Power System Quality and Reliability

ECEg-6312

WEEK 8

Power Quality Case Studies and Mitigation using PQC

Course Instructor: Demsew Mitiku (PhD)

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Topic Overview

- This week's discussion focuses on sample power quality case studies and mitigation mechanism using power quality conditioning techniques in an electrical power systems to enhance system performance and reliability.
- Furthermore we will discuss about:
  1. Power Quality Analyzer
  2. Matlab/Simulink Model and Analysis using PQC
  3. Harmonic Analysis in Matlab

Learning Outcomes

By the end of this lesson, students will be able to:

- Analyze sample power quality (PQ) case studies to identify key disturbances such as **harmonics**, voltage **sag**/swell, and waveform distortions affecting system performance.
- Perform harmonic analysis using MATLAB tools (e.g., FFT analysis) to quantify Total Harmonic Distortion (THD) and assess compliance with standards such as IEEE 519.
- Evaluate and apply appropriate Power Quality Conditioning (PQC) techniques (e.g., DSTATCOM, **DVR**, or **Filters**) to mitigate identified disturbances and improve system reliability and efficiency.

1. Introduction

- In this lecture, we will examine common power quality problems in electrical power systems and explore effective mitigation techniques.
- These concepts will be illustrated through practical case studies using standard **IEEE test** networks and **industrial** power supply system.
- Power Quality in Modern Power Systems is defined as deviation of voltage/current from ideal sinusoidal waveform due to:
  - Power electronic **converters**
  - **Renewable** energy integration
  - **Nonlinear** loads

Defining "Good" Power Quality

- "**Good**" Power Quality is the provision of a **steady** and **reliable** electrical supply that stays within specific tolerance limits, ensuring that connected equipment operates without **malfunction** or **premature failure**.
- The Three Pillars of Power Quality:

1. Steady Voltage Magnitude

  - Maintaining supply voltage within prescribed RMS (Root Mean Square) ranges.
  - Standard: Typically ±5% to ±10% of the nominal rating (e.g., ANSI C84.1).

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2. Constant Frequency:

- Stability at the nominal 50 Hz or 60 Hz.
- Deviations can lead to timing errors in electronics and overheating in motors.

3. Pure Sinusoidal Waveform:

- A "clean" sine wave free from **distortions**, **spikes**, or **notches**.
- Distortions (Harmonics) are caused by non-linear loads like **VFDs**, LED lighting, and **computers**.
- Real-world grids face "**pollution**" from **switching** events, **lightning**, and heavy industrial startups.

Classification of PQ Problems

- Power quality issues are generally categorized by the duration and nature of the disturbance.

1. Transients (Impulsive & Oscillatory) [1]:

  - **Definition:** Sudden, high-frequency events that last for microseconds.
  - **Causes:** Lightning strikes, electrostatic discharge, or switching of inductive loads (e.g., motors).
  - **Impact:** Insulation breakdown and permanent hardware damage.

2. Voltage Variations [2]:

  - **Sags (Dips):** A decrease in RMS voltage (0.1 to 0.9 pu) for 0.5 cycles to 1 minute.
  - **Swells:** An increase in RMS voltage (1.1 to 1.8 pu).
  - **Long Duration:** Sustained Overvoltages or Undervoltages (lasting >1 minute).

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3. Harmonics [1],[2]:

- **Definition:** Voltages or currents at frequencies that are integer multiples of the fundamental frequency (e.g., 180Hz is the 3rd harmonic of 60Hz).
- **Causes:** Non-linear loads like VFDs, rectifiers, and switched-mode power supplies.
- **Impact:** Transformer overheating, neutral wire overload, and "ghost" tripping of breakers.

4. Grounding Issues:

- **Definition:** Problems arising from poor connections between the electrical system and the earth.
- **Impact:** Electrical noise, safety hazards (shock), and data errors in sensitive communication equipment.

Need for Power Quality (PQ) Monitoring

- **Power Quality monitoring** is the proactive process of measuring and evaluating electrical parameters to ensure a stable supply [3], [4].
- It serves as an essential strategy for identifying "invisible" disturbances before they result in catastrophic failures.

1. Ensure System Reliability and Continuity

  - Detect voltage sags, swells, and interruptions that can trip critical loads (drives, PLCs, data centers).
  - Enable event correlation (faults, switching) to prevent recurring outages.

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2. Protect Equipment and Extend Asset Life

- Identify harmonics and unbalance that cause:
- Transformer and motor overheating
- Capacitor bank overstress/failure
- Support condition-based maintenance rather than reactive repairs.

3. Maintain Power Quality Compliance

- Verify adherence to standards such as IEEE 519 (THD/TDD limits at PCC).
- Provide auditable reports for regulators, utilities, and large customers.

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4. Quantify Harmonics and Distortions

- Measure THD, individual harmonic spectra, flicker indices.
- Locate dominant harmonic sources (e.g., 5th, 7th from 6-pulse converters).

5. Optimize PQ Mitigation Strategies

- Provide data to size and place:
    - Passive filters (LC)
    - Active filters / DSTATCOM / DVR / UPQC
- Validate before–after performance (e.g., THD reduction to <5%).

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6. Improve Energy Efficiency

- Reduce I^2R losses and stray losses caused by harmonics.
- Improve power factor and voltage profile → lower operating costs.

7. Support Integration of Renewable Energy

- Monitor **inverter-induced harmonics** and **voltage fluctuations** from PV/wind.
- Ensure stable operation of microgrid and distributed generation (DG) systems.

8. Enable Advanced Analytics and Smart Grids [4]

- Feed high-resolution data into SCADA/EMS and analytics platforms.
- Facilitate predictive diagnostics, anomaly detection, and grid modernization.

2. Case Study 1: Harmonic Analysis of IEEE 13-Bus System

- This case study focuses on the **IEEE 13-Bus Distribution System**, a standard radial network often used to test unbalanced power flow and harmonic convergence.
- In this scenario, we analyze the impact of highly non-linear loads—specifically 15kW DC motors—on system-wide Total Harmonic Distortion (THD).

1. Network Configuration Overview

- **Test System:** IEEE 13-node Test Feeder, known for its short, heavily loaded, and unbalanced characteristics as shown in **Figure 1**.
- **Generation Sources:** Synchronous generators located at Bus 1 and Bus 4.
- **System Voltage:** Primarily **15 & 69 kV** with step-down transformers to **400V** for industrial loads.

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2. Load Profile Breakdown

- **Linear Loads:** Connected at Buses 2, 8, 12, and 13 to represent baseline residential or commercial consumption.
- **Non-Linear Loads (The Problem):** Two 15kW DC Motor Drives connected at Bus 7 and Bus 10.
- **DC motors** are modeled with rectifier interfaces that draw current in rapid, non-sinusoidal pulses.

3. Expected Harmonic Signatures

- **Dominant Orders:** Six-pulse rectifiers typically used in **15kW** drives will inject high **5th**, **7th**, 11th, and 13th harmonic currents.
- **Interaction:** Harmonics from Bus 7 and 10 may interact with system capacitance, causing resonance.

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4. Simulation Objectives in MATLAB/Simulink

- **Baseline:** Measure THD at the Point of Common Coupling (PCC) before motor startup.
- **Impact Analysis:** Analyze waveform notches and current ripple signature.
- **Verification:** Ensure the system meets IEEE 519 standards (typically <5% voltage THD).
- **To address the distortion** caused by the **15kW DC** motors at **Bus 7** and **10**, a **double tuned shunt LC** Passive Filter is designed and implemented.
- **The goal is to provide a low-impedance path** for specific harmonic frequencies (**f5=250Hz** and **f7=750Hz**), "trapping" them before they propagate to the rest of the IEEE 13-bus network.

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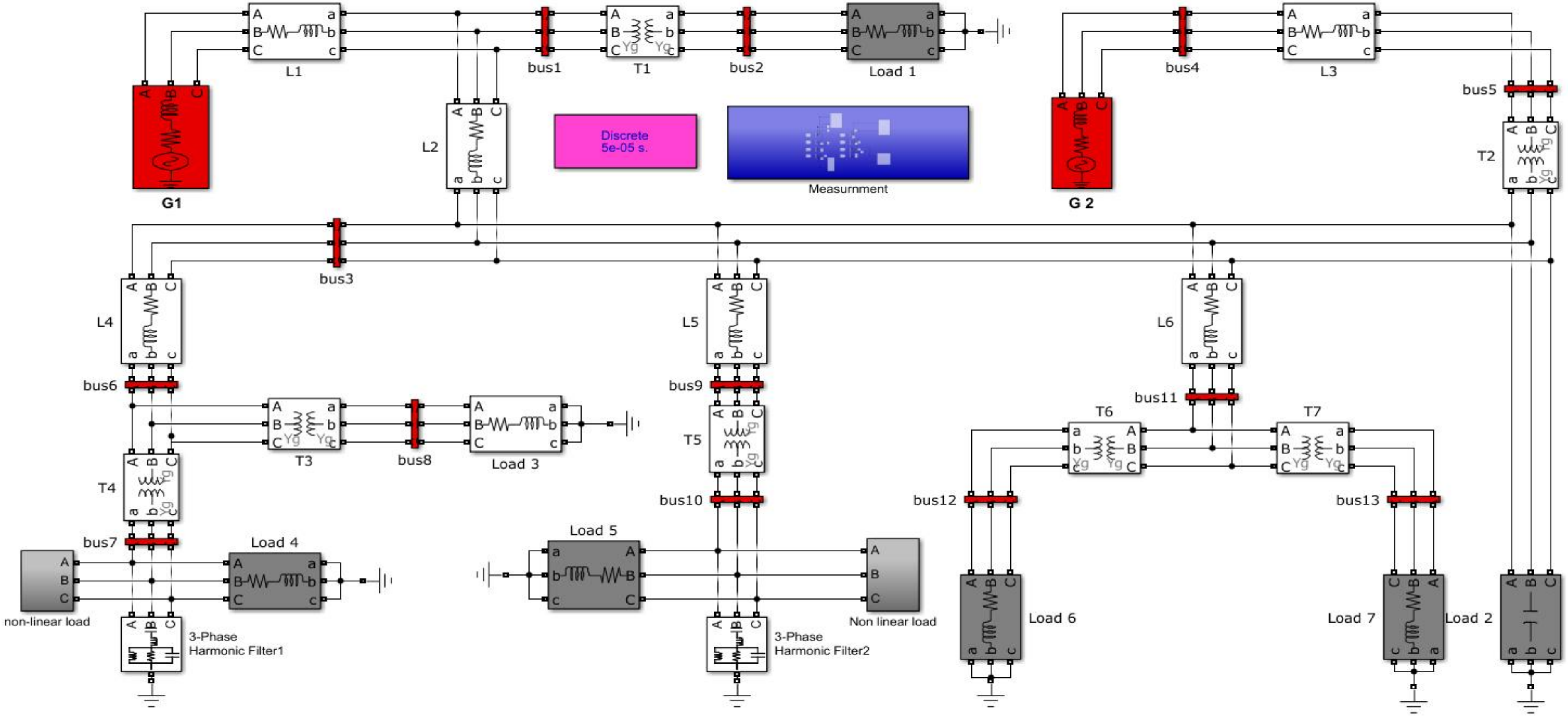

Figure 1: IEEE 13 Bus System For Harmonic Analysis.

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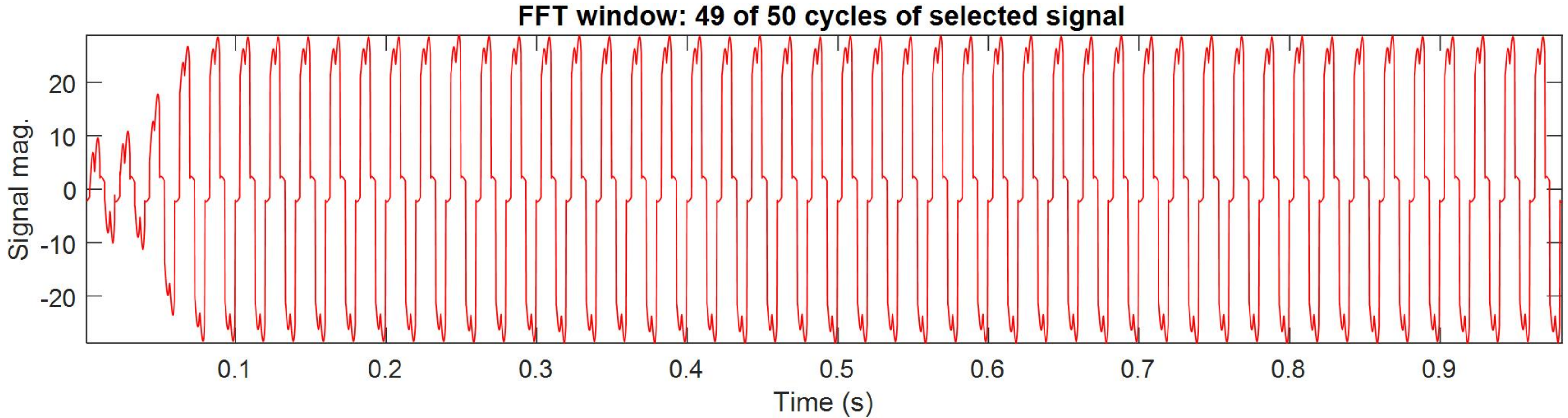
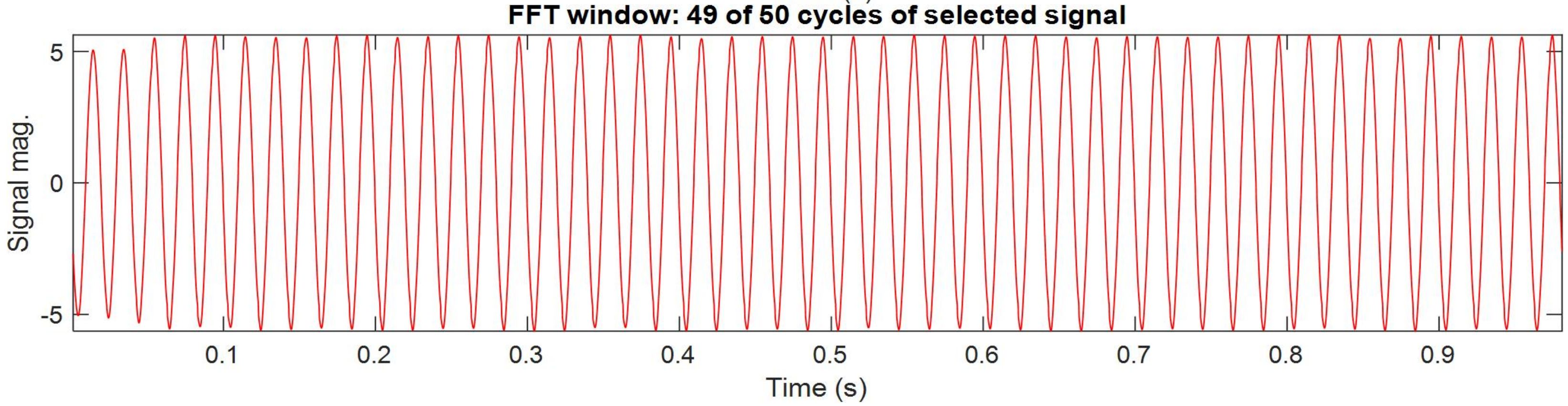


a. Current before SPF.



b. Current after filtering.

Figure 2: The Current waveform at bus 7 in IEEE 13 Bus System.

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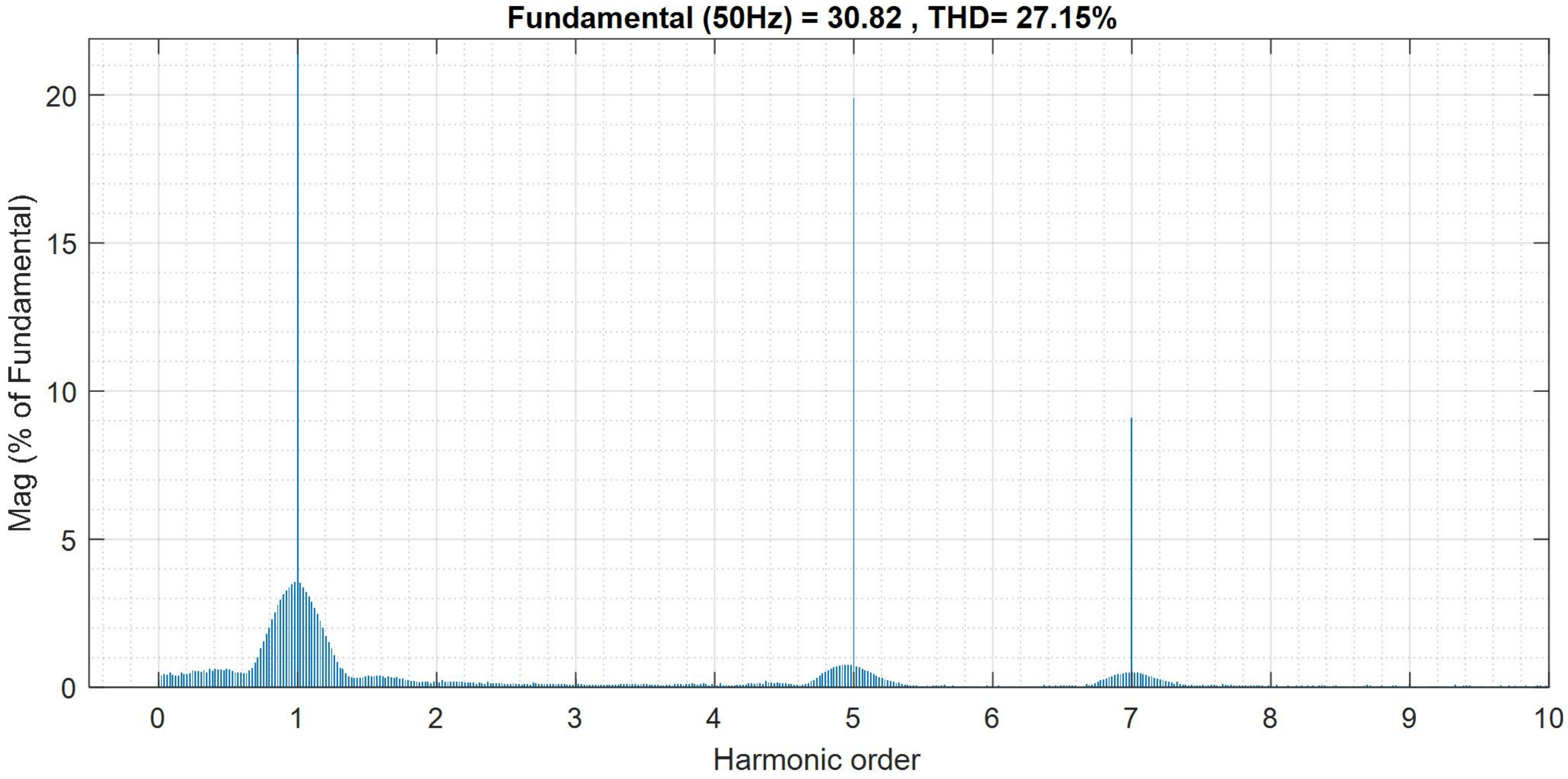

Figure 3: The Harmonic Spectrum of Current waveform at Bus 7 in IEEE 13 Bus System before SPF.

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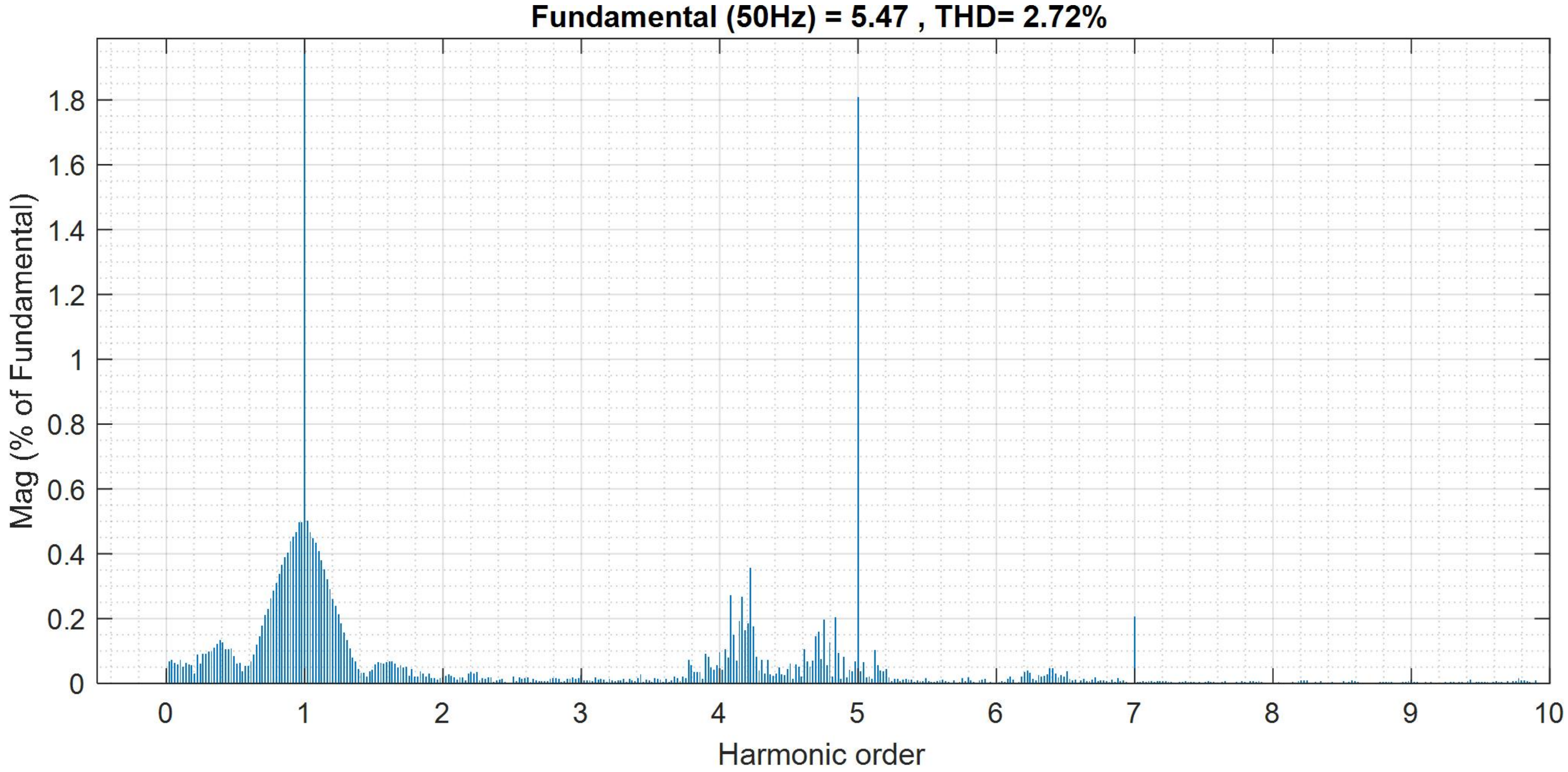

Figure 4: The Harmonic Spectrum of Current waveform at Bus 7 in IEEE 13 Bus System after SPF.

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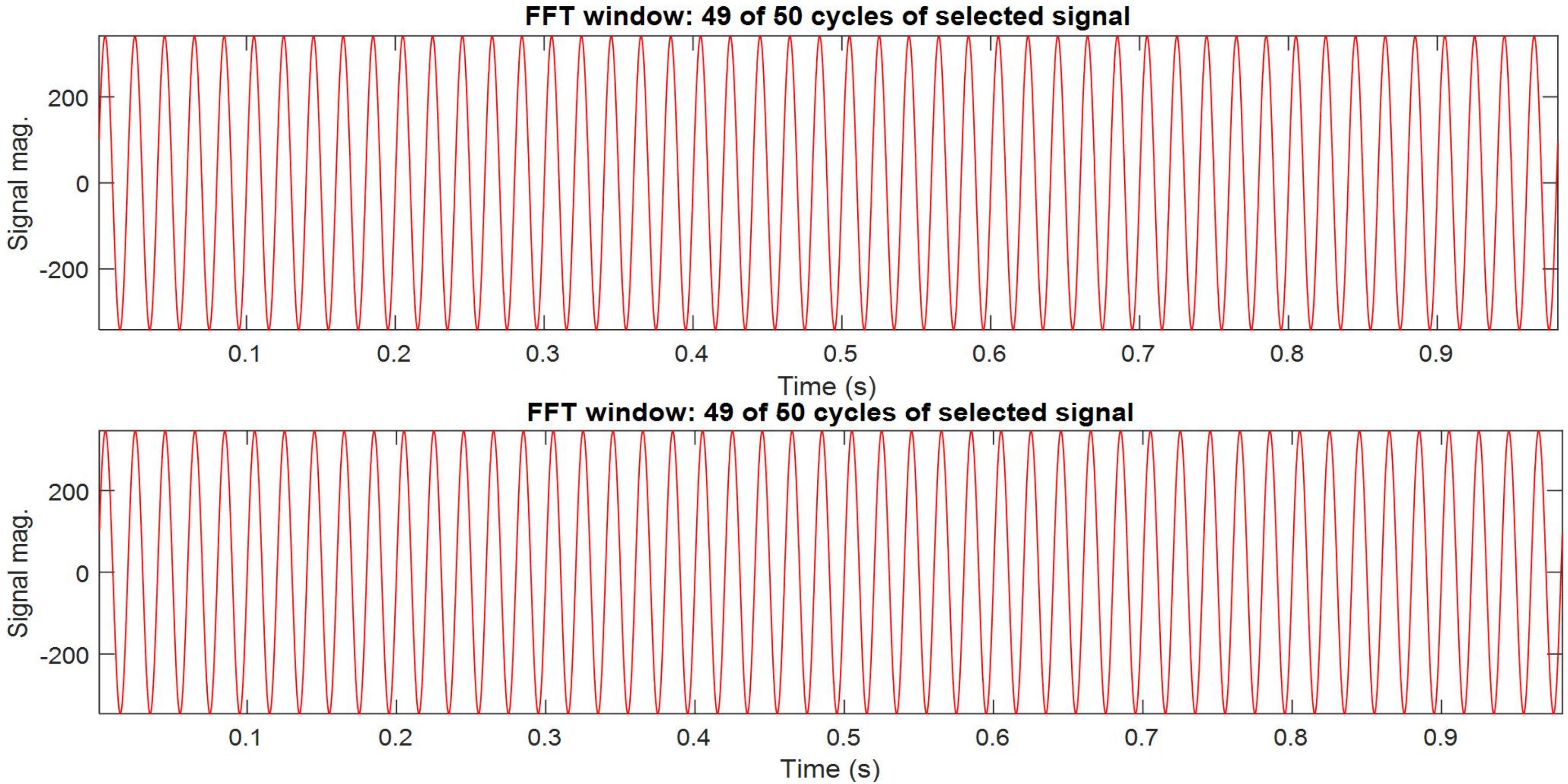

a. Voltage before SPF.

b. Voltage after SPF.

Figure 5: The Voltage waveform at bus 7 in IEEE 13 Bus System before and after SPF.

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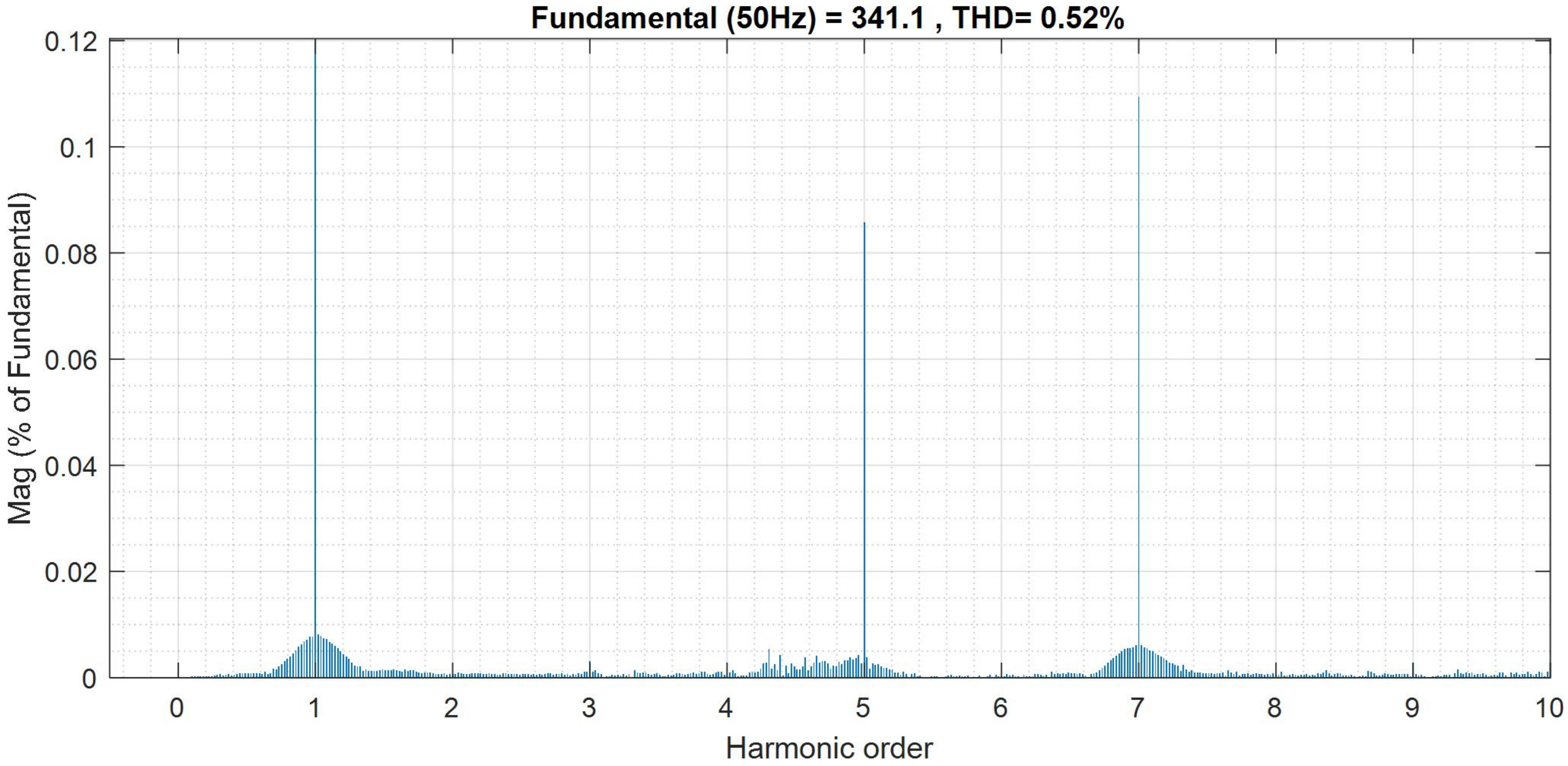

Figure 6: The Harmonic Spectrum of Voltage waveform at Bus 7 in IEEE 13 Bus System before SPF.

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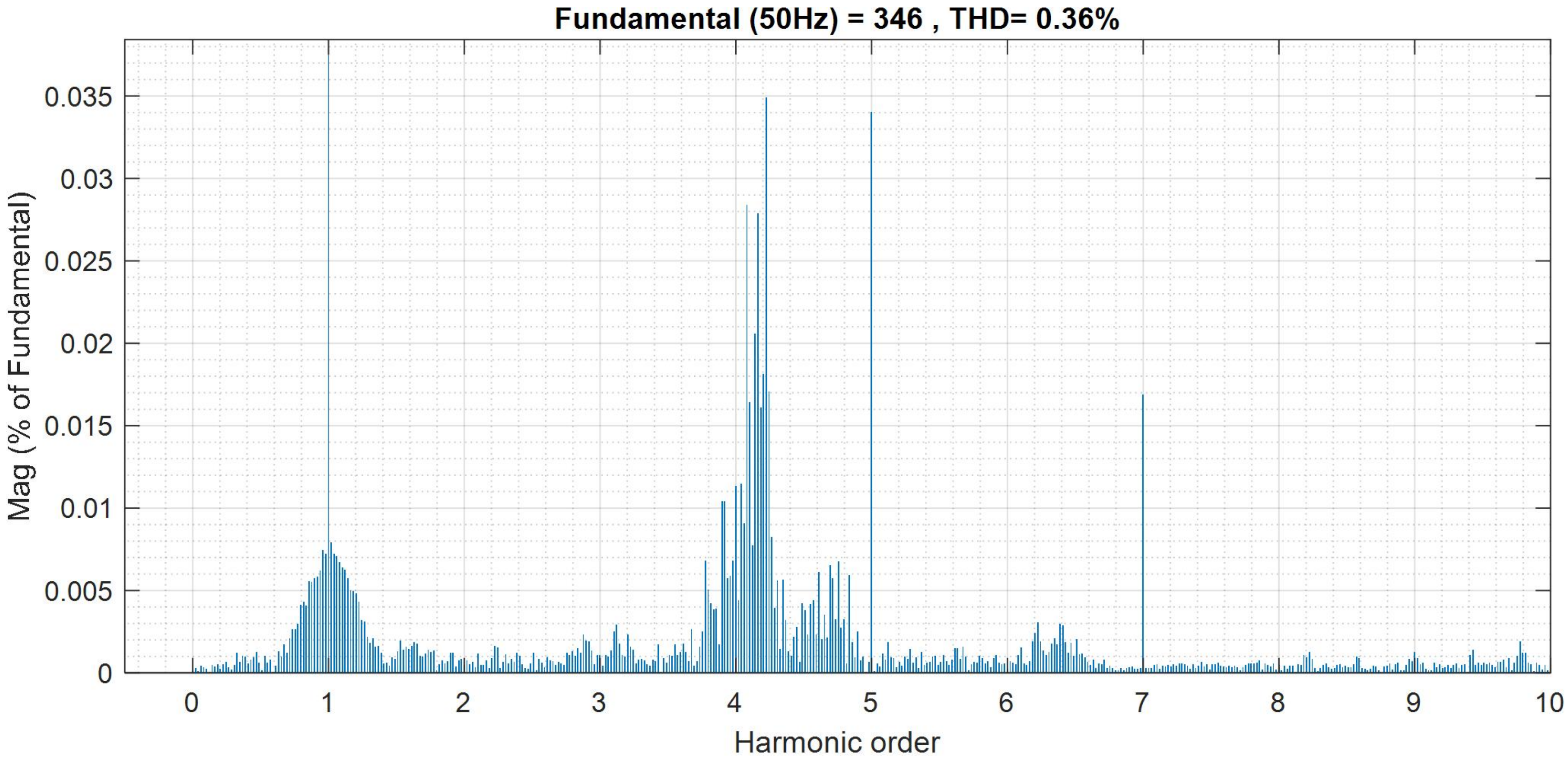

Figure 8: The Harmonic Spectrum of Voltage waveform at Bus 7 in IEEE 13 Bus System after SPF.

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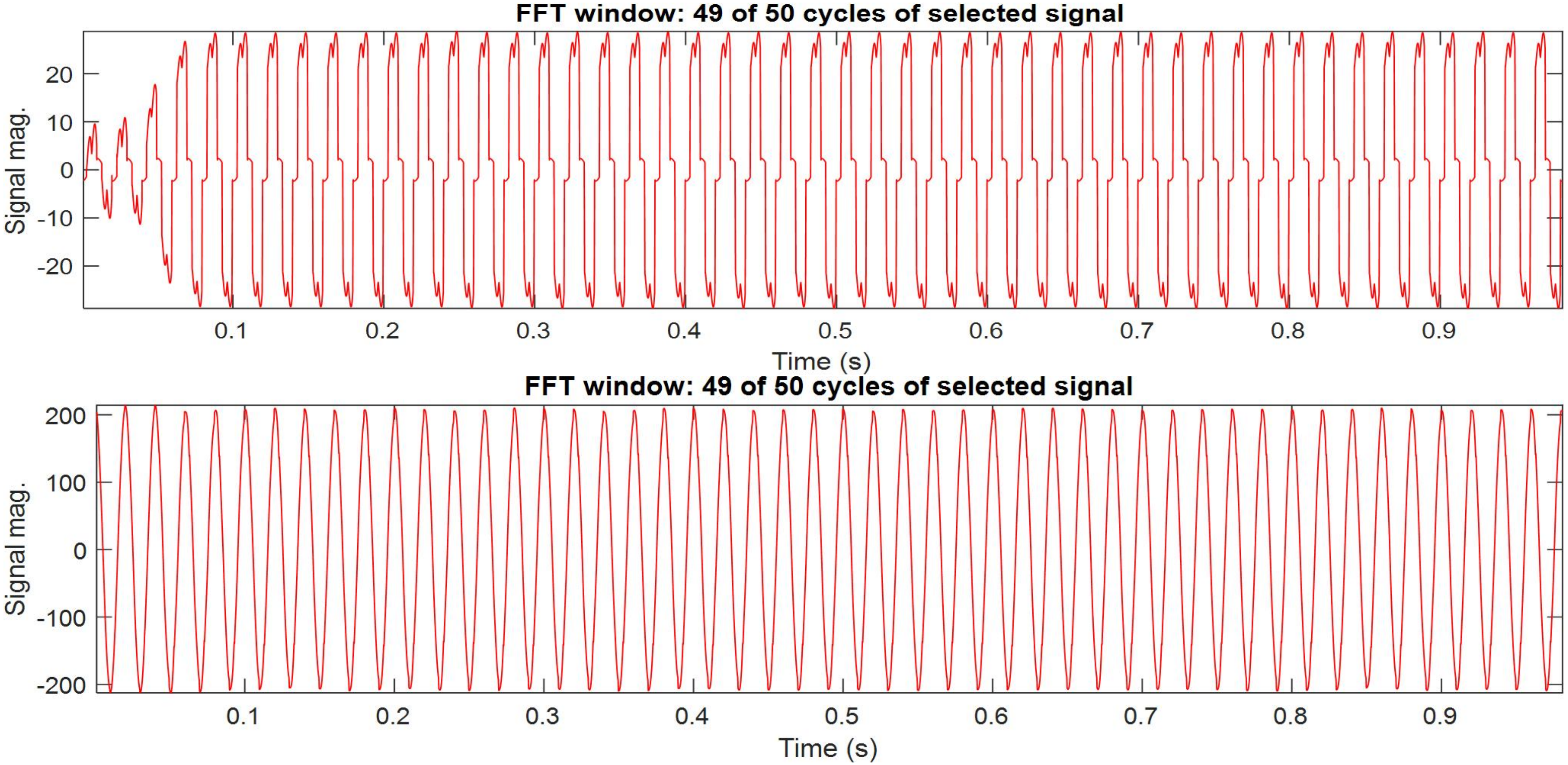

a. Current before SPF.

b. Current after filtering.

Figure 9: The Current waveform at Bus 10 in IEEE 13 Bus System before and after SPF.

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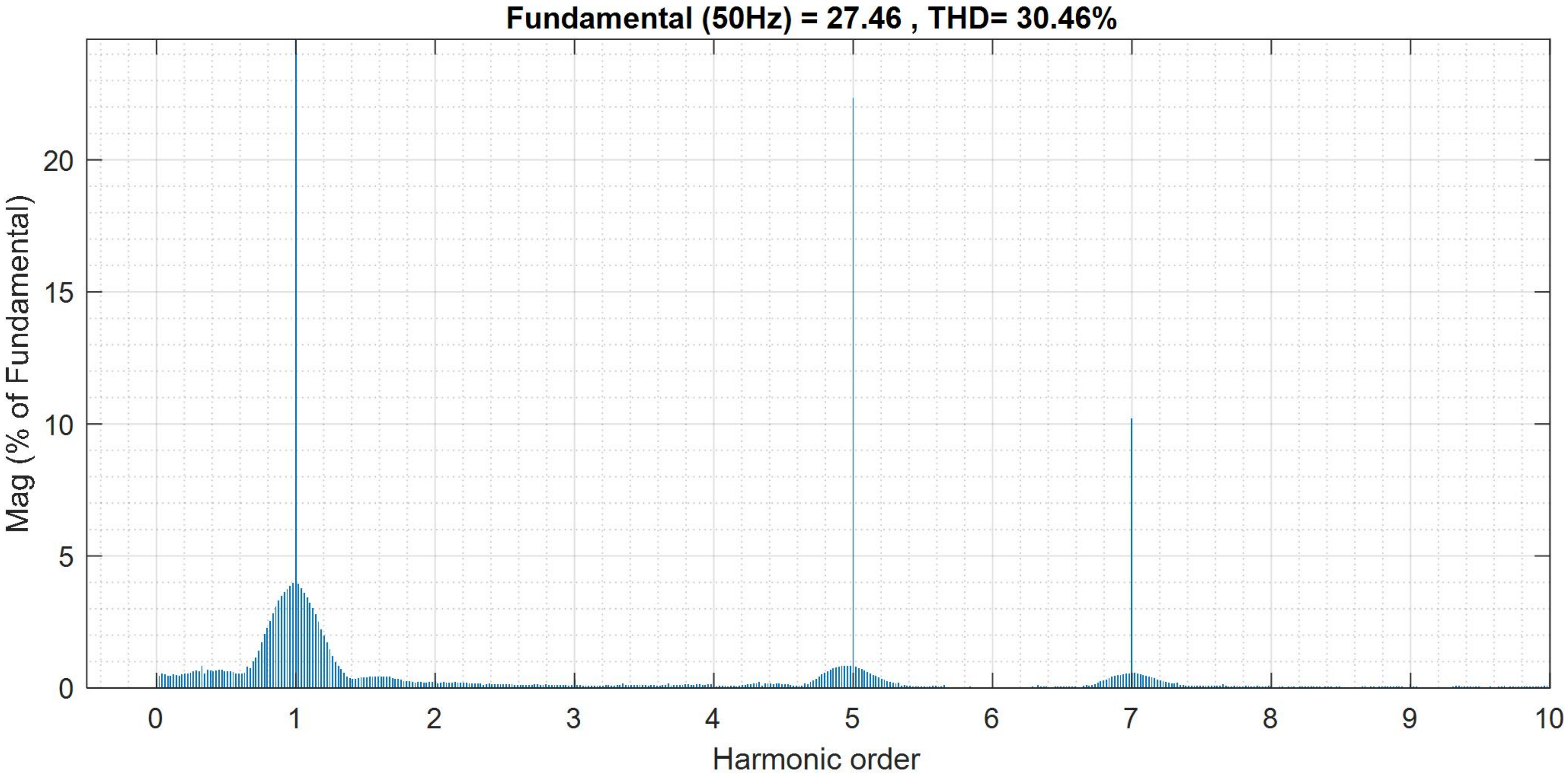

Figure 10: The Harmonic Spectrum of Current waveform at Bus 10 in IEEE 13 Bus System before SPF.

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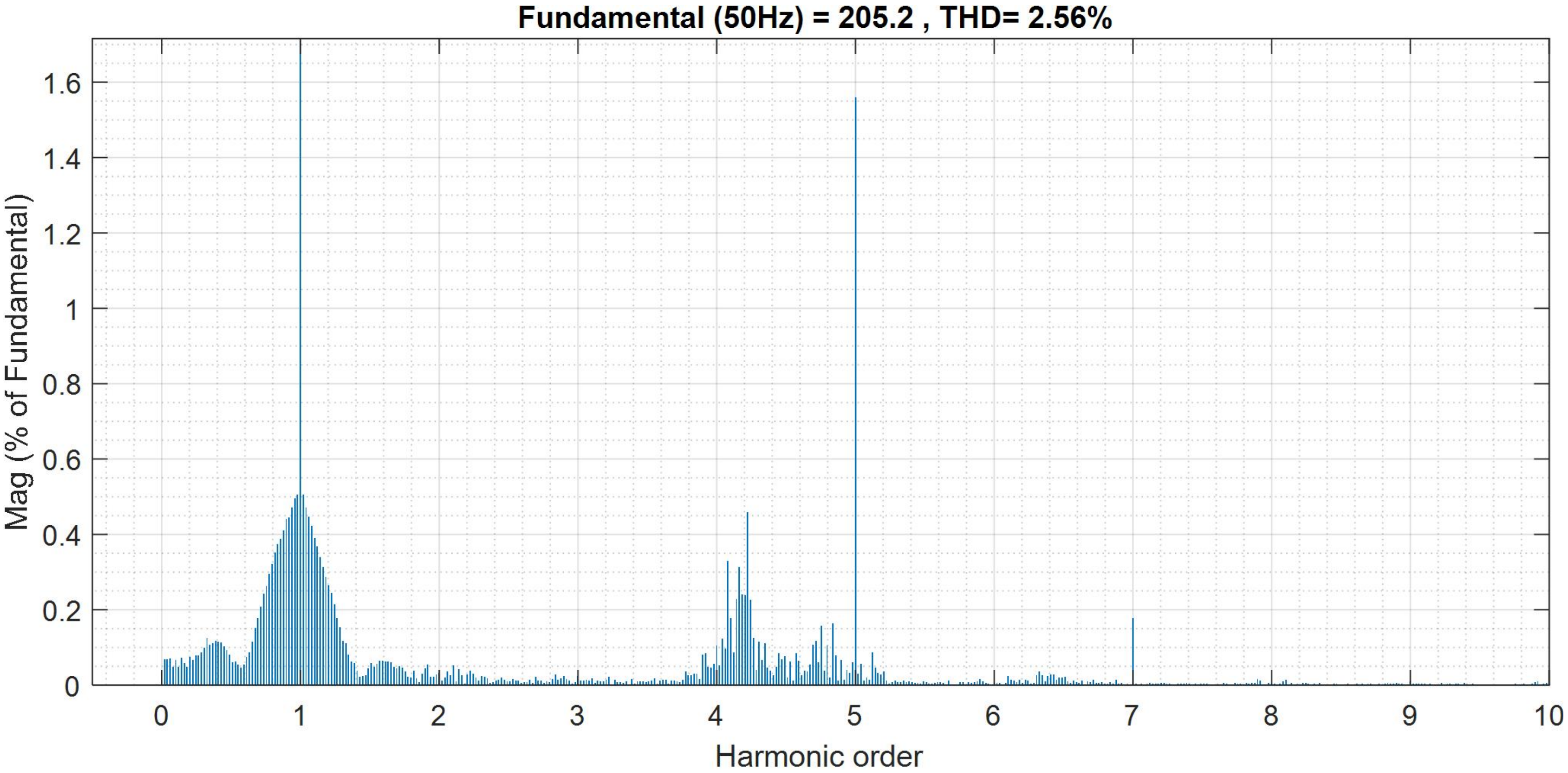

Figure 11: The Harmonic Spectrum of Current waveform at Bus 10 in IEEE 13 Bus System after SPF.

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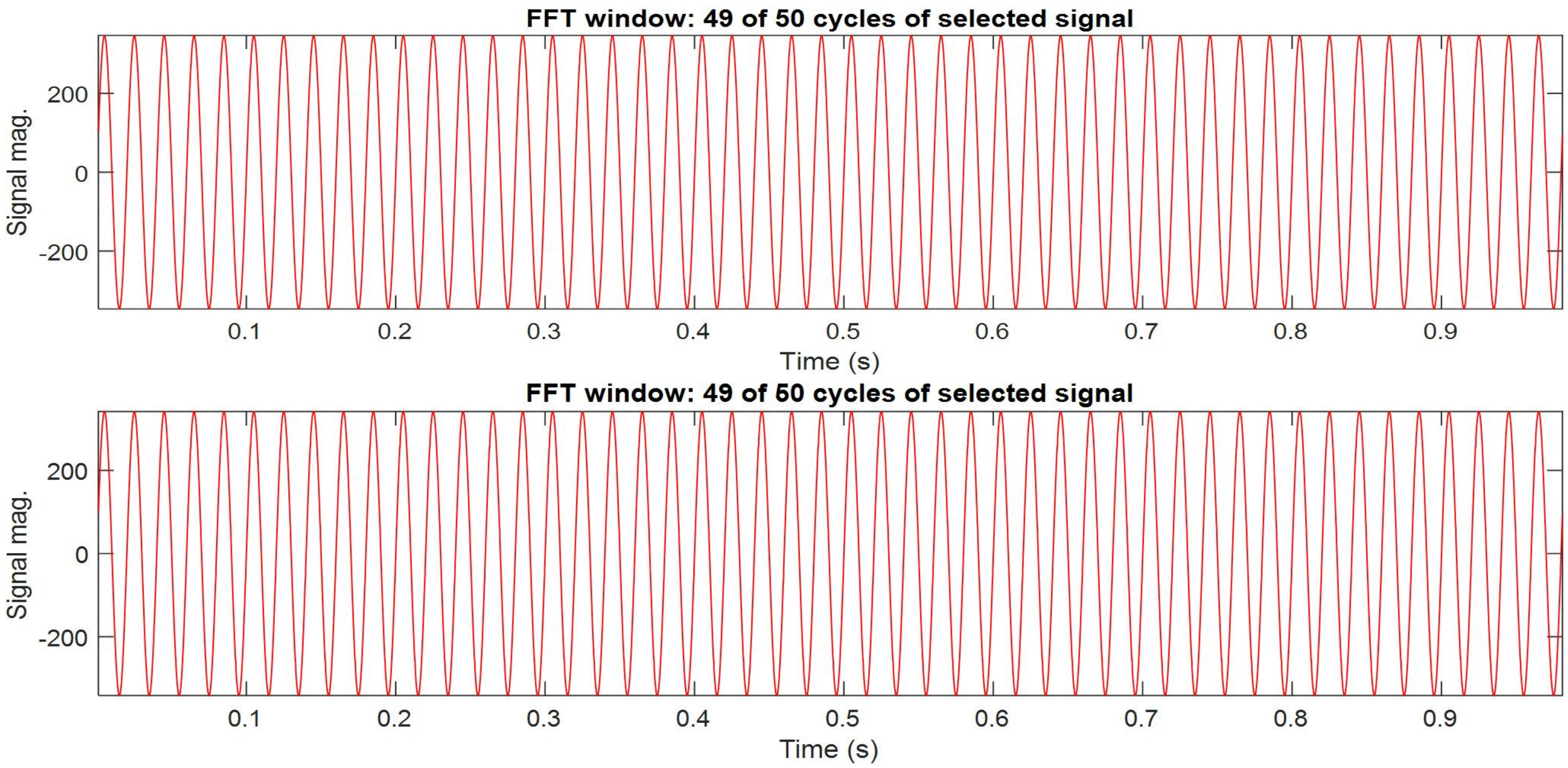

a. Voltage before SPF.

b. Voltage after SPF.

Figure 12: The Voltage waveform at bus 10 in IEEE 13 Bus System before and after SPF.

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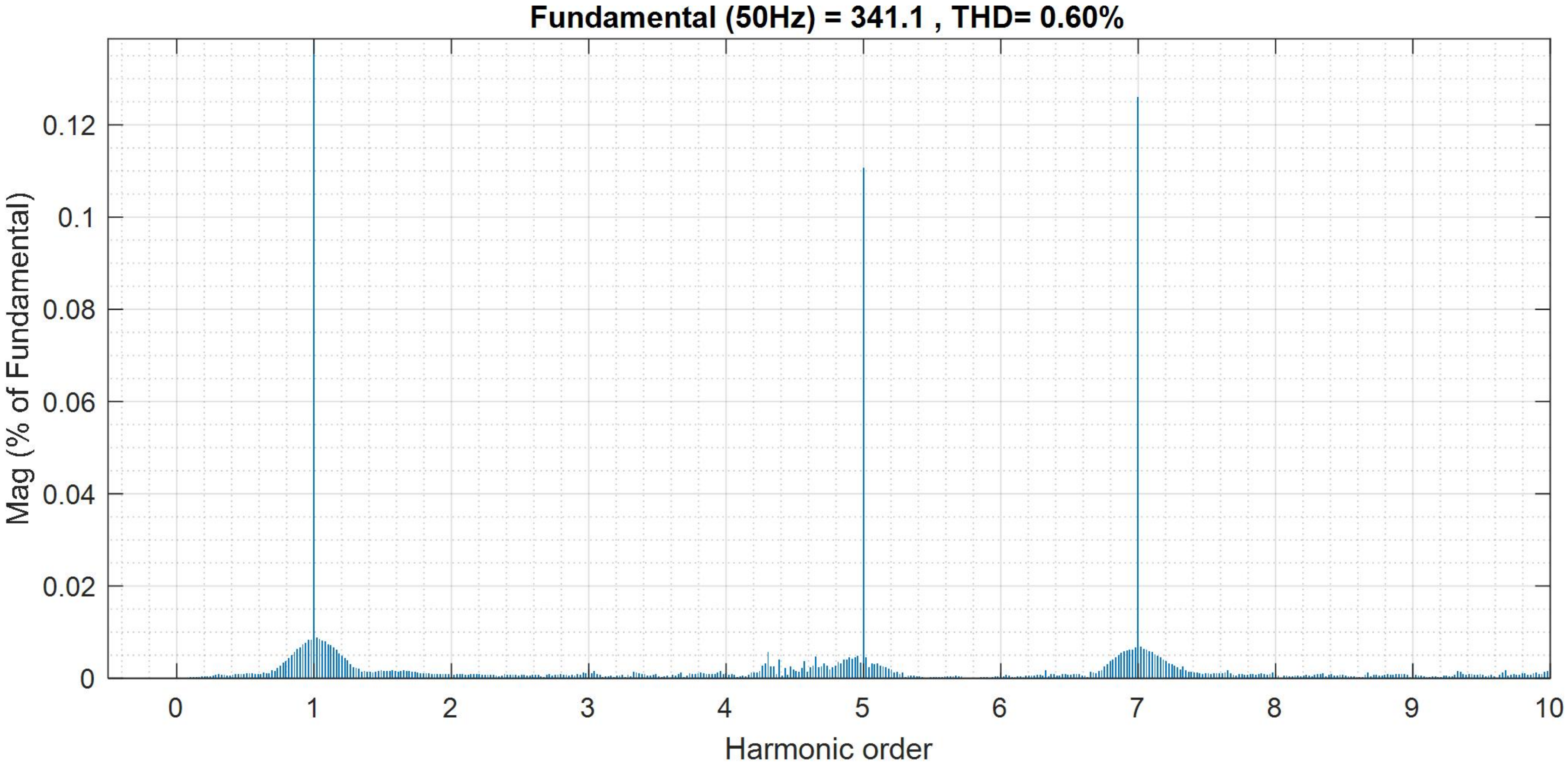

Figure 13: The Harmonic Spectrum of Voltage waveform at Bus 10 in IEEE 13 Bus System before SPF.

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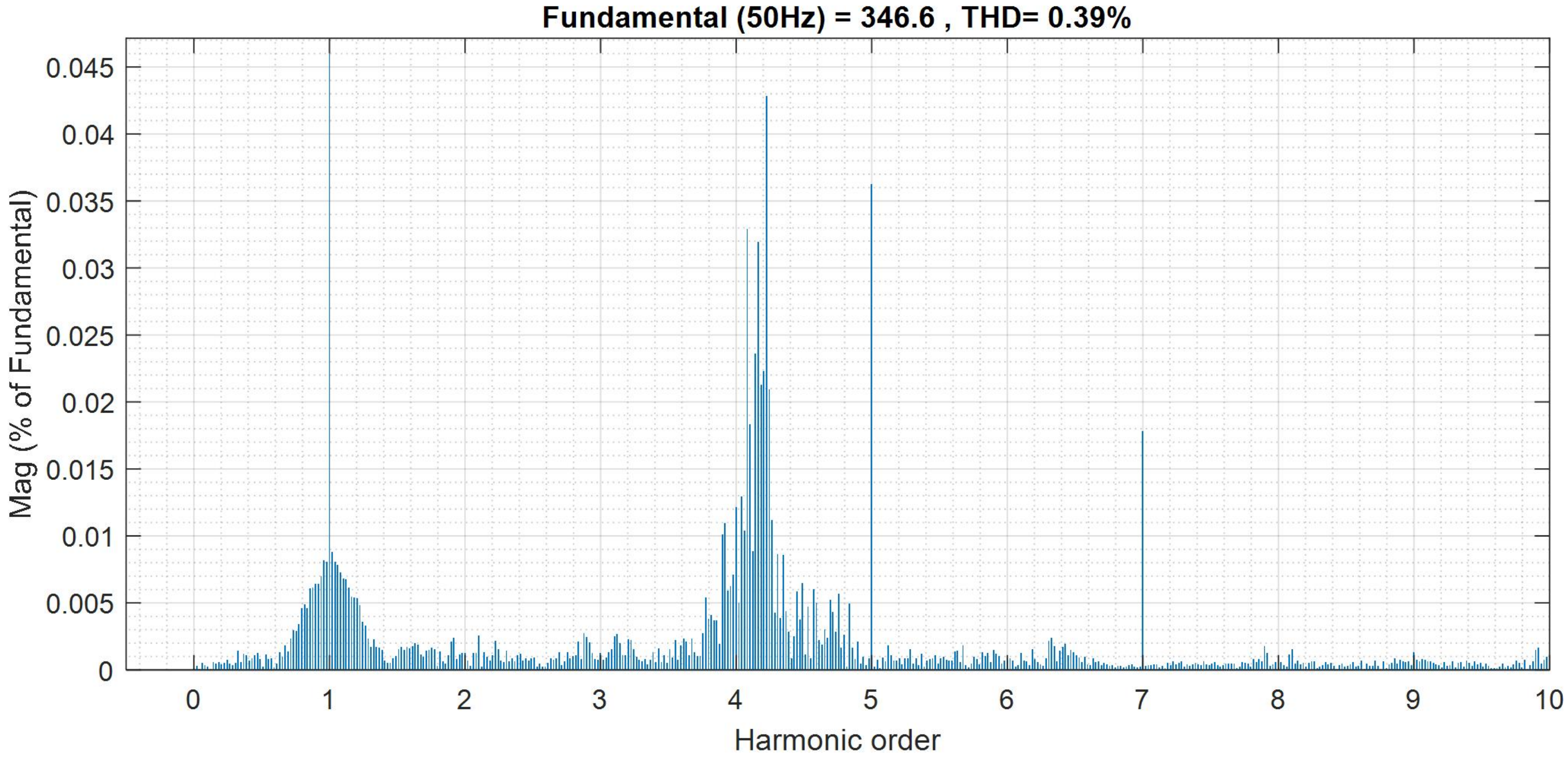

Figure 14: The Harmonic Spectrum of Voltage waveform at Bus 10 in IEEE 13 Bus System after SPF.

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- The implementation of the Double Tuned Shunt Passive Filter (tuned for 5th and 7th harmonics) shows a dramatic improvement in the power quality profiles at the primary points of distortion (Bus 7 and Bus 10).

1. Current Harmonic Distortion (ITHD) Results:

  - The most significant impact is seen in the current waveforms, where the non-linear drawing of the 15kW DC motors was most aggressive.
  - Bus 7: THD plummeted from 27.15% to 2.72%.
  - Bus 10: THD plummeted from 30.46% to 2.56%.
  - Observation: A nearly 10-fold reduction, bringing the system well within the strict IEEE 519 ITHD limits.

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2. Voltage Total Harmonic Distortion (VTHD) Results:

- While the base voltage distortion was relatively low, the filter further refined the waveform purity at the Point of Common Coupling (PCC).
  - **Bus 7:** THD reduced from 0.52% to 0.36%.
  - **Bus 10:** THD reduced from 0.60% to 0.39%.
  - **Observation:** This ensures that sensitive electronic loads sharing these buses are protected from voltage "flat-topping" or notches.
- **Conclusion on Mitigation:** The double-tuned filter successfully "traps" the 5th and 7th harmonic currents at the source.

3. Case Study 2: Voltage Sag & Harmonic Mitigation using DVR

- To protect a **sensitive industrial load** within a distribution system from voltage sags caused by network faults and to provide simultaneous harmonic filtering using a Dynamic Voltage Restorer.

1. The Problem: Voltage Sags in Industrial Grids:

  - **Definition:** A sudden reduction in RMS voltage (typically 10% to 90%) for durations of 0.5 cycles to 1 minute.
  - **Cause:** Short-circuit faults (L-G, L-L-G) occurring on adjacent feeders or heavy motor startups.
  - **Impact:** Tripping of PLC controllers, VFDs, and sensitive robotics, leading to expensive production downtime.

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2. The Dynamic Voltage Restorer (DVR): Injects a dynamically controlled voltage in series with the supply via an injection transformer

3. DVR System Architecture in Simulink:

- **Voltage Source Converter (VSC):** Converts DC energy (from a battery or capacitor) into the required AC injection voltage.
- **Injection Transformer:** Couples the VSC output to the distribution line while providing electrical isolation.
- **Passive Filter:** A small LC filter at the VSC output to remove high-frequency switching noise (ripples).
- **Control Strategy:** Typically uses dq0 transformation (Synchronous Reference Frame) to detect the sag in real-time and trigger the PWM inverter.

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4. Dual Functionality: Sag + Harmonics

- It is series-connected power electronic device that acts as a "custom power" controller and,
- Injects a dynamically controlled voltage in series with the supply via an injection transformer as shown in **Figure 15.**
- Beyond sag mitigation, the DVR is programmed to detect harmonic frequencies in the supply voltage.
- It injects "anti-harmonics" (180° out of phase) to cancel out distortion, ensuring the industrial load receives a pure 60Hz/50Hz sine wave.

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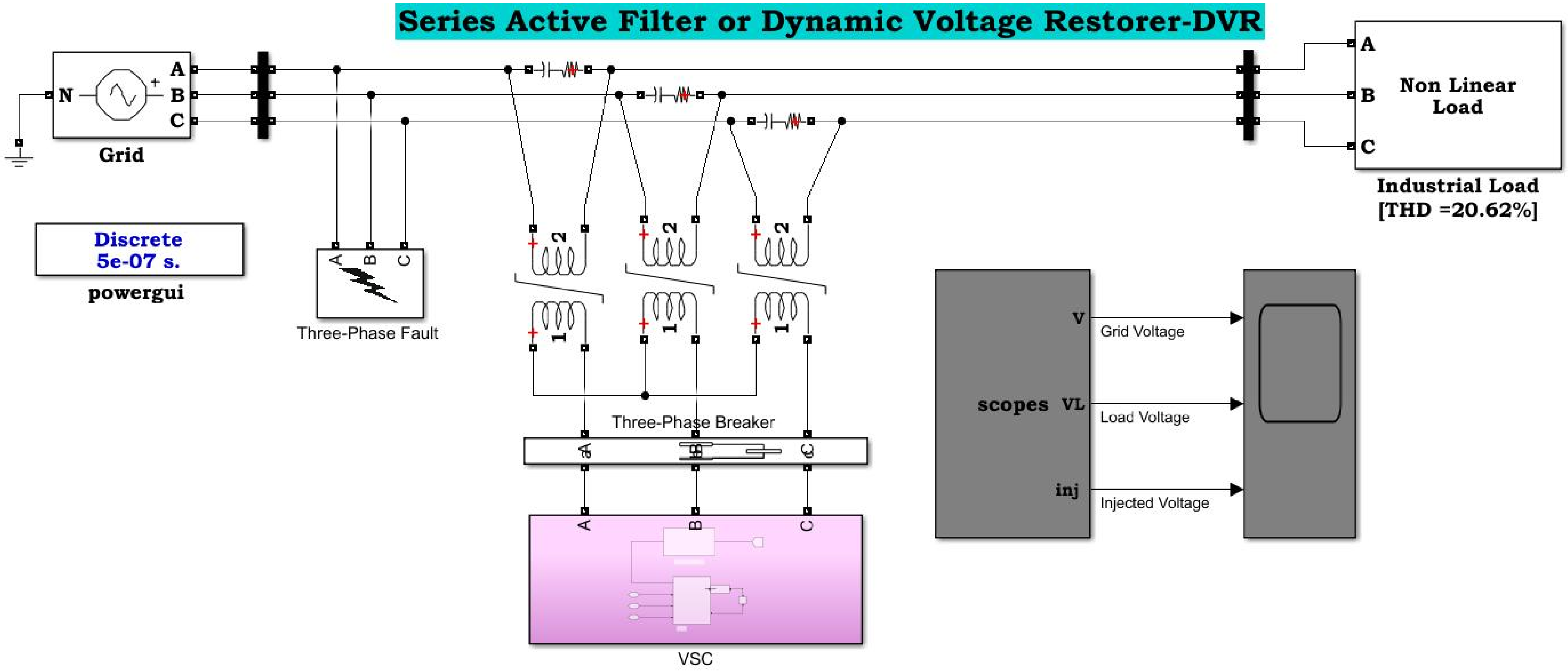

Figure 15: Simulink Model of an Industrial Power Supply System with the DVR for Voltage Sag and Harmonic Mitigation.

Dynamic Performance & Simulation Timeline

- To evaluate the DVR's agility in responding to overlapping power quality events: a system fault (Voltage Sag) and supply-side harmonic injection.

1. Simulation Event Timeline (Total Duration: 0.5s): The model is designed to test the DVR under "worst-case" transitions to prove its effectiveness as a custom power device.

  - ***t=0.15s***: A three-phase fault occurs on the line, triggering a significant Voltage Sag (0.5p.u).
  - ***t=0.20-0.4s***: The supply introduces 5th and 7th order harmonics, further polluting the waveform.
  - ***t=0.20s***: DVR STARTUP. The DVR is switched into the circuit to begin active compensation.
  - ***t=0.35s***: DVR BYPASS. The DVR is disconnected to observe the immediate return of PQ disturbances.
  - ***t=0.30s***: The fault is cleared by the system protection; supply returns to nominal.

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2. DVR Response Analysis:

- **During DVR Operation ($\mathbf{0.25}\boldsymbol{s} < \boldsymbol{t} < \mathbf{0.35}\boldsymbol{s}$):**
  - **Sag Correction:** The VSC injects the missing fundamental voltage, restoring the load voltage to 1.0 p.u.
  - **Harmonic Cancellation:** The DVR identifies the 5th and 7th harmonics and injects opposing voltage components, "cleaning" the load-side waveform.
- **Before/After DVR Operation ($\boldsymbol{t} \leq \mathbf{0.25}\boldsymbol{s}\ \boldsymbol{and}\ \boldsymbol{t} \geq \mathbf{0.35}\boldsymbol{s}$):**
  - The load is exposed to severe undervoltage and high THD, demonstrating the vulnerability of industrial equipment without conditioning.

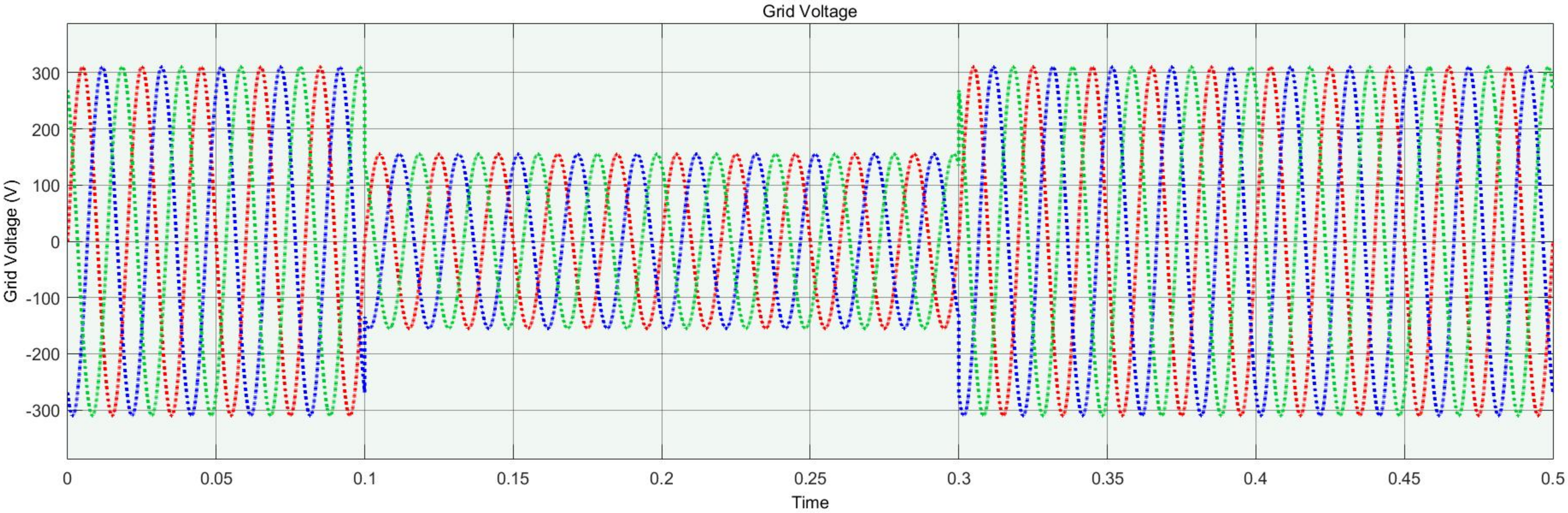

Figure 16: The Grid Supply Voltage with a Voltage Sag Problem (V_{sag}=0.5 p.u).

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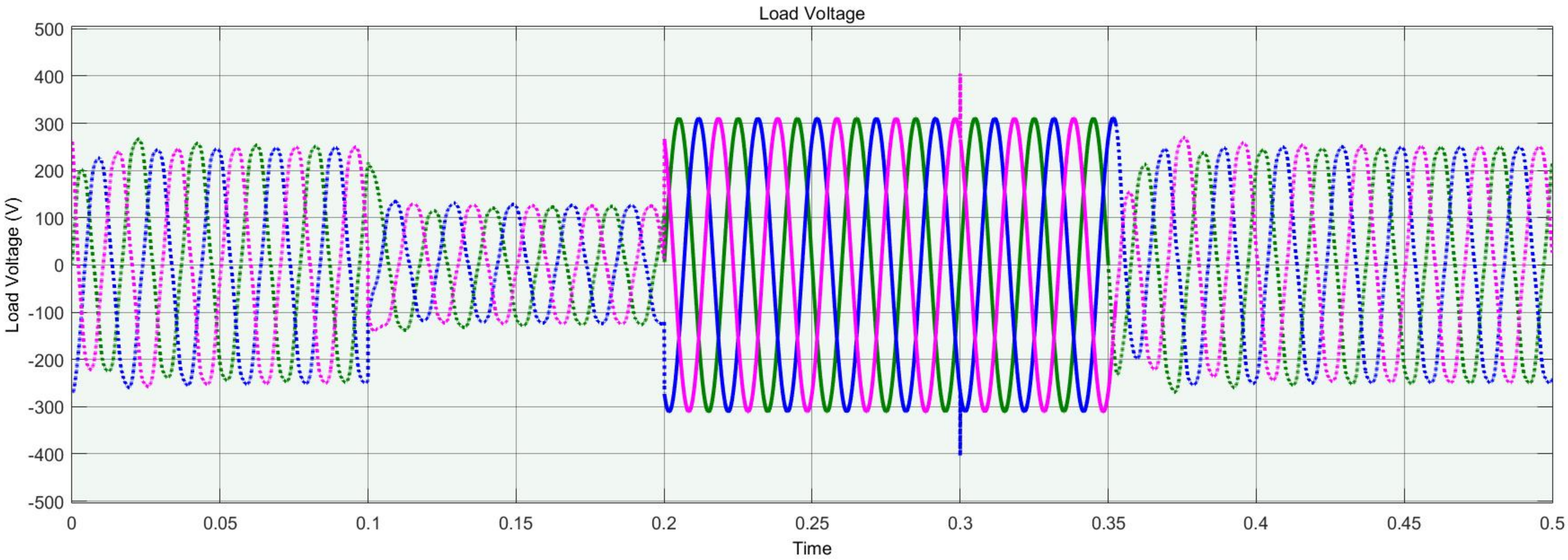

Figure 17: The Load Voltage with a Voltage Sag Problem (V_{sag}=0.5 p.u).

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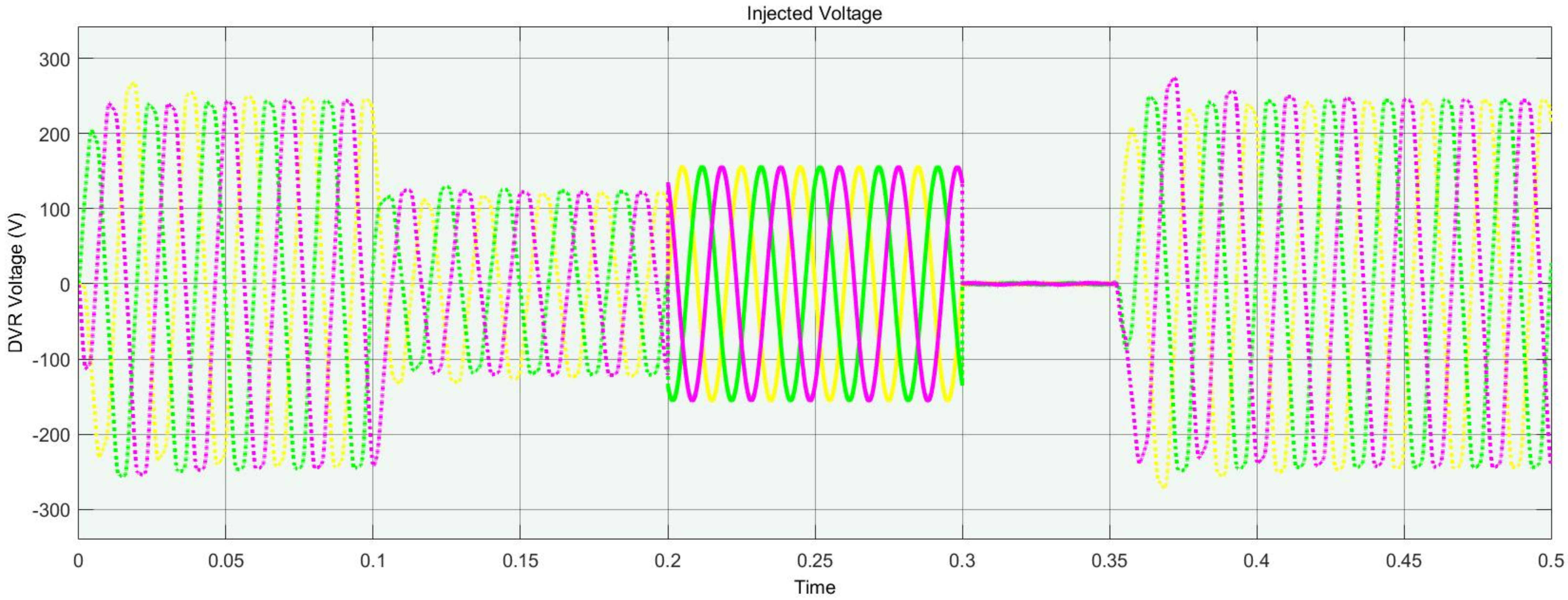

Figure 18: The Voltage Injected by the DVR with a Voltage Sag Problem (V_{sag}=0.5 p.u).

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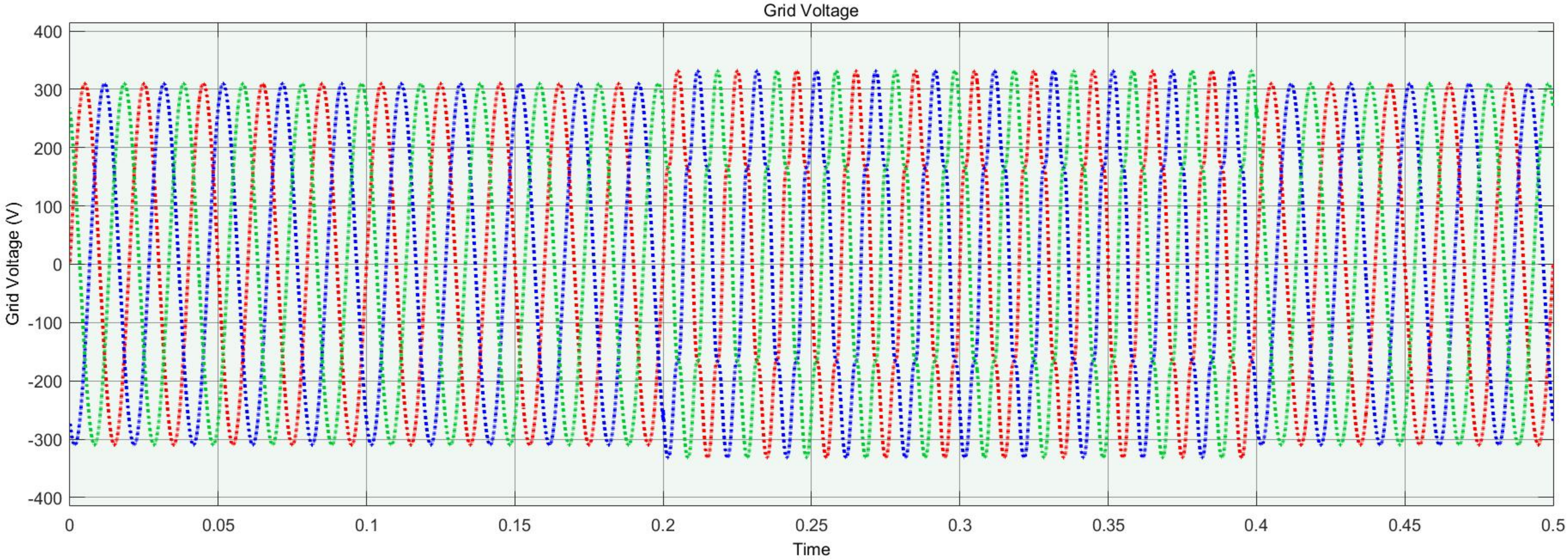

Figure 19: The Grid Supply Voltage with a Voltage Harmonic Injection (THD=20.62%).

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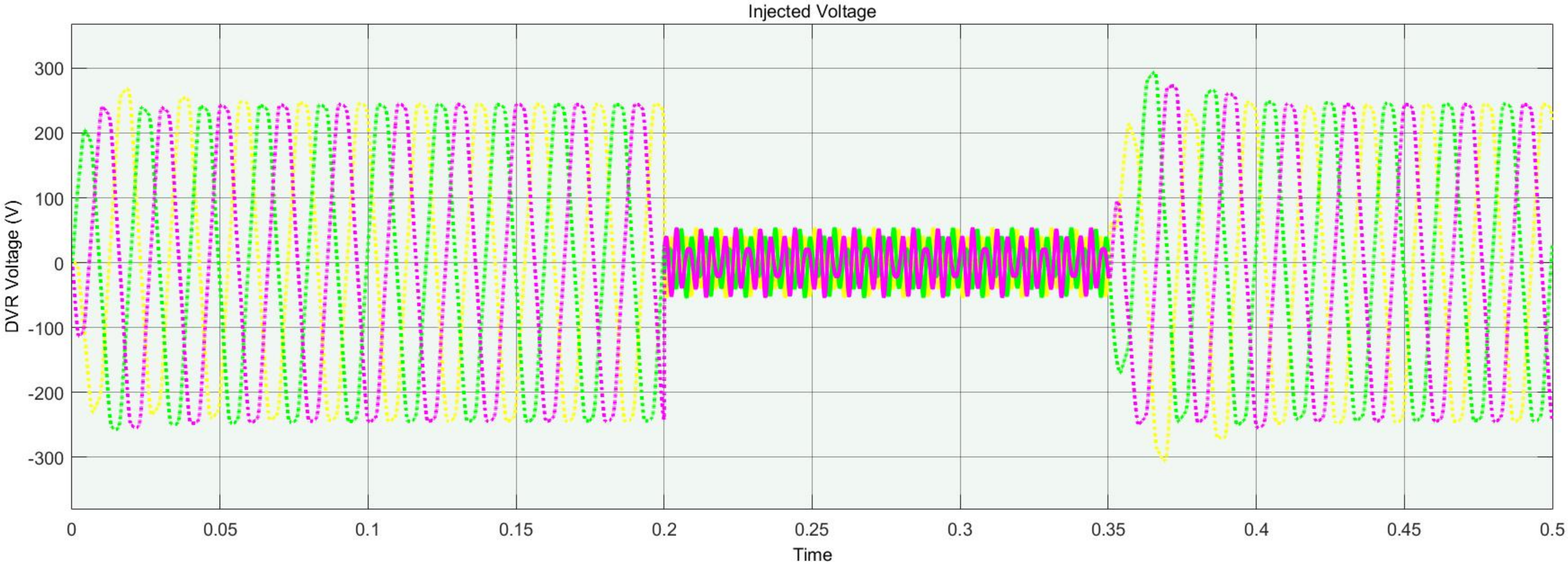

Figure 20: The Voltage Injected by the DVR for Harmonic Mitigation.

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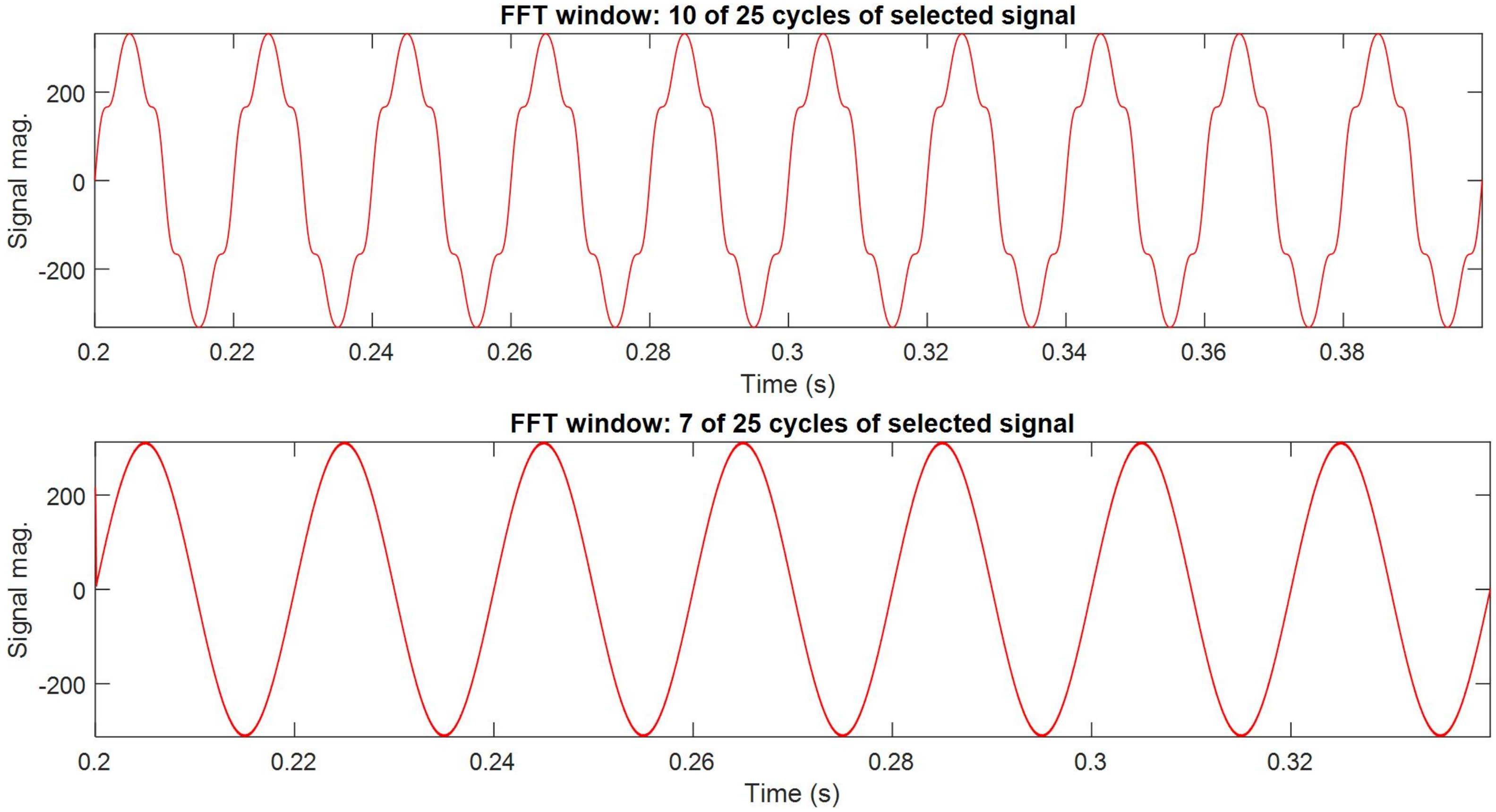

a. Grid Voltage with DVR.

b. Load Voltage with DVR.

Figure 21: The Grid and Load Voltage Signal with DVR Harmonic Mitigation.

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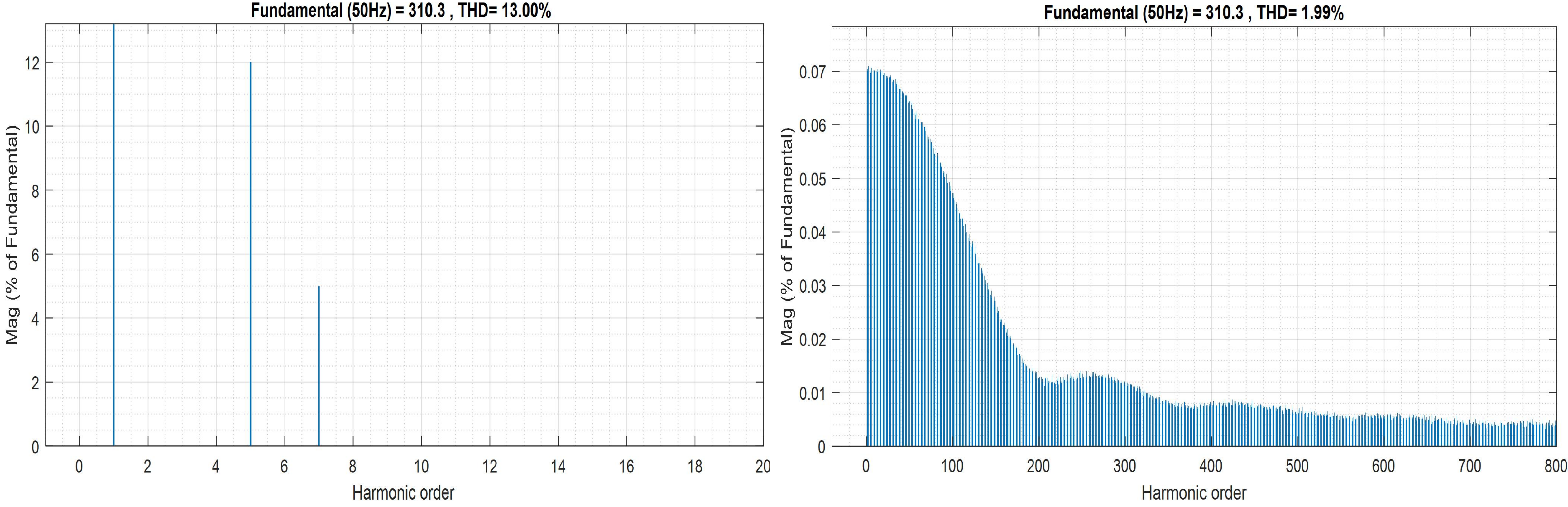

a. Grid Voltage Harmonic Spectrum.

b. Load Voltage Harmonic Spectrum.

Figure 22: Voltage Harmonic Spectrum.

References

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[2]. M. H. J. Bollen, Understanding Power Quality Problems: Voltage Sags and Interruptions. New York, NY, USA: IEEE Press, 2000

[3]. IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Standard 1159-2019, 2019.

[4]. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, IEEE Standard 519-2022, Dec. 2022.

Thank You!