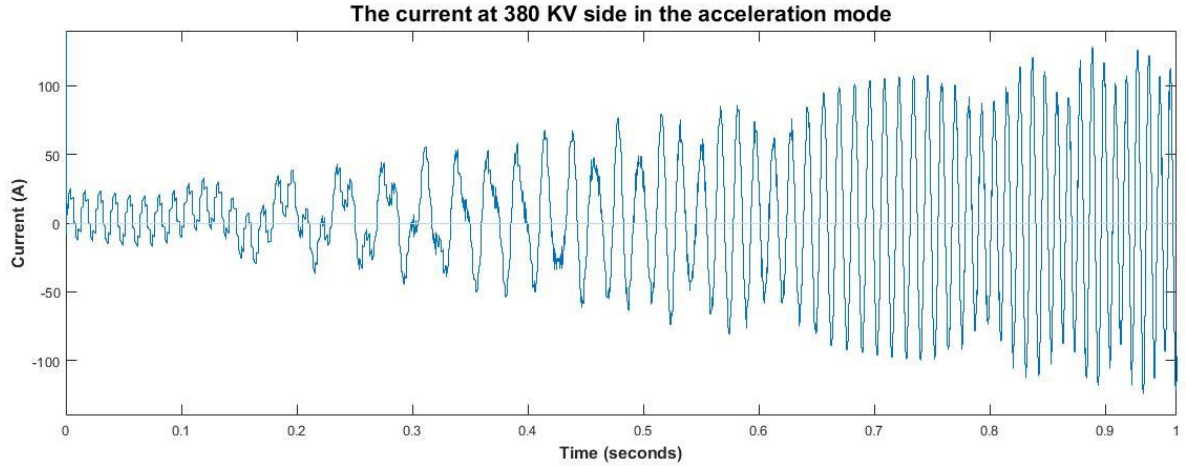


Figure 6.4. Small section of the current wave at 380 KV side in the acceleration mode

This waveform is subjected for FFT analysis. The harmonic spectrum and THD index are shown in Figure 6.5.

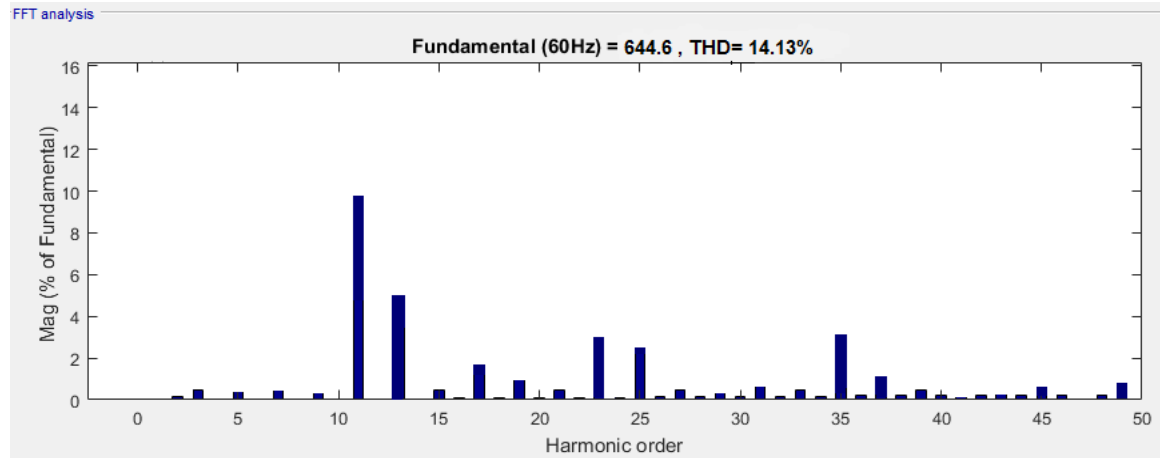


Figure 6.5. Harmonic spectrum and THD index of the current wave at 380 KV side in the acceleration mode

$$\text{THD} = 14.13\%$$

From Figure 6.5, the THD is 14.13% which is much higher than the IEEE standard limit.

Therefore, a corrective action is needed to reduce the THD for minimum value.

Based on the data that obtained from SEC [75], the active filter will be connected at 33 KV side. Therefore, the filter will be connected at 33 KV bus system in this study. This is shown in Figure 6.6, the DC voltage source in this case is 33 KV DC.

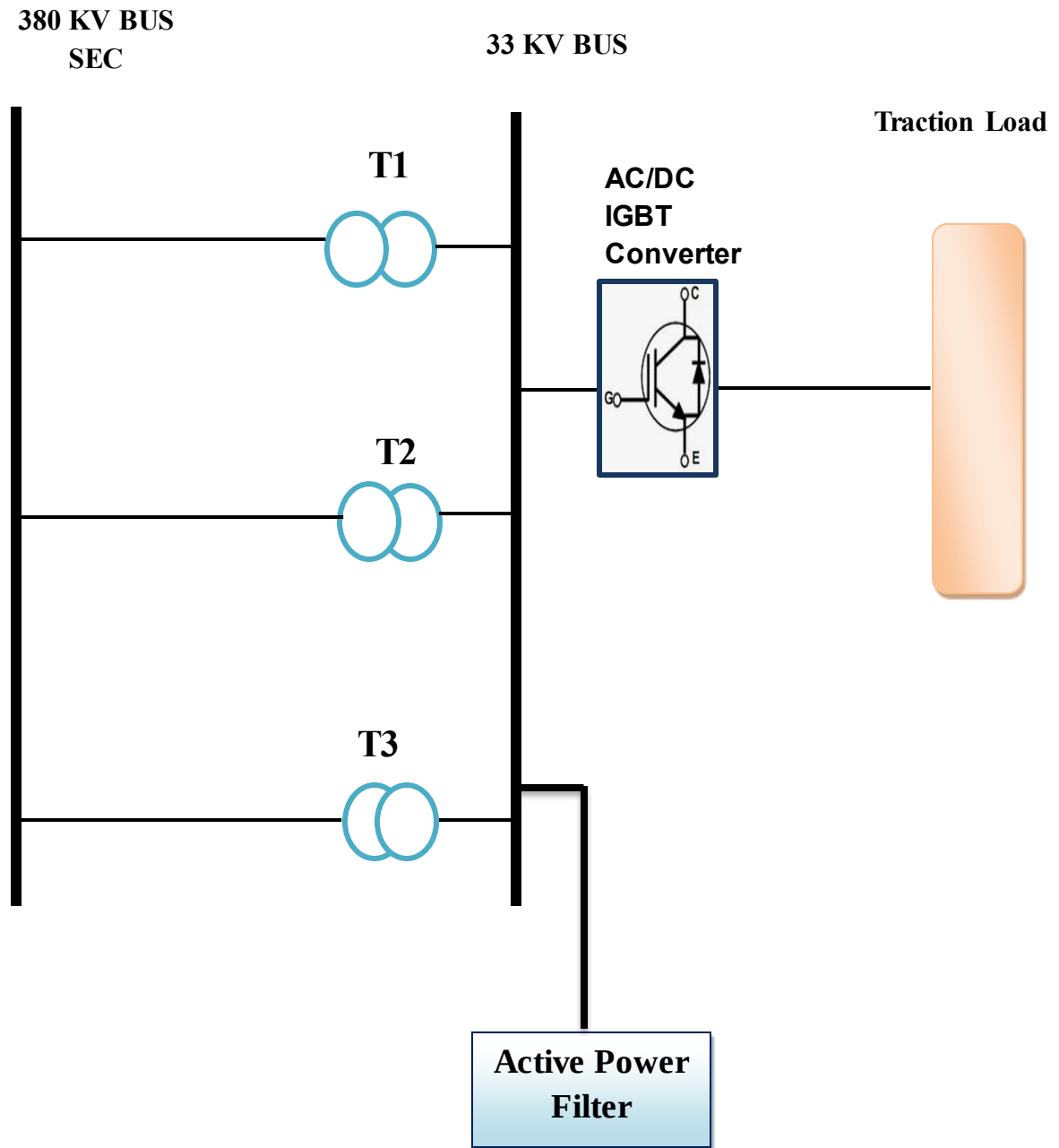


Figure 6.6. Block diagram of Riyadh metro when the active filter is connected at 33 KV side

The ratings of the active filter components are shown in Table 6.4 below.

Table 6.4. The ratings of the active filter components

Component	Voltage (KV)	P (MW)	Current (A)
Voltage source	35 KV	60	-
Inverter	35 (DC) / 33 (AC)	-	1700 (DC)

After connecting the filter at 33 KV bus, the total harmonic distortion decreased significantly from 14.13% to 2.98% only. This is shown in Figure 6.7.

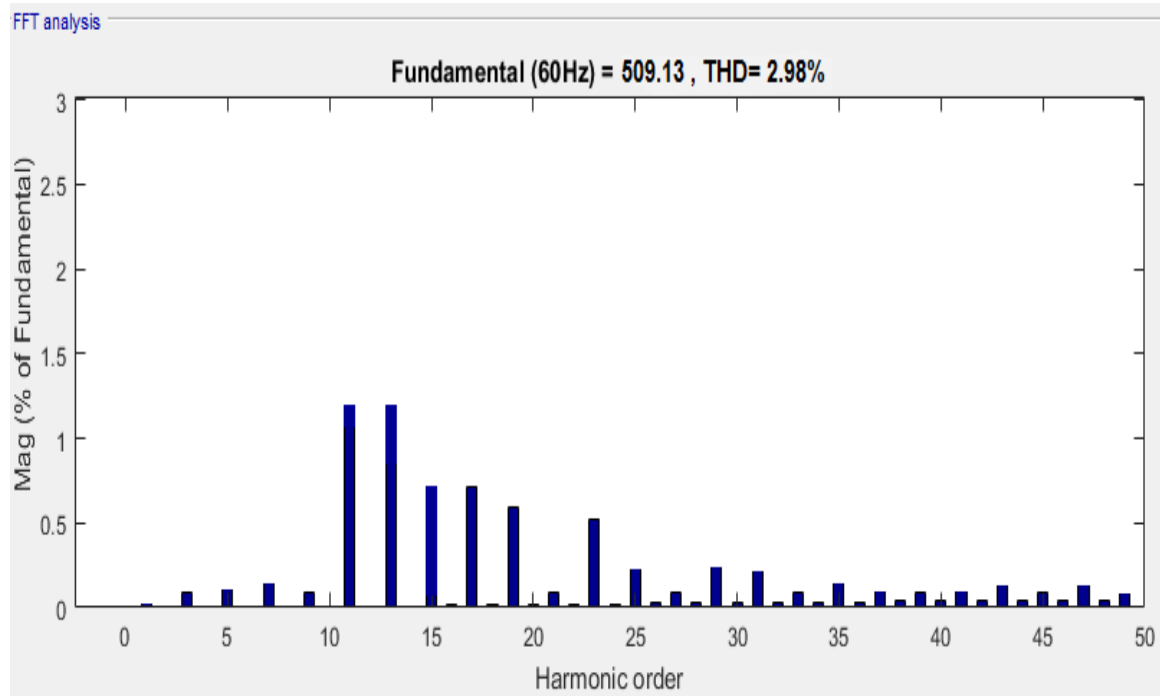


Figure 6.7. Harmonic spectrum and THD index of the current wave at 380 KV side in the acceleration mode after connecting the active filter

$$\text{THD} = 2.98\%$$

When the traction reaches its maximum speed, it starts moving with invariable speed, this takes 2 minutes.

Figure 6.8 shows a small section of the current wave at 380 KV side for the invariable speed mode.

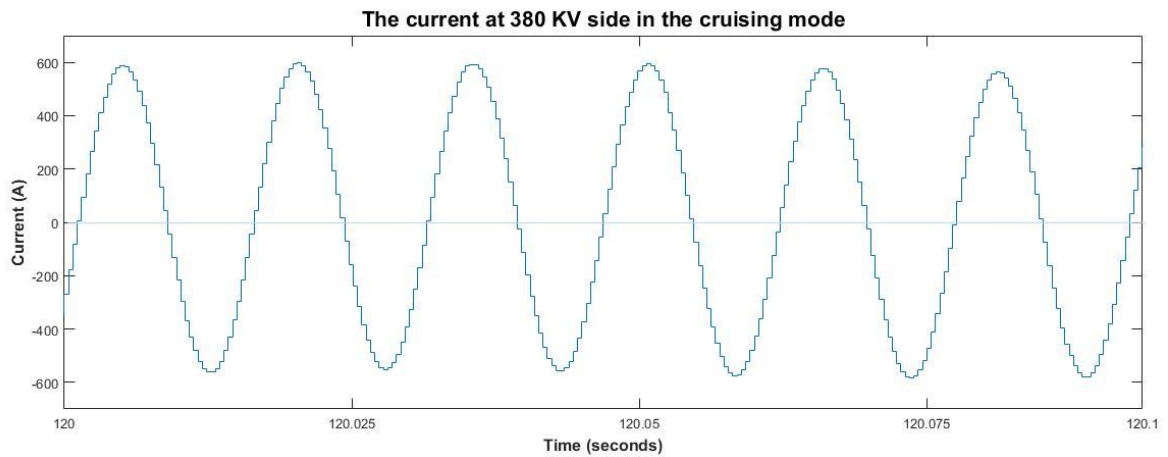


Figure 6.8. The voltage wave at 380KV side in the cruising mode

The harmonic spectrum and THD index for this wave is shown in Figure 6.9

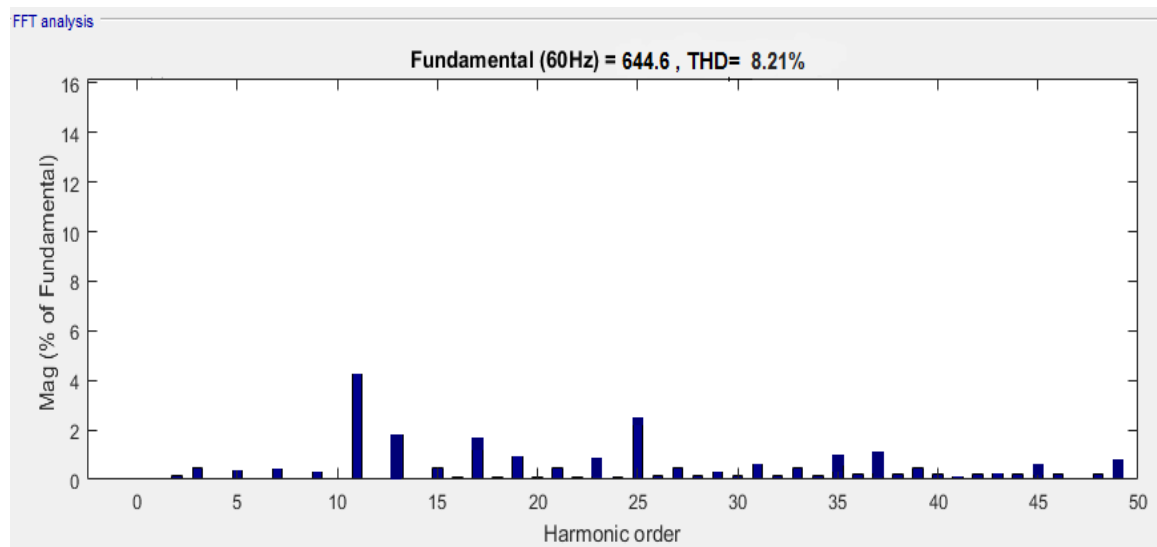


Figure 6.9. Harmonic spectrum and THD index of the current wave at 380KV side in the cruising mode

$$\text{THD} = 8.21\%$$

After connecting the active filter, the THD index has decreased from 8.21% to 1.65 % as shown in Figure 6.10.

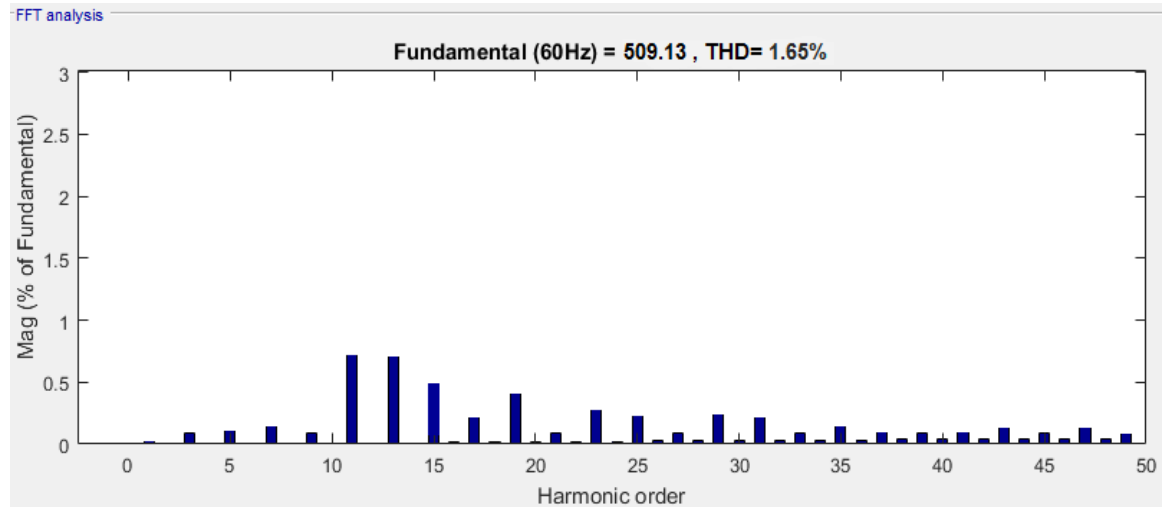


Figure 6.10. Harmonic spectrum and THD index of the voltage wave at 380KV side in the cruising mode after connecting the active filter

$$\text{THD} = 1.65\%$$

The last stage of the travelling is the deceleration mode. In this stage, the traction decelerates its speed till reaches zero speed. Figure 6.11 shows a snap shot of the current wave in the deceleration mode.

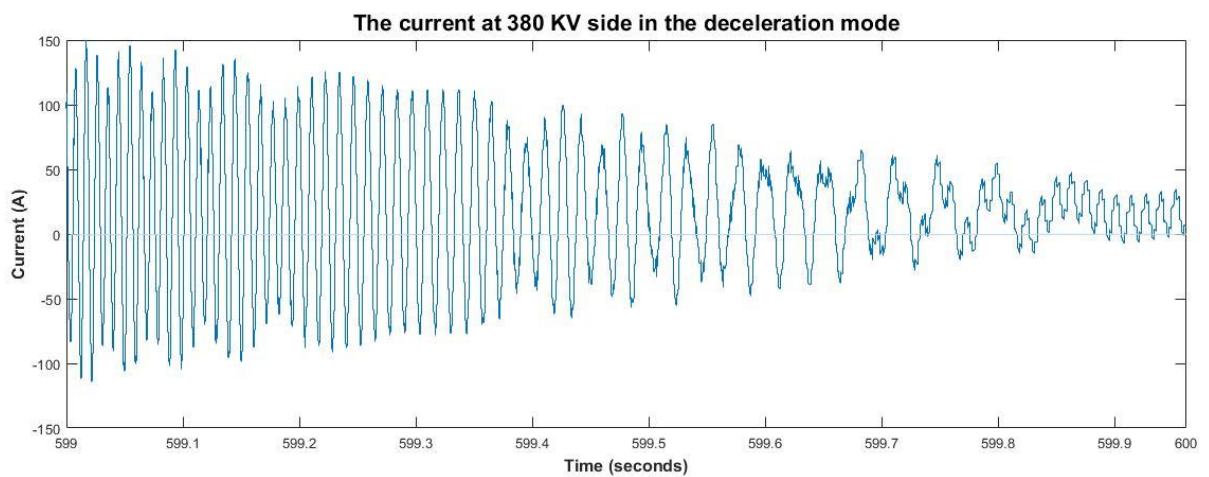


Figure 6.11. The current wave at 380 KV side in the deceleration mode

The current wave is highly distorted. The THD index is 16.13% as shown in Figure 6.12.

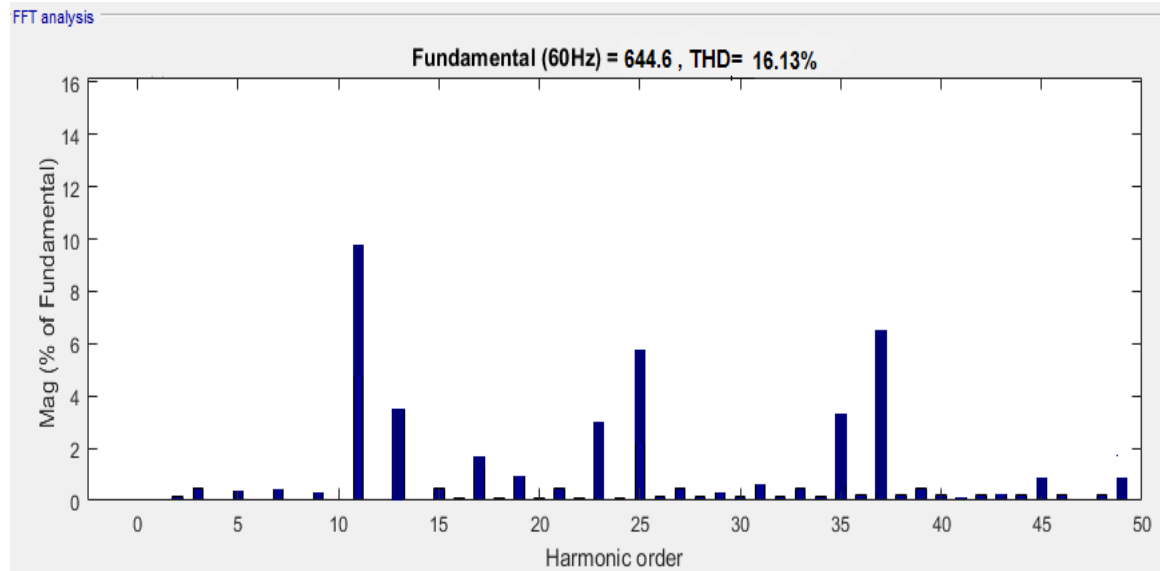


Figure 6.12. Harmonic spectrum and THD index of the current wave at 380KV side in the decelerating mode

$$\text{THD} = 16.13\%$$

After connecting the active filter, the THD has decreased below the IEEE standard distortion limits from 16.13% to 3.14% only, as shown in Figure 6.13.

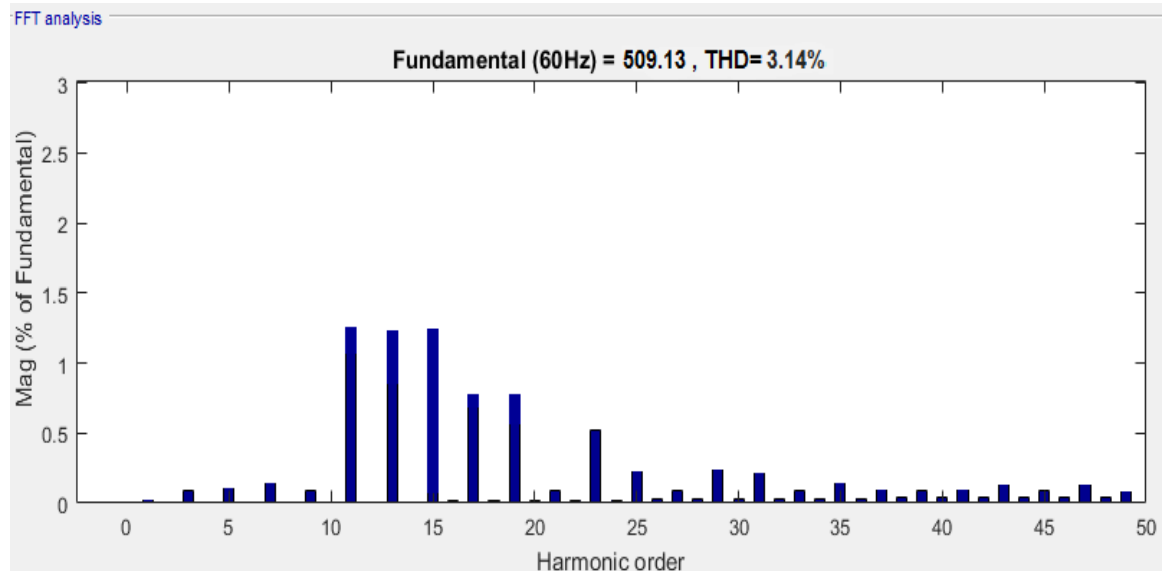


Figure 6.13. Harmonic spectrum and THD index of the current wave at 380KV side in the deceleration mode after connecting the active filter

$$\text{THD} = 3.14\%$$

Figure 6.14 shows a snap shot of the voltage wave at 380 KV side

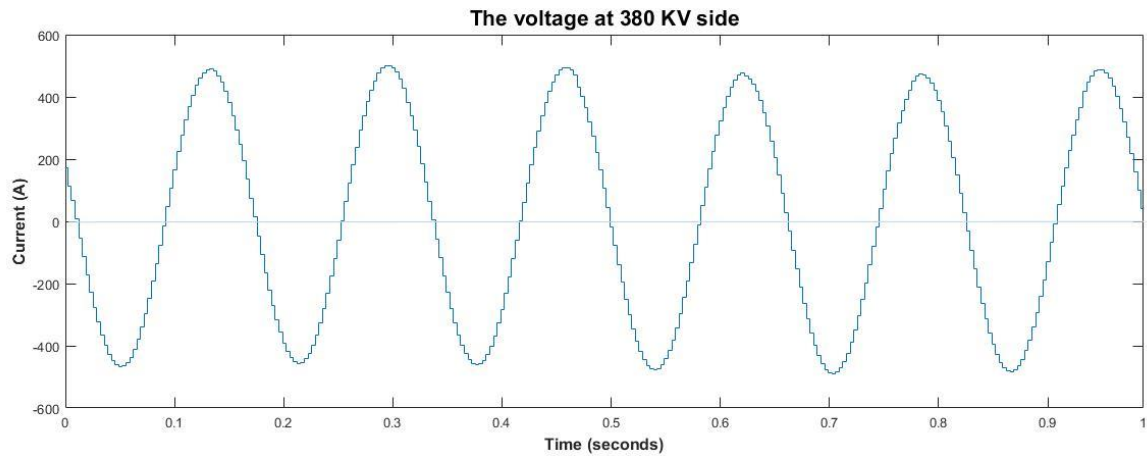


Figure 6.14. The voltage wave at 380 KV side

Figures 6.15, 6.16 and 6.17 show the harmonic spectrum and the THD index of the voltage wave at 380 KV side when the traction is operating in the accelerating mode, cruising mode and deceleration mode respectively.

The highest value of the THD in the voltage wave has occurred when the traction operates in the deceleration mode and acceleration mode respectively. Whereas during the cruising mode a few harmonics are generated and injected to the system.

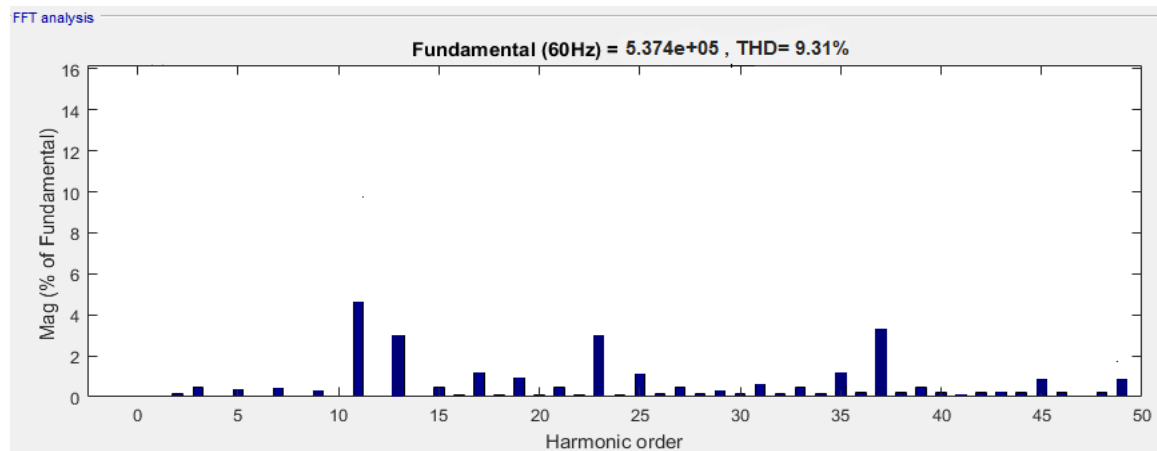


Figure 6.15. Harmonic spectrum and THD index of the voltage wave at 380 KV side in the acceleration mode

$$\text{THD} = 9.31\%$$

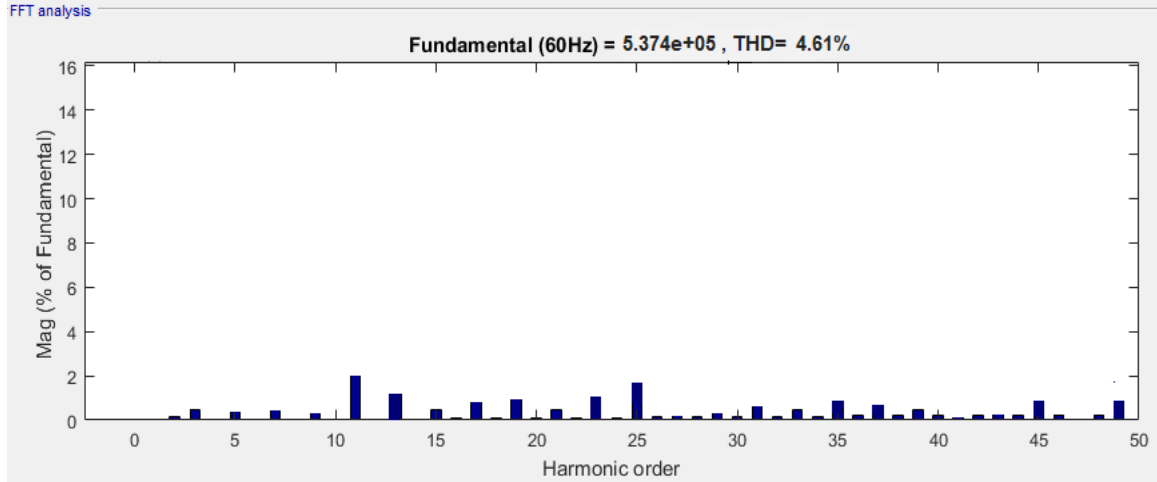


Figure 6.16. Harmonic spectrum and THD index of the voltage wave at 380KV side in the cruising mode

$$\text{THD} = 4.61\%$$

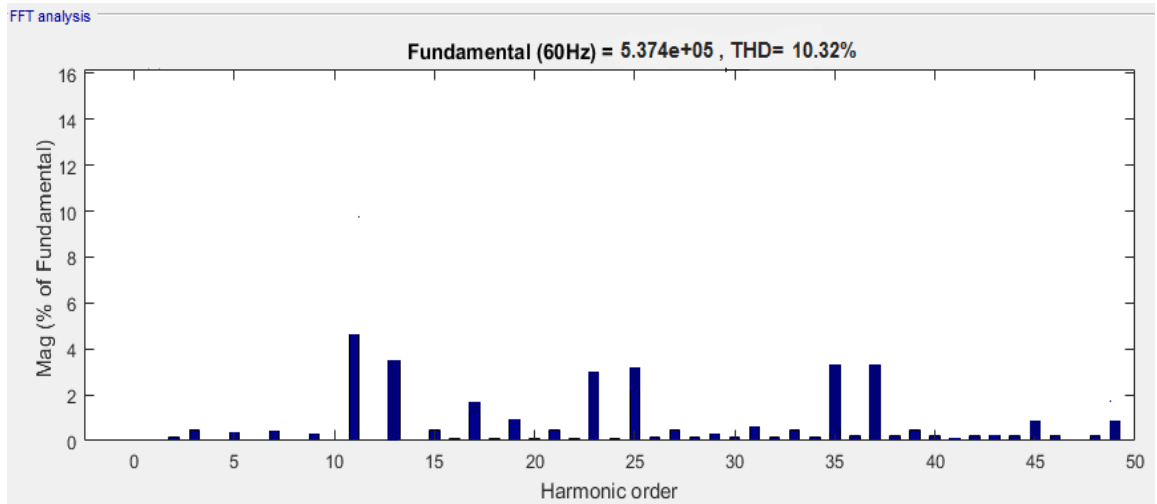


Figure 6.17. Harmonic spectrum and THD index of the voltage wave at 380KV side in the deceleration mode

$$\text{THD} = 10.32\%$$

In order to suppress the undesirable harmonic from the power system. The active filter is connected at 1.06 KV side. The Harmonic spectrum and the THD index in the voltage wave in the acceleration, cruising and the deceleration mode are shown in Figures 6.18, 6.19 and 6.20 respectively.

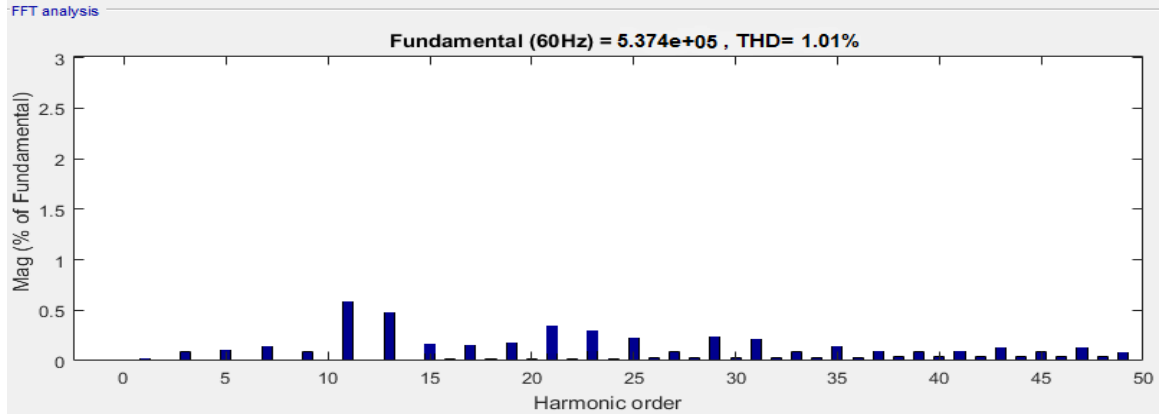


Figure 6.18. Harmonic spectrum and THD index of the voltage wave at 380KV side in the acceleration mode after connecting the active filter
 THD = 1.01%

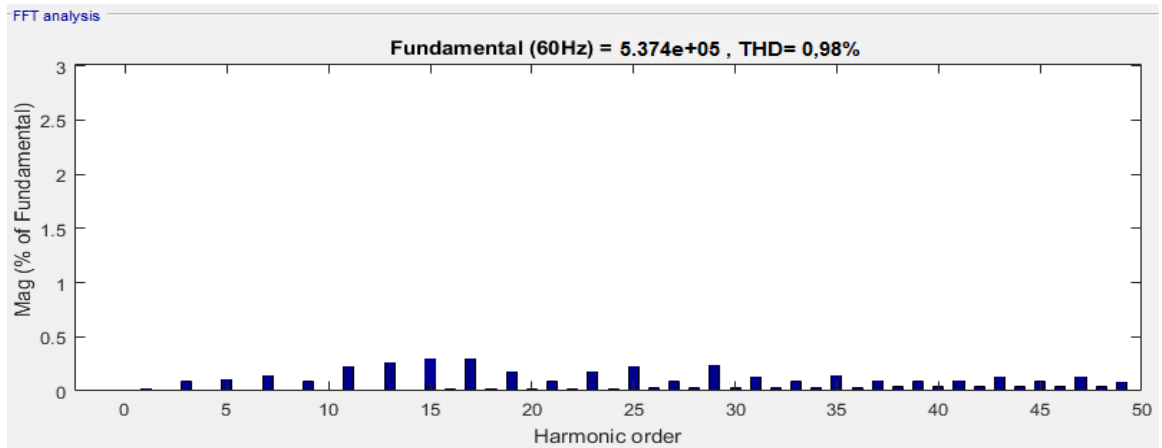


Figure 6.19. Harmonic spectrum and THD index of the voltage wave at 380KV side in the cruising mode after connecting the active filter
 THD = 0.98%

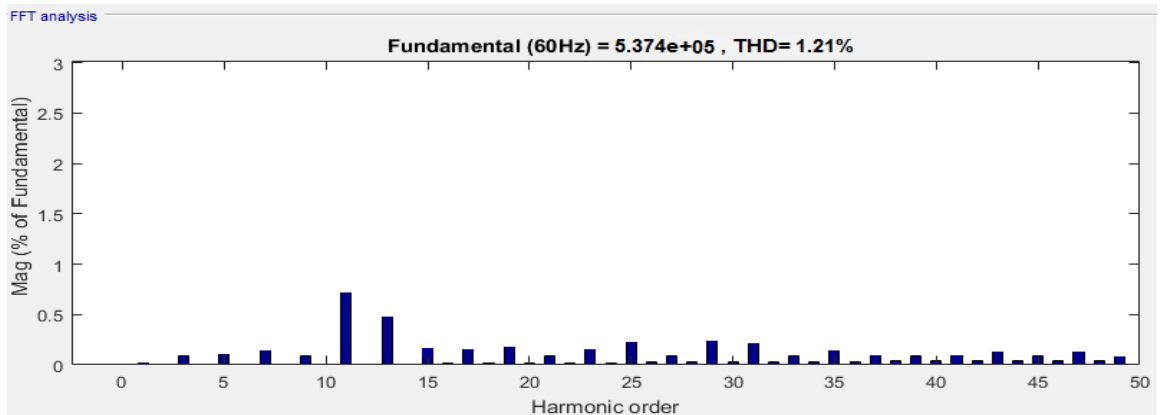


Figure 6.20. Harmonic spectrum and THD index of the voltage wave at 380KV side in the deceleration mode after connecting the active filter
 THD = 1.21%

After analyzing the current and voltage waves at 380 KV side in the three different operating modes. FFT analysis has been applied to study the impact of traction system on other buses.

Figure 6.21 shows the harmonic spectrum and THD index of the current waves at 380 KV side along the full period of the traction journey.

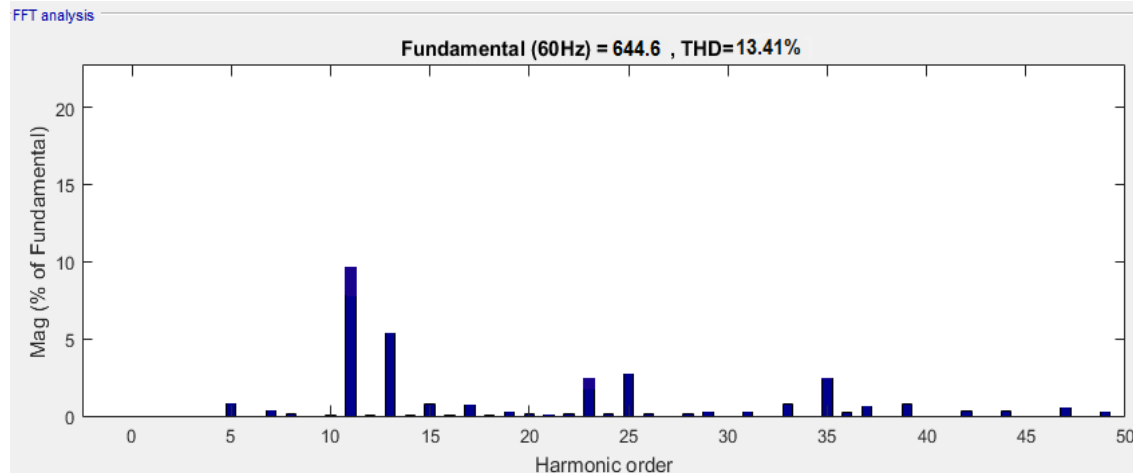


Figure 6.21. Harmonic spectrum and the THD index of the current wave at 380 KV side along the full period
THD = 13.41%

After connecting the filter, the THD index has decreased from 13.41% to 2.43% only which is below the IEEE standards distortion limit. This is shown in Figure 6.22.

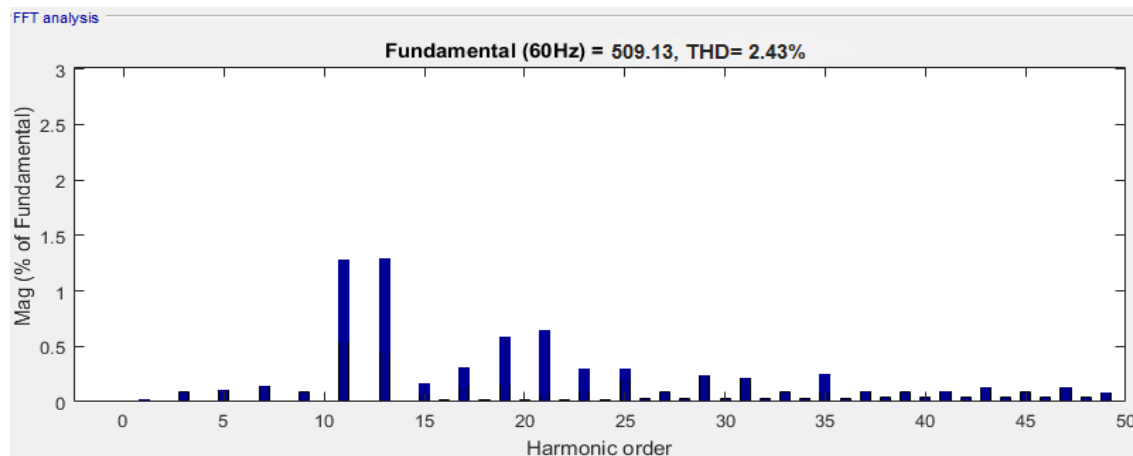


Figure 6.22. Harmonic spectrum and the THD index of the current wave at 380 KV side along the full period
after connecting the Filter

$$\text{THD} = 2.43\%$$

Since the traction is connected at 33 KV side, high amount of harmonic has injected in to voltage wave at this side, this is very clear in Figure 6.23. The THD has reached 29.64% which is much higher than the allowed value according to the IEEE standard limits.

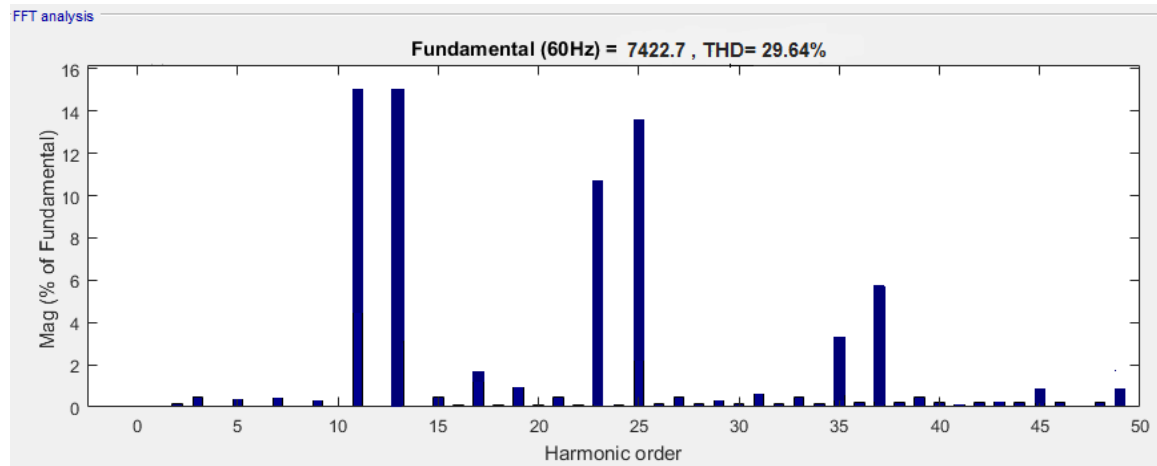


Figure 6.23. Harmonic spectrum and the THD index of the current wave at 33 KV side along the full period

$$\text{THD} = 29.64\%$$

The 11th, 13th and 25th harmonics are the dominant harmonics in the current wave at 33 KV side. After connecting the filter, the THD has decreased significantly from 29.64% to 3.12% as shown in Figure 6.24.

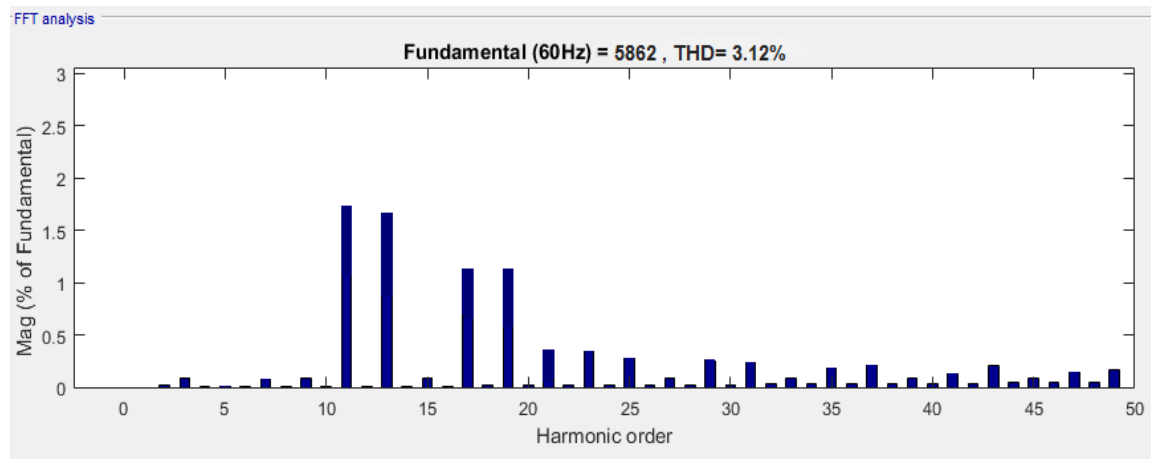


Figure 6.24. Harmonic spectrum and the THD index of the current wave at 33 KV side along the full period after connecting the filter

$$\text{THD} = 3.12\%$$

The voltage waves have been subjected for the same analysis that has been applied on the current waves.

Figures 6.25 and 6.26 show the harmonic spectrum and THD index in the voltage wave at 380 KV and 33 KV sides respectively along the full period.

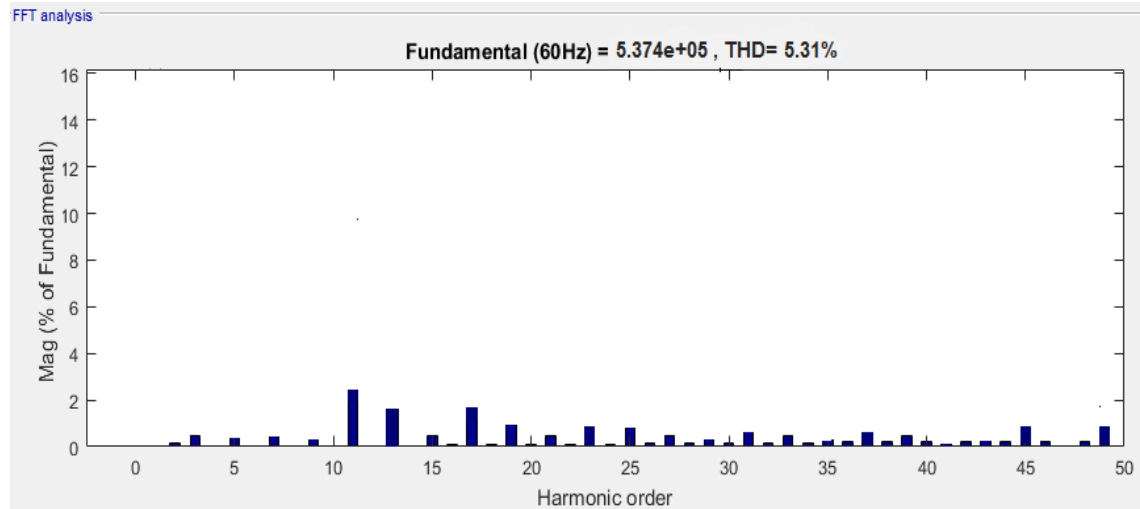


Figure 6.25. Harmonic spectrum and THD index of the voltage wave at 380 KV side along the full period

$$\text{THD} = 5.31\%$$

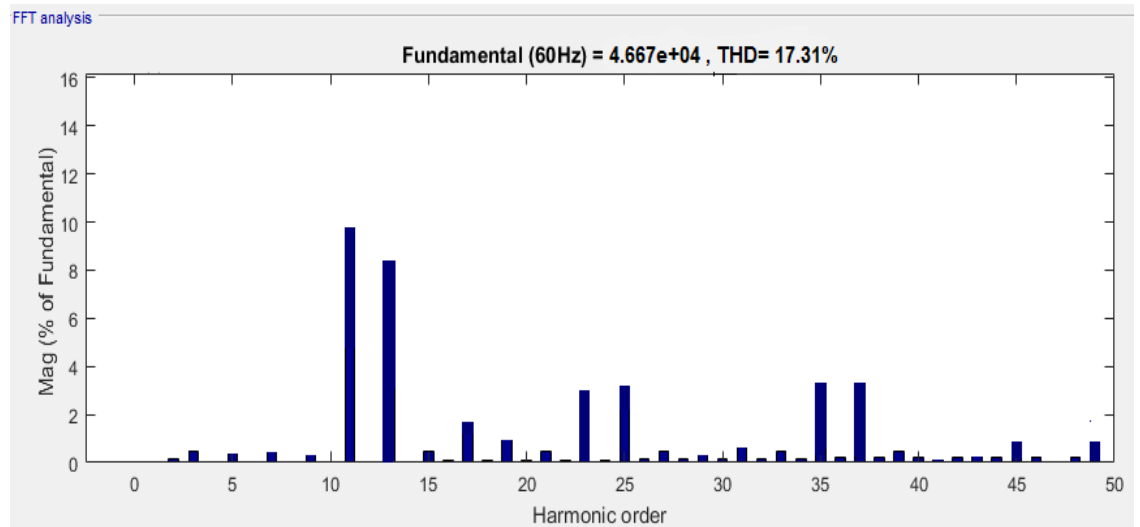


Figure 6.26. Harmonic spectrum and THD index of the voltage wave at 33 KV side along the full period

$$\text{THD} = 17.31\%$$

It is clear that, the individual and total harmonic distortions have exceeded the IEEE standard limit. Therefore, after connecting the active filter, the harmonic spectrum of the voltage waves at 380 KV side and 33 KV side are shown in Figures 6.27 and 6.28 respectively.

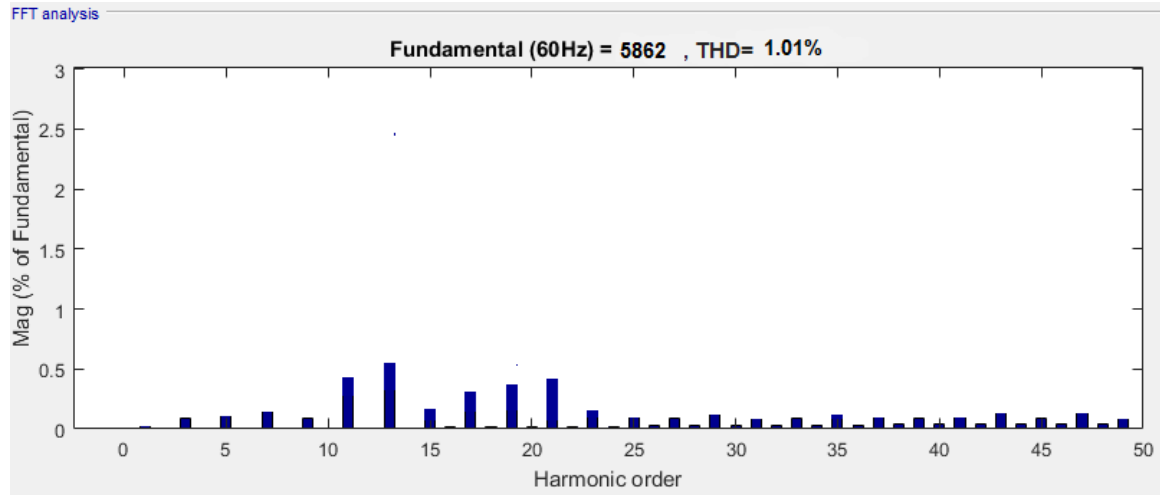


Figure 6.27. Harmonic spectrum and THD index of the voltage wave at 380 KV side along the full period after connecting the active filter

$$\text{THD} = 1.01\%$$

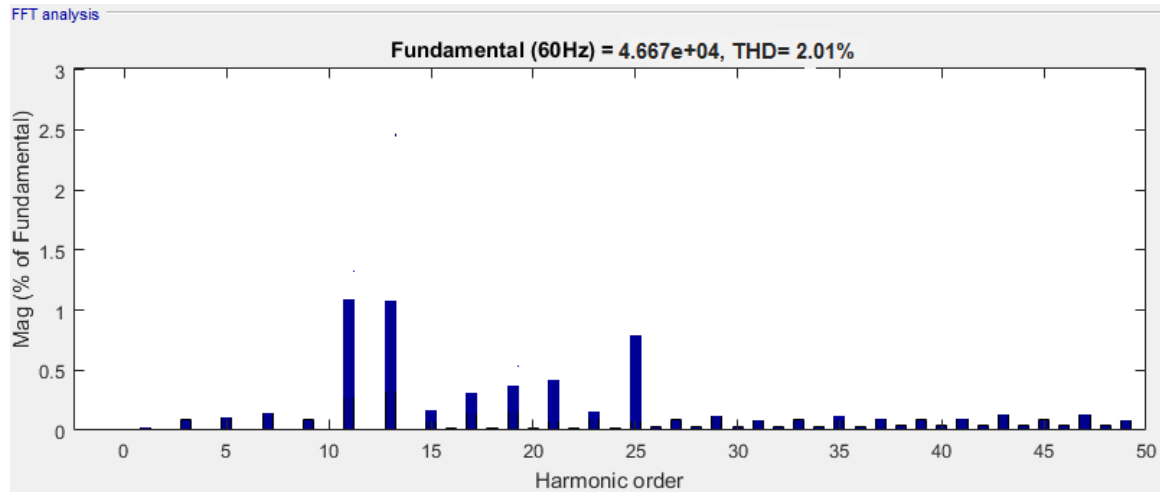


Figure 6.28. Harmonic spectrum and THD index of the voltage wave at 33 KV side along the full period after connecting the active filter

$$\text{THD} = 2.01\%$$

The THD ratios in the voltage and current waveforms before and after connecting the active filter at 380 KV side are shown in Tables 6.5 and 6.6 respectively.

Table 6.5. THD index in the voltage waves at the different buses when the traction is heavily loaded

Voltage Level (KV)	THD_v(% in the fundamental)		IEEE standard Limits
	Before adding the filter	After adding the filter	
380	5.31	1.01	1.5%
33	17.31	2.01	5.0%

Table 6.6. THD index in the current waves at the different buses when the traction is heavily loaded

Voltage Level (KV)	THD_i(% in the fundamental)		IEEE standard Limits
	Before adding the filter	After adding the filter	
380	13.41	2.43	3.75%
33	29.64	3.12	5.0%

The THD at 380 KV side in the acceleration mode, cruising mode and the deceleration mode before and after connecting the active filter is shown in Table 6.7.

Table 6.7. THD index in the voltage waves at the PCC (380 KV side) in the three dynamic modes of the train with heavy load

Dynamic mode	THD_v(% in the fundamental)		THD_i(% in the fundamental)	
	Before adding the filter	After adding the filter	Before adding the filter	After adding the filter
Acceleration	9.31	0.92	14.13	2.98
Cruising	4.61	0.89	8.21	1.65
Deceleration	10.32	1.21	16.13	3.14
IEEE Standard Limits	1.5		3.75	

From Tables 6.5, 6.6 and 6.7. It is very clear that the THD has decreased significantly in the voltage and current waves at the PCC and at the load side as well. Also, the individual harmonics have reduced below the IEEE standards distortion limits.

Figure 6.29 shows the active power consumption before and after connecting the active filter at the PCC.

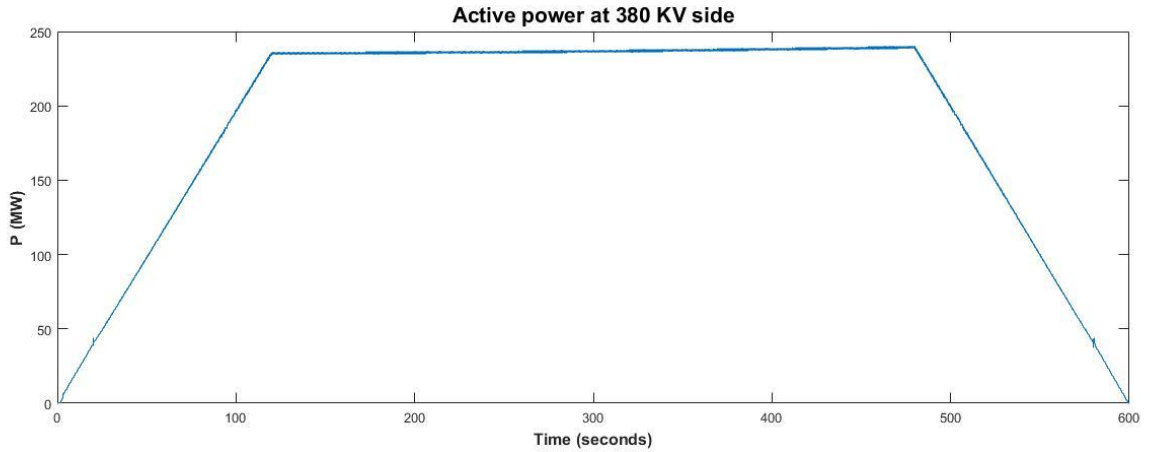


Figure 6.29. Active power consumed by the traction before and after connecting the active filter at the PCC

The total current absorbed from the utility side has decreased by 30%. The active power remains constant without change after connecting the APF, this means the power factor has improved from 0.75 to be 0.95. Thus, the reactive power consumption has reduced accordingly. This is shown in Figures 6.29 and 6.30 respectively.

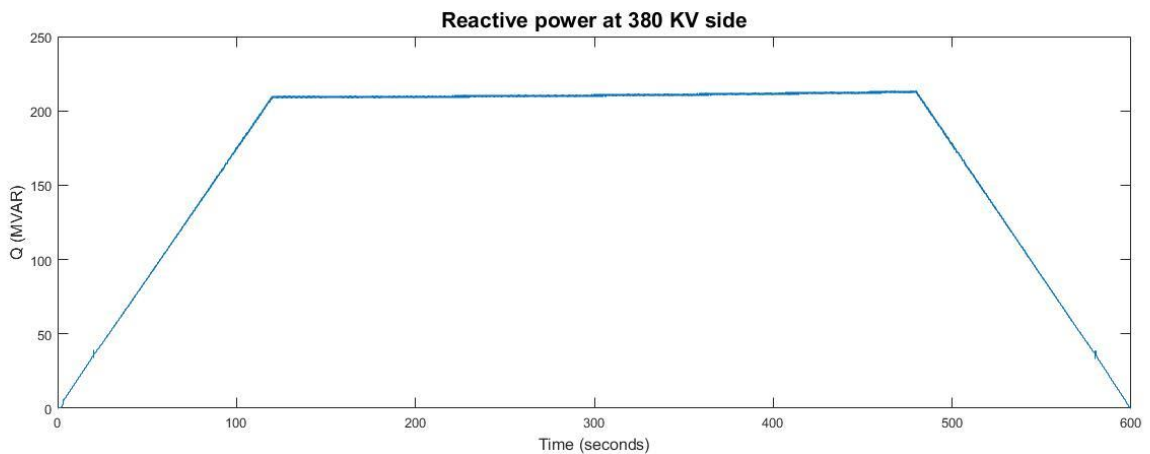


Figure 6.30. Reactive power consumed by the traction before connecting the active filter

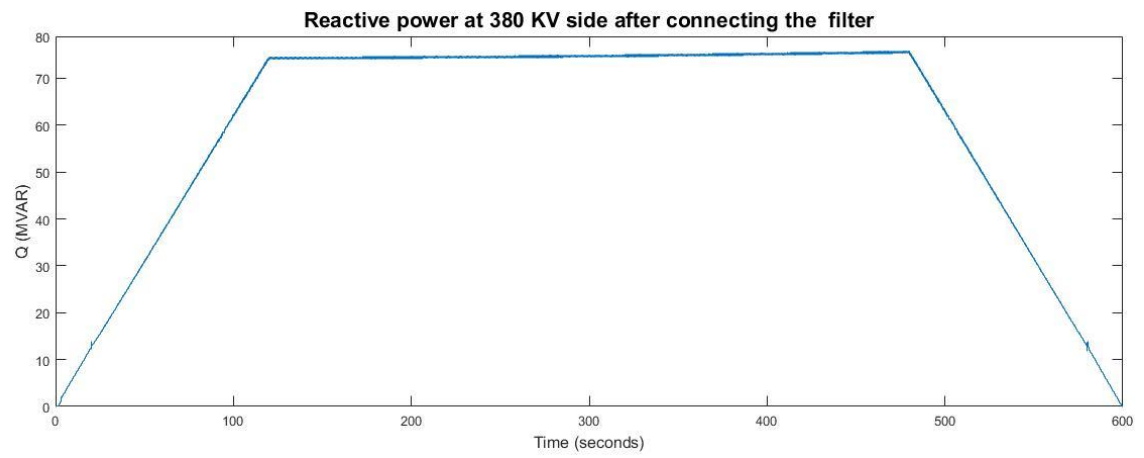


Figure 6.31. Reactive power at 380 KV side after connecting the active filter

CHAPTER 7

CONCLUSION

7.1 Conclusion

A dynamic load of an electric traction has developed in MATLAB/Simulink software. This model includes all components and control accessories. The three different dynamic modes which are, acceleration mode, cruising mode and the deceleration mode have been considered in the proposed model to simulate the behavior of the traction system in the real life.

The developed model of the traction system is built by using a brushless DC motors (BLDC) which have become the most suitable due to its a valuable advantage over the conventional DC motors.

The developed model of the traction is connected to a power system to study the impact of such kind of tractions on the utility grids. The traction is tested under two different loading conditions. Firstly, the electric traction has been operating while carrying a large number of passengers which is the case of heavy load. Then, a light load case was analyzed which is the case of carrying few passengers.

The study shows that; the loading slightly affects on the impact of the traction on the power system. However, in the heavy load case, a higher current will be absorbed from the utility grid which is the normal condition.

FFT analysis has used to analyze voltage and current waves at different buses in the system. It has been found that, the current and voltage waves at the traction side are highly affected compared to the voltage and current waves at the PCC. It has been found that, Electric railway load identified by its nonlinear and impact, the grid has serious power quality impact, as negative sequence and harmonic. The total harmonic distortion (THD) has the highest value at 1.06 KV side which is the nearest point to the traction load whereas, it was relatively low at the PCC.

Also, voltage and current waves have been analyzed in the acceleration mode, cruising mode and deceleration mode separately. It has been found that, large amount of harmonics is injected in to the PCC when the traction was operating in the acceleration and deceleration mode. However, THD was very low when the traction moves with invariable speed. Thus the minimum ratio of the THD occurred during the cruising mode.

To enhance the power system quality, an active filter has been designed and integrated with the system.

The active filter has been controlled by using PI controller. The output current of the filter is determined according to the output signal from a PWM. A negative feedback technique has been used to control the active power filter operation.

When the filter was connected at the traction side, it reduced the individual and total harmonic distortion (THD) significantly at the traction side. But, some of the individual harmonics at the PCC have exceeded the IEEE standard limits. Then, the filter has connected at 1.06 KV side, the individual and total harmonic distortion (THD) are decreased significantly below the IEEE standard 519 distortion limits.

Also, when the filter connected at 110 KV side, which is the PCC, it has been observed that, the individual and the total harmonic distortion at the PCC and at the other buses has reduced significantly below the maximum IEEE standard limits. However, the filter in this case must have high power rating. Thus, the optimal position of the filter is to be connected at the load side.

A real case of Riyadh metro system has considered to validate the proposed model. The traction was assumed to be working with a heavy load. The output results for Riyadh metro system were having the same behavior of the previous case when the traction was tested under heavy load.

The active filter has been connected to Riyadh metro system at 33 KV side which is representing the load side. The active filter has absorbed the undesirable harmonics and therefore, individual and total harmonic distortions have been suppressed and reduced significantly.

7.2 Future Work

- The proposed model of the traction system can be tested in real time based software to have more realistic results.
- Study the impact of the electric traction system on the power system stability.
- Study the case of supplying the traction system from a renewable energy source and then, evaluate the performance of this integration.
- Study the impact of tractions that work with AC motors on power system.

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APPENDIX

Table 1 shows the IEEE standard limits of the individual and total harmonic distortion in the voltage (V) according to the voltage level at the PCC.

Table 1
IEEE 519 Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage distortion	Total Voltage Distortion
$\leq 69\text{KV}$	3.0%	5%
69 to 161KV	1.5%	2.5%
$\geq 161\text{KV}$	1.0%	1.5%

Tables A.2 to A.4 show the IEEE standard limits of the individual and total harmonic distortion in the current (I) according to the ratio between the short circuit current and the load current at the PCC.

Table A.2
IEEE Standard 519 Current Distortion Limits (in % of IL) for 120V to 69,000V

ISC / IL at PCC	<11	11<h<17	17<h<23	23<h<35	35>h	TDD
<20	4.0%	2.0%	1.5%	0.6%	0.3%	5.0%
20 to 50	7.0%	3.5%	2.5%	1.0%	0.5%	8.0%
50 to 100	10%	4.5%	4.0%	1.5%	0.7%	12.0%
100 to 1000	12%	5.5%	5.0%	2.0%	1.0%	15.0%
>1000	15%	7.0%	6.0%	2.5%	1.4%	20.0%

Table A.3

IEEE Standard 519 Current Distortion Limits (in % of IL) for 69,000V 161000

I_{SC} / I_L at PCC	<11	$11 \leq h \leq 17$	$17 \leq h \leq 23$	$23 \leq h \leq 35$	$35 \geq h$	TDD
<20	2.0%	1.0%	0.75%	0.3%	0.15%	2.5%
20 to 50	3.5%	1.75%	1.25%	0.5%	0.25%	4.0%
50 to 100	5%	2.25%	2.0%	0.75%	0.35%	6.0%
100 to 1000	6%	2.75%	2.5%	1.0%	0.3%	7.5%
>1000	7.5%	3.5%	3.0%	1.25%	0.7%	10.0%

Table A.4

IEEE Standard 519 Current Distortion Limits (in % of IL) > 161000

I_{SC} / I_L at PCC	<11	$11 \leq h \leq 17$	$17 \leq h \leq 23$	$23 \leq h \leq 35$	$35 \geq h$	TDD
<50	2.0%	1.0%	0.17%	0.3%	0.15%	2.5%
≥ 50	3.0%	1.5%	1.15%	0.45%	0.22%	3.75%

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