Optimization of Battery Energy Storage Systems for Enhancing Power Quality in LV and HV Power Grids

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Abstract: This research focuses on optimizing Battery Energy Storage Systems (BESS) using MATLAB/Simulink to improve power quality in both low-voltage (LV) and high-voltage (HV) power grids. An artificial intelligence-based HL_GA algorithm is employed to develop a controller for the BESS converter system, aiming to manage voltage and current distortions effectively. The study evaluates the BESS impact on a 400V phase-to-phase load line, analyzing distortion levels under varying load conditions. Significant reductions in current waveform distortion (from 4.84% to 4.03%) and voltage waveform distortion (from 4.27% to 3.82%) are observed at the LV line, accompanied by a 6% increase in active power output. At the HV line, serving heavy loads and electric drives, the controller achieves reductions in Total Harmonic Distortion (THD%) to 4.03% for voltage waveforms and 3.45% for current waveforms. These findings underscore the effectiveness of the BESS and HL_GA controller in enhancing power quality, stabilizing LV and HV grids, and reducing THD levels across both voltage and current outputs.

Keywords: Battery Energy Storage Systems (BESS), Power Quality Enhancement, LV and HV Power Grids, MATLAB/Simulink, Artificial Intelligence Optimization, Total Harmonic Distortion (THD).

I. INTRODUCTION

The optimization of analysis using artificial intelligence techniques for low tension (LT) and high-tension (HT) lines in Battery Energy Storage Systems (BESS) and Distributed Static Synchronous Compensator (D-STATCOM) represents a critical advancement in modern power systems. As renewable energy integration increases, alongside the need for enhanced efficiency and reliability, traditional methods are often insufficient in managing dynamic and nonlinear characteristics. Artificial intelligence, encompassing machine learning algorithms, neural networks, and optimization techniques, offers a promising solution. This study explores how AI can predict load variations, mitigate voltage fluctuations, improve power quality, and optimize overall system performance in LT and HT lines integrated with BESS and D-STATCOM. Through comprehensive analysis and empirical findings, this research aims to contribute insights into the transformative potential of AI in power system optimization, paving the way for more resilient and sustainable energy infrastructures. Recently, the necessity to limit gas emissions has increased the significance of solar and wind energies [1]. When demand is low, energy storage systems (ESSs) store extra energy and release it when need is met. Moreover, energy storage has gained attention due to the need for transportation options with lower CO2 emissions [2]. Energy storage systems for renewable energy sources are frequently employed in electrochemical, mechanical, electrical, and hybrid configurations [3].

Due to the recent necessity to minimize gas emissions, the relevance of solar and wind energies has increased. When demand is low, energy storage systems (ESSs) store extra energy and release it when need is met. Furthermore, interest in energy storage has increased as a result of the need for transportation options with lower CO2 emissions. Renewable energy sources frequently use hybrid, mechanical, electrical, and electrochemical systems as energy storage devices. An overview of ESS technologies and how well suited they are for wind power facilities is given in. The authors evaluate the development, categorization, guiding principles, and comparative analysis of ESS improvements from 1850 to 2022. focuses on and makes comparisons between energy storage solutions. Batteries, flow batteries, and fuel cells for storing hydrogen are examples of electrochemical energy sources. Flywheel energy storage, compressed air energy storage (CAES), and pumped hydroelectric energy storage are examples of mechanical storage. Flywheel energy storage, also known as FES, uses a revolving flywheel to store kinetic energy. A number of factors, including cost, efficiency, environmental impact, and availability of technology, will influence the choice of mechanical energy storage system [4]. When there is a high demand for energy, compressed air is stored in subterranean caves and released.

A. Types of Energy Storage Systems

- **Battery Energy Storage Systems (BESS):** BESS are widely used for their versatility and scalability in storing electrical energy. They range from small-scale applications like residential solar storage to grid-scale installations for stabilizing renewable energy fluctuations and providing backup power.
- **'Pumped Hydro Storage':** This is the largest and most established form of grid-scale energy storage. It utilizes surplus electricity to pump water uphill to a reservoir during off-peak hours, which is then released downhill through turbines to generate electricity during peak demand.
- **Compressed Air Energy Storage (CAES):** CAES systems store energy by compressing air into underground caverns or tanks. When electricity demand rises, the compressed air is released and expanded through turbines to generate electricity, offering large-scale storage capacity and supporting grid stability.

- **Flywheel Energy Storage:** Flywheels store kinetic energy in a rotating mass, providing fast response times and short-duration storage solutions. They are used in applications requiring high reliability and quick energy dispatch, such as backup power and frequency regulation.
- **Thermal Energy Storage:** This type stores energy in the form of heat or cold using materials like molten salts, water, or phase change materials. It is utilized for efficient heating, cooling, and electricity generation in buildings, helping to manage peak energy demand and integrate renewable energy sources.
- **Hydrogen Energy Storage:** Hydrogen can be produced through electrolysis using surplus electricity and stored for later use in fuel cells or combustion engines to generate electricity. It offers long-duration storage capabilities and can be integrated into various sectors including transportation and industrial processes.
- **Superconducting Magnetic Energy Storage (SMES):** SMES systems store energy in a superconducting coil, providing high efficiency and rapid response times for applications requiring instantaneous power delivery, such as stabilizing grid frequency and supporting critical industrial processes.

B. Battery Energy Storage Systems

A system called Battery Energy Storage System (BESS) was created to store electric charge in batteries that have been specially designed for this purpose. The fundamental notion is that this energy can be stored for use at a later date. A great deal of research has produced battery advancements that have made the idea of a battery energy storage system a viable product on the market. A subset of energy storage systems is battery energy storage systems (BESSs) (ESSs). The ability of a system to store energy via thermal, electro-mechanical, or electro-chemical solutions is referred to as an energy storage system. Usually, a BESS makes use of an electrochemical solution. In essence, energy is captured by all energy storage systems and stored for use at a later time. Pumped hydro, compressed air storage, mechanical flywheels, and now BESSs are a few examples of these technologies. In an effort to maintain a balance between energy production and consumption, these systems supplement sporadic energy sources including wind, tidal, and solar power. Peak electrical system demand is reduced as a result of energy storage, and ESS owners are frequently reimbursed through regional grid market programs. Additionally, regulators provide incentives—and in certain situations, mandates—to promote involvement.

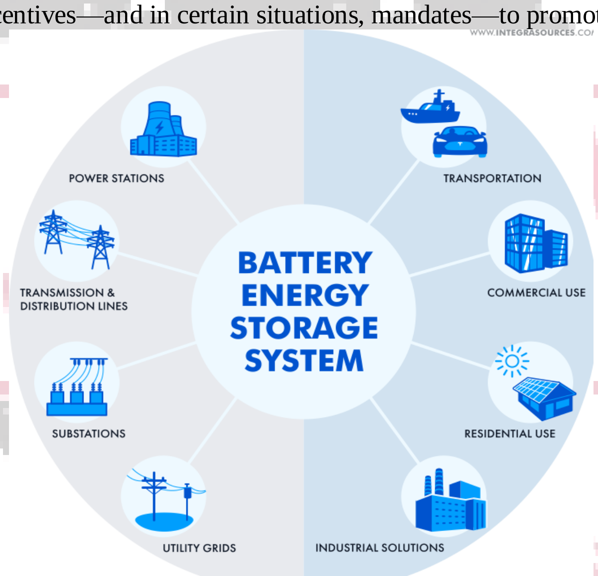

Figure 1 Battery Energy Storage Systems

C. Micro-Grids

A microgrid is a localized energy network equipped with its own control capabilities, allowing it to disconnect from the main grid and operate autonomously. While traditionally, homes, businesses, and other buildings rely on the centralized grid for electricity to power appliances, heating/cooling systems, and electronics, this interdependence means that grid repairs can disrupt everyone. A microgrid addresses this vulnerability by operating interconnectedly with the grid under normal conditions but can autonomously switch to local energy generation during crises like storms, outages, or for strategic reasons.

Microgrids integrate various energy sources such as distributed generators, batteries, and renewable resources like solar panels. Depending on its energy mix and management, a microgrid can operate indefinitely. It connects to the main grid at a point of common coupling to maintain voltage levels unless there's a grid issue necessitating isolation. Through automatic or manual switches, a microgrid can disconnect from the main grid and function independently as an "island." This capability not only provides backup during emergencies but also optimizes costs and supports local resources that might be too small or unreliable for traditional grid use, promoting energy independence and environmental sustainability in communities.

Microgrids are increasingly prevalent in urban areas, communities, and campuses, representing a shift towards decentralized generation. Their ability to "island" makes them resilient, ensuring continuous service during grid disruptions and supporting critical services like emergency response and shelter. By enhancing local resiliency and improving grid stability, microgrids contribute to efficient, cost-effective, and clean energy solutions, bolstering overall grid competitiveness and responsiveness in the energy sector.

1.4.1 Benefits of Micro-grids

- Provide efficient, cost-effective, and environmentally friendly energy
- Enhance the reliability and stability of the regional electrical grid
- Serve as critical infrastructure to boost reliability and resilience
- Alleviate grid congestion and peak loads
- Enable highly efficient Combined Heat and Power (CHP), reducing fuel consumption, transmission losses, and carbon emissions
- Integrate CHP, renewable energy sources, thermal and electric storage, and advanced system and building controls
- Enhance competitiveness in Regional Transmission Organization (RTO) markets
- Offer grid services such as energy, capacity, and ancillary services
- Support community safe havens during regional crises and aid first responders
- Utilize local energy resources, promoting job creation
- Distribute risk across various assets rather than concentrating it
- Utilize electric and thermal storage capabilities to locally manage variable renewable generation, especially on-site solar

A well-designed regional power grid that combines large central plants with distributed microgrids can be constructed with reduced total capital costs, lower installed generation capacity, higher capacity factor across all assets, and increased overall reliability.

II. LITERATURE REVIEW

[1] As the demand for low-carbon transportation solutions increases, this study explores energy storage technologies tailored for photovoltaic and wind systems. Energy storage systems (ESSs) have regained prominence as integral components of renewable energy frameworks, selected based on performance characteristics, cost considerations, and system requirements. Common ESS types include mechanical solutions such as flywheel energy storage, compressed air energy storage (CAES), gravity energy storage (GES), pumped hydroelectric storage (PHES), and hydrogen fuel cells. Additionally, hybrid systems combining multiple technologies and electrical variations like supercapacitors (SES), superconducting magnetic energy storage (SMES), and thermal energy storage (TES) play crucial roles in efficiently managing surplus renewable energy, ensuring consistent and reliable power supply. Optimal selection of storage technologies for photovoltaic and wind applications demands careful analysis of energy and power requirements, efficiency, cost-effectiveness, scalability, and durability.

[2] This article investigates the integration of energy storage systems (ESS) in power plants (EVs) to reduce costs, enhance EV flexibility, and mitigate peak demand. Emphasis is placed on improving the efficiency of EVs, crucial during electricity production. The study employs probability distribution functions to forecast stochastic load at fast charging stations (FCS) and the elastic load of electric vehicles, using this data to regulate ESS power levels to maintain EV endurance during power outages. Annual ESS value calculations incorporate ESS component lifespan and annual interest rates. The ideal ESS size is determined based on annual ESS prices, penalties for peak-time power purchases, and energy use violations. Simulation and sensitivity analyses account for uncertainties such as market prices, arrival times of electric vehicles, residual EV energy levels at FCS, and converter ratings. Results suggest that increasing penalties during peak periods can reduce peaks while maintaining FCS rates.

[3] This paper introduces a model designed to optimize the size of an Energy Storage System (ESS) within a microgrid, focusing on reliability criteria. Balancing investment costs against operational savings, the model minimizes initial ESS investment and expected microgrid operating costs. By integrating ESS into microgrid infrastructure, the model effectively manages potential energy shortfalls from conventional unit outages and intermittent renewable energy sources, ensuring compliance with microgrid reliability criteria. Mixed-Integer Programming (MIP) techniques are employed to formulate the optimization problem, allowing discrete decision variables like storage unit number and size to be integrated into the optimization process. Illustrative examples demonstrate the model's effectiveness in enhancing microgrid operational efficiency and reliability by accurately sizing ESS based on anticipated energy demands and renewable generation variability.

[4] Liu et al. (2018) propose a distributed energy management approach tailored for multi-microgrid (MG) systems, aimed at minimizing aggregated operational costs using the Alternating Direction Method of Multipliers (ADMM). This approach ensures privacy for microgrid owners by eliminating the need to share sensitive operational data such as generator cost functions and daily load profiles among microgrids. Each microgrid independently conducts load and generation forecasts based on its specific grid characteristics, enhancing forecast accuracy. The center-free structure of the method enhances scalability and reliability in communication, facilitating effective management of multiple microgrids within a distributed energy network. This approach optimizes operational efficiency, respects privacy, and ensures robust forecasting capabilities in multi-microgrid environments.

[5] Abusief et al. (2016) investigate the dynamic behavior of a stand-alone network similar to a microgrid, proposing a novel control methodology to coordinate Battery Energy Storage Systems (BESS) and Distributed Generators (DGs). The study focuses on a medium-voltage distribution network powered by photovoltaic (PV) generation and BESS in a remote area of Libya. Central to the study is a master/slave control strategy regulating frequency and voltage during islanded operations. This approach optimally integrates BESS and DG outputs without explicit communication channels, with the BESS acting as a slack node in the control scheme. Practical testing highlights the strategy's effectiveness in maintaining grid stability and optimizing energy management in remote and isolated settings, leveraging frequency and voltage as control parameters to enhance reliability and efficiency.

[6] Bahloul & Khadem (2018) present a comprehensive design framework for an Energy Storage System (ESS) providing Enhanced Frequency Response (EFR) services to the UK grid. The study focuses on developing a robust power management system aligned with Transmission System Operator (TSO) requirements. Simulations evaluate battery-only and hybrid battery-super capacitor ESS configurations, demonstrating promising regulation dynamics for both topologies. The hybrid configuration minimizes battery usage and energy required for State of Charge (SoC) control, highlighting its advantage in enhancing grid stability and response capabilities for critical frequency regulation services. By optimizing battery resource utilization and integrating supercapacitors, the hybrid ESS configuration offers an efficient solution meeting stringent regulatory requirement and enhancing overall grid efficiency and performance.

IV. OBJECTIVES

- The aim of this thesis is designing and placement of a battery energy storage system to study its affect on the power quality in a LV and HV power grid with variable loads.
- The study is focused on evaluation of distortion levels in the electrical parameters waveforms at various points of loading in the system design.
- The system performance is expected to be improved by designing of a converter control, system derived by the AI optimization algorithm suited to meet the load demands.
- The total harmonic distortion (THD%) in the voltage and current waveform should be considerably reduced by using the device making the finally developed system more efficient and stable.
- The analysis shall evaluate the active power and reactive power improvement with stable outputs as per the designed converter control system.

IV METHODOLOGY

To model the various components of battery energy systems, researchers have created a variety of modeling methodologies. Deterministic or probabilistic methods are used to model the performance of each individual component. This chapter covers the fundamental modeling frameworks for a battery system that is linked to the grid. Its purpose is to provide power for electric drive and reactive load operations, specifically targeting the 400V load line.

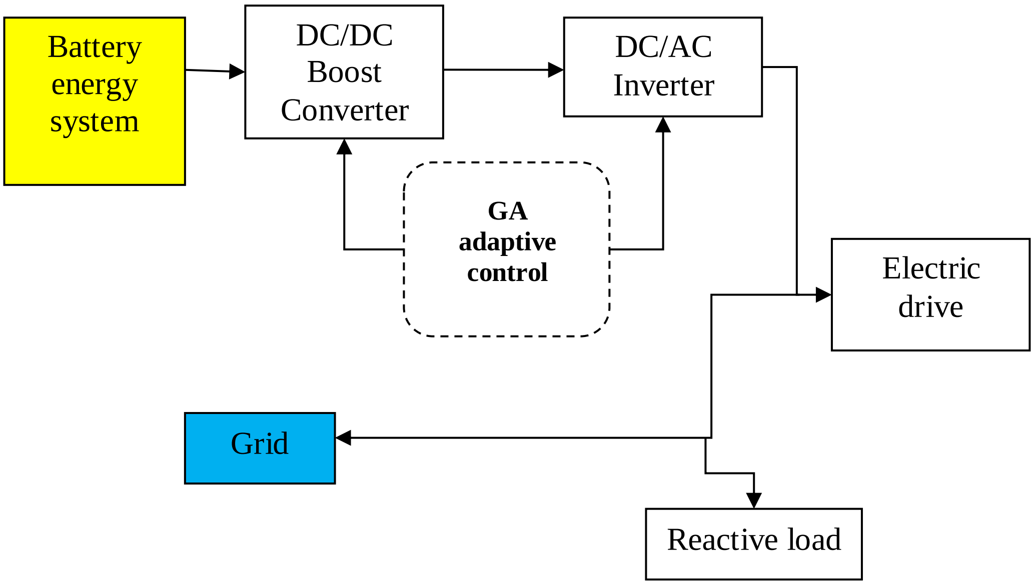

Figure 2 Block diagram showing how the AI-switched regulating compensator is implemented in the battery system

Battery energy storage system'

Batteries, a 'power conversion system' (PCS), and a 'battery management system' (BMS) control system make up the three main parts of the battery energy storage system (BESS). The two main electronic components in the system are the PCS and the batteries, both of which are developing quickly [43]. A BESS's main structure is shown in Figure 3. It is composed of a battery that provides DC power to the PCS, which converts it into AC power, and a transformer that modifies the voltage to fit the loads and utilities. The BMS is in charge of both the PCS and the batteries.

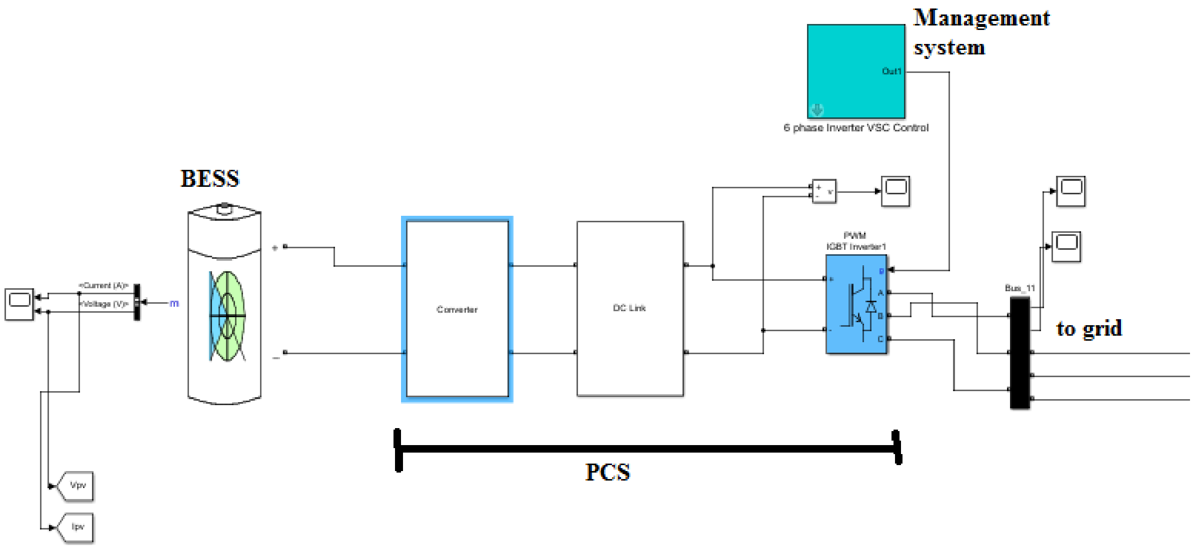

Figure 3 BESS model simulated for examination

Inverter modeling' in (PCS)

The inverter system discussed in this study features a 'three-phase grid-connected' 'Voltage Source Inverter' (VSI), which is commonly employed in distributed generation interfaces. A synchronous frame 'Space Vector Pulse Width Modulation' (SVPWM) regulator is utilized for controlling the inverter.

When transferring generated power to the grid or supplying AC loads, DC-AC converters (inverters) are essential. These inverters can output single-phase or three-phase power. Several common types of grid-integrated inverters are used in photovoltaic systems: central plant inverters, string inverters, multi-string inverters with their own DC-DC converters, and microgrid inverters (AC modules).

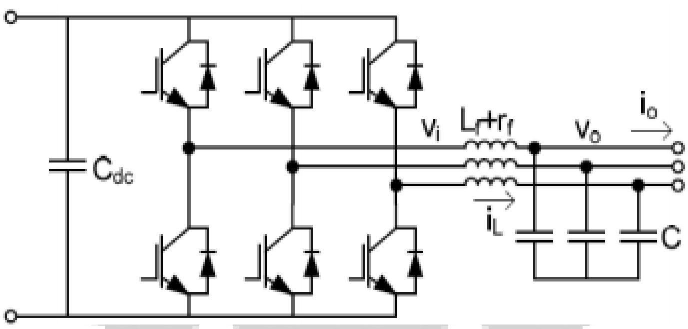

Figure 4 Block diagram for a three-phase inverter

Table 1 'Inverter Parameters'

'Power electronic device '	IGBT/Diodes
'Snubber resistance'	5000 ohms
'Forward voltages'	0
'Ron'	$1x10^{-3}$ ohms

BMS control for PCS using vector modulation

Considering that the three-phase sine wave's instantaneous voltage is:

$U_a = V_m \text{Sin (wt)}$

$U_b = V_m \text{Sin (wt - } 2\pi/3)$

$U_c = V_m \text{Sin (wt + } 2\pi/3)$

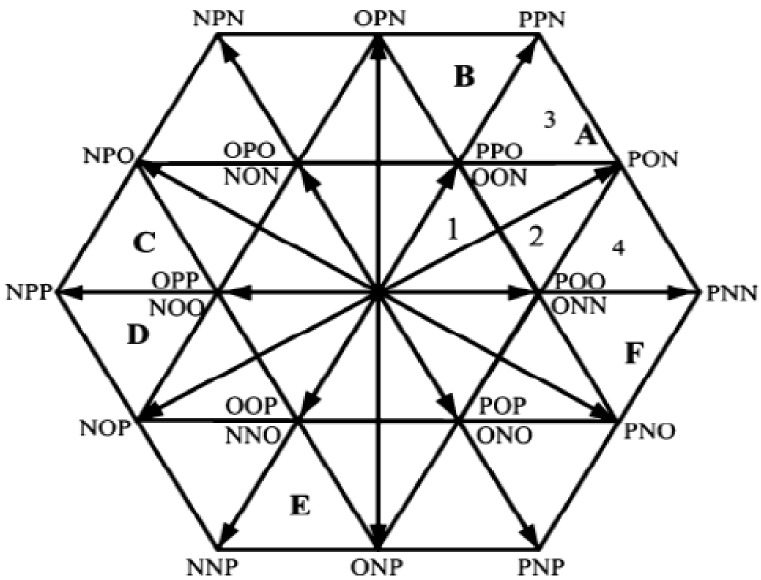

Figure 5 The three-level converter's space-vector diagram

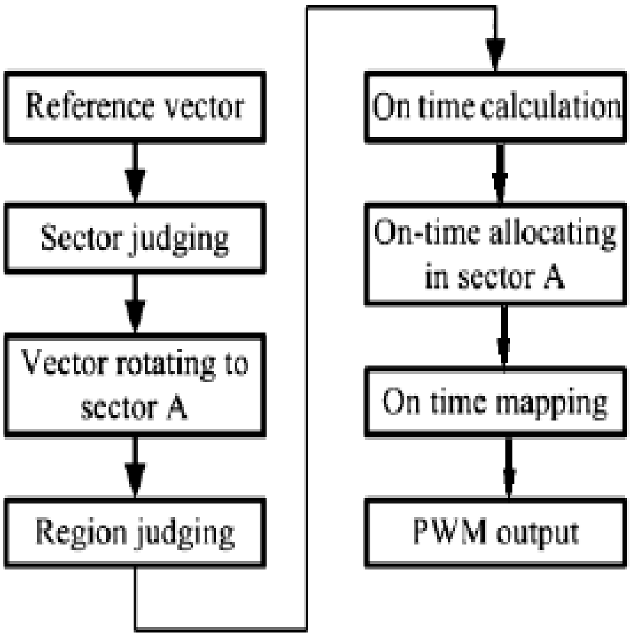

Figure 6 Process flow for the three-level SVPWM calculation Calculation made simpler

Assume that reference vector A remains in sector A's region 2, and that reference vector B is produced by rotating vector A 60 degrees counterclockwise, as depicted in Fig. 6.

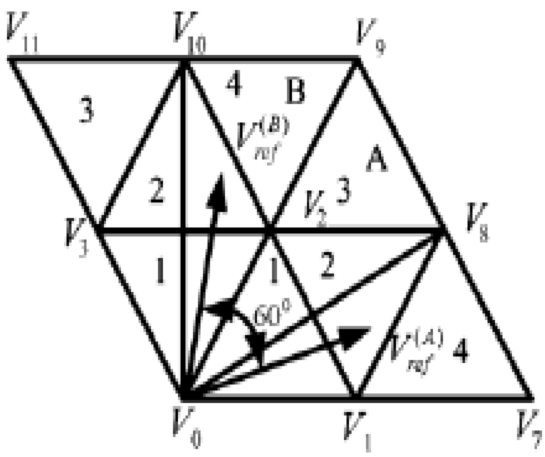

Figure 7 Two vectors with 60o shifting in the sector A and B.

So the reference vector V_{ref} can be expressed in the followingform.

Table 2. Relationships Of Voltages Constructing The ReferenceVectors In Six Sectors.

Sectors	Phase Voltage A	Phase Voltage B	Phase Voltage C
A	U_a	U_b	U_c
B	$-U_b$	$-U_c$	$-U_a$
C	U_c	U_a	U_b
D	$-U_a$	$-U_b$	$-U_c$
E	U_b	U_c	U_a
F	$-U_c$	$-U_a$	$-U_b$

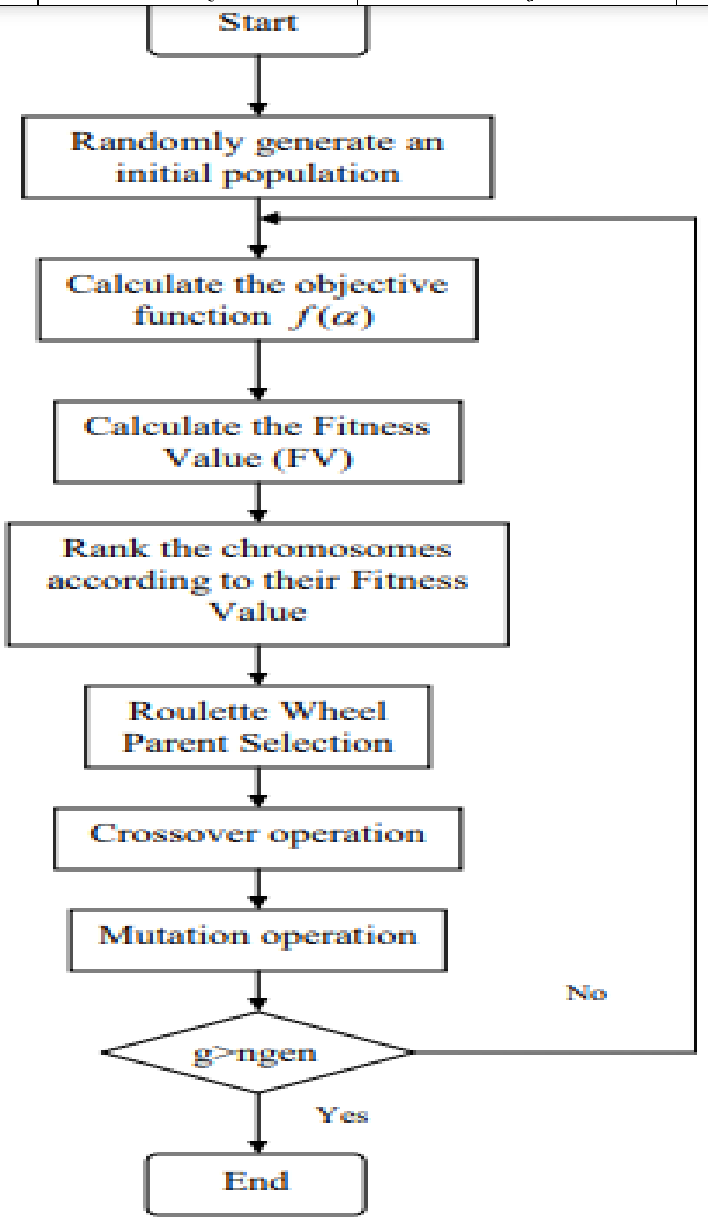

Figure 8 Operation of Proposed 'Genetic Algorithm method'

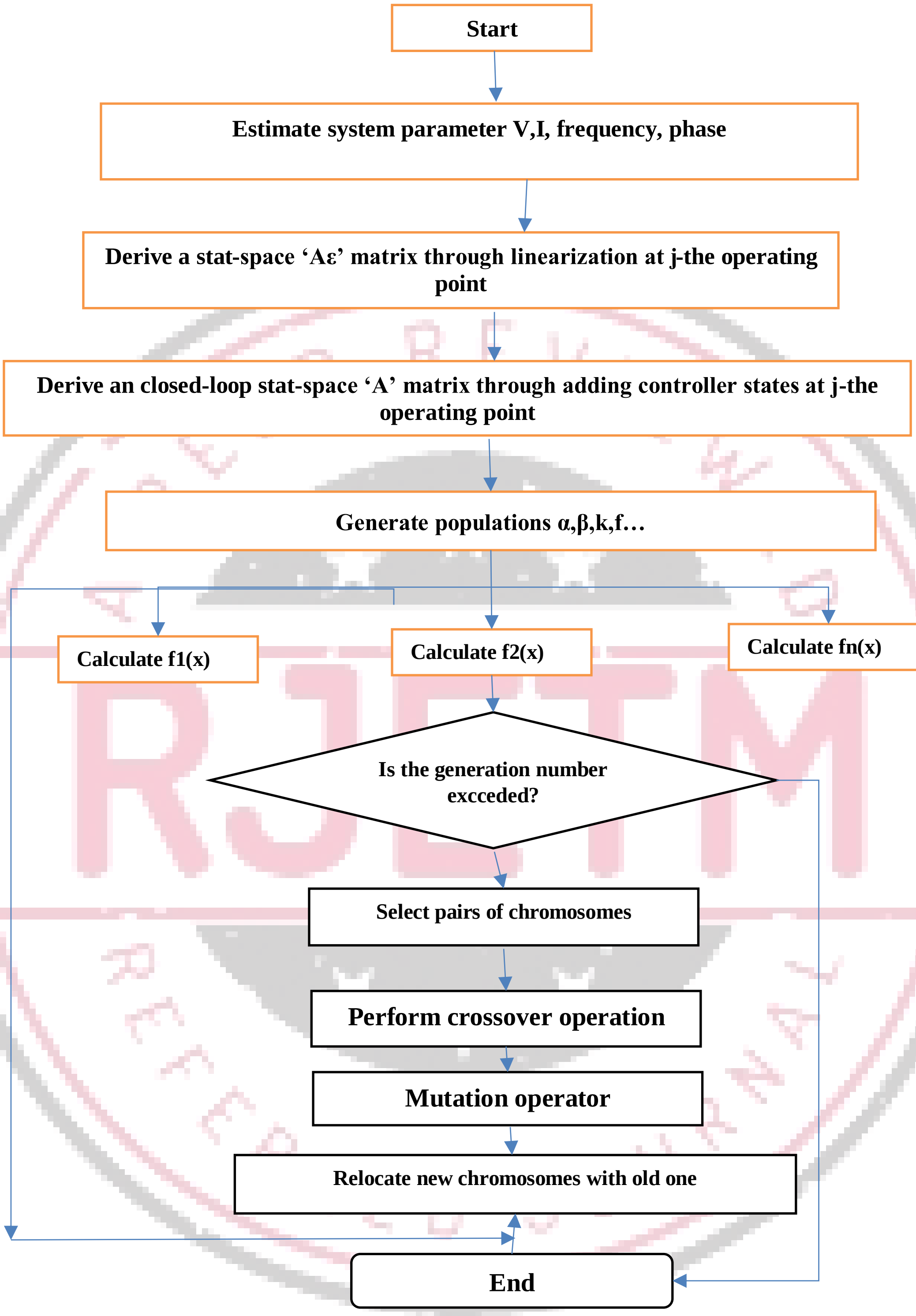

Figure 9 Flow chart for the compensator designing

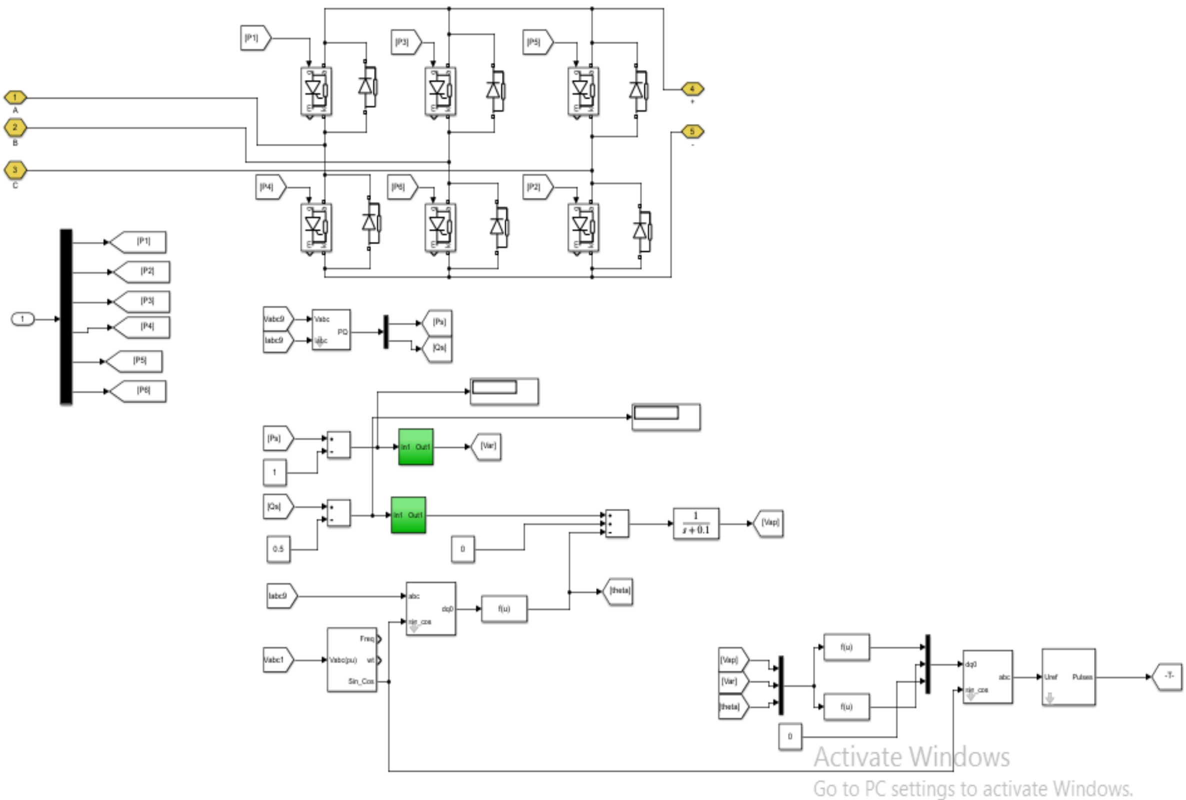

Figure 10 ProposedPI scaling 'Genetic algorithm' based 'PWM' generation for 'power optimization control' for the compensator

V. RESULT AND DISCUSSION

MATLAB, short for MATrix Laboratory, is a versatile programming package tailored for rapid and seamless numerical computations and data analysis. It features an extensive library of built-in functions catering to a wide range of mathematical operations and includes specialized toolboxes for disciplines like statistics, optimization, and solving partial differential equations. In this study, MATLAB serves as the platform for demonstrating and simulating the performance of implemented algorithms. Measurement toolboxes and built-in functions for graph generation are utilized extensively. The research leverages MATLAB functions to compute simulation results and conduct performance comparisons between the implemented model and existing ones.

The work has centered on the modeling and construction of battery energy systems, guided by a converter system that uses a genetic algorithm technique based on artificial intelligence to regulate them. The system is specifically designed to drive reactive load and electric drive at the high-tension line. It is powered by battery storage energy as a resource and is then connected into the grid. The compensator is specifically made for battery energy storage systems, which have stable output at 410V at the line. It is optimized by two converters, the output of which is governed by a controller that guides the system's correction of the power factor and maintenance of the line voltage for a variety of load types.
The artificial learning harmonic limiting genetic algorithm was used in the controller's design, and the system was called HL_GA. By using appropriate genetic evaluation and genes parameters for improved efficiency from the same architecture, a battery energy storage system integrated with the grid and the front-end conventional converter layout based on the bridge converter technology have been studied for improved performance.

System 1: BESS with converters directed by PI subjected PWM signal generation

System 2: 'BESS' with converters directed by 'HL_GAbased' control system.

The chapter has discussed output from the battery system connected with grid in the following mentioned cases:

CASE 1: Analysis of 'BESS at the LV' load terminal for comparative analysis of two controllers designed and their performance before 'grid integration'

CASE 2: Analyzing the effects of driving huge loads (electric drive and reactive load) on the high voltage line

The analysis focuses on evaluating the distortion levels in voltage output and current using various controls within two distinct MATLAB/SIMULINK-designed systems for the parallel compensator prior to its integration with the grid. Additionally, a comparative assessment of power system electrical parameters, including power factor at the line and enhancements in active power, is conducted before integration with the grid.

5.1 Modelling of BESS:

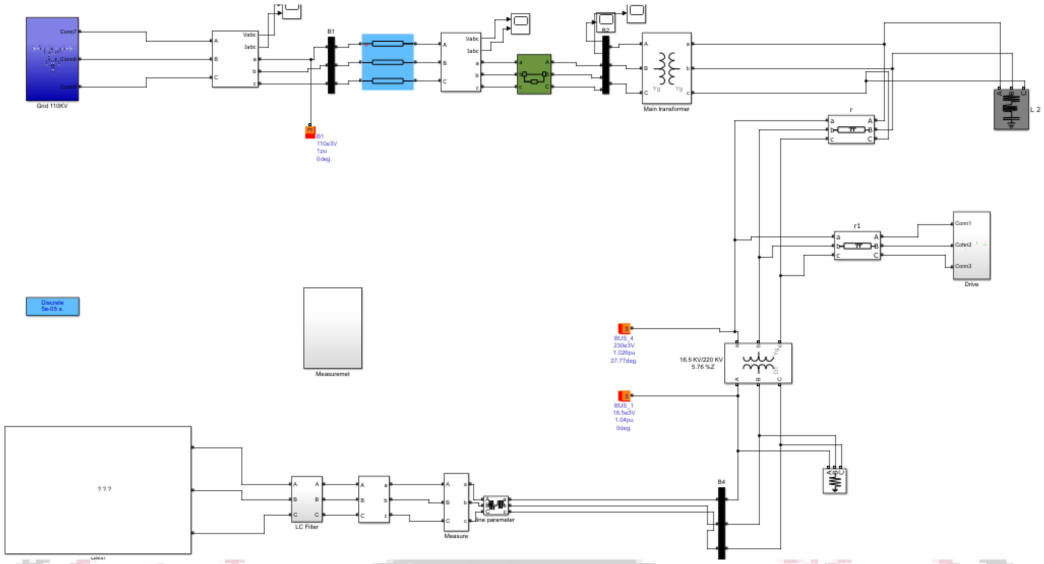

Figure 11 Modeled 'BESS' with grid integration in 'MATLAB/SIMULINK'

5.2 CASE 1: Analysis of BESS at the LV load terminal for comparative analysis of two controllers designed and their performance before grid integration

This case has focused on the evaluation of the 'system' in the 'low voltage' (LV) side of the BESS having line voltage 410V. the system parameters are measured at the bus terminal after the converter before it is integration with the 'grid system' via a transformer. The converter control drives two converter that produces output at the LV line which is measure in terms of active and reactive power available there and the efficiency of the two converters is further compared.

LV line quality analysis with system 1 controllers driving local loads

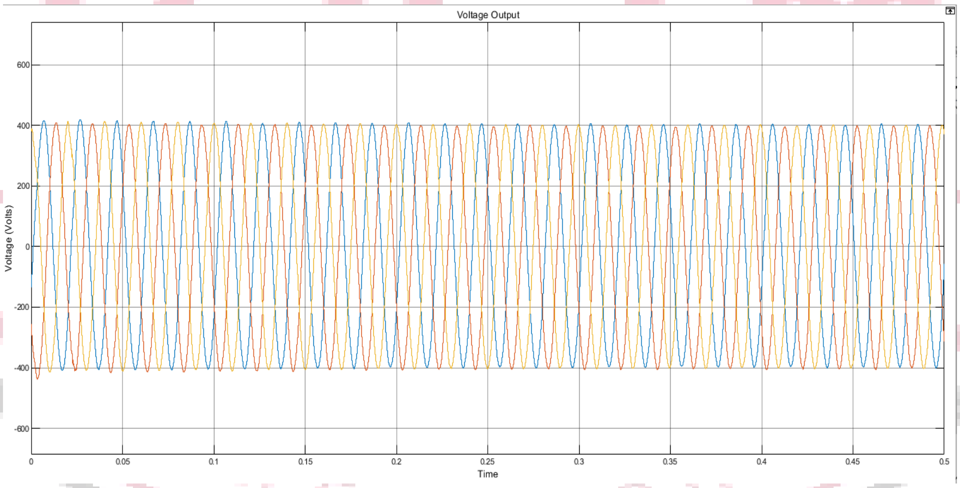

Figure 12 The voltage output from the converter powering loads prior to grid integration in System 1.

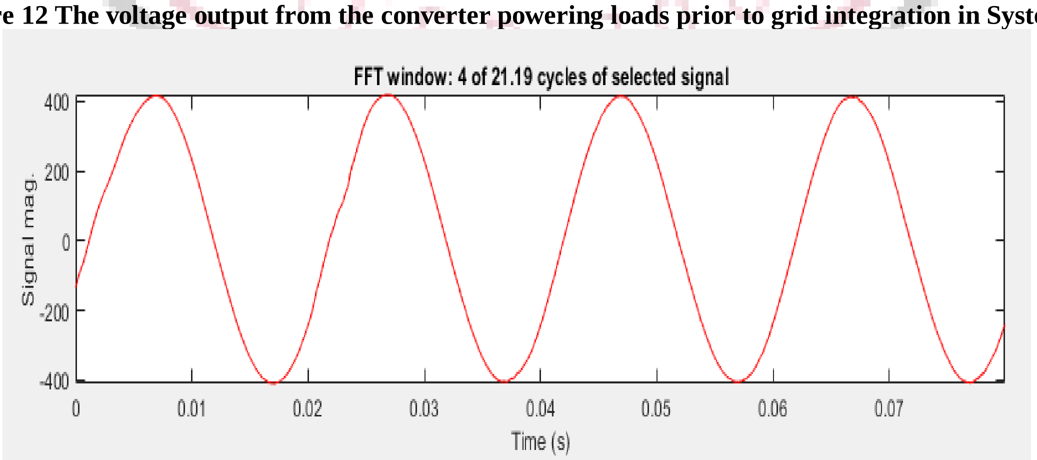

Figure 13 FFT analysis of voltage output from the converter in the LV line driving loads in System 1.

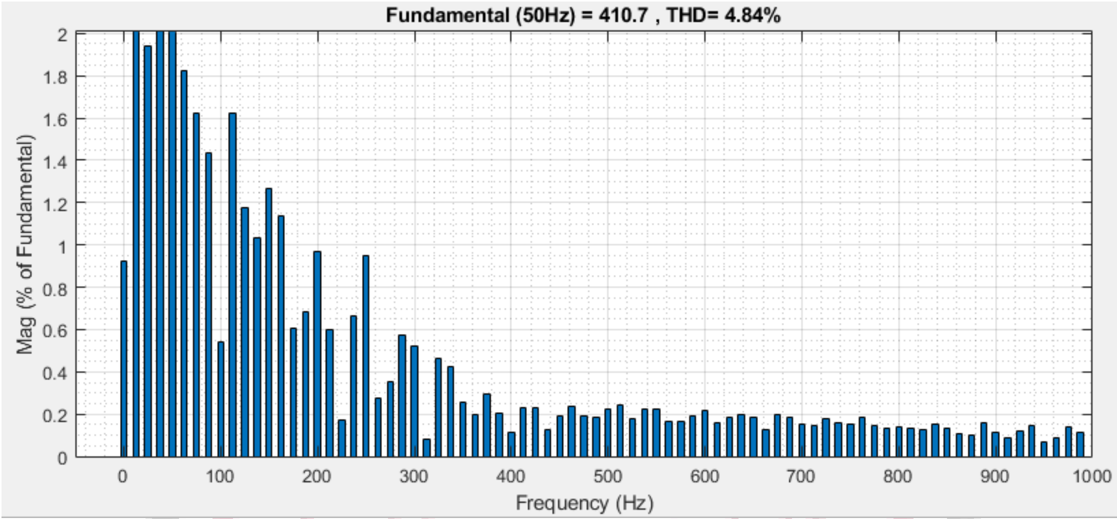

Figure 14 THD% in Voltage output in LV lineof system 1 driving loads

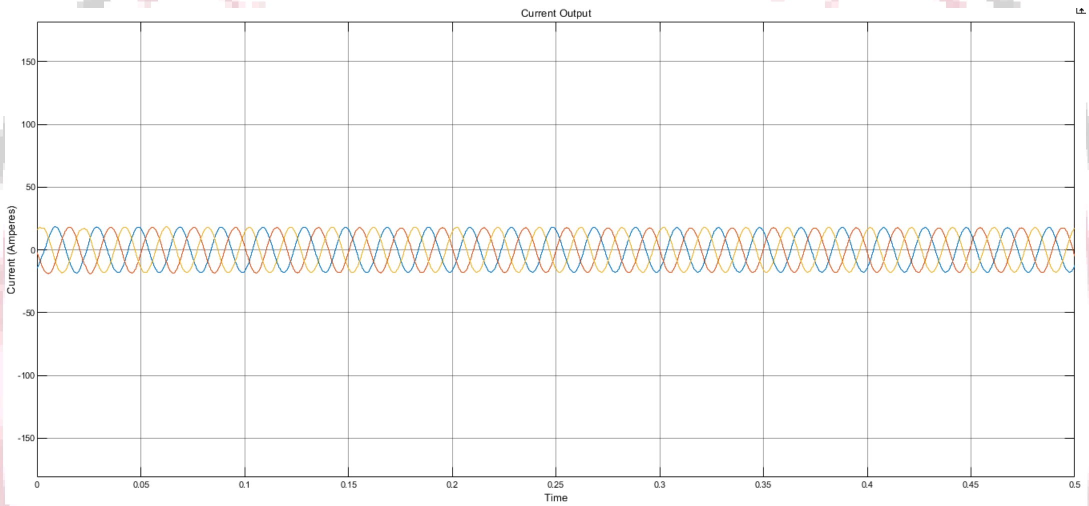

Figure 15 The current output from the converter supplying loads prior to grid integration in System 1.

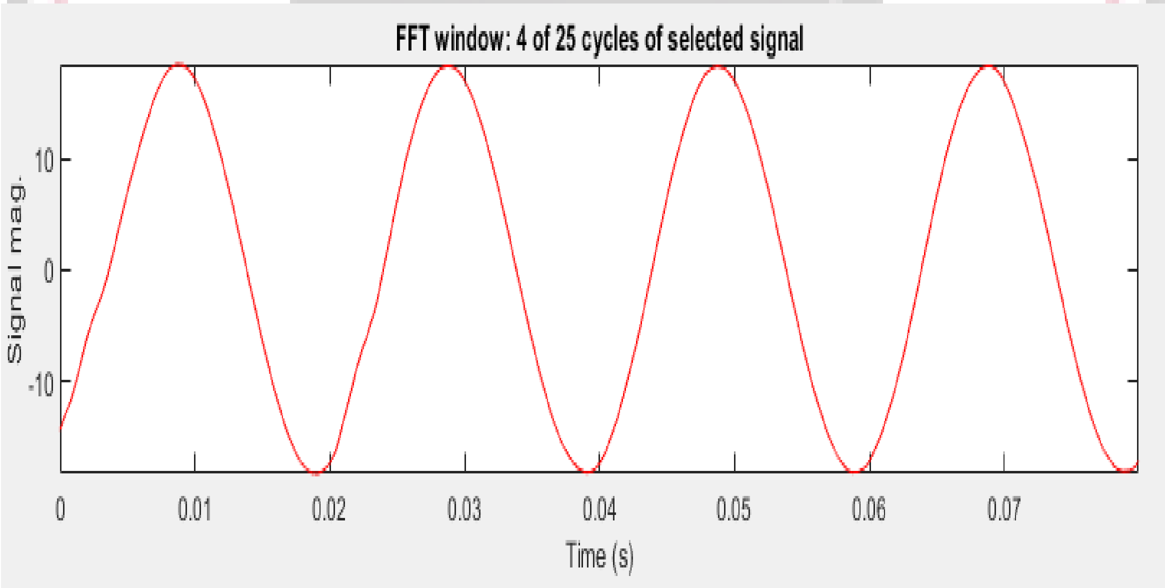

Figure 16 FFT analysis of the current output from the converter in the LV line driving loads in System 1.

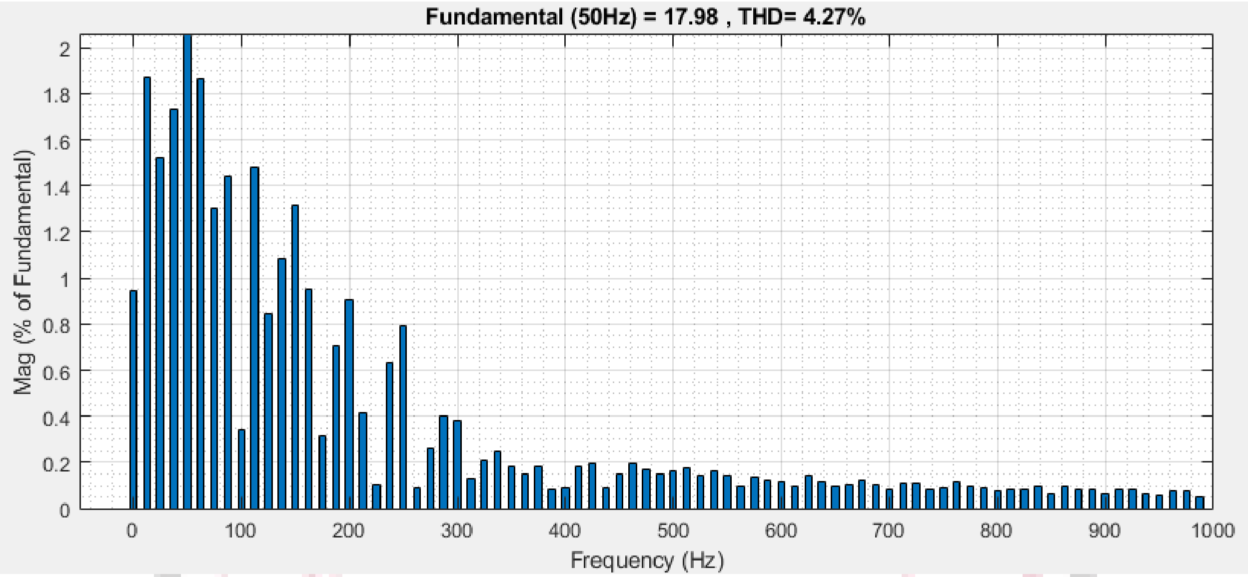

Figure 17 'THD% measured 'in current output from the converter in 'LV line driving' loadsin system 1

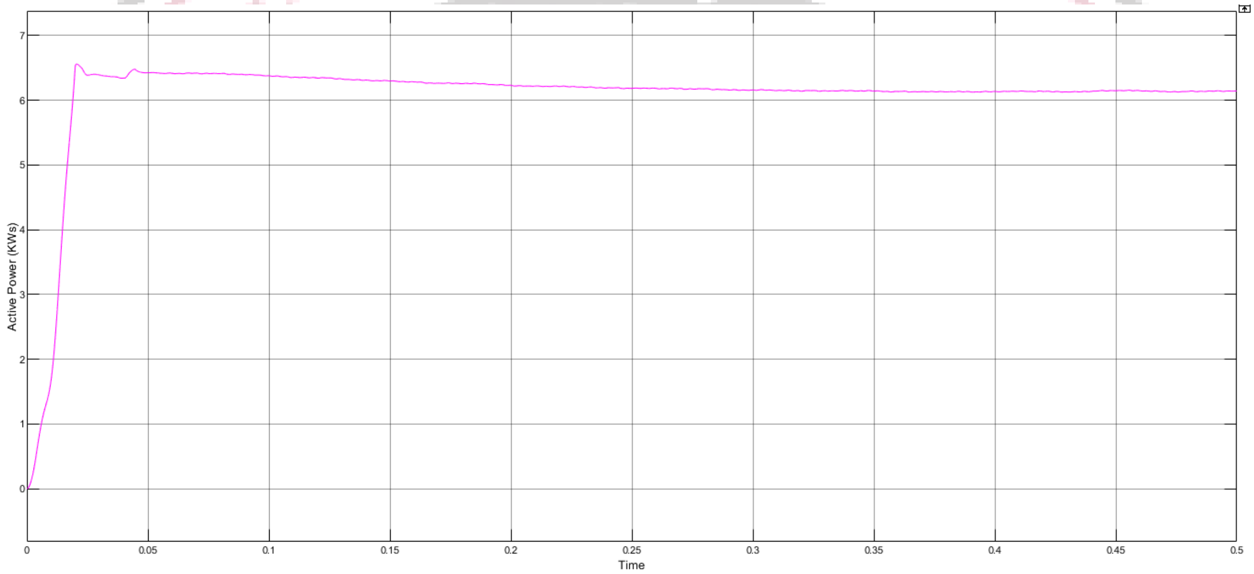

Figure 18 Active Power output in 'BESS system' driving LV line loads having converters with control of system 1

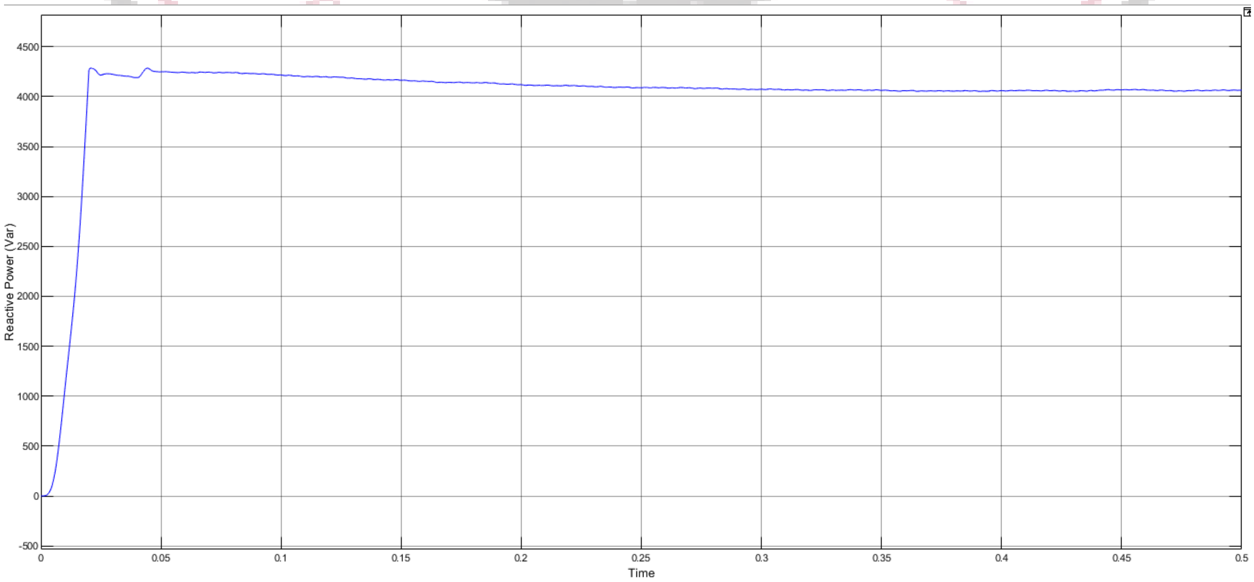

Figure 19 Reactive Power in LV line with converters having control as in system 1

LV line quality studies with system 2 controllers that drives local loads

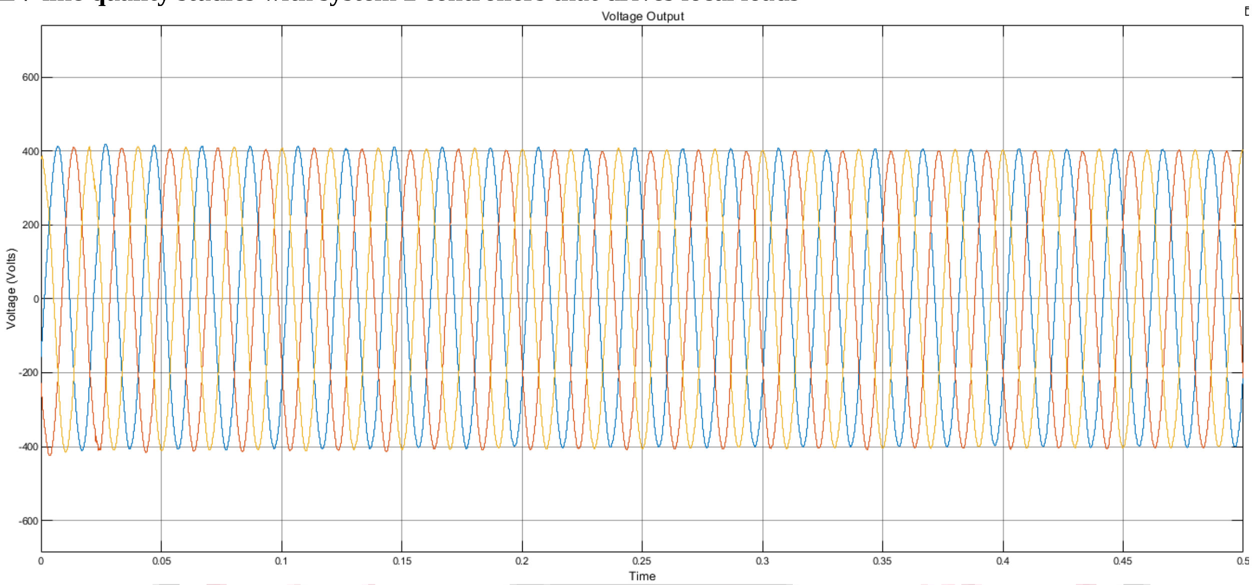

Figure 20 Voltage output from the converter driving loads before grid integration in system 2

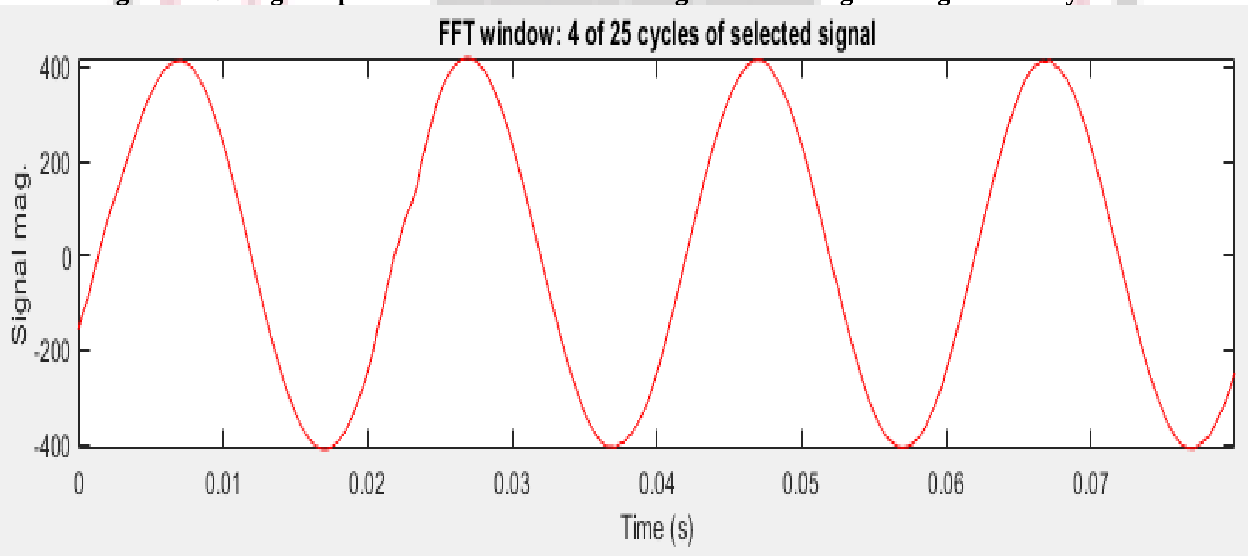

Figure 21 FFT analysis of Voltage output from the converter in LV line driving loadsin system 2

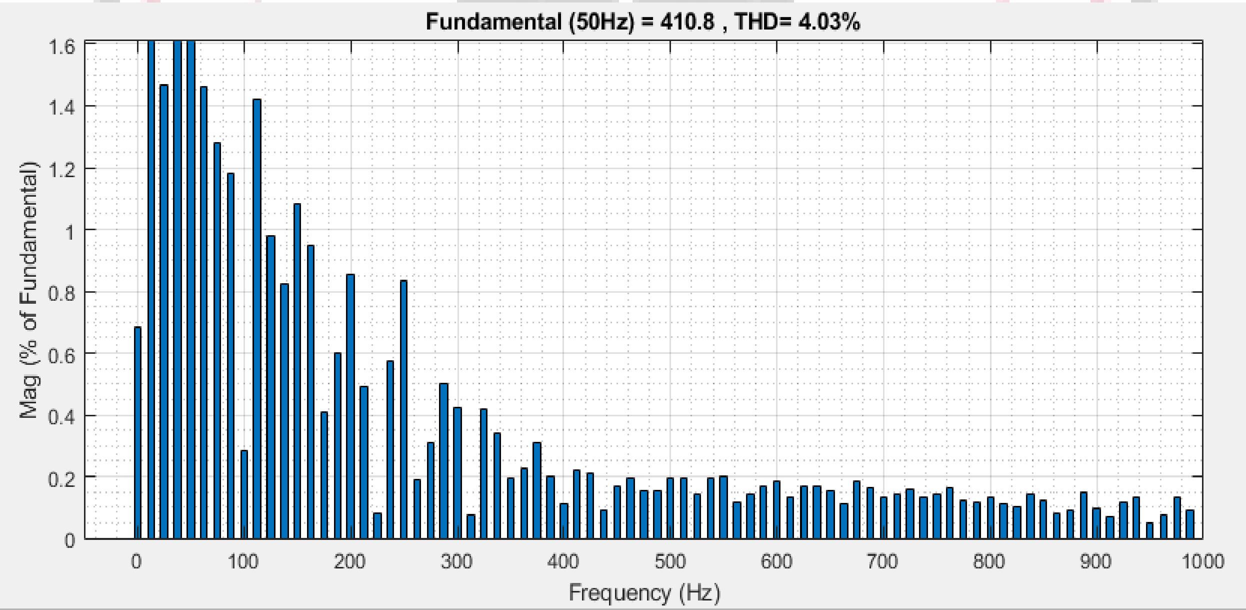

Figure 22 THD% of Voltage output from the converter in LV line driving loadsin system 2

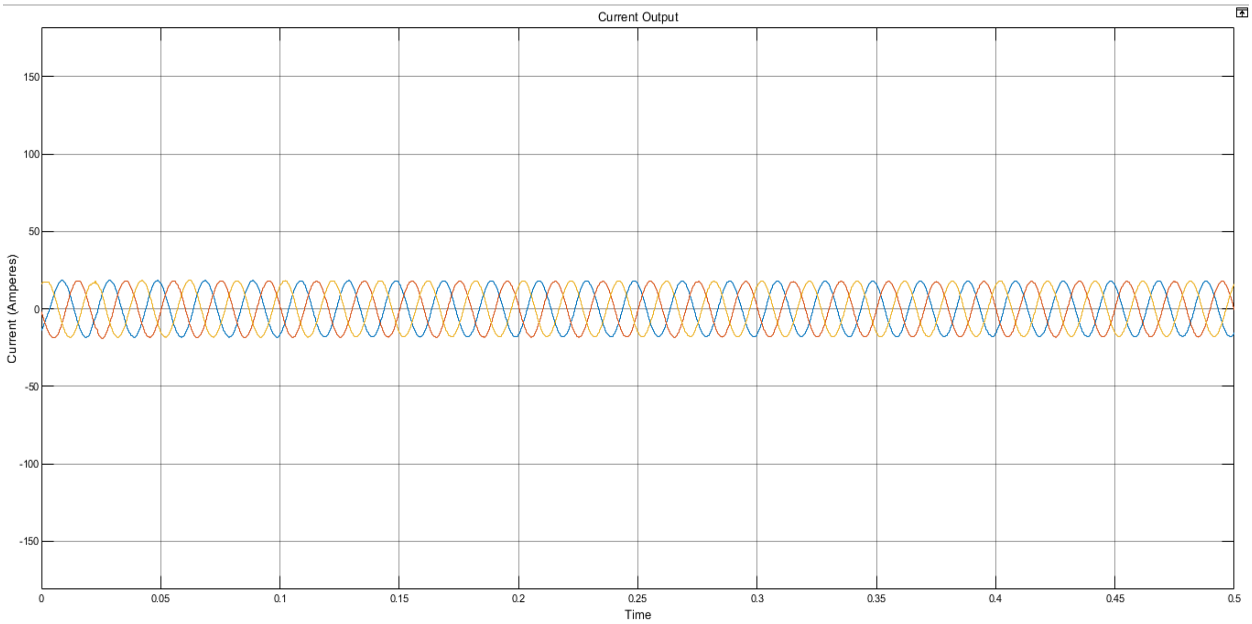

Figure 23 Current output from the converter driving loads before grid integration in system 2

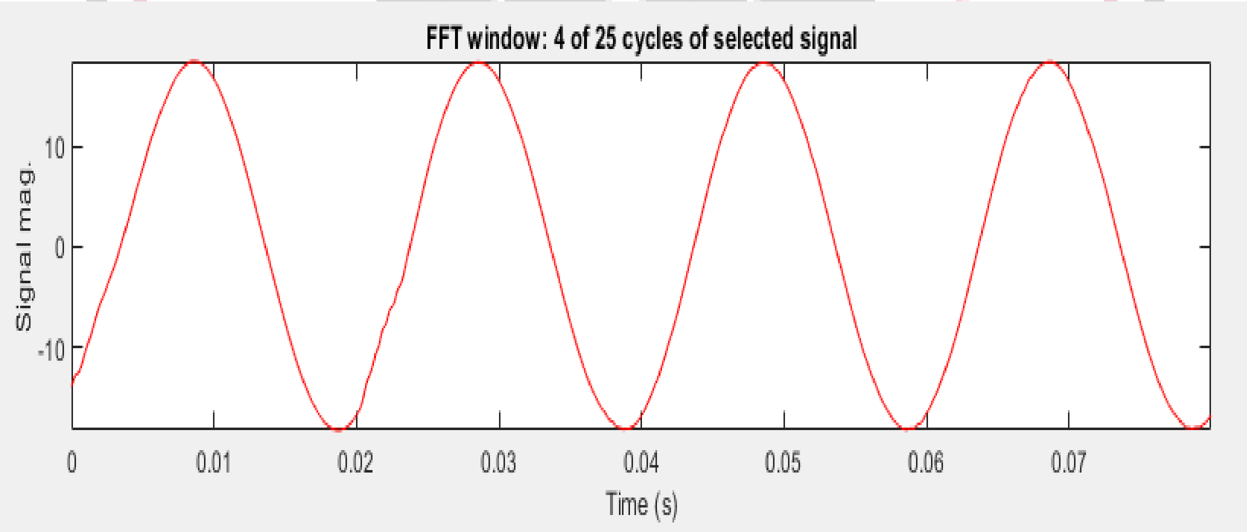

Figure 24 FFT analysis of current output from the converter in LV line driving loadsin system 2

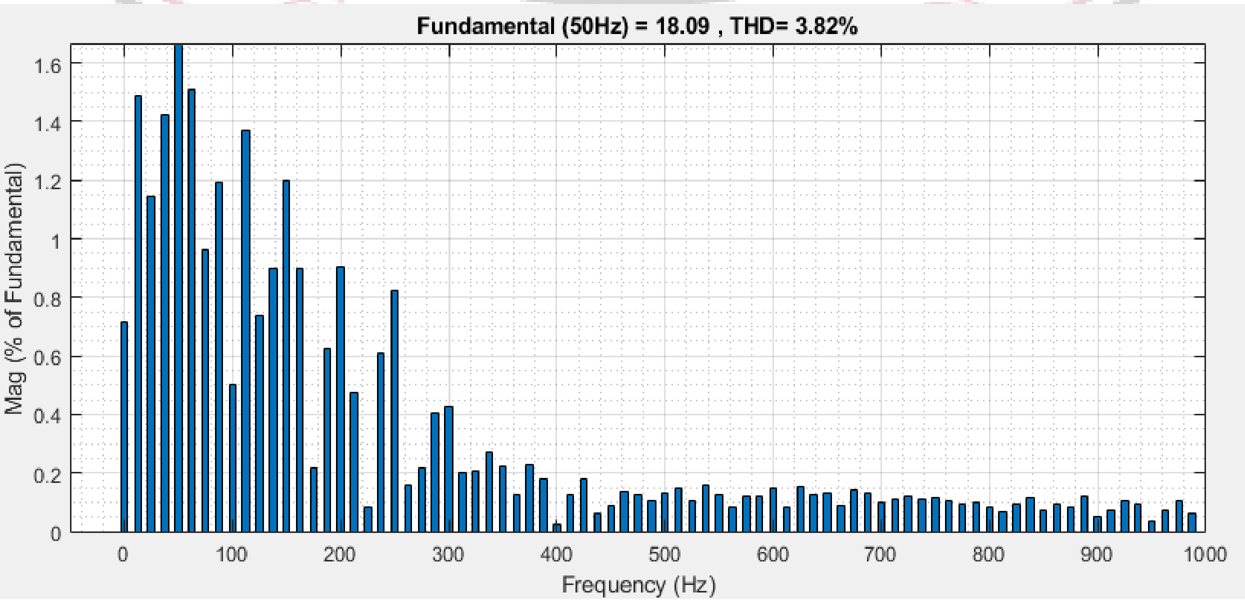

Figure 25 THD% measured in current output from the converter in LV line driving loadsin system 2

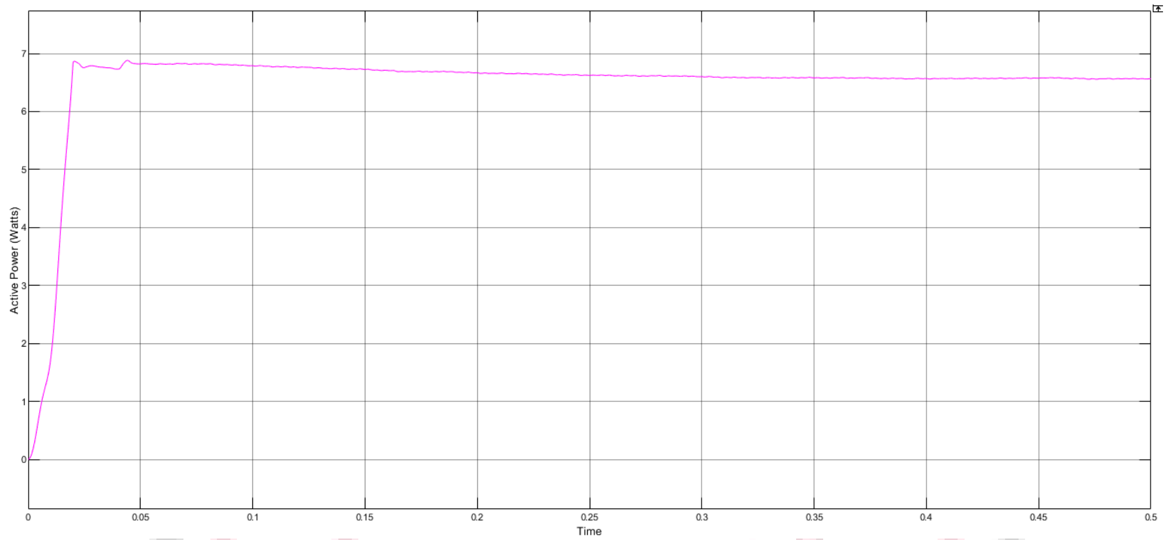

Figure 26 Active Power output inBESS system driving LV line loads having converters with control of system 2

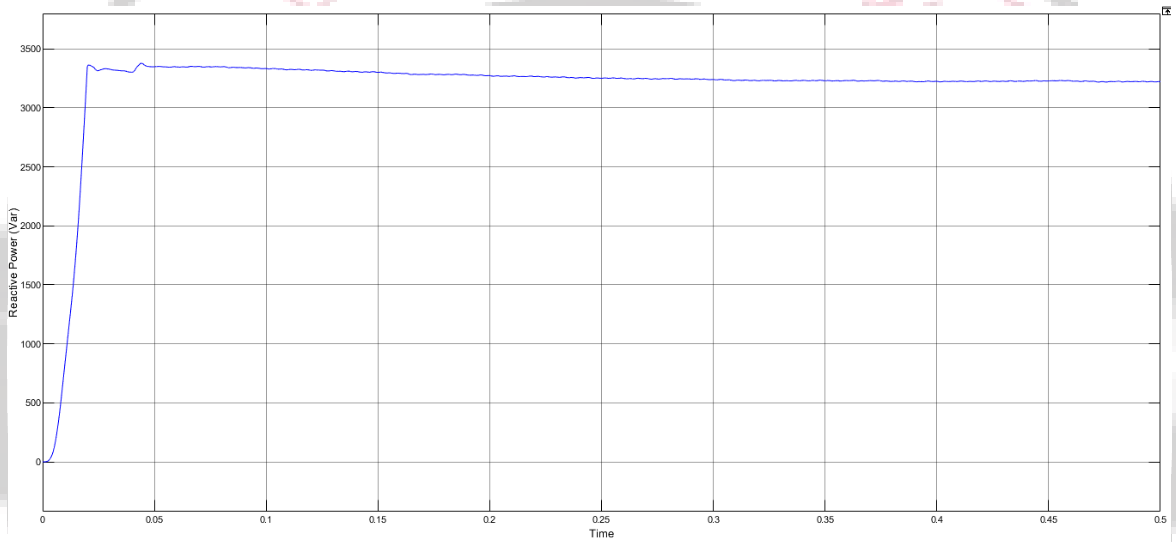

Figure 27 Reactive Powerin LV line with converters having control as in system 2

Table 3 Comparative analysis of distortion parameters on the low-voltage line of the BESS using two converter control methods

Parameters/ Model	'System 1 performance at the LV line'	'System 2 performance at the LV line'
'Active Power' (KWatts)	6.142	6.565
'Voltage' (Volts)	410	410
'Current' (Ampere)	17.98	18.09
'THD% in voltage'	4.84	4.03
'THD% Current'	4.27	3.82

The proposed converter aims to enhance the active output power of the system framework and ensure stable output. The inverter converts DC input to AC, which is then integrated into the grid system via a transformer connected to a high-tension line. Various loads are also connected to this system, and their analysis follows. The HL_GA control proposed for the inverter's controller improves the active output power, allowing connection of higher-power loads compared to the previous model. Additionally, there is a slight improvement in the power factor

CASE 2: Analyzing the impacts on the high voltage line driving heavy loads (electric drive and reactive load)

The converters performance is evaluated after the systems are connected to the grid through a power transformer. Here the high voltage line of 11KV drives two types of loads i.e reactive and electric drive if variable nature. The analysis has been drawn for both the loads in the two systems crying different types of converter control and the THD% is evaluated at these load terminals. This is done to study the impacts on the HV line quality at the loading points due to changes in the converter control system.

Analysis of impacts on the high voltage line at the electric drive and reactive load terminal after integration with grid in system 1

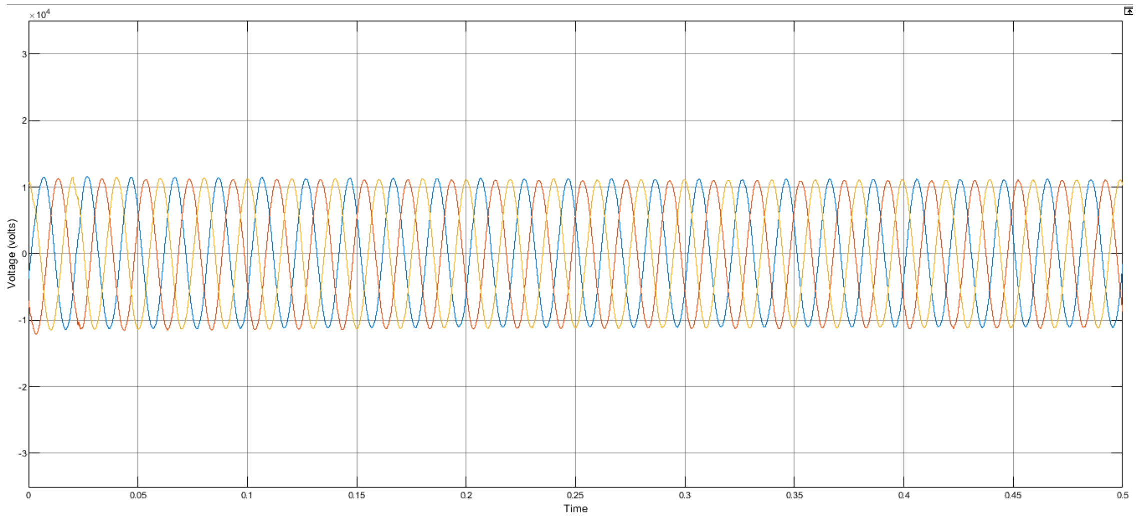

Figure 28 Voltage available at the HV line load terminal of electric drive in system 1

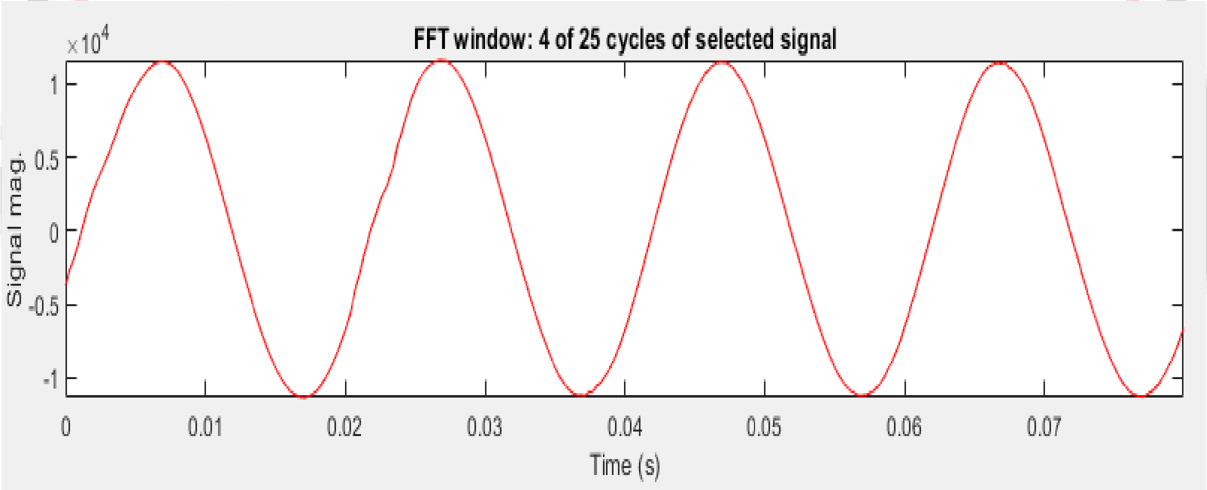

Figure 29 FFT analysis of Voltage available at the HV line load terminal of electric drive in system 1

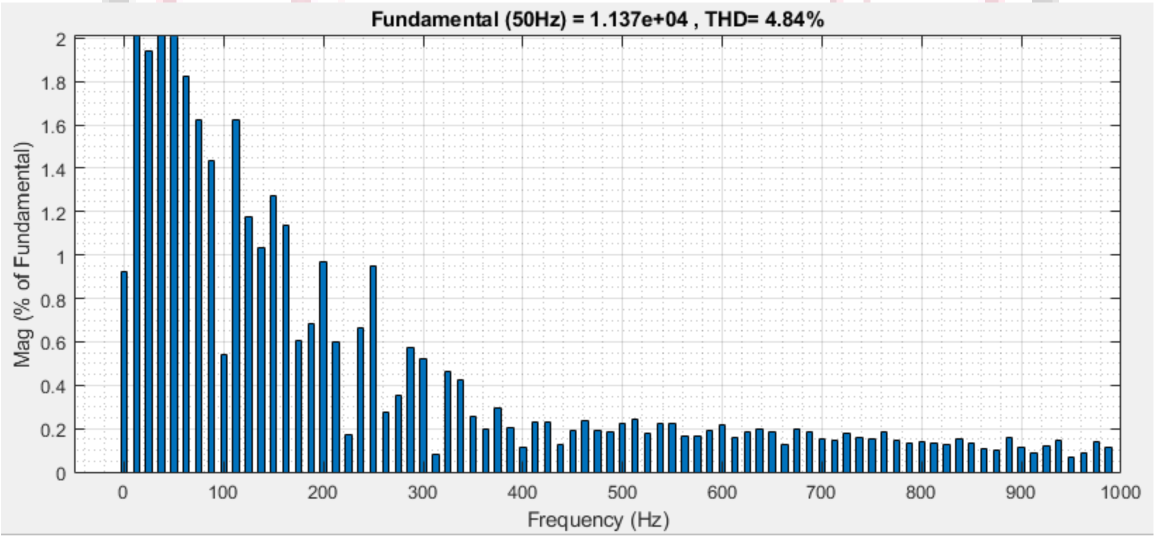

Figure 30 THD% of Voltage available at the HV line load terminal of electric drive in system 1

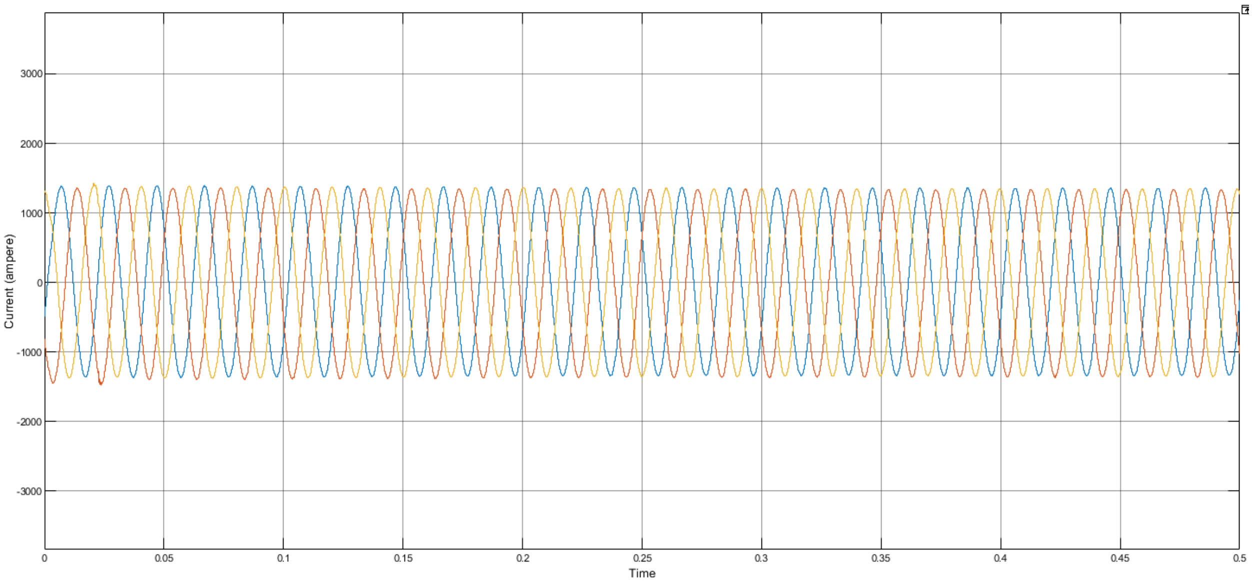

Figure 31 Current available at the HV line load terminal of electric drive in system 1

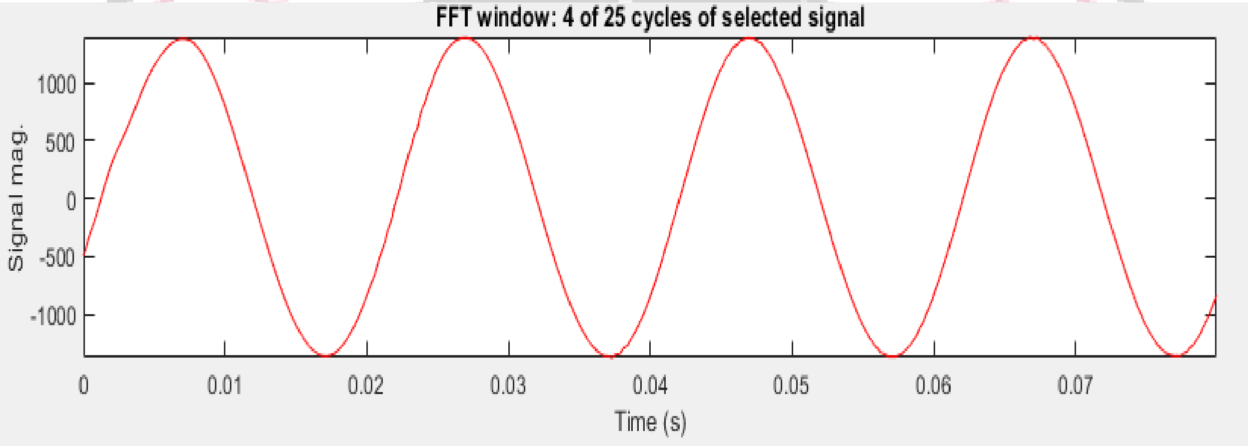

Figure 32 FFT analysis of Current available at the HV line load terminal of electric drive in system 1

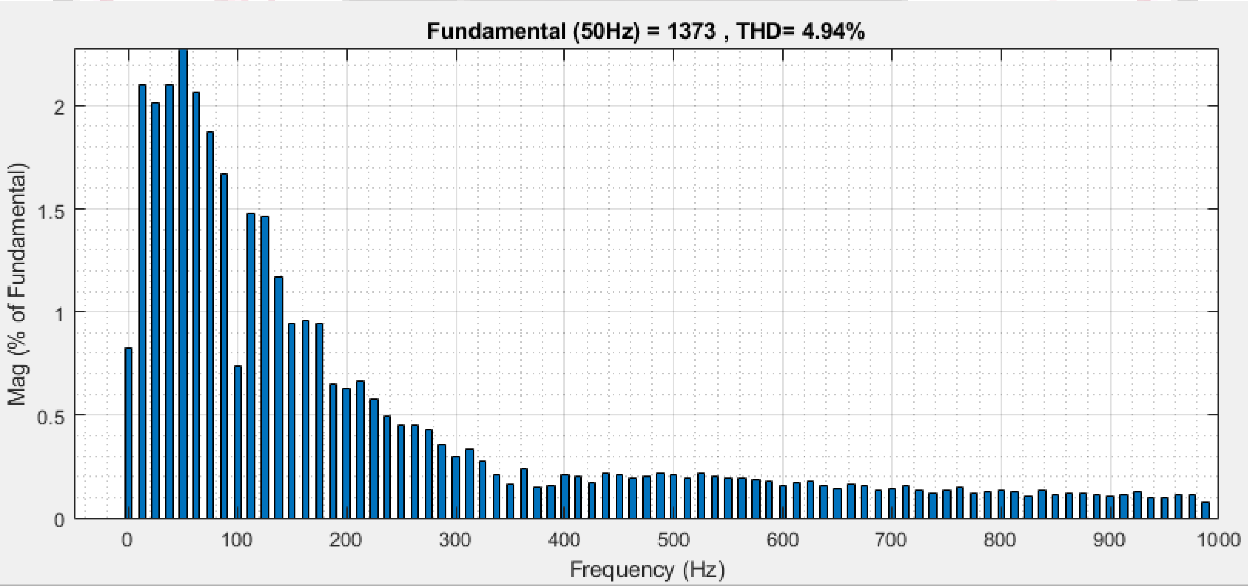

Figure 33 THD % in Current available at the HV line load terminal of electric drive in system 1

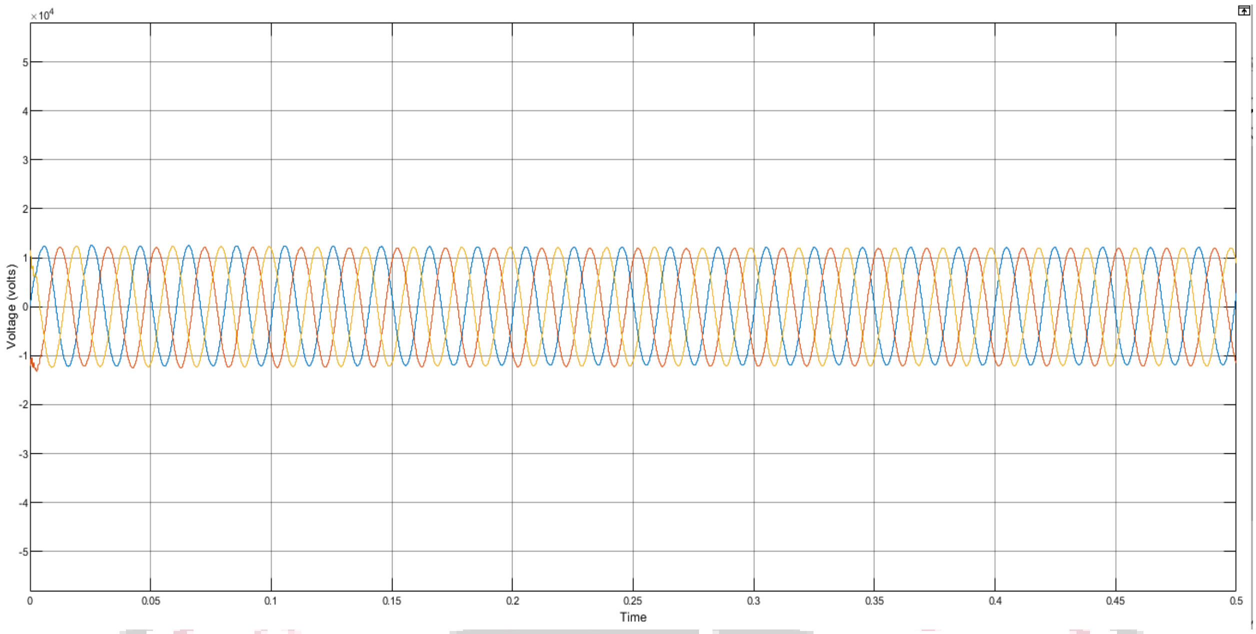

Figure 34 Voltage available at the HV reactive load terminal line of system 1

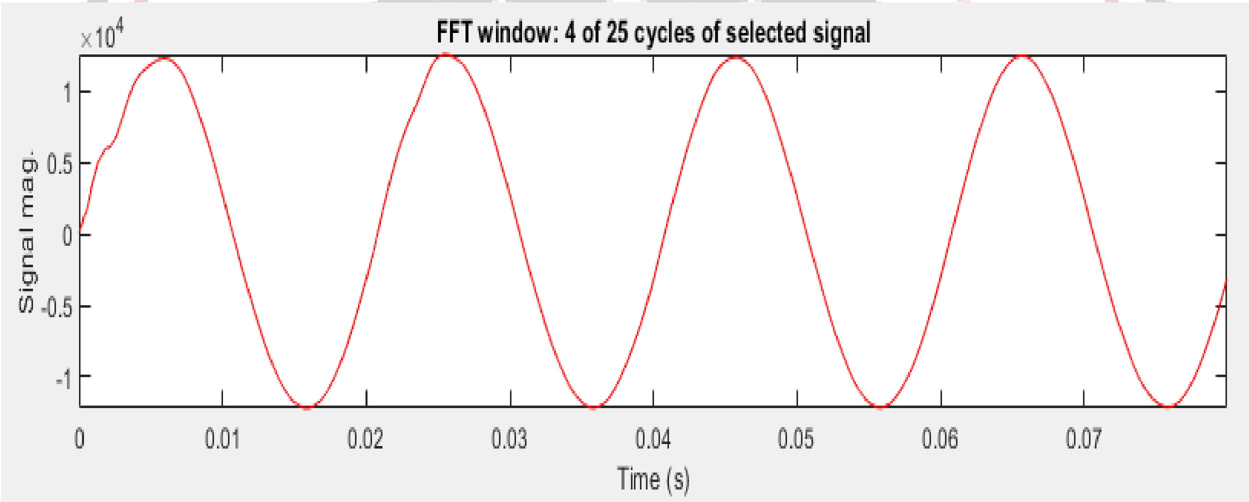

Figure35 FFT analysis of Voltage available at the HV reactive load terminal line of system 1

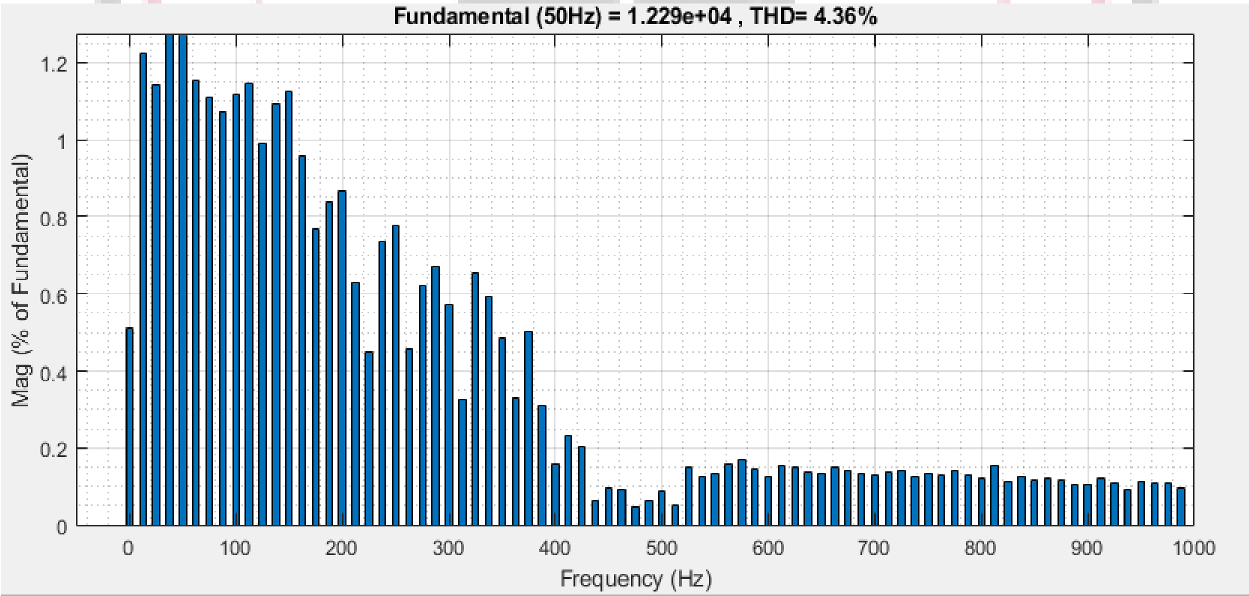

Figure 36 THD% in Voltage available at the HV reactive load terminal line of system 1

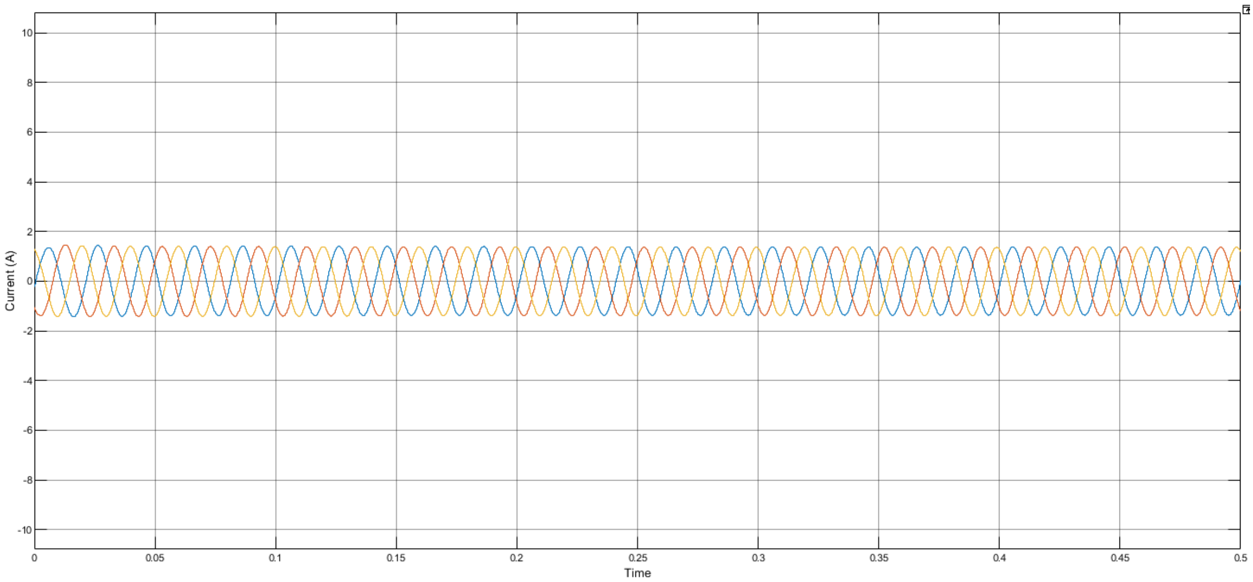

Figure 37 Current available at the HV reactive load terminal line of system 1

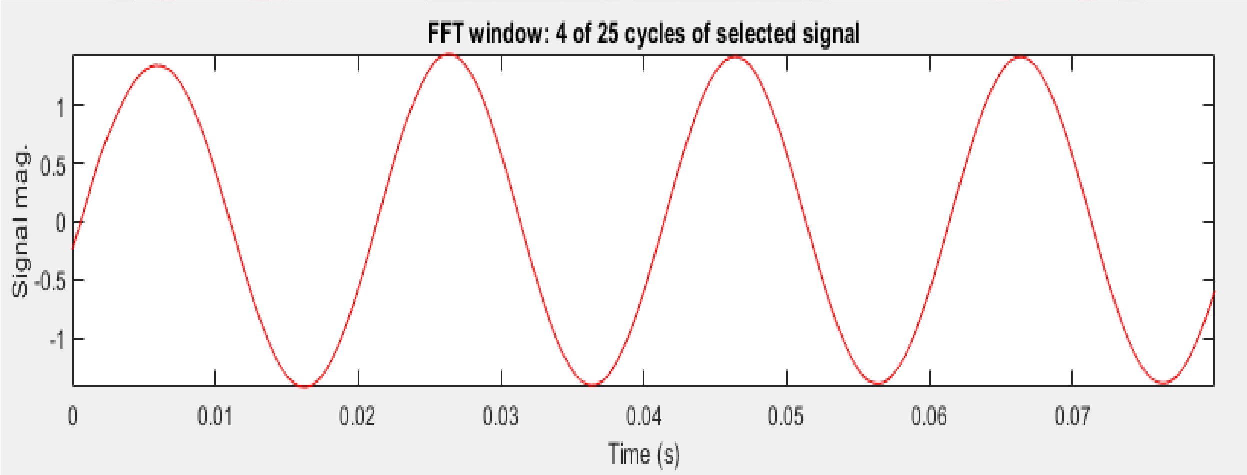

Figure 38 FFT analysis of Current available at the HV reactive load terminal line of system 1

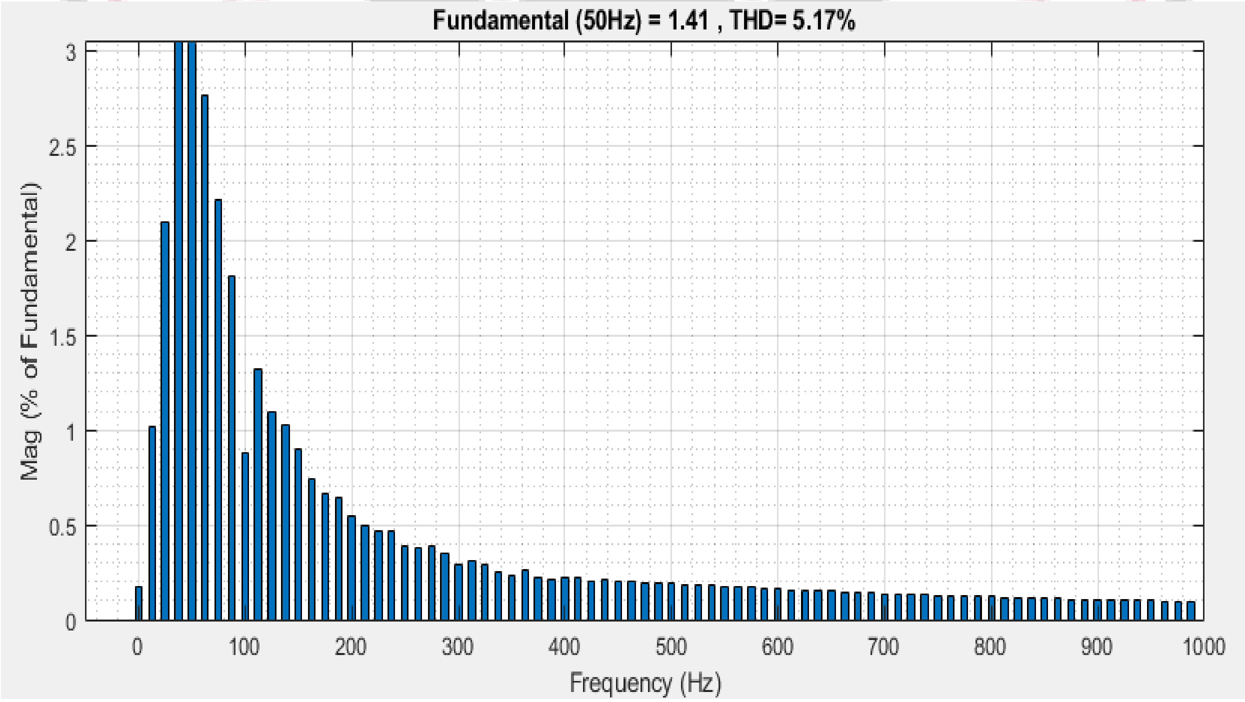

Figure 39 THD% in Current available at the HV reactive load terminal line of system 1

Analysis of impacts on the high voltage line at the electric drive and reactive load terminal after integration with grid in system 2

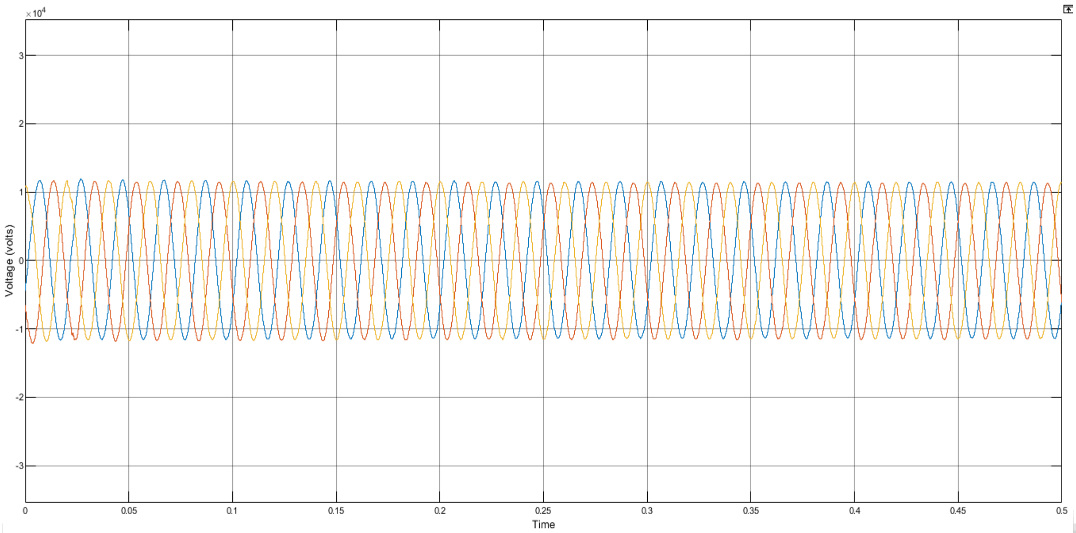

Figure 40 Voltage available at the HV line load terminal of electric drive in system 2

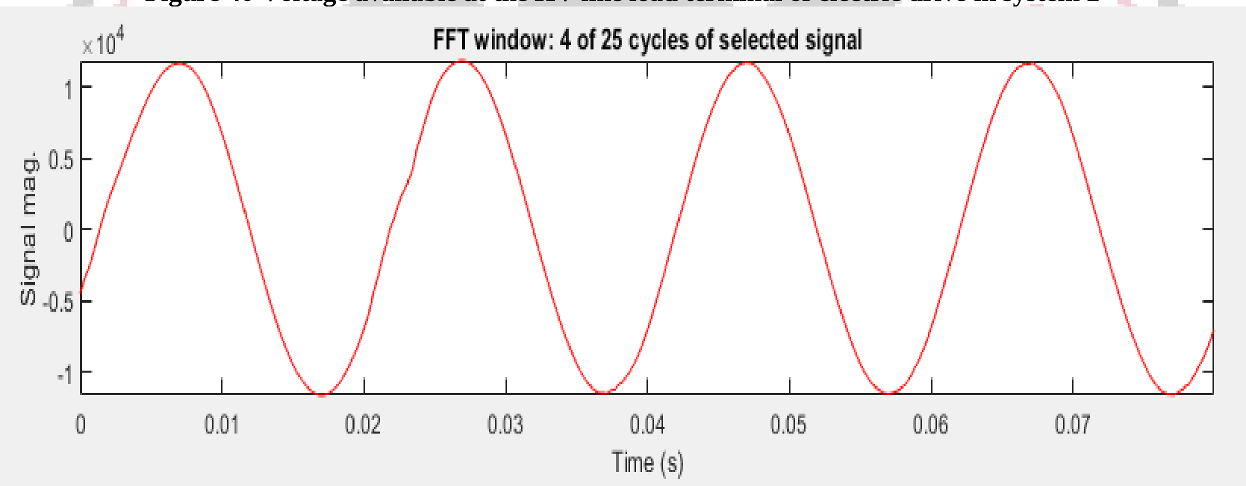

Figure 41 FFT analysis ofVoltage available at the HV line load terminal of electric drive in system 2

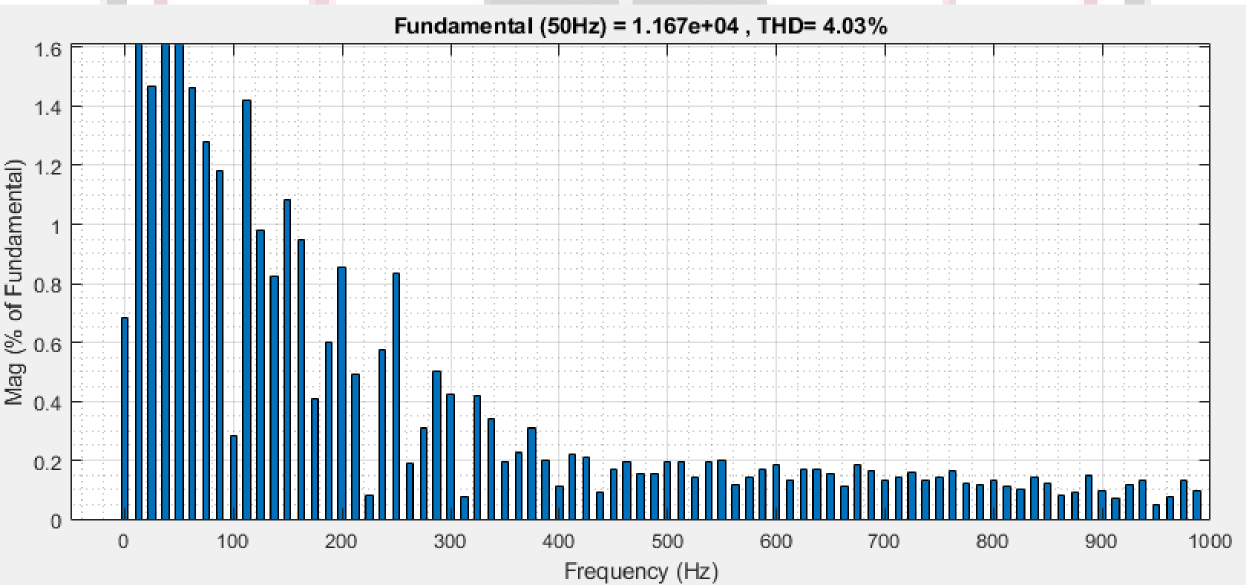

Figure 42 THD% in voltage available at the HV line load terminal of electric drive in system 2

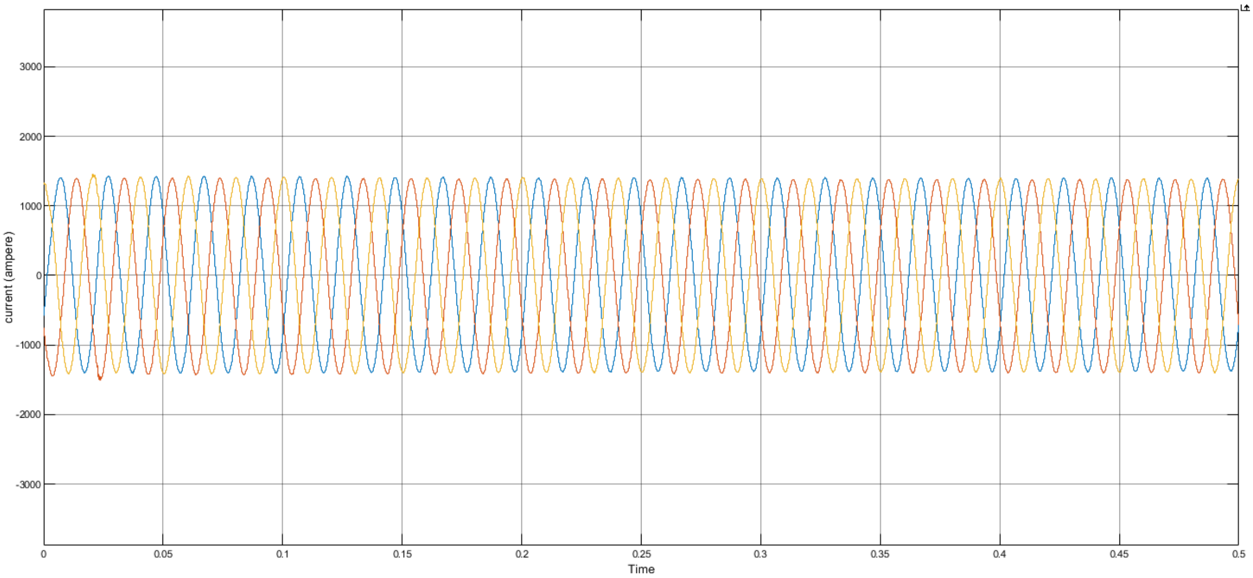

Figure 43 Current available at the HV line load terminal of electric drive in system 2

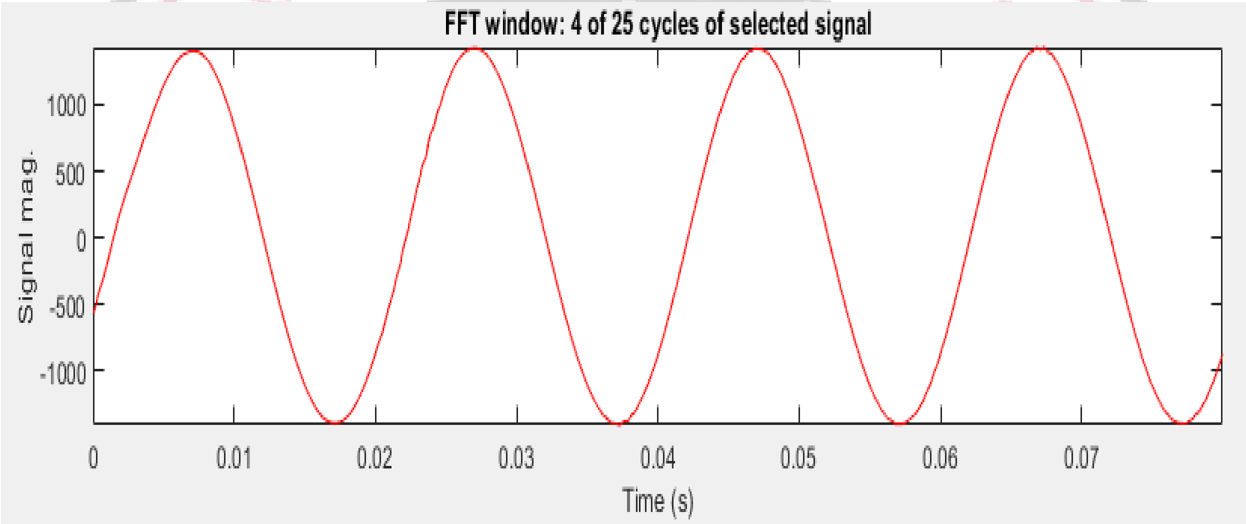

Figure 44 FFT analysis of current available at the HV line load terminal of electric drive in system 2

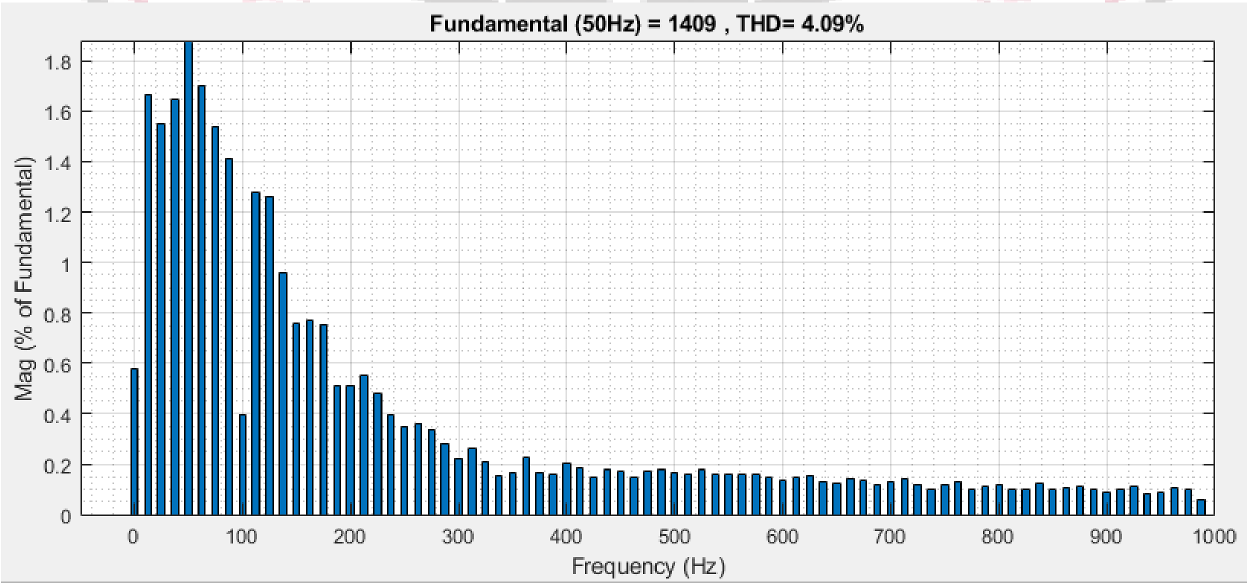

Figure 45 THD% incurrent available at the HV line load terminal of electric drive in system 2

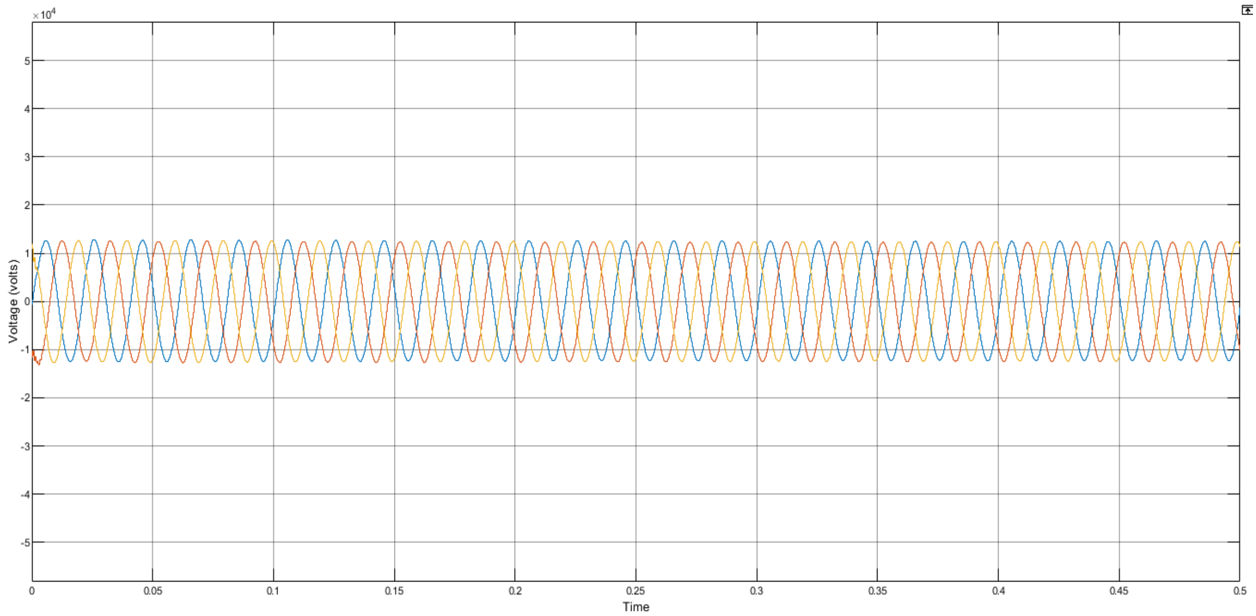

Figure 46 Voltage available at the HV line reactive load terminal of system 2

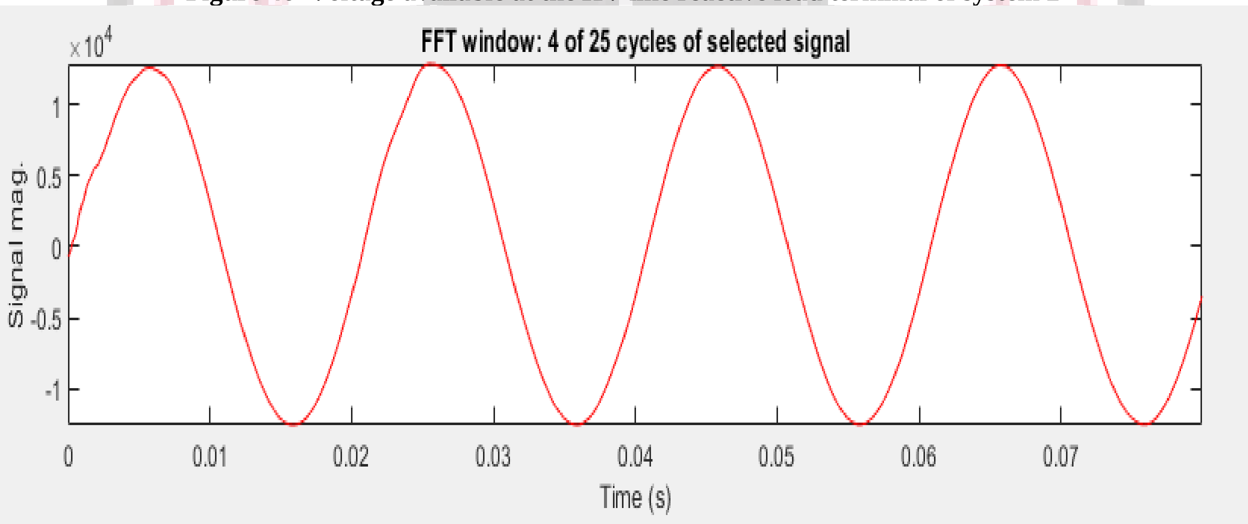

Figure 47 FFT analysis of Voltage available at the HV line reactive load terminal of system 2

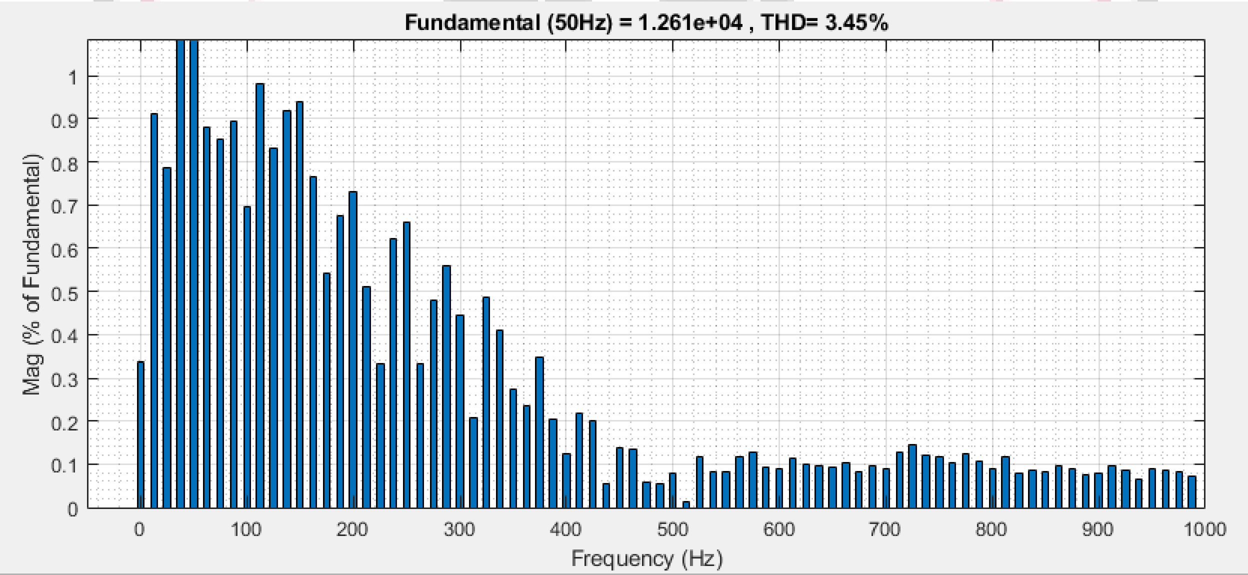

Figure 48 THD % in Voltage available at the HV line reactive load terminal of system 2

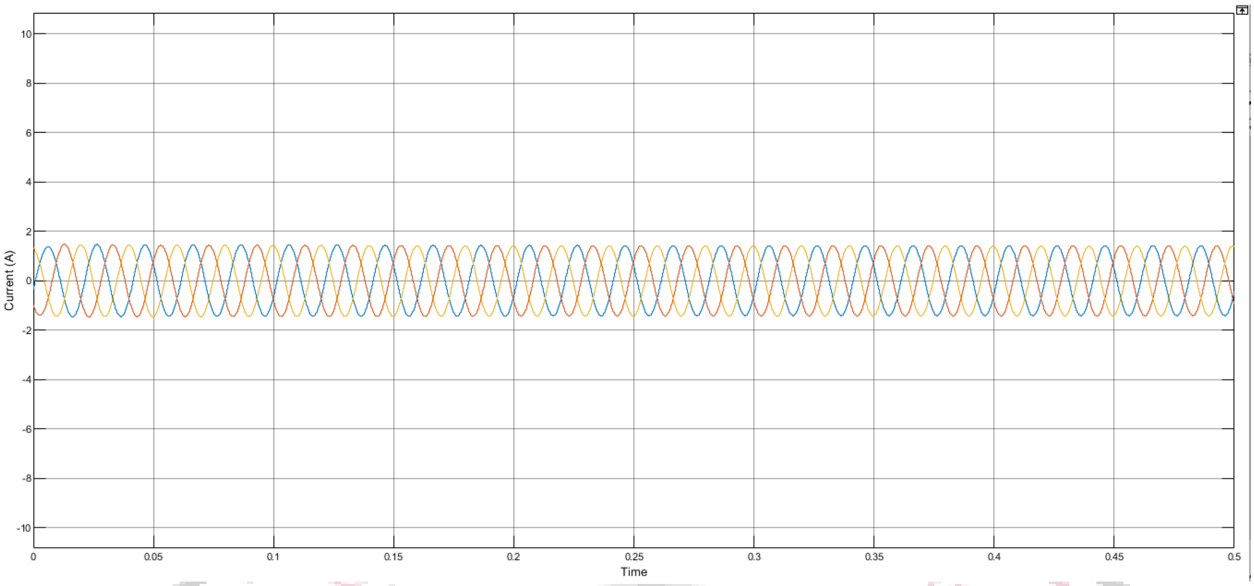

Figure 48 Current available at the HV line reactive load terminal of system 2

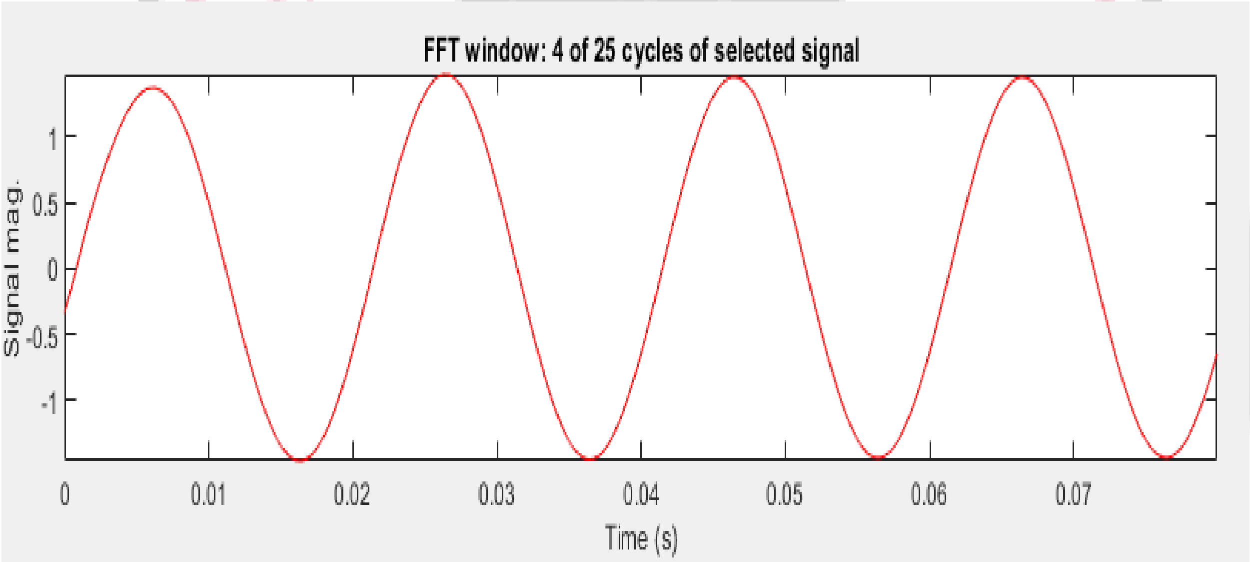

Figure 49 FFT analysis of Current available at the HV line reactive load terminal of system 2

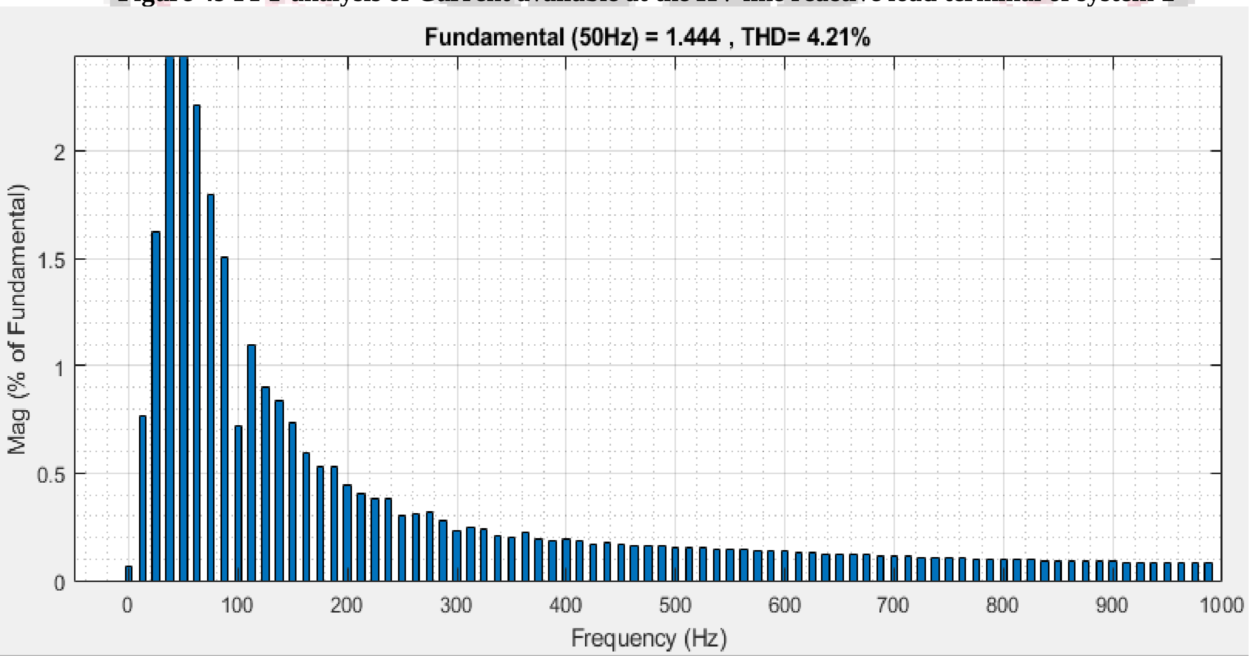

Figure 50 THD% in Current available at the HV line reactive load terminal of system

Table 4 Comparison of two controllers with distortion measurement at the high-voltage line of the BESS				
Parameters	**(System 1 in HV Line)**		**(System 2 in HV line)**	
	'Electric drive terminal'	**'Reactive load terminal'**	**'Electric drive terminal'**	**'Reactive load terminal'**
THD% in voltage	4.84	4.36	4.03	3.45
THD % in current	4.94	5.17	4.09	4.21

Based on the previous figures evaluating THD% at the load terminals of two loads, it is evident that the current distortion levels at the load terminals, which are expected to vary, are reduced with the HL_GA controller in system 2. Specifically, THD% levels decrease from 5.17% to 4.21% at the reactive load point and from 4.94% to 4.09% at the electric drive load point compared to system 1. Similar variations are noted in the THD% of voltage waveforms at the load points. While these differences between the systems are slight, the developed controller has proven to be an effective choice for managing the inverter within the framework.

VI. CONCLUSION

This study demonstrates successful optimization of Battery Energy Storage Systems (BESS) integrated with an AI-based controller to enhance power quality in LV and HV power grids. By employing the HL_GA algorithm, the BESS effectively mitigates voltage and current distortions, leading to significant improvements in active power output and THD reduction. The research highlights BESS's crucial role in improving grid stability amidst renewable energy source fluctuations and load variations. Future research directions include further refining control strategies, assessing scalability for grid-scale applications, and integrating BESS with smart grid technologies for enhanced system efficiency and reliability. Ultimately, this study advances the application of BESS in modern power systems, supporting the transition to sustainable and resilient energy infrastructures.

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