Harmonics mitigation by advanced control module in an electrical grid with multiple electrical vehicle charging stations

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Abstract. As per the development in the transportation in present scenario there is a vast increase of utilization of electrical vehicles and will be increase by 50% in near future. With increase in electrical vehicle utilization the number of charging stations and their ratings are also gradually increasing. With increase in number of electrical vehicle charging stations harmonic contamination in the grid is also increased. These harmonics effects other loads connected to the grid which may damage them. In this project new converter topology KY converter is introduced replacing conventional Buck converter for charging the batteries of the vehicles. The new KY converter is updated with advanced control module for maximum mitigation of harmonics. A comparative harmonic analysis is carried out determining the best converter using MATLAB Simulink software. The THDs of all the voltages and currents from generation to distribution buses are analyzed using FFT analysis tool in 'powergui' block of Simulink module. All the graphs are generated considering time as reference plotted for buck and KY converters.

Keywords: electrical vehicle, KY converter, MATLAB Simulink, THD (total harmonic distortion), FFT (Fast Fourier Transformation), powergui (Power Graphical User Interface).

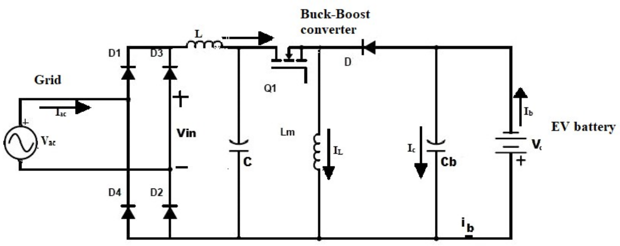
I. INTRODUCTION

As per the high energy usage, environmental pollution and rising fossil fuel prices, current dependence on internal combustion engine (ICE) technology employed in vehicles should be reduced and the widespread use of electric vehicle (EV) as the transportation of choice in 20 to 30 years time should be increased. It is estimated that EV vehicle penetration will increase gradually where 35% is projected at 2020 and will reach 50% by the year of 2024 [1-2]. The general effect on distribution systems caused by the spread of EV will be substantial load increase and large increment of system voltage and harmonic distortion. Another issue that should be considered is the coincidence between the charging start time and the eventual evening load peak period, which varies with customer and country.

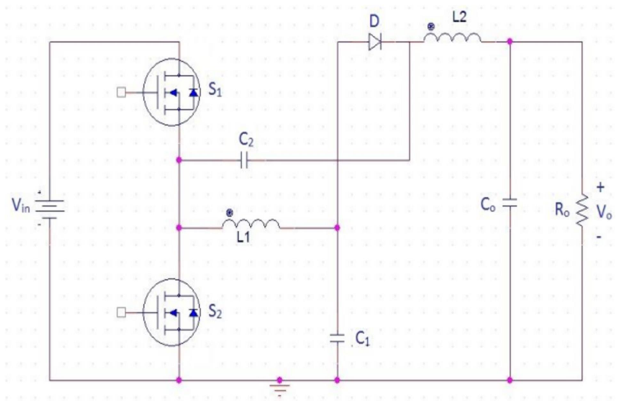
For charging, EV batteries need DC current so the grid AC current will be converted to DC by battery charger. The charger is basically the rectifier/inverter with controller integrated with protection circuit. This is where the concern rises because inverter/rectifier is known asa harmonic source. So one of the concerns with electric vehicle charging is the harmonic contamination to the electrical grid. There is no agreement however on how much the total harmonic distortion (THD) can be released to the network during charging. In one of the published report, total current harmonic distortion (THDi) is reported between 2.36% to 5.26% at the beginning of charging and reaching up to 28% at the end of charging. However total voltage harmonic distortion (THDv) is claimed only to range between 1 and 2% with power factor close to unity. For commercial chargers, THDi from measurement recording values are between 60% to 70% [1,3-4].

The concern of the engineers and researchers are when a large number of EVs charging simultaneously to the power system grid. What is the sum of THD when EV multiplies in numbers? Many believe that THD will increase with the number of vehicles. It is however difficult to find a report that discusses this issue. Moreover the values indicate in the previous paragraph was reported [3-4] more than 10 years ago so the values do not represent the actual amount of harmonic generated from state-of-the-art charger technologies that is used in modern electric vehicles.

The study reported in this paper tries to investigate the harmonic distortion from a single EV and a group of EVs. The measurement was performed on an older type of EV and two modern types of EV. The results of the study are useful in understanding the harmonic distortion contribution from EV connected to the grid for charging.



(a)



(b)

Figure 1: a) Buck Boost converter b) KY converter for EV battery charging

This paper is organized as follow. First EV technology is briefly reviewed. The harmonic distortion limit then highlighted. Harmonic measurement during a single vehicle charging is then presented. Finally the harmonic distortion during charging of a group of EV is discussed and commented.

Electric vehicle that will be seen creating issues on the power system gridwill be of two types. First type is plug in hybrid where there is a combination of ICE and battery. The second type will be all electric vehicle where this vehicle depends solely on battery. For both types of EV, electrical power is needed from the grid for charging.

II. BUCK-BOOST AND KY CONVERTERS CONFIGURATION

A. Buck-Boost Converter

The buck–boost converter is a type of DC-to-DC converter (also known as a chopper) that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is used to “step up” the DC voltage, similar to a transformer for AC circuits. It is equivalent to a flyback converter using a single inductor instead of a transformer. Two different topologies are called buck–boost converter. DC-DC converters are also known as choppers. Here we will have a look at Buck Boost converter which can operate as a DC-DC Step-Down converter or a DC-DC Step-Up converter depending upon the duty cycle, D. The input voltage source is connected to a solid state device. The second switch used is a diode. The diode is connected, in reverse to the direction of power flow from source, to a capacitor and the load and the two are connected in parallel as shown in the figure 1 above.

The controlled switch is turned on and off by using Pulse Width Modulation(PWM). PWM can be time based or frequency based. Frequency based modulation has disadvantages like a wide range of frequencies to achieve the desired control of the switch which in turn will give the desired output voltage.

Time based Modulation is mostly used for DC-DC converters. It is simple to construct and use. The frequency remains constant in this type of PWM modulation. The Buck Boost converter has two modes of operation. The first mode is when the switch is on and conducting.

Mode I : Switch is ON, Diode is OFF

The Switch is ON and therefore represents a short circuit ideally offering zero resistance to the flow of current so when the switch is ON all the current will flow through the switch and the inductor and back to the DC input source.

The inductor stores charge during the time the switch is ON and when the solid state switch is OFF the polarity of the Inductor reverses so that current flows through the load and through the diode and back to the inductor. So the direction of current through the inductor remains the same.

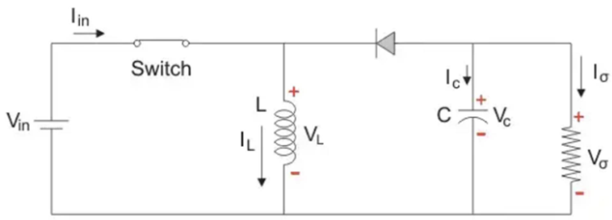


Figure 2: Buck-Boost converter ON state

Mode II : Switch is OFF, Diode is ON

In this mode the polarity of the inductor is reversed and the energy stored in the inductor is released and is ultimately dissipated in the load resistance and this helps to maintain the flow of current in the same direction through the load and also step-up the output voltage as the inductor is now also acting as a source in conjunction with the input source.

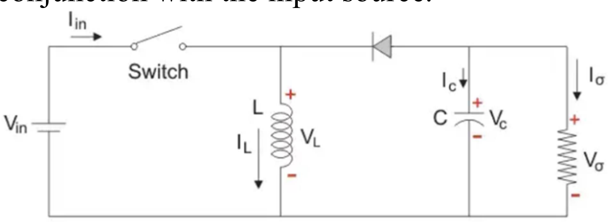


Figure 3: Buck-Boost converter OFF state

B. KY converter

The topology of the KY buck-boost converter [5] is shown in Fig 1. This combines a synchronous buck converter formed by two power switches S1, S2, capacitor C1, inductor L1 and the KY boost converter formed by two power switches S1, S2, power diode D, output inductor L2, capacitor C2 and output capacitor Co with the common output load Ro, respectively. The principle of operation of the converter is explained based on volt-second balance and charge balance of the inductors and capacitors over a switching time period respectively. It is assumed that the components used in the circuits are ideal. There are mainly two operating modes, Mode I (switch S1 is ON and S2 is OFF) and Mode II (switch S1 is OFF and S2 is ON) respectively. The functionality of the circuit under two operating modes is discussed below.

Mode I (S1 ON, S2 OFF):

In this mode the input voltage provides energy for C1 and L1 making C1 getting charged and L1 to be magnetized as shown in equivalent circuit diagram, Fig 4. At the same moment, the input voltage along with capacitor C2 supplies the energy for inductor L2 and to the output which causes C2 to be discharged and L2 getting magnetized [6].

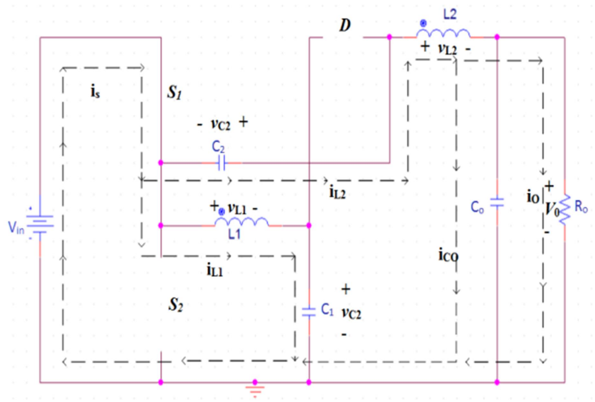


Figure 4: Equivalent Circuit Diagram under Mode I

Mode II (S1 OFF, S2 ON):

The equivalent circuit diagram during this mode of operation is shown in Fig 5. The energy stored in inductor L1 and capacitor C1 are released to capacitor C2 and to the output via inductor L2 causing C1 to be discharged and L1 to be demagnetized [7]. At the same moment, the voltage across L2 is vC2 minus Vo, thus making C2 to be charged and L2 being demagnetized.

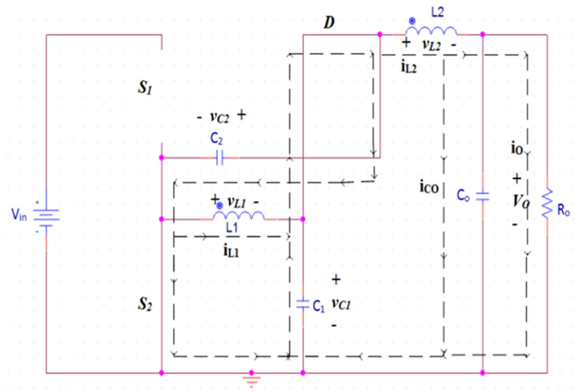


Figure 5: Equivalent Circuit Diagram under Mode II

It can be observed that the converter can generate the output voltage less than input voltage (buck operation) for duty ratio less than 0.5 and produce the output voltage more than input voltage (boost operation) for duty ratio greater than 0.5.

III. EV BATTERY CHARGING CONTROL

In the proposed control structure, the feedback signal that is used as an input for the controller is the voltage at the point of charging (POC). The controller output is the regulated charging rate, or the charger current draw (IDi). Since unidirectional power flow is assumed, the charging current minimum limit is zero and its maximum limit is taken from the EV charger specifications or the maximum rating of the charging station, whichever is lower. For each EV, based on the POC voltage and the EV battery SOC, the controller decides on the regulated charging current [8].

An error of the Vdc* and Vdc is given to a PI (Proportional Integral) speed controller which generates a controlled output corresponding to the error signal. The error voltage Ve at any instant of time k is as; Ve(k) = Vdc*(k) – Vdc(k) (8) and the output Vc(k) of the PI controller is given by, Vc(k) = Vc(k-1) + Kp.(Ve(k) – Ve(k-1)) + Ki.Ve(k) (9) where Kp is the proportional gain and Ki is the integral gain constant [9] [10].

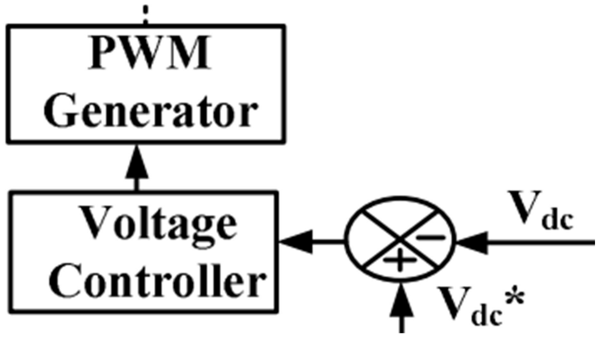


Figure 6: Constant voltage feedback control

The output of the PI controller Vc is given to the PWM generator which produces a PWM signal of fixed frequency and varying duty ratio. A saw tooth waveform is compared with the output of PI controller as shown in Fig. 7 and PWM is generated as; If md(t)

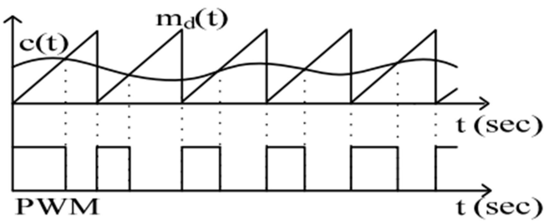


Figure 7. Generation of PWM signal by comparing a saw tooth waveform with the controller output

IV. SIMULATION ANALYSIS

The buck-boost converter and KY converter EV charging modules are connected to distribution grid for analyzing the harmonics contamination at the 11kV bus. The below figure 8 is the modeling of the proposed test system with 3-ph thyristor controlled rectifier (AC-DC). The EV charging modules are connected to the DC side of this rectifier.

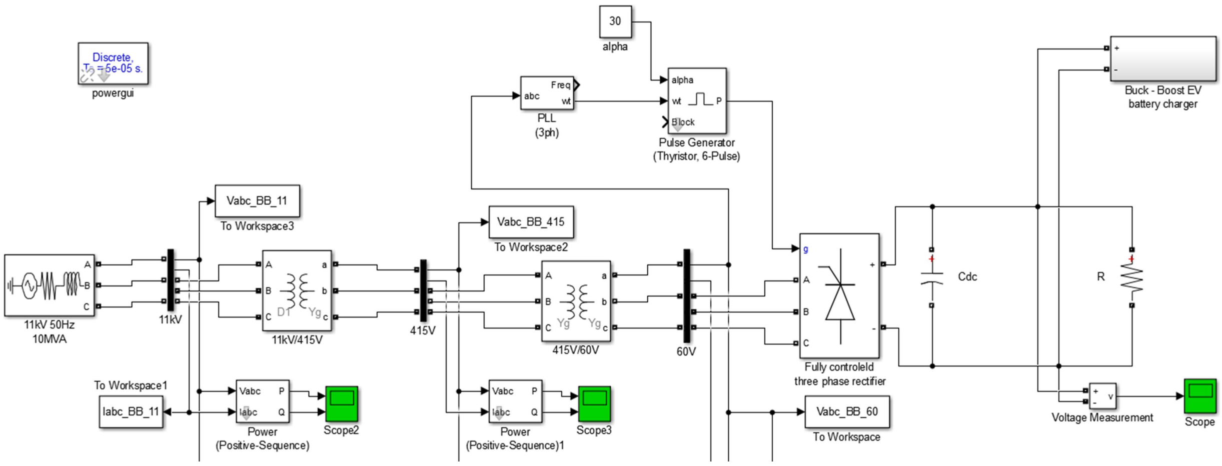


Figure 8: Simulink modeling of the test system

The internal modeling of the Buck-Boost converter EV charging module is shown below.

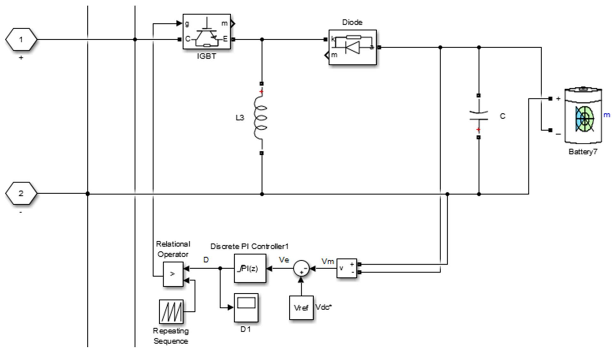


Figure 9: Buck-Boost converter EV charging modeling

To control the voltage input to the battery a feedback loop control is adopted with Vref taken at 52V. For the same the below are the battery characteristics with voltage controller.

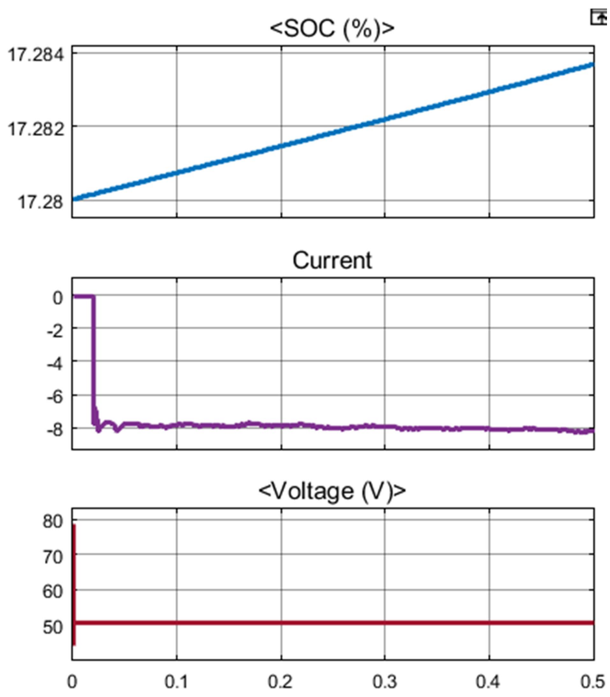


Figure 10: EV Battery characteristics

The output of the thyristor bridge can be seen below with magnitude at 84V and higher ripple content.

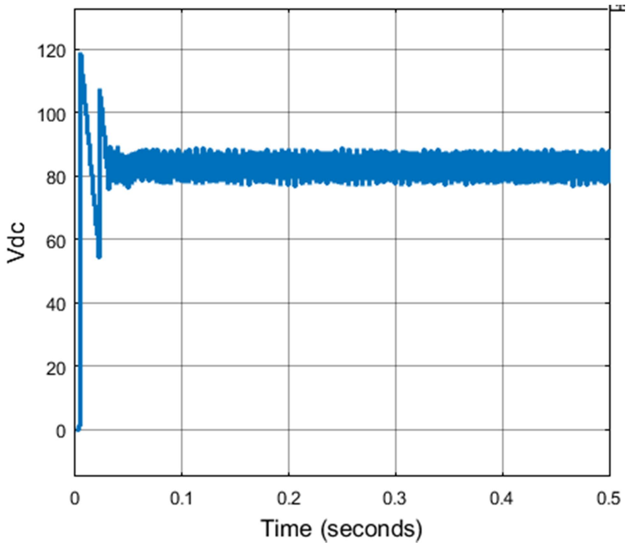


Figure 11: DC link voltage with Buck-Boost converter charging modules

The below are the 3-ph voltages and currents at the 11kV bus when connected with Buck-Boost converter modules in the EV charging station.

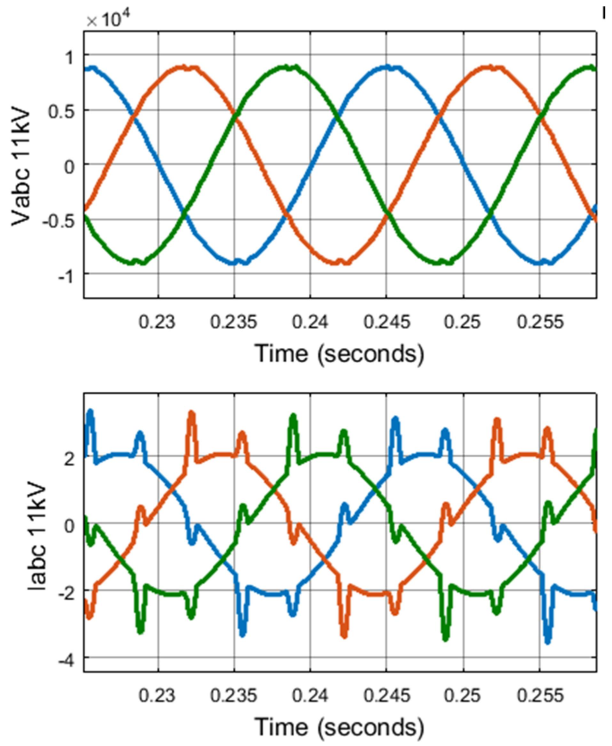


Figure 12: 11kV bus voltages and currents with Buck-Boost converter charging modules

The EV module is further updated with KY converter with same voltage feedback control taking Vref at 52V. The modeling of the KY converter charging EV battery can be see below.

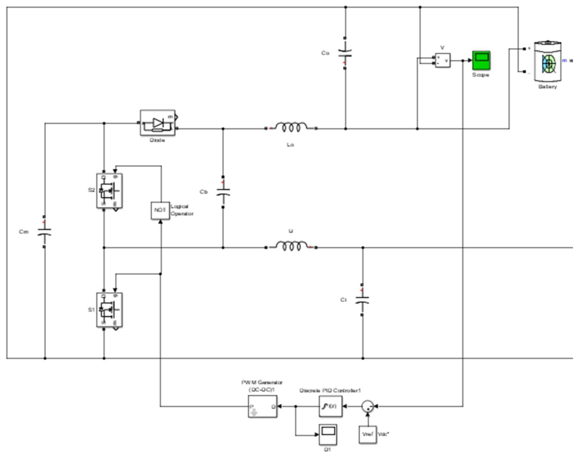


Figure 13: KY converter modeling

The thyristor bridge output DC voltage when the EV charging module is updated with KY converter can be seen in figure 14 below.

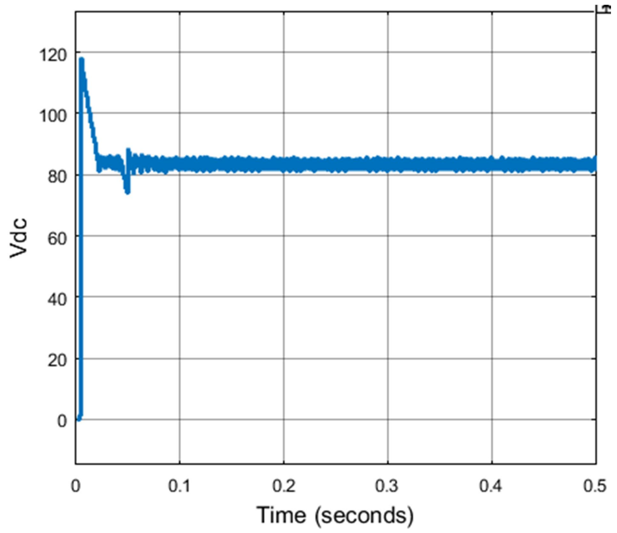


Figure 14: DC link voltage with KY converter charging modules

As observed the DC link voltage ripple is reduced as compared to Buck-Boost converter when the EV charging station is operated with KY converter. For the same the 11kV bus voltages and currents are shown below with reduced harmonics in the currents when operated with KY converter.

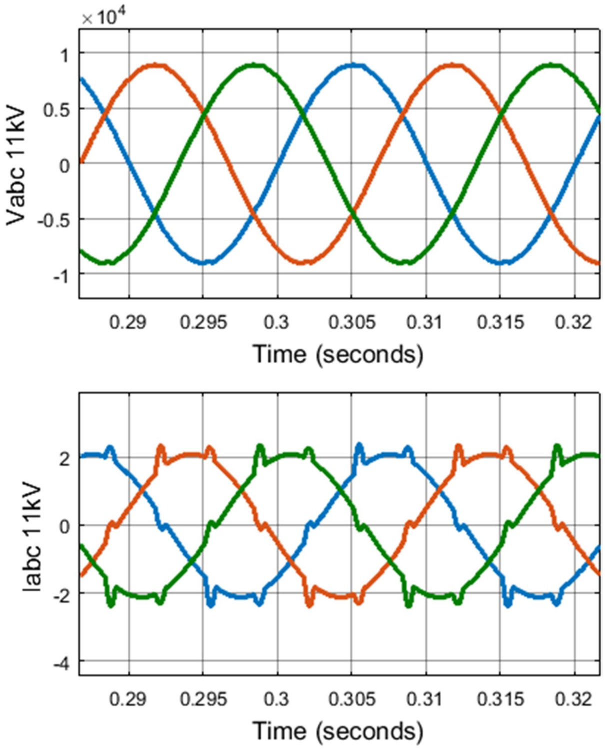


Figure 15: 11kV bus voltages and currents with KY converter charging modules

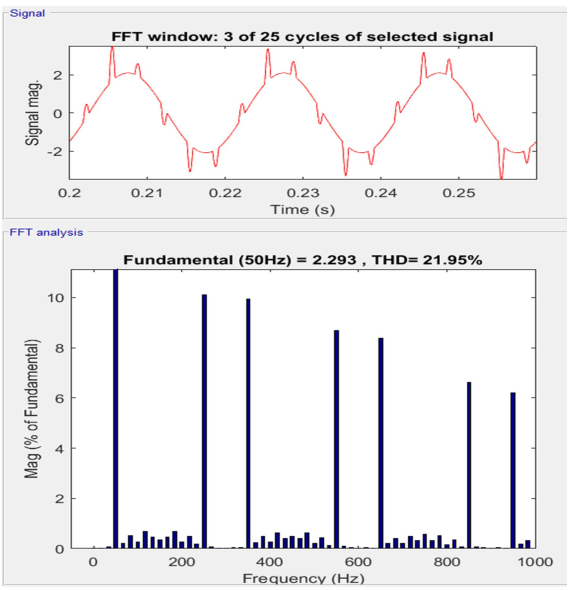


Figure 16: THD of source currents at 11kV bus with Buck-Boost converter

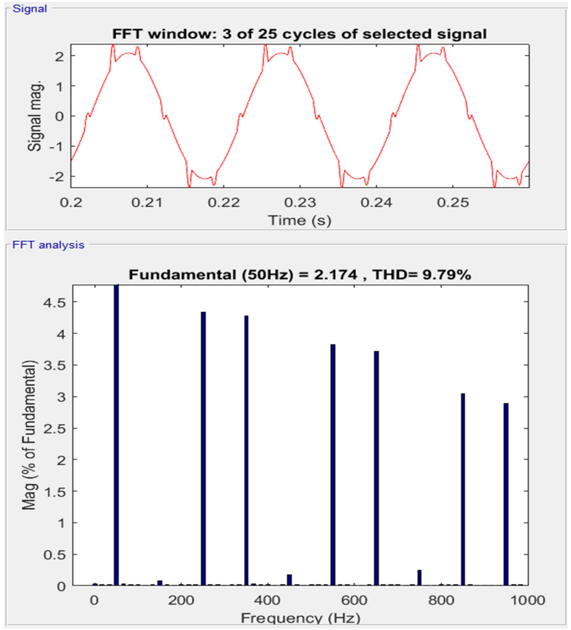


Figure 17: THD of source currents at 11kV bus with KY converter

The above are the THDs of the source currents at 11kV bus with Buck-Boost and KY converters determined using FFT analysis tool in powergui toolbox.

V. CONCLUSION

This paper presents design and implementation of the buck-boost and KY converters. A simple PI controller is proposed and designed to regulate the output voltage of the converter. Simulation results are presented to verify the functionality of the converter with the controller under steady state and dynamic conditions. From the results generated it is validated that the harmonic contamination is reduced to 9.79% from 21.95% when the system is updated with KY converter modules replacing Buck-Boost converters in the EV charging station. The harmonic analysis is done using FFT analysis for both the topologies at the same 11kV bus location.

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