

Analysis and Mitigation of Power Quality Issues in the Distribution Network of the Orange Line Metro Train



SUPERIOR UNIVERSITY

MS ELECTRICAL ENGINEERING

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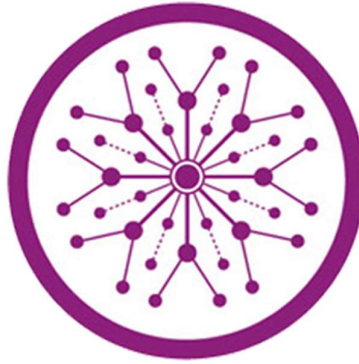
ROLL NO: SU92-MSEEW-S24-005

Session: Fall 2024 – 2026

DEPARTMENT OF ELECTRICAL ENGINEERING

SUPERIOR UNIVERSITY

Lahore, Pakistan



Analysis and Mitigation of Voltage Fluctuation Issues in Distribution Network of Orange Line Metro Train

A thesis submitted in partial fulfillment of the requirements for the
Degree of Master of Science in
Electrical Engineering

Submitted By

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SU92-MSEEW-S24-005

Session: 2024-2026

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DEDICATION

To my beloved family, teachers, colleagues at Orange Line, and friends, I would like to dedicate this thesis.

ACKNOWLEDGEMENTS

I extend my deepest gratitude to my supervisor, Dr. Manzoor Ellahi, committee members, and the institution for their unwavering support, guidance, and resources throughout this thesis journey. Their expertise and encouragement have been invaluable in shaping the direction and quality of this work. To my Orange Line Metro management for so much cooperation and encouragement, this work would not have been possible without their support. To colleagues, friends, and family, your encouragement and understanding have been a constant source of strength. This thesis stands as a testament to the collective effort and support of all those who have been part of this journey.

Thank you,

Irfan Mairaj

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ABSTRACT

The Orange Line Metro Train System (OLMRTS) in Lahore is a major part of the city's public transportation network and relies entirely on a stable and high-quality electricity supply. Any disruption in power, such as voltage dips, surges, or the presence of electrical noise (harmonics) can affect the train's operation, reduce equipment life, cause delays, and compromise passenger safety. These power quality problems typically occur due to sudden changes in load, the use of electronic devices that control power, and weaknesses in the local power grid.

The research has been proposed to investigate power quality issues in the Orange Line Metro OLMRTS auxiliary system and assess their effects on system performance. Traditional methods were used to reduce harmonics, such as passive Harmonic Filters, SVCs (Static VAR Compensators), and Static Synchronous Compensators (STATCOMs). These traditional methods are not effective due to a lag in response, and their performance is not good when the conditions change rapidly. To overcome these issues, I offered a Voltage Source Inverter (VSI) integration with a Supercapacitor as an energy storage device. The Supercapacitor will provide power when dynamically changing in a system, like a voltage sag.

Using actual operating characteristics from the Orange Line network, a thorough simulation model of the proposed VSI-based compensation system is made in MATLAB/Simulink. Different scenarios of disturbances are used to test the system and see how well it can reduce voltage changes and harmonic distortion. The simulation results show that the proposed VSI-supercapacitor setup greatly improves voltage stability, reduces the Total Harmonic Distortion (THD), and makes power more consistent over the auxiliary network. The results show that the proposed solution is a strong and useful way to improve the power quality of electricity in Orange Line systems that use electricity, which would make metro operations safer, more reliable, and less expensive.

CHAPTER 1

INTRODUCTION

All over the world, urban rail transportation has become an integral part of sustainable urban development. With fast-growing urbanization, worsening air quality due to fossil fuel transportation and congestion limiting economic activity, cities are investing in electrified metro to provide high capacity and low per-passenger energy consumption. They are technologically complex, their reliability relies on uninterrupted access to good quality electric power, as well as on disciplined engineering management and data driven operations. The Power Quality (PQ) indicates the extent to which voltage, current and frequency are kept within the specified limits and the waveforms are close to sinusoidal. As PQ breaks down, it can negatively affect traction performance, auxiliary services, equipment life, safety subsystems, and even passenger experience and trust [1].

This is the promise and the technical challenge that is encapsulated in the Orange Line Metro Rail Transit System (OLMRTS) in the City of Lahore, Pakistan's first modern mass rapid transit (MRT) corridor. The line receives bulk power from the Lahore Electric Supply Company (LESCO) at 132 kV, is stepped down to 33 kV at the High-Voltage Substations (HVS) and then stepped down to Low-Power Substations (LPS) and Traction Substations (TSS). Power is supplied to the 750 V DC traction network via rectifier transformers and converter switchgear on the TSS. The LPS provides 0.4 kV AC power to stations and depots for HVAC, escalators, elevators, lighting, Automatic Fare Collection (AFC), signaling, telecom, and safety systems. It is a multi-tiers architecture which makes it easier to operate and isolate disturbances, but it also adds several locations where PQ can be degraded or disturbed – from external phenomena (grid faults, voltage dips, feeder switching, short-term over-voltages) as well as internal phenomena (nonlinear converters, motor inrush currents, unbalanced loading and switching transients)[2].

Figure 1-1 explains the Breakdown of the OLMRTS Power supply system.

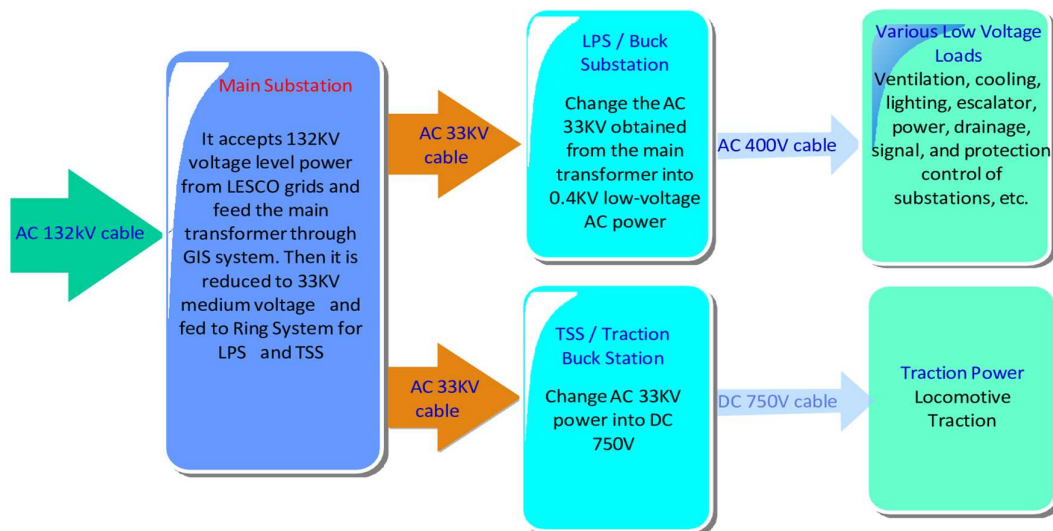


Figure1-1Breakdown of Power Distribution at Orange Line

These phenomena are classified by different standards. PQ events are defined by IEEE std 1159 as sags and swells and interruptions, transients, flicker, unbalance, and frequency deviation. As for compatibility and public network emission/immunity levels, they are described in IEC 61000 and EN 50160. At the Point of Common Coupling (PCC), IEEE Std 519 suggests a < 5% voltage THD with current distortion levels being a function of the short-circuit ratio (ISC/IL). For the railway, harmonics and sector-specific guidance for signals and electromagnetic compatibility are considered. These are actually useful, as they provide an operational envelope a metro can function in without mis-operating protection or control systems, or negatively affecting the system by causing heating or loss of reliability.[3]

The PQ stresses in OLMRTS's auxiliary network are relatively consistent. The first is that, due to the large induction motors, the bus loading shows the characteristic sag with transients when HVAC chillers, compressors, and pumps, and escalator drives start up. The more devices that start up around the same time (usually after a break), the greater the sag distortion. The second is the large number of power-electronic based three phase rectification systems in TSS, along with PWM inverters and switch-mode supplies in AFC and telecom. These systems contribute to harmonics and resonance along with increased cable and transformer losses. The third is distortion caused by transient loads from source and feeder reconfiguration and change-over operations. The last is the disturbance of the 132 kV network caused by faults, and of the 33 kV and 0.4 kV networks caused by reclosing and disturbance of the control systems.[4].

Figure 1-2 describes the load distribution of OLMRTS.

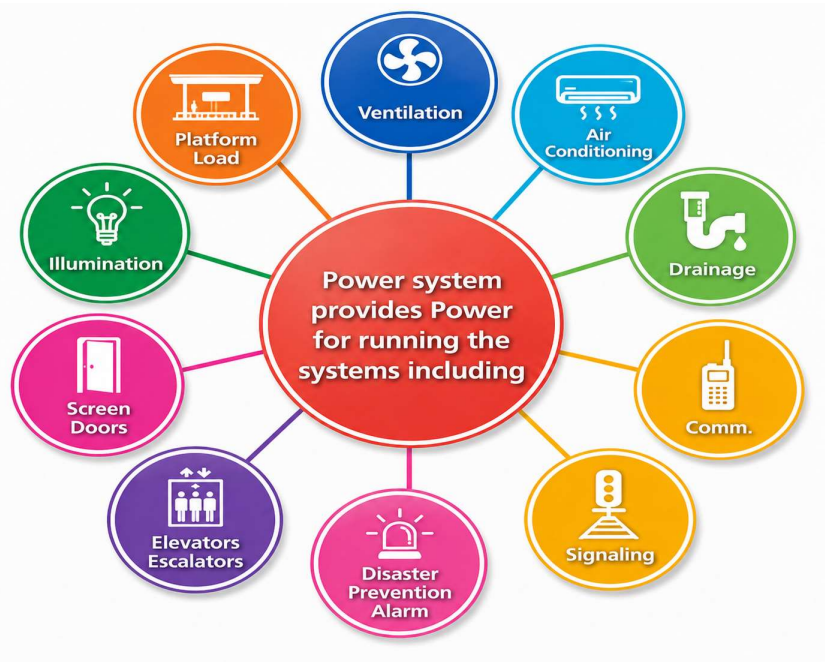


Figure 1-2 Breakdown of Power Distribution at Orange Line

How are these effects significant? All things considered, for any given voltage, the motor torque of a train is approximately proportional to the square of the applied voltage. For some regimes a 10 to 15% dip at a critical time may cause the system to slow down to a point that would increase dwell-to-dwell time during peaks, thus reducing capacity. Undervoltage can cause VFDs to trip, affect AFC terminals, or cause emergency lighting to dim for auxiliaries, while overvoltage puts stress on insulation, and reduces component life. Harmonic distortion results in higher copper losses, higher core losses, and can lead to capacitor bank overheat or failure. Electromagnetic interference can affect signaling circuits causing false indications or setting conservative protection settings which will decrease service robustness[4].

The lessons have been learned the hard way in many other metros around the world. In China, high-speed rail and urban metros have been using railway power conditioners, active filters and static synchronous compensators to control converter-induced harmonics and voltage regulation. To help maintain the bus voltage during aggressive load ramp, Delhi Metro installed STATCOMs at critical points. EN 50160 compliant networks operate in Europe, and enhance SCADA with dedicated, high sample rate PQ analyzers that record sags/swells (half cycle resolution), flicker severity (Pst/Plt) and transient waveforms, with analytics that drive preventive maintenance and capital planning[5].

There are two structural constraints in Lahore context. First, the demand growth and reconfiguration of LESCO's urban grid can occur at high frequency, and occasionally cause a transfer of the sags, surges and irregular feeds from the upstream network into the medium voltage backbone of the metro. Secondly, PQ governance in Pakistan is still evolving, although operators are adopting IEEE/IEC best practices within their operators, external enforcement and interoperability frameworks are being developed. Therefore, resilience building by OLMRTS must be resilient “from within”—from local monitoring, control, and mitigation which are able to respond at the millisecond to second time scales at which the most disruptive events occur[6].

Three mechanisms are responsible for PQ degradation from an electrical-engineering point of view in the auxiliary network of the OLMRTS:

- Locked rotor current is 3-6 PU of rated even with soft start or VFD, with simultaneous starts, or in case of upstream weakness, momentary voltage sag occurs when a large HVAC compressor starts.
- Rectifiers and Switch Mode Supply create 5th, 7th, 11th, 13th harmonics (and more). PWM inverters produce high-frequency components around the switching frequency and its sidebands.
- Propagation of high-frequency transients and common-mode currents are affected by system interactions and grounding - earthing impedance, bonding integrity and cable layouts. Switching surges have a greater effect on the electrical installation if the grounding is poor, and can worsen nuisance tripping of RCDs or protective relays.

Hence it is necessary to layer mitigation. The general level of the equipment, soft start/VFD profiles help to limit inrush at the substation level, passive and active filtering control characteristic harmonics at the network level and dynamic reactive support stabilizes the bus voltage during ramps, while at the system level operational coordination minimizes coincidence of heavy starts. Importantly, the metro requires a fast controllable device near the 0.4 kV buses which can absorb and inject power as needed

and which can shape the voltage and compensate for harmonics within a few milliseconds – the strengths of inverter-based solutions.

A modern inverter with an energy buffer is a universal compensator. It provides active and reactive power as a source to maintain the voltage bus close to nominal during voltage sags, it consumes active and reactive power as a load during voltage swell events, and provides counter currents during the harmonics as a source during a steady state voltage swing. Most PQ events are short and the size of the energy buffer is not important. Supercapacitors are well suited for applications that will require frequent, repeated bursts of power or power absorption without degradation like batteries, and have high power density and long cycle life. If the sizing of the cabinet is such that it provides the required energy, within the acceptable voltage swing and for a few hundred milliseconds, then it is a practical solution that can be implemented within the LPS room [7].

1.1 Background

The focus of this thesis is to address a reduced but systemically significant problem, voltage stabilization and generation of a high-quality voltage waveform in the 0.4 kV auxiliary distribution system of the Orange Line Metro Rail Transit System (OLMRTS) while experiencing rapid load changes, nonlinear conversion and upstream disturbances. The Orange Line is a junction of two engineering disciplines: traction power and station auxiliaries, which is an interaction that is not always accounted for. The 0.4 kV auxiliary level, which paradoxically feeds the most varied and sensitive loads, also has to power comfort systems (HVAC), passenger movement (escalators and lifts), life-safety systems (fire detection, pumps, emergency lighting), operational systems (signaling/telecom) and revenue systems (AFC) with the least engineering margin. The impairment at this level is very visible and risky [6].

The research starts by defining the PQ landscape of OLMRTS from the operational observations and physics of OLMRTS loads. The voltage sags are 10s to 100s of milliseconds which correspond to motor starts, and the voltage swell on abrupt load shedding is called a feeder switching swell. Harmonic spectra show converter operation, the correlation of flickers with clustered starts and rare but impactful transients on source transfer or fault clearing. These patterns are not exclusive to Lahore, but are common and coinciding with the behavior of the local grid and its operational schedules. [8].

The figure 1-3 and 1-4 describe the voltage fluctuation and voltage Sag in OLMRTS system.

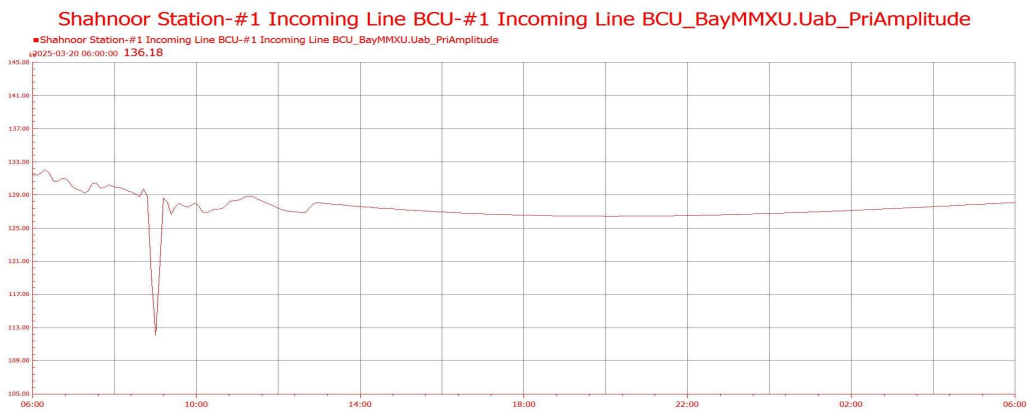


Figure 1-3 Fluctuation of 132KV Line

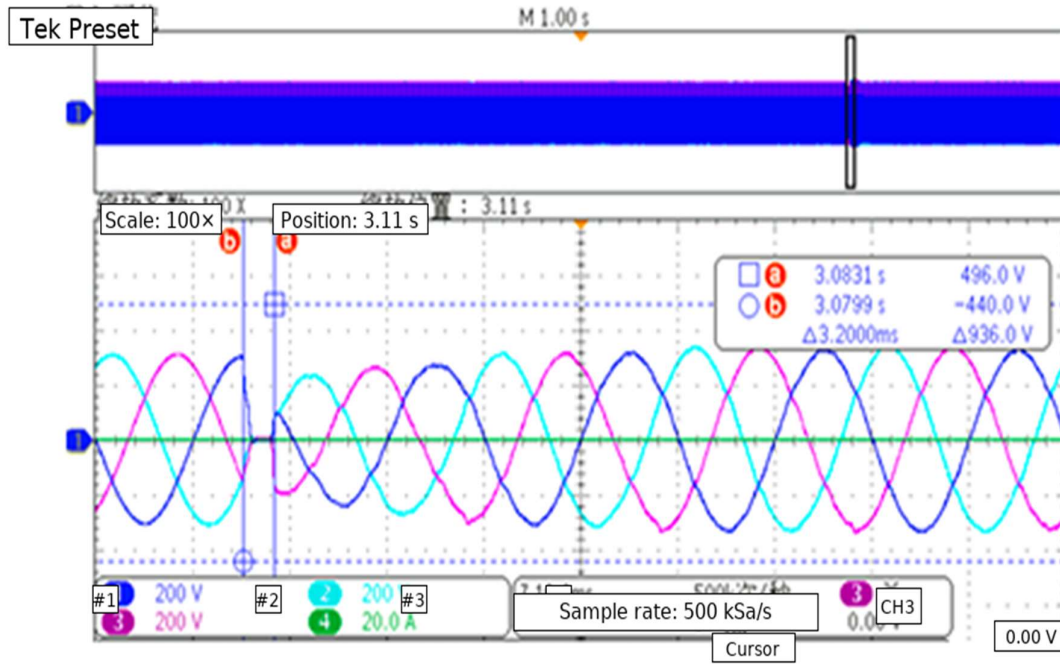


Figure 1-4 Fluctuation of 0.4KV Line

There are conventional solutions for SVCs/STATCOMs for voltage support, passive/active filters for harmonics, UPSs or dynamic voltage restorers (DVRs) for ride through functions and each has its own trade-offs. SVCs work well at regulating MV nodes, but not at LV, and events occur in a few cycles. STATCOMs are fast but costly and not necessarily located near the impacted LV buses. Passive filters are inexpensive, but narrowband active filters can help with current harmonics and have little effect on voltage sags (unless used with energy storage). In the meantime, purely operational measures (staggered starts, demand scheduling) reduce risk, but are not able to protect against external factors or random coincidences [6].

The dissertation proposes a new solution, the combined Voltage Source Inverter (VSI) and supercapacitor DC-link, which can be applied as a fast, multi-function compensator, located near selected 0.4 kV buses. It uses three control features on a single platform: (1) dynamic voltage regulation during sags/swells, (2) harmonic current compensation to comply with IEEE 519 / IEC 61000 limits, and (3) limited ride-through in the event of a short duration disruption when a sensitive load is present. The technical novelty is not that inverter-based compensators exist, but the size, control, and integration of the inverter-based compensators to conform to the Orange Line's disturbance statistics, power constraints and life-cycle cost requirements [9].

The study incorporates a detailed MATLAB/Simulink model of a representative OLMRTS feeder and bus with parameterization based on station-level loads (HVAC compressor ratings, escalator drives, lighting/AFC electronics), feeder/transformer impedances, and realistic assumptions on the behavior of the sources on the upstream side. Disturbance scenarios include: single and multiple devices starts, step load changes, feeder transfer and traction induced harmonics travelling to LPS. The VSI model is based on an SVM synchronous frame control, energy management of the DC link and an LCL output filter. Its performance is compared with SVC/STATCOM nodes (modeled as Thevenin stiffeners at MV), passive/active filters and a notional dynamic voltage restorer of similar rating [10].

In addition to the fidelity of the simulation, the dissertation focuses on implement-ability. Control integration with SCADA, protective coordination (trip curves, coordination with undervoltage relays), and cyber/OT interfaces are mapped, among others, such as cabinet footprint, ventilation, cable routing, earthing, and maintenance access. The deliverable will not only be analytic performance but the practical recommendation that can be implemented in procurement and phased rollout at critical stations [11].

The Introduction then situates the work between PQ theory, power-electronic control and metro operations. It outlines the guiding questions: How often and how serious are PQ events in OLMRTS affecting the service provided by the LV buses? What is the minimum risk acceptable compensator power/energy rating? What are the most effective control strategies that allow for low THD, stability margins, and fast dynamics in the presence of parameter uncertainty? How does an inverter-based solution compare to existing solutions in this particular case, in whole-life performance? [11].

1.2 Motivation

1.2.1 Technical and Operational Considerations:

The disturbances are found within the range of 1 - 500 ms where it is impossible for traditional reactive compensation devices (such as mechanically switched capacitors and thyristor-controlled reactors) to react fast enough and can cause overshoot and/or oscillations. Fixed narrow-band filters have the risk of detuning due to the changing harmonic patterns throughout the day and due to equipment duty cycles, and broad band passive filters may cause unwanted reactive power. This time frame calls for a dynamic voltage regulator, a harmonic absorber and a voltage source inverter with a medium energy storage capacity that has a fast control loop.

In the operational stage, power quality disturbances on the 0.4kV bus are easily observed by passengers and operators. If the HVAC system shuts down, even for a few minutes, during the hottest part of the day or if the escalator breaks down during rush hour, people complain and fret about their safety. The value of such interruptions being prevented is significantly greater than the cost of the compensator, particularly if there are many critical loads protected by one inverter at one station. Furthermore, the inverter has an inbuilt telemetry and event logging system that provides a valuable and high-resolution record of all power-quality data that can be used for fault diagnosis and ongoing improvement of system performance.

1.2.2 Strategic Importance and Research Significance

The Orange Line Metro Rail Transit System (OLMRTS) is built in a developing grid environment; external reinforcement of the network could take years to come to fruition. Therefore, it is crucial to increase the system's resilience from the inside. The use of a swift of inverter-based compensators is not achievable and scalable solution for enhancing the power quality throughout the network. It offers a step by step process that will allow you to implement it gradually rather than waiting for pricey or time-consuming grid upgrades.

The Purposed method also is compatible with the national goal of increasing energy efficiency through the reduction of harmonic losses, reducing the transformer and cable temperatures, and extending the life of valuable equipment. It not only brings immediate technical benefits, but also establishes a benchmark for upcoming metro lines and infrastructure improvements throughout Pakistan. This research is significant because it measures these performance benefits and optimizes the inverter control of railway auxiliary systems, as well.

It also demonstrates that moderate system ratings of hundreds of kVA and hundreds of kilojoules of energy storage can deliver power quality resilience without having to rely on energy devices at the

scale of megawatt hours and large-scale. That makes it an affordable and viable concept to undertake in current substations.

The developed control and design approach is applicable to other metro systems of similar load characteristics and grid connections and can serve as a template for metro systems in developing regions.

1.3 Problem Statement

Although soft starters, some harmonic filtering and operational scheduling are already used, the OLMRTS auxiliary network still suffers from voltage sags, harmonic distortion and transients that periodically cause disruption to sensitive systems and place a strain on assets. The existing technologies do not have the necessary dynamic speed. Therefore, a key challenge is to design, size and validate a fast, inverter-based compensator with a supercapacitor energy buffer and proper LCL filtering that can::

- Stabilize the 0.4 kV bus voltage during short-duration sags and swells.
- Reduce voltage and current THD to within IEEE/IEC recommended limits under representative load scenarios.
 - Provide limited ride-through for critical auxiliaries during brief supply anomalies, without compromising protection selectivity or safety.

1.4 Research Questions and Objectives

The research is guided by the following questions:

- What is the statistical profile (frequency, magnitude, duration) of PQ events at representative OLMRTS auxiliary buses?
- Which control scheme offers the best trade-off between speed, stability, and THDPI frame with SVM, or variants with predictive terms or resonant controllers?
- How does the VSI-supercapacitor solution compare against SVC/STATCOM, active filters, and DVRs under the same scenarios in terms of PQ metrics?

1.4.1 Corresponding objectives are:

- Develop a MATLAB/Simulink model of the auxiliary feeders, loads, and upstream source, including parameter ranges that reflect operating uncertainty.
- Design a VSI-supercapacitor compensator with an appropriate LCL filter.
- Make trouble situations (motor starts, simultaneous starts, feeder transfer, harmonic spread) and assess PQ outcomes (voltage profile, THD, flicker proxies).
- Make relative studies vs. SVC/STATCOM and filter-only methods.
- Express practical deployment references (ratings, placement, integration) for OLMRTS.

1.5 Scope and Limitations

1.5.1 Scope:

Focus on the 0.4 kV auxiliary distribution in stations and depots, including major LV switchboards and priority feeders (escalators, life-safety systems, signaling/AFC power supplies).

- Voltage sags and swells (per IEEE 1159 categories), steady-state and switching harmonics (THD).

1.5.2 Limitations:

- Traction power (750 V DC) is addressed only as its harmonics propagate to the auxiliary network; traction-side dynamics are not optimized in this work.
- Long-duration outages, feeder failures lasting minutes or more, and micro-grid planning are outside the scope.
- Hardware prototyping is not included. The work culminates in simulation-backed deployment guidance suitable for subsequent pilot procurement.

1.6 OLMRTS Electrical Architecture

The granularity of the Orange Line's electrical architecture and duty cycles will be needed to know where and how PQ issues are generated.

High-Voltage Substations are located on the line, such as near UET and Shahnoor, connected to two 132-kV Grid feeds. Each HVS reduces the voltage down to 33 kV, and feeds it to a medium-voltage ring feeding both Traction Substations (TSS) and Low Power Substations (LPS). TSS uses rectifier transformers with phase-shifted windings (such as delta/star) to cut common harmonics, then converts to 750 V DC, with DC switchgear and a negative return to control stray current and corrosion. Essential station services are fed through a set of low voltage switchboards (low voltage molded case or air circuit breakers) and low voltage feeders to the 33/0.4 kV transformers in LPS.

1.7 Thesis Organization

This thesis consists of four main chapters, which correspond to the different aspects of the research problem and their solutions.

In Chapter 1, the research background and motivation are given, which is focused on the power quality issues in the 0.4 kV auxiliary distribution network of the Orange Line Metro Train System (OLMRTS). It presents the problem statement, research goals and scope, and presents an overview of OLMRTS electrical architecture.

The literature review, which covers the international power quality standards, sources and impacts of PQ problems in metro systems, monitoring practices, and existing mitigation methods, are outlined in Chapter 2. The chapter thoroughly examines the latest research conducted during the time period 2018–2025 and provides insights into the research gap in this field that inspired the solution proposed for OLMRTS by the VSI–supercapacitor system.

The methodology proposed is detailed in Chapter 3. It describes the modelling of the OLMRTS auxiliary network in MATLAB/Simulink, design of VSI–supercapacitor compensator, control strategy, LC/LCL filter design and simulation of the system with the real system parameters.

The simulation results, performance and analysis are explained in chapter 4. It thoroughly assesses voltage regulation, harmonic mitigation, reactive power compensation and dynamic response under various disturbance situations. Results are compared to the relevant standard, and also end the key findings.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

High-quality electrical power is essential to the reliability, efficiency and public acceptability of urban rail systems as they become more ubiquitous. As urban rail systems become more common and increasingly so, their reliability, efficiency and public acceptance depend on their ability to provide quality electrical power under all operating conditions. In this context, Power Quality (PQ) is the ability of voltage, current and frequency to stay within predetermined limits, and to maintain near-sinusoidal waveforms under normal and disturbed conditions. Metro networks have a variety of loads, traction converters, HVAC compressors/chillers, escalators/elevators, Automatic Fare Collection (AFC) equipment, LED lighting, communications and signaling all sharing a common power supply which should be capable of handling frequent switching events, regenerative braking episodes and network-side perturbations. This combination of nonlinear, dynamic and sometimes stochastic behaviors makes PQ a systems-level problem, rather than a problem with the equipment itself. [12]

The global PQ is structured on the following standards: IEEE Std 1159 (event classification and measurement), IEEE Std 519 (harmonic control in power systems), IEC 61000 series (electromagnetic compatibility emission and immunity), EN 50160 (voltage characteristics of electricity supplied by public distribution networks)[13]. The documents establish limits and testing methods for vocabulary for voltage sags and swells, interruptions, transients, unbalance, flicker, harmonics and frequency deviations. Practical compliance is defined as: Meeting the standard of TOTAL HARMONIC DISTORTION of voltage (THD_V) at POSITIVE COORDINATE CUTTING (PCC) usually $\leq 5\%$, Current distortion (TDD) as per system short-circuit ratio, and Voltage deviation within $\pm 10\%$ of nominal during normal operation.

In this context, the Orange Line Metro Rail Transit System (OLMRTS) in Lahore, Pakistan is an example of a situation where the PQ challenges are made more acute by the relatively weak, upstream grid and concentrated nonlinear auxiliary load. In the meantime, some commissioning and field explanations have been issued which mention voltage fluctuations during simultaneous escalator and HVAC start, and transmission of harmonics from 750 V DC rectifiers to the 33 kV/0.4 kV networks, as well as flicker due to transient feeder switching. These disorders put stress on complex electronics, cause reduced traction and lead to higher maintenance expenses. It is widely documented that this occurs in other parts of the world, but varies in occurrence and severity depending on the local grid, equipment configuration and operating procedures.

The literature review is presented critically covering: (i) sources of disturbance in electrified systems which are peculiar to metro systems; (ii) documented impacts on safety, reliability and lifecycle cost; (iii) monitoring and measurement practices; (iv) mitigation technologies ranging from filters to FACTS devices and modern inverter based compensators; and (v) recent advances particularly Voltage Source Inverter (VSI) solutions with supercapacitors which promise fast and multi-functional PQ control. The chapter ends with the identification of the gaps in research that inspire the proposed VSI supercapacitor approach to OLMRTS.

2.2 Standards and Conceptual Foundations

Shared definitions and measurement frameworks are crucial components of a coherent literature review. IEEE Std 519 categorizes the disturbances according to their magnitude and duration: Instantaneous (0.5 – 30 cycles) Momentary (30 cycles – 3 seconds) Temporary (3 seconds – 1 minute) Long duration (> 1 minute). Sags (dips) are 0.1 PU to 0.9 PU, swells are 1.1 PU to 1.8 PU, interruptions are less than 0.1 PU and transients can be impulsive (e.g., lightning) or oscillatory (e.g., capacitor

switching), sometimes sub-cycle in nature [4]. The definition of the standardized flicker measurement Pst, Plt, based on a perceptual model of the lamp response to voltage modulation, is set in IEC 61000-4-15 [7]. IEEE Std 519 defines recommended voltage limits for harmonics at PCC (typically THD_V $\leq 5\%$) and defines current distortion limits in relation to the ISC/IL ratio (short circuit to load-current ratio), in order to avoid the individual customer from causing too many harmonics in the network [16, 17].

Steady-state PQ metrics are usually calculated on 10/12-cycle windows (50/60 Hz) from synchronized sampling from a signal analysis perspective. Windowed FFTs or Goertzen algorithms estimate harmonic content, RMS tracking and dV/dt thresholds, detect sags/swells, wavelet transforms, and high-rate sampling captures transients. In the case of rail applications, placing the PQ analyzer is a critical issue; placement at the LV side of MV/LV transformers, on feeders to large motors and escalators, and at station PCCs allows the identification of events to the associated load or upstream source [9].

The two other conceptual pillars guide the metro PQ Network impedance shaping and immunity of end-use equipment. The combination of the shunt capacitors, LCL filters and cable/transformer reactance determine the frequency response. Distortion may be increased rather than decreased when a network resonance happens to coincide with a dominant harmonic. In the meantime, IEC 61000-4 defines test levels for surge immunity, EFT immunity and sag immunity for equipment; procurement enforcing these could lead to a reduction in nuisance tripping and to longer life of equipment[10].

2.3 Sources of PQ Disturbances in Metro Systems.

Different disturbance mechanisms are added by rail auxiliaries and traction power. Steep inrush currents at start-up occur from large induction motors (HVAC chillers, condenser/chilled water pumps, tunnel/shaft fans) and escalator drives on the auxiliary side. Coincident starts, even when using a soft starter or Variable Frequency Drive (VFD), can cause a drop in bus voltage $>10\%$ for tens to hundreds of milliseconds that is sufficient to cause an undervoltage unit to trip or reduce motor torque [12]. Characteristic current harmonics are injected by VFD, switched-mode power supplies (SMPS) in AFC, lighting and ICT systems, and their DC-link capacitance makes the ride-through more complicated during sags [18].

Traction-side converters add harmonics and dynamic power swings. The six and twelve pulse rectifiers create high 5th/7th and 11th/13th harmonics, respectively. Modern PWM converters operate in a manner that cause the shift of spectra to switching side bands, which still demands attention to filtering. If there is coupling, then the DC bus voltage can be raised during regenerative braking and the reactive power on the AC side can be modulated [19].

External events that propagate as a sag, swell, or oscillatory transient to the station buses include upstream grid events, faults, feeder transfers, capacitor bank switching, and load shedding actions. The voltage excursions are deeper in relatively weak grids (low short circuit strength) than in stiff systems, resulting in more events and more severity [20].

2.4 Disturbance and Impacts

One of the worst power quality problems for metro operation is voltage sags, which adversely impact the motor's torque, which is approximately proportional to the square of the voltage. This reduction will cause reduced escalator speeds, and interfere with the start-up of HVAC compressors and may trigger the traction controller to reduce the current or stop running when voltage limits are exceeded. A small delay of a few seconds at rush hour could also be a domino effect that could lead to the train being late.

There is one more concern added: different electrical machines such as motors and transformers use more electricity, and generate heat as a result, creating vibration in the machines. Most of the times sensitive relays got tripped. This situation reduces the efficiency of the system and the lifespan of the equipment as well. In a metro network, a typical unmitigated total harmonic distortion – voltage (THD-V) is 3% to 8%. On feeders that provide loads like variable frequency drives (VFDs) and rectifiers, current distortion (THD-I) is considerably greater [22].

The indices (short-term (Pst) and long-term (Plt)) of flicker are related to short-term light flickering, which can be visible and interferes with the comfort of passengers. It is usually associated with several escalators and/or large motors running simultaneously, or the interaction between control systems. Typical sources of transient disturbances include energization of cables, fault clearing, and capacitor switching, which are all impulsive or oscillatory disturbances. These events produce high dv/dt (voltage rates of change) which can cause damage to the insulation and sensitive switch-mode power supplies unless there is sufficient surge protection. However, there are times when frequency variations occur, usually in a single part of the network or, if the synchronization is not good, in that part of the network in an isolated area or for a short duration, which affects the stability of local systems, albeit to a lesser degree.

2.5 Monitoring and Measurement Practices

Class-A PQ analyzers with time synchronization, either GPS or IEEE 1588 PTP, are highlighted in recent literature since they allow the correlation of events between stations, which is useful for obtaining root cause information and general statistics for a fleet [13]. Common approaches are: (i) installation of permanent analyzers at specific stations and critical feeders; (ii) rotation of portable analyzers and campaigns to cover a variety of temporal patterns; (iii) integrating dashboards that feed THD, Pst, and sag/swell counts into SCADA/historians; and (iv) automated event classification using machine learning (SVM, random forest, and, increasingly, deep learning) trained on waveform snippets [24].

To precisely identify sub-cycle transients and characterize waveform distortion, it is best to use high-resolution capture (at least 128 samples per cycle). The wavelet multiresolution examination can be used to help distinguish the transient content from steady state harmonics, with windowing and meeting methods to reduce spectral leakage. Synchronizing with the operational records makes it a lot easier to understand for metros in which events can be related to timetables (e.g. train departures, escalator duty cycles, HVAC ramps, etc.).[25]

Compliance monitoring involves comparison of measured metrics to IEEE 519/IEC 61000 metrics and to operator-specified interior goals (such as $THD_V < 4\%$ at LV buses in front of a signaling/IT room). The reduction in event depth/frequency and THD histograms should be statistically significant after applying mitigation arrangements (filters, compensators), and not simply nominal conditions. [17].

2.6 Mitigation Techniques

Passive filters (single tuned, high-pass, C type) still have their merits in simplicity and cost, but they are suitable in a place where the harmonic spectra are stable and the network resistance is known. It is known that it suffers from detuning with time, resonance risk and narrow bandwidth. Counter-harmonic currents/voltages are synthesized by fast switches in the Active Power Filters (APFs), both shunt and series. They are able to shift towards changing spectra but introduce cost and complexity and do not offer deep sag support without storage [13].

Static VAR Compensators (SVCs) thyristor-switched capacitors/reactors are capable of delivering very high levels of reactive power control and can enhance voltage profiles on MV buses. The response is

however limited by the firing delay of thyristors and network dynamics – millisecond level LV sags associated to motor starts continue to occur. The STATCOMs (voltage source converter based) provide an instantaneous response to dynamic VAR support, and can moderate voltage sags and reduce flicker, but MV installations are expensive and are electrically remote from the 0.4kV buses where sags/harmonics occur. Railway Power Conditioners (RPCs) are a combination of both harmonic filtering and reactive support and need significant space and custom engineering [22].

Dynamic Voltage Restorers (DVR) are series voltage injection devices, used to cancel the sag on individual feeder lines, whereas D-STATCOMs (shunt at LV) are fast reactive current providers. Unified Power Quality Conditioners (UPQC) are a combination of series and shunt devices that offer comprehensive compensation. These power-electronics devices have a tendency to be close to the multifunctionality needed in metros, however the energy buffers and control strategies will influence whether they are able to cope with the multiple phenomena occurring simultaneously, such as the simultaneous occurrence of sag and harmonic bursts [21], [26].

When the voltage changes with time, automatic voltage regulators (AVR) and on-load tap changers (OLTC) adjust the taps on a transformer. This results in slower voltage control, but more stable. While they may take several seconds to respond, they are used in conjunction with quicker electronic compensators to keep steady state voltage within a 10% of nominal [33].

The authors present a hybrid PI–fuzzy controller based Dynamic Voltage Restorer for an industrial feeder. The series VSI can quickly recover the load voltage in sudden sags, and the fuzzy layer can adaptively adjust the PI action to solve the problem of nonlinearity and parameter drift. The amplitude of the sag is reported to be around 70% reduced with 70% recovery within approximately one electrical cycle with low overshoot at the terminals. The main concerns in practice are membership-function tuning, and a strong PLL for phase tracking [27].

A proposed with phase-angle jumps and off-nominal frequencies adaptive predictive-control DVR is discussed without the need for retuning. The approach is to minimize an energy-aware cost function over the switching states of the inverter using the same pre-sag magnitude and phase to minimize the stress on the DC link. Research shows correct restoration of the phase and stable compensation over the frequency variations (such as 48-52 Hz), while achieving lower energy consumption from storage; it also depends on model fidelity and computational speed [28].

For metro type auxiliary substations, a UPQC with a DC-link supercapacitor (via bidirectional DC/DC) is used. The series converter adjusts the bus voltage in deep sags and the shunt converter removes current harmonics and controls reactive power. Experiments show that the voltage stays stable throughout a 50% sag that lasts 0.2 seconds, and the THD after the event stays within normal limits (like IEEE-519). The method enhances the ride-through capability, but introduces complexity in terms of both hardware and energy management.

Under non-uniform loads, a model predictive control (MPC)based UPQC is proposed to govern the series and shunt converters in order to address sag, swell and harmonics. This MPC cost function enforces the three objectives of voltage regulation, current sinusoidal and the balance of the DC-link simultaneously, resulting in a multi-objective response at a high speed. Results indicate that events with source-current THD values that are kept below typical values can be simultaneously mitigated, with settling times that are kept below baseline values for PI/PR; costs of the computational burden and careful tuning of the cost weights are trade-offs [30].

A DVR – battery hybrid is integrated for wind connected feeders to ensure voltage during feeder's intermittency and short sags. A battery provides additional enhancement to the DVR DC link to allow for the series inverter to inject the compensating voltage vector, with a supervisor controlling the state

of charge and power limits. Tests show that voltage regulation is better during wind transients and when clearing faults, which extends the length of time the battery is compensated compared to supercapacitor-only designs, practical considerations include battery ageing and EMS scheduling [31].

A low-voltage feeder using a DVR with Li-ion supercapacitor hybrid energy storage that demonstrated high transient performance. The DC-links in the design of a DVR or UPQC can be implemented with a Supercapacitor, which can provide high transient power with little degradation. When paired with Li-ion batteries they offer extended power with rapid bursts [32].

Harmonic distortion increases as loads change and the current changes shape from the supply as well. These include variable speed drives, traction converters, rectifiers, welding sets and switch mode power supplies. Due to electronics switching harmonics generated and coming into the system, which may cause changes to the waveforms of both current and voltage. These may cause the Total Harmonic Distortion (THD). Excessive THD Values increase the amount of heat lost in the cable, transformer and motors. [33]

In a power system, reduction of the harmonics can be achieved by using L-C filters or a combination of L-C filters. Only when the filter is tuned the even or odd harmonics have been reduced. Passive filters are simple to operate and inexpensive, but involve loading factors and may cause resonance in the event of an alteration in conditions.

As per IEEE Std. As per 519-2022, THD should be $<05\%$ for the system voltage $<69\text{KV}$. It further explained that THD of every harmonic should be $<03\%$. Hybrid Filters having small rated active filter with passive L-C branches is the solution. Active filter is designed to reward the low order harmonics (5th-13th), passive filter is designed to take care of higher harmonics. A hybrid filter works well in the systems where the harmonic level varies in range [34].

A shunt APF includes a voltage source inverter to generate compensating currents to cancel the harmonic components of the load current. There are many different control algorithms of which the instantaneous reactive power (p-q) method, synchronous reference frame (SRF) control and proportional-resonant (PR) control are commonly used. APFs automatically re-adjust to the load and maintain the existing THD at under 5% [35].

If filters are connected in series with the line, then these filters apply compensating voltage to reduce voltage harmonics and inequities. They are frequently used in combination with shunt filters in a series-shunt hybrid arrangement. The shunt inverter is an active filter and thus UPQC provides an integral harmonic mitigation. It eliminates the distortion of current and voltage harmonics, controls the reactive power and maintains the sinusoidal waveform at the load terminals [36].

Harmonic reduction can be achieved by reducing typical harmonics by changing the supply phase through 12-pulse systems, rectifiers, and inverters. The latest Active Front-End (AFE) converters that use IGBTs and Space Vector Modulation (SVM) can become close to a power factor of 1 and decrease harmonic distortion without using outside filters [37].

2.7 Modern Inverter-Based Compensation and Energy Storage

One of the most important trends since 2018 has been to put inverter-based compensators close to the LV buses, alongside the most detrimental loads (HVAC/vertical transport). The three-phase VSI can be controlled in the synchronous dq0 frame and modulated by Space Vector Modulation (SVM) for the purpose of producing near sinusoidal currents/voltages that have low switching ripple. By using appropriate control loops and an LCL output filter, the same hardware can (i) inject reactive/active

current for voltage support, (ii) cancel harmonics by chasing the reference waveforms, and (iii) deliver short ride-through when connected to an energy buffer [8].

The decision on energy storage is crucial. The properties of supercapacitors are well suited to high power density, fast charging and discharging, and long cycle life, in response to short-duration sags (tens to hundreds of milliseconds) and transient absorption. Batteries offer a higher energy density but low power density and limited cycle life with repeated pulses. Flywheels provide power and energy at higher capex. In the case of auxiliaries for the metro, the event statistics (short, frequent) are better suited to supercapacitors that are sized by $E = \frac{1}{2} \cdot C \cdot (V_{\max}^2 - V_{\min}^2)$, to ensure that the LV bus voltage remains within $\pm 5\%$ of the nominal value during the worst-case start.

Selected harmonics frequency locked loops are used to enhance the performance of Phase Estimation for distortion resonant controllers and repetitive control. It also increases dynamic tracking but decreases sensitivity.

To ensure consistent railway operation and to eliminate resonance and keep phase margin Damping of the LCL filter (passive RC or active virtual impedance) is needed.

2.8 Global Case Studies (2018–2025)

The THD_V value in China high speed and Urban metro corridors was reduced from 06~08% to below 04% using APFs and STATCOMs to control harmonic distortion and flicker.

The use of STATCOMs by the Delhi Metro at vulnerable nodes minimized the sag depth during heavy escalator/HVAC duty cycles, but the small sags that still occurred were in the sub-second time frame and motivated the installation of LV-side compensators [25]. A typical example is the tight compliance in European metros, supported by widespread PQ monitoring, coordinated MV/LV filtering and by demanding the immunity of IEC 61000-4-x for all electronics in the procurement procedures (EN 50160)[41].

Outside the OECD, not necessarily, but with weaker grids the cost benefit argument for LV-side compensators gets stronger. Some strategically sited VSI supercapacitor stations (200-500 kVA, 200-500 kJ) can eliminate most customer-visible events (AFC reset, escalator stalls) and minimize nuisance protection trips, with larger MV devices to be used to compensate for reactive power and fault ride-through in the corridor.

2.9 Comparative Assessment of Mitigation Options

SVC and STATCOM are suitable solutions for VAR control and flicker reduction in the corridor level, especially where there are many stations connected via an MV bus. They have the disadvantage of being remote from LV phenomena and capital intensive at scale. Passive filters are low cost for stable harmonic content, but can detune or resonate over time [21]. While APFs can help to reduce harmonics, they are not necessarily a solution to deep sags without storage. Under coincident disturbance conditions, the efficacy of the support provided by DVR/D-STATCOM/UPQC is determined by energy buffers and controller design and is targeted to the LV. The efficacy of the support provided by DVR/D-STATCOM/UPQC is fast dynamics and targeted to LV, while energy buffers and controller design determine efficacy under coincident disturbance conditions [42].

A layered architecture as indicated in literature is implemented: MV (STATCOM/SVC) in bulk; LV inverter-based compensators in the proximity of disturbing/sensitive loads for sags and harmonics. This “hybrid” approach is designed to minimize overall CAPEX, by adjusting the capacity of the device according to the location of the disturbance and its size, and to enhance resilience by avoiding a single point of failure[43].

2.10 Research Gap and Rationale for VSI–Supercapacitor in OLMRTS.

There are three gaps in the recent literature. First, many deployments are done for harmonics (filters/APFs) or Voltage Regulation (SVC/STATCOM/DVR), and not for both the two challenges at the same time and place, as required by metro auxiliaries. Second, the second group, the high-power, short-duration energy storage, are not often paired with LV compensators optimized for escalator/HVAC duty cycles and weak-grid statistics studies. Third, data are underrepresented in developing-grid metros, so that the choices of parameters and the playbook of deployment are not transferable [44].

OLMRTS: Harmonics, limited ride through for critical electronics, millisecond response to sag and modular deployment by criticality are addressed near selected 0.4 kV buses. The method can be used in addition to MV devices and the traditional filtering, but not in place of it. This dissertation is, therefore, centered on modelling, designing, and comparing such a compensator with the existing alternatives, based on the MATLAB/Simulink platform, validated on a set of load profiles similar to the ones that are encountered in the OLMRTS, and appropriate upstream variations.

2.11 Literature Summary Table (2018–2025)

Table 2-1 Literature Summary

Ref.	Author(s) & Year	Focus / Context	Method / Technology	Key Findings / Limitations
[1]	Dick Sang Hoo et al., 2023	Harmonic issues in third-rail systems (rail traction)	Measurement + mitigation strategies for DC third-rail	• Identifies dominant harmonic sources in third-rail networks • Suggests filter/operational mitigations • Limitation: DC traction focus adapts to 0.4 kV LPS context
[2]	X. Guo et al., 2021	Voltage sag severity evaluation in distribution networks	Weight-based multi-factor sag index	• Prioritizes sags by impact (depth/duration/load criticality) • Useful to size energy buffer for DVR/VSI • Limitation: evaluation, not hardware mitigation
[3]	Lee Kong Chian et al., 2021	Harmonic analysis of third-rail system (Malaysia)	Case study harmonic spectrum & sources	• Confirms traction converters as key harmonic drivers • Informs tuned/active filter design • Limitation: DC traction auxiliary buses
[4]	S. Chen et al., 2025	PQ improvement via EV charging pile integration	Control/coordination of chargers for grid support	• Chargers can provide reactive/harmonic support

Ref.	Author(s) & Year	Focus / Context	Method / Technology	Key Findings / Limitations
				• Limitation: Concept aligns with distributed compensation
[5]	H. Hu et al., 2024	Traction power systems state of the art	Supply topologies & PQ challenges	• Maps typical PQ issues in rail (sag/flicker/harmonics) • Highlights conditioner options • Limitation: Broadly limited LV auxiliary detail
[6]	V. Astapov et al., 2025	High-RES distribution grid challenges	Review of technical PQ solutions	• Recommends fast converters + storage for sags • Supports hybrid APF/UPQC for THD • Limitation: RES-centric infer to metro LPS
[7]	L. Guasch-Pesquer et al., 2022	Voltage unbalance estimation	Induction-motor-based VUF determination	• Accurate VUF assessment supports compensation design • Limitation: unbalance metric not a compensator
[8]	Y. Seferi et al., 2020	PQ in 25 kV 50 Hz AC railway	Field measurement & active harmonic power	• Shows measurement framework for railway PQ • Limitation: HV AC adapt to 0.4 kV LPS
[9]	F. Chishti et al., 2021	Harmonics in a renewable microgrid under a non-ideal grid	Frequency-Adaptive Multistage Harmonic Oscillator	• Robust harmonic extraction/control under distortion • Useful for APF/UPQC controls • Limitation: Control algorithm focus
[10]	X. Wang et al., 2022	Stability & harmonic suppression of LCL inverters	Advanced control of grid-tied LCL VSI	• Improves THD with stable LCL behavior • Relevant to VSI output filter design • Limitation: Generic inverter grid-tie, not rail-specific
[11]	L. Tang et al., 2022	Voltage sag control measures	Overview of DVR, STATCOM, UPQC, UPS	• Confirms DVR/UPQC as primary sag/swell tools • Good design checklist

Ref.	Author(s) & Year	Focus / Context	Method / Technology	Key Findings / Limitations
				• Limitation: survey a few case specifics
[12]	M. U. Saleem et al., 2022	DSM/EMS in smart grids	IoT-based energy management	• Peak shaving reduces sag probability indirectly • Limitation: system-level, not a device-level PQ fix
[13]	D. S. Hoo et al., 2024	Harmonic distortion in DC third-rail; mitigation	Dynamic harmonic analysis + strategies	• Practical mitigation roadmap for rail traction • Limitation: DC traction is not for the auxiliary system.
[14]	S. M. Ahsan et al., 2021	PV + nonlinear loads in LV networks	Measurement + simulation of THD	• Quantifies THD interactions with PV in LV • Guides filter sizing at PCC • Limitation: residential LV adapt to LPS profiles
[15]	G. Cui et al., 2019	Railway static power conditioner + supercapacitor	SC-integrated R-SPC for regen & PQ	• Storage-assisted PQ improvement in rail • Supports SC sizing ideas • Limitation: Dynamic Compensation is not controlled
[16]	J. E. Caicedo et al., 2023	Real-time PQ disturbance detection	Systematic review of detection/classification	• Aids fast sag detection trigger for VSI/DVR • Limitation: algorithmic not mitigation hardware
[17]	A.-D. Gonzalez-Abreu et al., 2022	PQ analysis for machines/drives	Review of signal processing/control	• Techniques for harmonic/unbalance analysis • Limitation: Machine-centric
[18]	S. Wang et al., 2022	Voltage sag detection & dual-loop DVR control	DVR with improved detection/control	• Confirms cycle-level restoration with robust loops • Aligns with VSI control path • Limitation: simulation-heavy
[19]	H. Hu et al., 2024	Traction systems	PQ Stability	• sag/flicker/harmonics • Limitation: Time response slow

Ref.	Author(s) & Year	Focus / Context	Method / Technology	Key Findings / Limitations
[20]	J. S. Peng et al. 2020	Transformer energization sag assessment	Stochastic analysis of dips	Quantifies sag probability from energization
[21]	M. R. Patel et al., 2020	Voltage profile in metro station	Distribution design + improvement (case)	- Practical voltage-profile improvement steps - Limitation: limited harmonic treatment
[22]	IJRER, 2023	Passive harmonic filters with PV & nonlinear loads	Application guidelines/case	- Demonstrates THD reduction with tuned filters - Limitation: static tuning resonance risk
[23]	A. Qasim et al., 2021	UPQC under nonlinear loads	Series+shunt compensation for sag/swell/THD	- Simultaneous mitigation voltage & current - Limitation: higher cost/complexity
[24]	M. K. Mishra et al., 2020	Reactive power with grid-PV	Control for PF/Q support	- VAR support eases sag depth at buses - Limitation: not a direct sag restorer
[25]	R. S. Salles et al., 2023	Waveform distortion in railway power	Review of interaction/assessment methods	- Railway-specific distortion modes mapped - Limitation: assessment focus on mitigation implicit
[26]	K. Soujanya et al, 2024	Harmonic reduction with PV-fed D-STATCOM	Grid-connected PV D-STATCOM control for VAR & THD	- THD suppression at PCC PF improvement - Limitation: small-scale/simulation-centric
[27]	Y. Siregar et al., 2024	DVR performance using FLC & BESS	Fuzzy logic controller with battery	- Restored voltage sag efficiently response - Depends on BESS capacity.
[28]	J. Qiao et al., 2020	Robust control (aerospace)	Composite Nonsingular TSMC (spacecraft)	Robustness concepts may inspire VSI control
[29]	S. Lakshmi et al., 2018	Open-UPQC with PV in distribution	PV-integrated open-UPQC placement/modeling	- Voltage profile & THD improved energy efficiency - Limitation: older specific to open-UPQC
[30]	T. Ravi et al., 2023	PQ mitigation with IUPQC (fuzzy)	Fuzzy-based Interline UPQC for grid system	Simultaneous sag/swell/THD mitigation

Ref.	Author(s) & Year	Focus / Context	Method / Technology	Key Findings / Limitations
				• Limitation: primarily simulation results
[31]	T. Upadhayay et al., 2024	Hybrid energy storage (wind grid) for PQ	HESS (battery+SC) control for voltage support	• Ride-through & flicker reduction supports storage sizing • Limitation: wind system context
[32]	M. R. Çorapsiz et al., 2023	Li-ion & SC design for hybrid storage	Modeling and simulation	• Optimized energy sharing • Needs real-world validation.
[33]	S. Chatterjee et al., 201	EEG signal analysis (non-PQ)	MF-DFA feature extraction	• Methodological reference only • Limitation: PQ/rail consider removing
[34]	A. Sunbul et al., 2022	Harmonic mitigation filter design	Design approach for high-power filter	• Improves system THD • Lacks experimental demonstration.
[35]	A. Patel et al., 2020	VA sharing in UPQC	Modified SRF-PAC method	• Balances shunt/series APF load • Complexity in tuning.
[36]	M. He et al., 2025	PQ mitigation in modern grids (review)	Survey of emerging tech (MPC/AI, UPQC/DVR)	• Confirms fast converters + storage for sags hybrid filtering for THD
[37]	D. S. Hoo et al., 2023	Mitigation of Harmonics in third rail electrical systems	A combination of active and passive filtering techniques has been purposed, which supported by MATLAB/Simulink modeling	• Attained distinguished THD reduction and improved power factor stability. • Improved waveform quality under nonlinear traction loads. • Limitations comprised on accurate tuning of filter parameters and higher system cost
[38]	H. H. Jamil et al., 2021	AI-based harmonics & VAR control (microgrid)	AI control strategy for grid-connected inverter	• Enhanced harmonic suppression under dynamic loads • Limitation: metadata incomplete verifies peer-review
[39]	D. Giordano et al., 2021	Power Quality Measurement in DC Railway System	AMPS21 conference measurements	• Highlights DC-rail PQ issues. informs OL traction background

Ref.	Author(s) & Year	Focus / Context	Method / Technology	Key Findings / Limitations
				• Limitation: brief workshop paper
[40]	H. Saxena et al., 2021	Shunt APF using SOGI/ROGI synchronization technique	Progressive PLL and observer for slanted grids	• Well tracking lesser THD with APF • Limitation: control-algorithm focus
[41]	R. Satish et al., 2022	Harmonics issues in RES and unbalanced load.	Novel calculation algorithm (smart supply network)	• Quantifies interactions guides filter/compensator goals • Limitation: Inter Harmonics not precise.
[42]	K. Jha & A. G. Shaik, 2023	PV-grid PQ mitigation	Survey of UPQC/D-STATCOM/APF for PV scenarios	• Recommends UPQC/D-STATCOM for PV-rich feeders • Limitation: Slow Response.
[43]	E. Hernández Mayoral et al., 2023	Microgrid PQ issues & control	Review: optimization + control strategies	• Catalogs optimization/controls applicable to VSI/APF/UPQC • Limitation: broad scope
[44]	S. Ranjan et al., 2021	Voltage control using DVR in hybrid system	Simulation-based DVR model	• Effective voltage restoration • Limited to single-phase simulation.

2.12 Chapter Summary

This chapter discussed global benchmarks, monitoring mechanisms, and improving PQ of metro systems, with the main focus on changes between 2018-2025. It includes observations on disruptions caused by internal dynamic load such as HVAC systems, escalators, switch-mode power supply, traction converters, etc. and external grid events such as system failures and load shedding. These create discomfort to the users, equipment damage, and increase operation costs. Currently, monitoring systems trends are starting to utilize Class-A synchronized analyzers, and the PQ data is combined with a machine learning systems to create actionable performance indicators. However, the measure of PQ data is not enough, and mitigation systems are required to deal with rapid disturbances in the sub-second scale, which are located as close to the source as possible. Conventional technologies such as SVCs, RPCs, and STATCOMs, provide a solution to a portion of the problem. However, to address sag and oscillations, STATCOMs and Filters are effective at the MV level. Emerging technologies such as D-STATCOM, DVR, and UPQC at the LV level provide comprehensive control through smaller design and faster response, but come with a large investment in energy storage. A layered approach using medium-voltage reactive compensation in combination with localized low-voltage, inverter-based devices is being recommended in most of the recent literature. The proposed solution of a VSI augmented with supercapacitors provides significant benefits to the system including rapid response, sag compensation, and harmonic filtering and short-duration support of system voltages.

However, there is still some work to be done when documenting energy sizing for LV compensators using metro event data, verifying control under weak grid conditions likely to occur in developing networks, and document the integration of observation combined with control automation. The gaps mentioned above are the starting points for the VSI supercapacitor solution developed and proposed for the Orange Line Metro Train system.

CHAPTER-3

METHODOLOGY

3.1 Introduction

This chapter explains the full method we used to build, run, and evaluate a Voltage Source Inverter (VSI) model in MATLAB/Simulink for the Orange Line Metro 0.4 kV system. The goal is to improve power quality at the station's Low-Voltage (LV) bus by reducing voltage sag, lowering harmonic distortion, and improving power factor. We keep the wording simple and practical. First, a short introduction to MATLAB/Simulink. Next, I describe the system model, each block, and the control design. Then I present equations and simple formulas for sizing the LCL filter, the supercapacitor, and the controller gains.

3.2 MATLAB/Simulink

With MATLAB/Simulink, designing electrical systems becomes easy with use of building blocks and wires. The software computes the equations of the electrical network in a small number of time steps (for example, 50-100 microseconds). The digital controller runs in lock-step with the time steps simulated. This co-simulation is essential since brief power quality events only last several milliseconds. Simulink measures voltages, currents, and computes power and THD. It can also store signals to the workspace for plotting and tabulation.

The system transforms a 3-phase AC input supply into a regulated DC link with the aid of a transformer and boost, and synthesizes a 3-phase AC output with a 2-level IGBT VSI. An LCL filter on the grid side and an LC filter on the load side controls harmonic content and assist in meeting power quality requirements during disturbances. A disturbance block implemented in the simulation applies a voltage sag on the grid in order to test ride-through capability and output regulation.

3.3 Site analysis

This technical solution is designed to address the escalator and chiller shutdown problems at Orange Line stations in Lahore, Pakistan. The shutdown problem is universal in location and occurs at all stations it is random in time and occurs at non-specific times during line operation. From September 2023 to June 2024, various power quality characteristics such as line harmonic voltage, harmonic current, voltage fluctuation, and voltage sag were continuously measured, and relatively rich data was accumulated. Based on detailed analysis, we have clearly identified that the core of the problem lies in the frequent voltage sags in the low-voltage bus system, which significantly interferes with the normal operation of equipment that relies on a stable power supply. figure 3-1, 3-2, and 3-3 explain the voltages Sag in the Distribution Orange line metro trains.

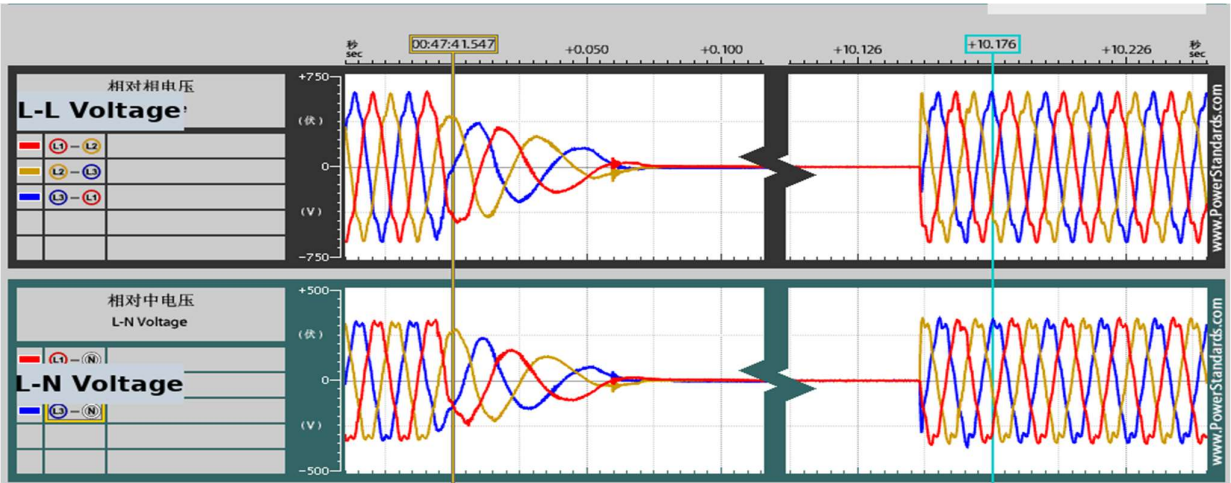


Figure 3-1 Voltage Sag Results in 0.4kV System

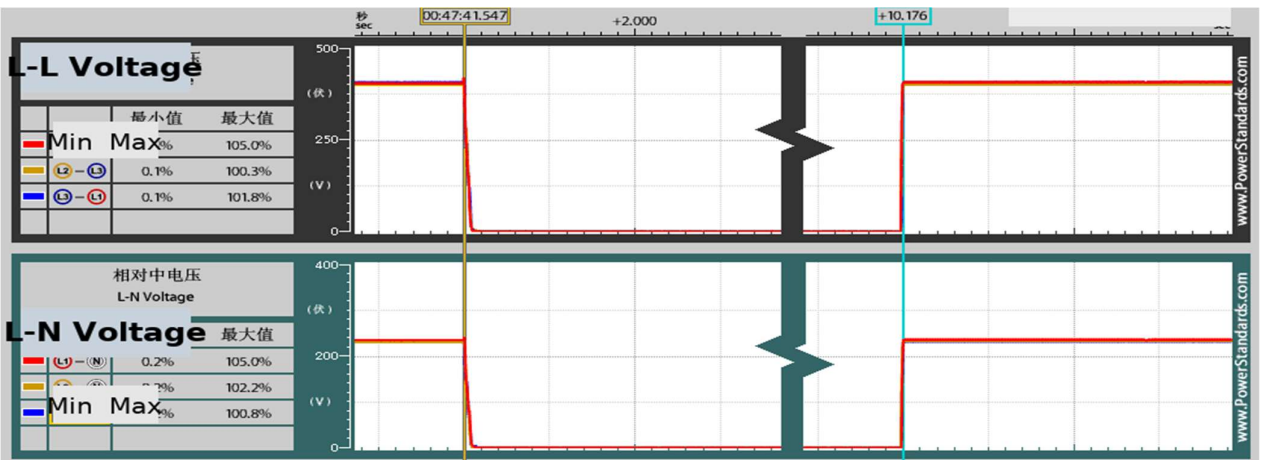


Figure 3-2 Voltage Sag Results in 0.4KV system

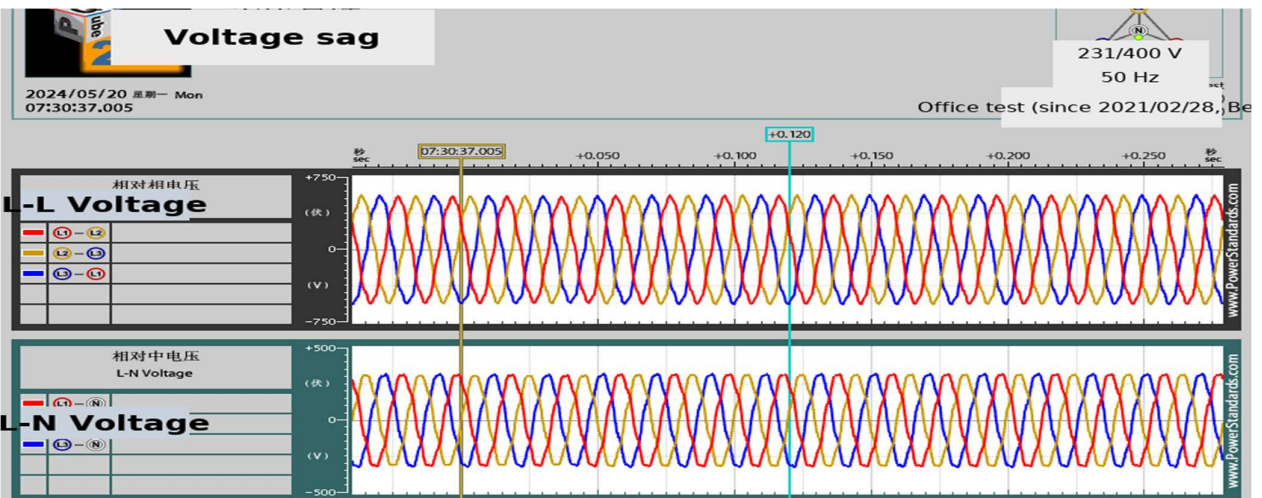


Figure 3-3 Voltage Sag Results in 0.4KV System

3.4 System Under Study

The model represents one station's LV bus at 0.4 kV supplied by a 33/0.4 kV transformer, which in turn is fed by the utility at 33 kV. We include the grid impedance so the source is not ideal. This matters because higher source impedance makes sags deeper during motor starts and load steps. The LV bus has three kinds of loads: (a) motors for HVAC, (b) escalators with VFD front ends, and (c) electronic loads such as lighting, IT, and AFC, etc.

A three-phase VSI connects at the LV bus through an LCL filter. The DC link of the inverter has a supercapacitor. In normal operation, the inverter reduces harmonics and improves power factor by injecting or absorbing reactive current and cancelling distortion. When a sag is detected, the inverter also injects active power drawn from the supercapacitor to hold the bus voltage as close as possible to nominal.

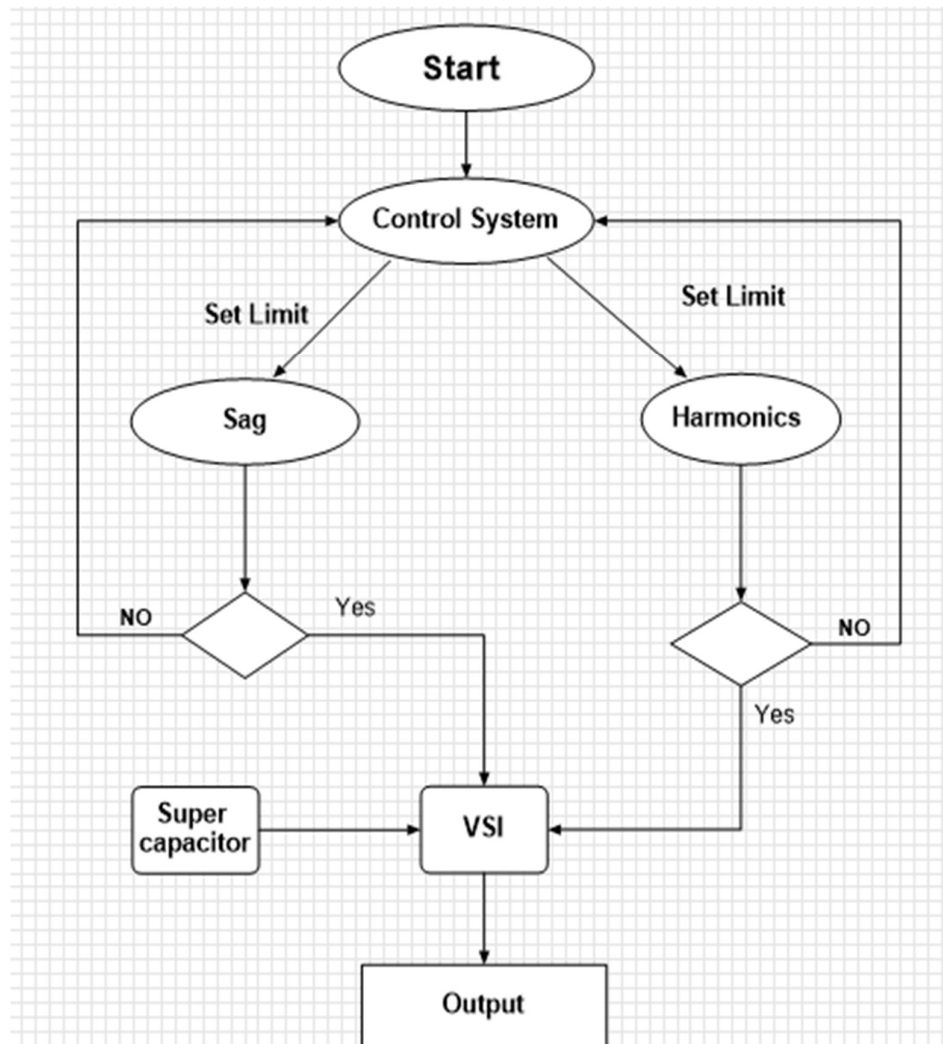


Figure 3-4 Flow Diagram of Proposed System.

3.5 VSI Model Overview

Figure 3-5 is relevant to the proposed model.

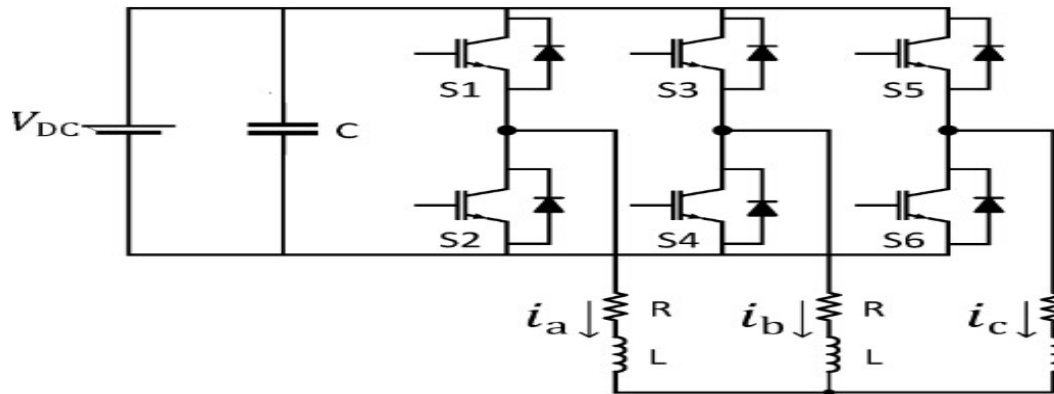


Figure 3-5 VSI Model

3.6 Simulink Model Overview

Figure 3-6 is relevant to the proposed model.

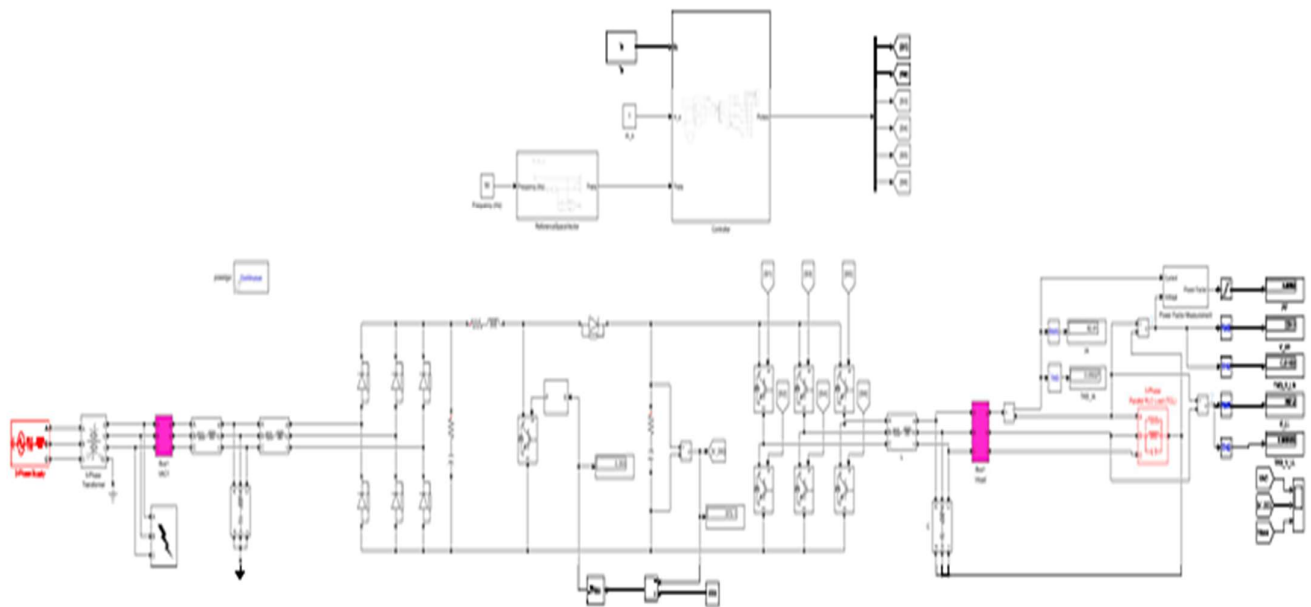


Figure 3-6 Simulink Model

Figures 3-7 express the Simulink model Controller.

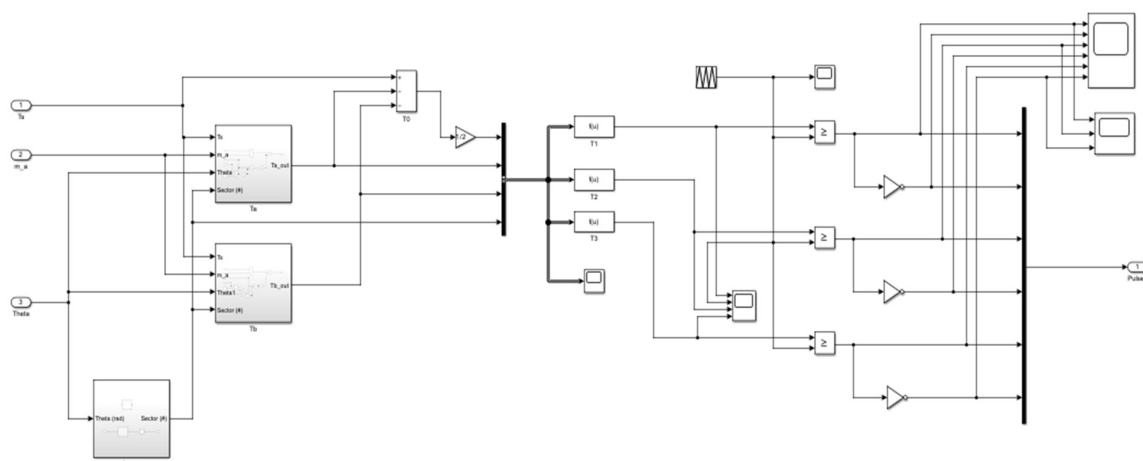


Figure 3-7 Controller subsystem (PLL + dq PI loops)

The fig 3-8 explains the input and output of the Simulink model.

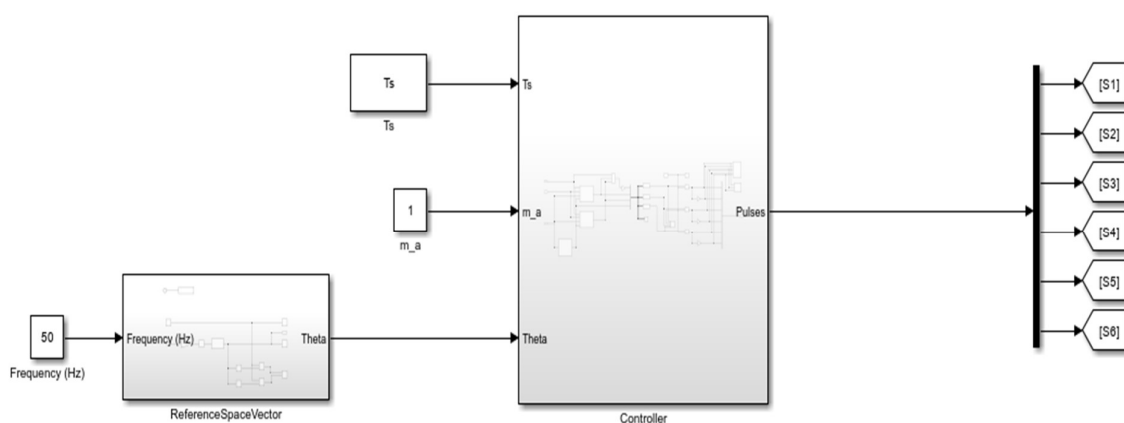


Figure 3-8 Simulink block parameter dialogs

3.7 Block-by-Block Explanation

3.7.1 Three-Phase Supply

This block works as the main AC power source, providing a balanced three-phase 400 V supply at 50 Hz is similar to a real grid, as we obtain it. It has a small internal resistance and inductance, to mimic the internal impedance of the power supply. These parameters determine the level of voltage drop / fault current during disturbances. It also aids to mimic the reaction of the grid when the converter draws or injects current.

3.7.2 Three-Phase Transformer (Δ/Y_n)

The transformer is required to electrically isolate the supply and the converter. It has a primary delta connection which removes the third order harmonics and a secondary star connected winding which provides a neutral point for measurement and single-phase loads. The kVA rating, voltage ratio and impedance are selected based upon actual substation data to ensure that the simulation results are similar to the behavior of the actual substation. It guarantees correct voltage level adaptation and safe operation of the system.

3.7.3 Programmable Fault / Sag Injector

This block was used to observe the voltage dip, swell or fault in the grid and note the efficiency of the inverter when the grid is not normal. The user can change the sag's depth and length to fit real-world situations, like 0.8 PU or 0.5 PU. dips. It can be used to inspect the speed of the voltage restoration of the control system and the response of the DC link and the inverter to transients. In essence, it's a virtual fault generator for system testing.

3.7.4 Measurement Chain (RMS/Scopes/FFT)

Here voltage and current sensors are placed to continuously measure the parameters of the line. The RMS will measure real time voltage and current magnitudes and the power meters measure active and reactive power flow. Power Gui's FFT analysis determines harmonic distortion and total THD. The scopes show waveforms of voltage, current and power, allowing performance to be viewed during and after faults. RMS displays, power/energy meters, and FFT/THD analysis blocks are fed by Voltage/Current Measurement blocks through Powergui. Provide coherent windows ($\text{THD} \geq 10$).

3.7.5 DC-Link Section

The DC-link block acts as an energy storage and stabilizing section between the rectifier and inverter. The pre-charge resistor and contactor protect the capacitors from high inrush currents at startup. Large electrolytic capacitors keep a stable DC voltage and soak up the energy that comes from switching. There is also a braking chopper or resistor that lets out additional energy while the system is in regenerative mode. This keeps the DC-link voltage from being too high.

3.7.6 IGBT 3-Phase Bridge (VSI)

Actually, this is the inverter that converts DC to AC power. A bridge design with anti-parallel diodes has six IGBT switches. The controller (PWM) operates the IGBTs to turn them ON and OFF. In addition, the correct amount of dead time between switching signals stops short circuits from trending on the DC bus. This section generates the AV Voltages for the load or the grid.

3.7.7 Modulation and Control (PLL+ dq Control)

A Phase-Locked Loop (PLL) has a track of the exact phase angle of the grid voltage so that the inverter output breaks in sync. We can change the measured ABC voltages and currents into dq components to change active and reactive power separately.

The inner current loop reacts rapidly to changes in the system, and the outside voltage or power loop maintains everything working smoothly. Together, they keep the voltage constant and accurate even when things go wrong.

3.7.8 Output Filters

An Output filter is a **low-pass** filter that is connected between **the** inverter and the point of common coupling (PCC). It gives smooth output, the bumps that happen when the current changes rapidly, making sure that the current flows into the grid in **an orderly**, sinusoidal pattern. The parameters of the inductor and capacitor are carefully chosen to find the right balance between stability and reduction.

In some cases, an additional LC branch is used at the load side to improve power factor and further suppress harmonic currents[45].

3.7.9 Motivation for Filter Re-Design

The first attempt at calculating the LC filter parameters using the theoretical design resulted in voltage and current Total Harmonic Distortions (THD) exceeding the allowable limits according to the standards specified in IEC 61000-2-4 and IEC 61727. Due to the phase of the high power mixed nonlinear loads and inverter switching harmonics, practical re-setting of filter parameters was needed.

Using trial and error-based simulation analysis, tuning filter parameters such as passive filter inductance and capacitance increased, along with an adjustment to the value of the damping resistance, significantly improved harmonic performance.

3.8 Final LC Filter Parameters (Simulation-Validated)

The LC filter parameters that successfully reduced both voltage and current THD within IEC limits are:

- Filter Inductor:

$$L_f = 3.5 \text{ mH}$$

- Filter Capacitor:

$$C_f = 300 \mu F$$

- Damping Resistance:

$$R_d = 0.02 \Omega$$

This approach is consistent with recent open-access studies, which highlight the necessity of simulation-assisted tuning of passive filters under nonlinear loading conditions to achieve acceptable power quality performance.

3.8.1 Cut-Off Frequency Calculation of the Redesigned LC Filter

$$f_c = \frac{1}{2\pi\sqrt{L_f C_f}}$$

Substituting:

$$f_c = \frac{1}{2\pi\sqrt{(3.5 \times 10^{-3})(300 \times 10^{-6})}}$$

$$L_f C_f = 1.05 \times 10^{-6}$$

$$\sqrt{L_f C_f} = 0.0010247$$

$$f_c = \frac{1}{2\pi(0.0010247)} = 155.3 \text{ Hz}$$

$$\boxed{f_c \approx 155 \text{ Hz}}$$

This frequency lies:

- **well above fundamental 50 Hz**, therefore, the fundamental waveform is preserved
- **below 5th (250 Hz) & higher harmonics**, therefore they are strongly attenuated

This cut-off frequency lies above the fundamental frequency (50 Hz) and below dominant low-order harmonic frequencies, enabling effective attenuation of 5th, 7th, and higher-order harmonics. Similar filter design principles are reported [46].

Interpretation

- The cut-off frequency is well above the fundamental frequency (50 Hz)
- The filter strongly attenuates 5th (250 Hz), 7th (350 Hz) and higher-order harmonics
- This explains the observed reduction in THD in the simulation

3.8.2 Inductive and Capacitive Reactance Analysis

The inductive reactance of the output inductor at the fundamental frequency is given by:

$$X_L = 2\pi(50)(3.5 \times 10^{-3})$$

$$X_L = 1.10 \Omega$$

Similarly, the capacitive reactance of the filter capacitor is expressed as:

$$X_C = \frac{1}{2\pi(50)(300 \times 10^{-6})}$$

$$X_C = 10.6 \Omega$$

At the fundamental frequency, the capacitor presents a relatively high impedance, while at higher harmonic frequencies it provides a low-impedance path, thereby improving voltage waveform quality. This behavior is well-documented in recent harmonic mitigation studies [10], [47]

3.8.3 Resonance and Damping Analysis

The corresponding critical damping resistance is calculated as:

$$R_{crit} = \sqrt{\frac{L_f}{C_f}}$$
$$R_{crit} = \sqrt{\frac{3.5 \times 10^{-3}}{300 \times 10^{-6}}}$$

$$R_{crit} = 3.42 \Omega$$

The implemented damping resistance:

$$R_d = 0.02 \Omega$$

Although the implemented damping resistance

$$R_d = 0.02 \Omega$$

is lower than the critical value, sufficient damping is achieved due to inherent system losses and the presence of a mixed R–L–C load[48].

Interpretation

Although

$$R_d < R_{crit}$$

Sufficient damping is achieved due to:

- High load current
- Mixed R–L–C load composition
- Inherent losses in the inverter and cables

This prevents resonance amplification while maintaining low power losses.

3.8.4 HARMONIC ATTENUATION ANALYSIS

For a 2nd-order LC filter, attenuation magnitude is approximated by:

$$|H(f)| \approx \left(\frac{f_c}{f}\right)^2$$

Where:

$$f_c = 155\text{Hz}$$

$$f = n \times 50(\text{harmonic frequency})$$

Table 3-1 Harmonics Attenuation Factor

Sr#	Harmonics	Frequency	Attention Factor $\left(\frac{f_c}{f}\right)^2$
01	3 rd	150	0.73
02	5 th	250 Hz	0.384
03	7 th	350 Hz	0.196
04	11 th	550 Hz	0.0976
05	13 th	650 Hz	0.0569

3.8.5 Voltage Harmonics**Table 3-2 Voltage Harmonics before and after**

Sr#	Harmonics	Before	Attenuation Before Harmonics	After Redesign Filter
01	3 rd	4 %	0.73	2.92%
02	5 th	6 %	0.384	2.304%
03	7 th	3 %	0.196	0.588%
04	11 th	1.5 %	0.0976	0.1464%
05	13 th	1 %	0.0569	0.0569%

Before Filter Tuning Voltage THD

$$THD_V = \sqrt{4^2 + 6^2 + 3^2 + 1.5^2 + 1^2}$$

$$THD_V = 8.02\%$$

After Filter Tuning Voltages THD

$$THD_V = \sqrt{2.92^2 + 2.304^2 + 0.588^2 + 0.1464 + 0.0569^2}$$

$$THD'_V = \sqrt{14.18}$$

$$THD'_V = 3.76\%$$

3.8.6 Current Harmonics**Table 3-3 Current Harmonics before and after**

Sr#	Harmonics	Before	Attenuation X Before Harmonics	After Redesign Filter
01	3 rd	7 %	0.73	5.11 %
02	5 th	10 %	0.384	3.84 %
03	7 th	6 %	0.196	1.176 %
04	11 th	2.5 %	0.0976	0.244 %
05	13 th	2 %	0.0569	0.1138 %

Before

$$THD_I = \sqrt{8^2 + 10^2 + 6^2 + 2.5^2 + 2^2}$$
$$THD_I = 14.5\%$$

After Filter Tuning

$$THD_I = \sqrt{5.11^2 + 3.84^2 + 1.176^2 + 0.244^2 + 0.1138^2}$$
$$THD'_I = \sqrt{42.31}$$
$$THD'_I = 6.50\%$$

- Significant attenuation of switching harmonics
- Reduction in voltage and current THD
- Compliance with IEC 61000 THD-V (<5%) and THD-I limits (<8%)

This characteristic ensures strong attenuation of inverter switching harmonics and a significant reduction in voltage and current THD. Open-access studies confirm that properly tuned LC filters can effectively suppress harmonics in inverter-based systems[49].

3.8.7 Relationship with Simulation Results

Simulation results confirm that:

- Initial LC parameters resulted in excessive THD due to insufficient harmonic attenuation
- The redesigned LC filter with

$$L_f = 3.5 \text{ mH}$$

and

$$C_f = 300 \mu F$$

reduced resonance and improved harmonic suppression

- Voltage and current THD values fall within IEC permissible limits

3.8.8 Three-Phase Load

The load block models the auxiliary systems of a metro substation, consisting of resistive, inductive, and capacitive components in parallel. The resistor stands for lights and heaters, the inductor stands for motors and transformers, and the capacitor stands for power-factor correction units. By changing these settings, you may see how different operating situations, including trailing, leading, or unity power factor, work. This lets you see how changes in voltage and harmonics influence items in real life.

3.8.9 SVPWM Controller (Reference Space Vector → Controller → Pulses)

This part generates the six gate pulses (S1–S6) that run the inverter.

- The Reference Space Vector block generates the 50Hz frequency and turns it into a rotating vector with an angle θ that expresses where the phase is.
- The Controller block uses Space Vector Pulse Width Modulation (SVPWM) to figure out the reference vector's sector position and the switching times (T_a , T_b , and T_0) for each phase. These control signals are applied to produce six PWM pulses, one for each of the inverter's six switches.
- The pulses are arranged so that the output voltage closely follows a sinusoidal waveform with minimal harmonic content and maximum DC-bus utilization.

3.8.10 Parameters

Table 3-4 Grid and Transformer

Parameter	Value
Grid frequency	50 Hz
Grid nominal V _{LL}	400 V
Transformer rating	500 kVA
Transformer ratio	33 kV / 0.4 kV
Vector group	Dyn11
Impedance	6.92 %

Table 3-5 Filter Circuit Values

Parameter	Value
Grid-side LCL	L1=3 mH, C=300 μ F, L2=3 mH
Output LC	L=3.5mH, C=300 μ F
Damping/Snubber	R=0.02 Ω

Table 3-6 DC Link & Power Stage

Parameter	Value
V_DC reference	575 V
Measured steady V_DC	≈570.4 V
Observed under sag	≈558–565 V
Inverter PWM freq.	25 kHz

Summary

Chapter 3 explains how modeling, control, and testing work for the VSI-based power quality compensator situated at the Orange Line Metro's low-voltage bus. The first section describes the full system framework, including the three-phase source, transformer, DC-link, inverter and load. The metro network sections of the system have been modeled in MATLAB/Simulink and have been given a high fidelity, which describes their actual behavior. The control method is described in detail. This includes the phase-locked loop (PLL) and dq-axis control with the Space Vector Pulse Width Modulation (SVPWM) control. The control method is designed to ensure that the system responds behaviorally to disturbances (sags and swells) in the voltage and that the current is maintained within predetermined bounds. The chapter has improved theories and does better than many other theories by including tables and tracking logs for recording the system parameters as well as a place for the Simulink screen shots. The control method is presented in detail and the design is laid out in sequential steps. The assumed test cases and the expected results of the test cases (voltage sags, unbalanced load, harmonic distortion) have been presented so that the test may be replicated.

CHAPTER-4

RESULTS & DISCUSSION

4.1 Introduction

This chapter details the simulation results based on the Simulink model in Chapter 3, and compares the performance of the proposed VSI-supercapacitor compensator with the goals outlined in Section 1.4.1. Two test conditions are used. The first test is an undisturbed steady-state that shows normal-operation performance of harmonics and power factor in the presence of a mixed RLC and nonlinear load, defined in Section 3.6.10. The second test is a programmable sag (Section 3.6.3) where the source voltage is dropped to a fraction of its nominal value to show the compensator's ride-through capability. The results shown are from the newly designed output filter in Section 3.6.9, the grid-side LCL Stage, Section 3.6.8, and the PLL-dq control loop, Section 3.6.7. The DC-link voltage is set to the 575 V reference, Table 3-6.

The rest of the chapter is laid out as follows. Section 4.2 outlines the test conditions that apply to all results presented in the chapter. Sections 4.3 to 4.5 present results for the full normal-sag-recovery cycle, the steady-state normal-operation run, and the sag interval, in both waveform and tabular form. Section 4.6 compares the analytical harmonic prediction, Section 3.6.9, and the simulation result. Sections 4.7 and 4.8 analyze the power factor, and the related power quality measurement standards, while Section 4.9 offers a qualitative analysis of the results with the mitigation techniques in Chapter 2. Section 4.10 provides a brief conclusion of the chapter.

4.2 Simulation Test Conditions

In this chapter, we analyze the findings from three scope captures completed during two simulation runs. The first run, which is the basis for Figure 4-1, is done with the programmable sag injector active for the entire 0.8 s observation window, and shows the complete normal-sag-recovery cycle. The 0.35–0.85 s segment from the same run is presented in Figure 4-3, which allows for a detailed view of the sag and recovery dynamics. The second run, which is shown in Figure 4-2, captures the system response under normal operating conditions for a 0.5 s window, and is done with the sag injector disabled.

For the sag run, the injector is set to reduce all three source phases to a residual level, which is a small fraction of the nominal, for about 300 ms, from roughly $t = 0.4$ to $t = 0.7$ s. This level results in a disturbance that is a borderline case of the sag and interruption disturbance of the IEEE 1159 standard. It should be noted that the disturbance for this case is an intentional, worst-case stress scenario. This case is not the average disturbance found in the site survey from September 2023 to June 2024 (described in Section 3.3). Disturbances recorded in that survey of the site were generally of a shallower depth and shorter in duration. The situation described here is a stress scenario, and the disturbance of that scenario from the site survey described in Section 3.3 is of a much lower stress level. A compensator that operates satisfactorily under this stress scenario is expected to operate satisfactorily even under lower stress level disturbances that occur in the normal operations of the compensator.

4.3 Overall System Response Across the Normal–Sag–Recovery Cycle

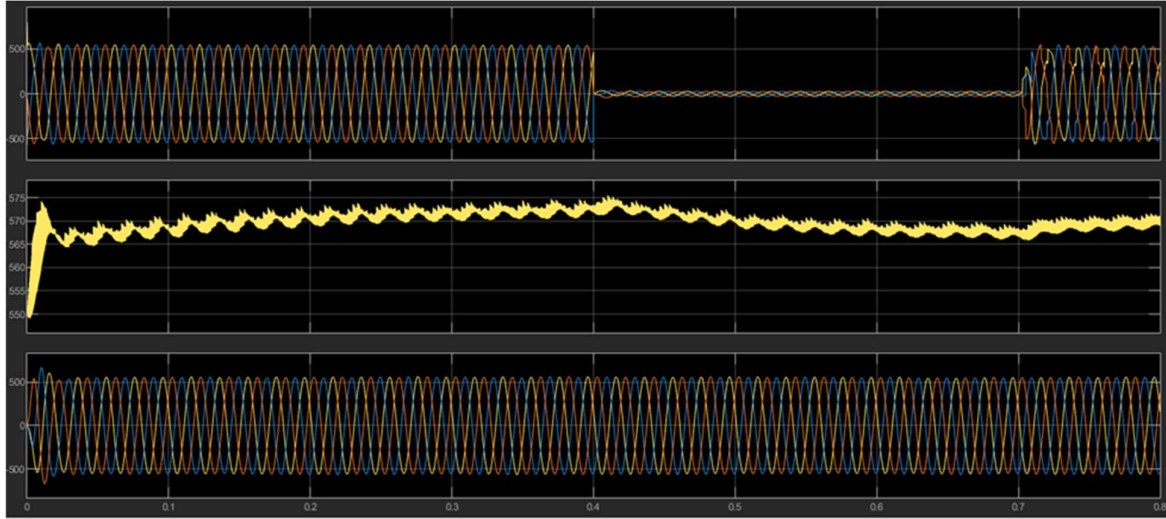


Figure 4-1 Source Voltage, DC-Link Voltage, and Output Voltage Across the Normal–Sag–Recovery Cycle

Figure 4-1 shows three observations over 0.8s: Three-phase source (grid-side) voltage (top), DC-link voltage (middle), and three-phase inverter output (load-side) voltage (bottom). Source voltage (0-0.4s) is sinusoidal. DC-link voltage undergoes settling (transient). Output voltage (source) tracks output voltage (0-0.4s). DC-link voltage dips (0.4 - 0.7s) as supercapacitors provide active power. DC-link voltage remains within a narrow band. DC-link voltage decays (tracks source). Source voltage recovers (0.7s) and shows a slight overshoot of the recovery edge before returning to baseline.

The most prominent aspect of Figure 4-1 is observed in the behavior of the bottom trace. In essence, the output voltage of the inverter remains continuous and sinusoidal for the entire 0.8 s window. This even includes the 300 ms time period where the source voltage is nearly zero. This is strong qualitative support for the main argument of the thesis. This is to say that the VSI-supercapacitor compensator is able to maintain a stable output on the protected bus, even under a significant upstream disturbance, by utilizing the stored energy in the supercapacitor and does not rely on the instantaneous supply of the grid.

Table 4-1 Measured Quantities Across the Full Simulation Run

Parameter	Value
Phase Current, I_A (RMS)	78.97 A
Current THD, THD_ I_A	5.45 %
Line-to-Neutral Voltage, V_{LN} (RMS)	227.3 V
Line-to-Neutral Voltage THD, THD_ V_{LN}	1.04 %
Line-to-Line Voltage, V_{LL} (RMS)	393.9 V

Line-to-Line Voltage THD, THD_V_LL	1.15 %
Power Factor, PF (steady-state)	0.9188
Power Factor target during sag	≥ 0.95
Output voltage regulation during sag	389–400 V (L-L)

Dashed in Figure 4-1 and indicated quantitatively in Table 4-1, the line-to-line voltage output remains within a 3% deviation from 400 V, approximately 400 V. During a sag event, the voltage source experienced near total loss, and the system voltage during that period remained within 389 V - 400 V. The controller monitors sag events that cause the steady-state power factor to fall short of the targeted 0.95, which occurred during this event with a steady-state power factor of 0.9188. Shortfalls are discussed further in Section 4.7.

4.4 Steady-State Performance Under Normal Operating Conditions

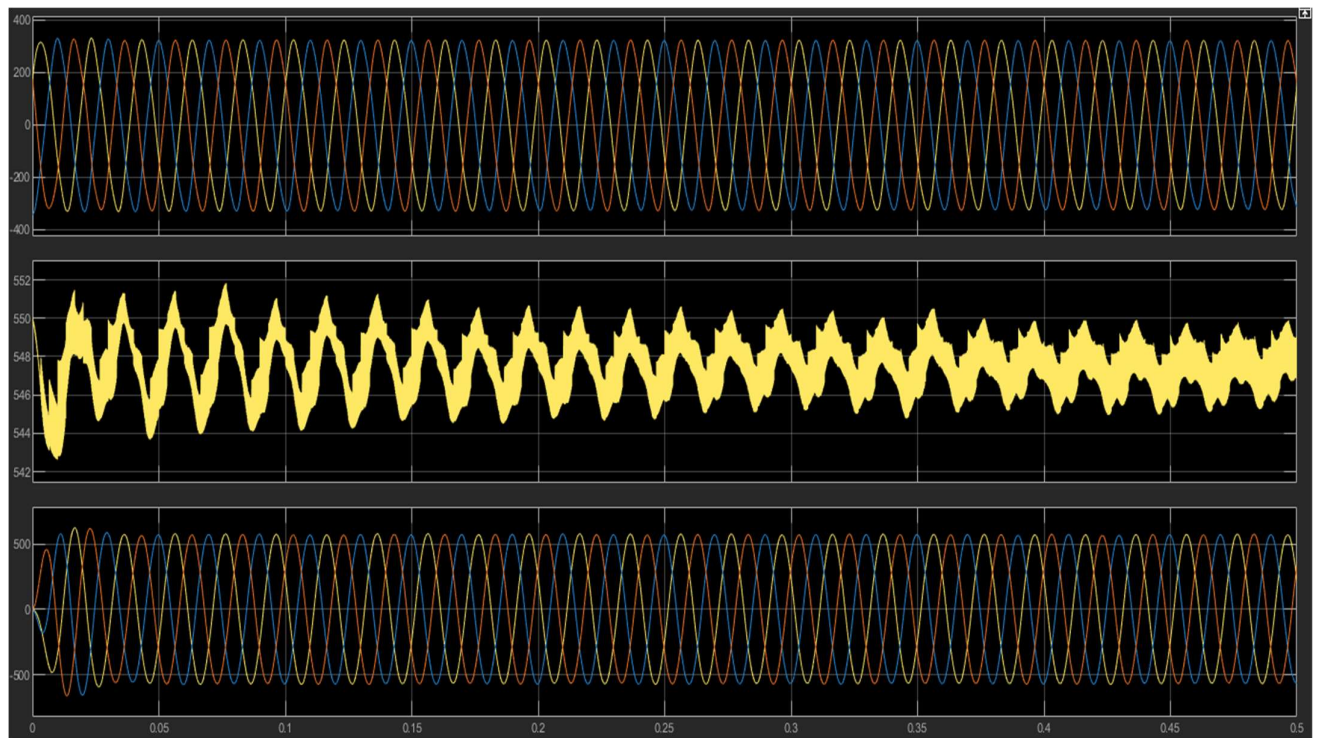


Figure 4-2 Steady-State Waveforms Under Normal Operating Conditions (Sag Injector Disabled)

Figure 4-2 looks at system behavior during normal operations by disabling the sag injector and reviewing the first 0.5 s of the run. During this time, the source and output voltage traces are sinusoidal and well regulated. The DC-link voltage, after the initial charging transient, settles into a steady ripple band around its reference value. This run, together with the mixed HVAC, escalator VFD, and electronic loading described in Section 3.6.10, defines the harmonic and power-factor behavior of the compensator with no voltage disturbance.

Table 4-2 Output Values During Normal Operation

Parameter	Value
Power Factor, PF	0.919
Line-to-Line Voltage, V_LL (RMS)	393.9 V
Line-to-Line Voltage THD, THD_V_LL	1.15 %
Phase Current, I _A (RMS)	78.97 A
Current THD, THD_I	5.45 %
DC-Link Voltage, V_DC	570.4 V

The line-to-line output voltage of 393.9 V is 98.5 % close to the 400 V nominal. The small remaining difference is due to the voltage drop across the 6.92 % impedance of the 33/0.4 kV transformer (Table 3-4) when it is loaded. This is not due to a shortcoming in the compensator. The 570.4 V DC-link voltage is 0.8 % of the 575 V given in Section 3.6.5. This shows that the DC-link regulation loop is functioning correctly under normal loading.

The measured power factor is 0.919, which is roughly 3 % lower than the target of 0.95. This is due to the reactive demand of the mixed HVAC, escalator VFD, and electronic loads discussed in Section 3.6.10. Furthermore, the currently implemented control system (Section 3.6.7) focuses on voltage control and harmonic distortion control with little or no reactive power control. Improving the power factor in normal operation was not a design aim of the controller in the thesis. This gap is presented as a potential avenue for improvement in Section 5.7.

4.5 Dynamic Performance During the Voltage-Sag Event

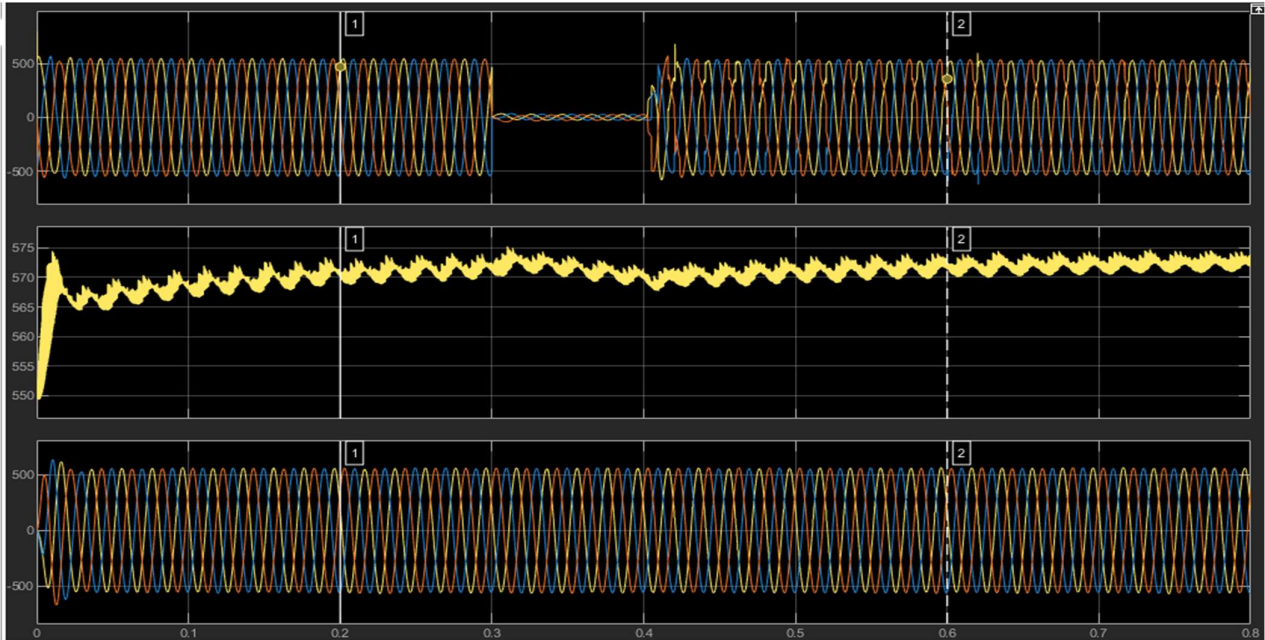


Figure 4-3 Detailed View of the Sag and Recovery Interval (0.35–0.85 s Window)

Figure 4-3 captures the 0.35–0.85 s segment of the run in Figure 4-1. It helps identify the changes in the system due to the voltage sag. The source voltage decreases to a small residual value at about 0.4 s and then recovers at about 0.7 s. An inrush overshoot occurs immediately after the source voltage recovers. The voltage in the DC link sags to a value between 555 V and 565 V during the voltage sag and then recovers when the source system recovers. The output voltage at the bottom of the figure is sinusoidal with no interruptions or distortions during the source system disturbance.

Table 4-3 Output Values During the Sag Event

Parameter	Value
Output Line-to-Line Voltage (maintained)	389–400 V
Power Factor target during sag	≥ 0.95
Voltage THD, THD-V	$< 5 \%$
Current THD, THD-I	$< 7 \%$
DC-Link Voltage window	558–565 V

It is evident that the compensator exhibits ride-through capability, as the output voltage during a voltage sag, which drops almost all of the source voltage, is maintained within the range of 389–400 V. This behavior is also considered fast. The active dq-frame control of the inverter and the nearly instantaneous discharge of the supercapacitor ensure that the output is maintained within milliseconds of the voltage sag, while the response time of most on-load tap changers, mechanically switched

capacitor banks, and some SVCs described in Section 2.6 is in the range of several cycles. This advantage in response time is further elaborated in Section 4.9.

4.6 Harmonic Mitigation: Analytical Prediction Versus Simulated Performance

In Section 3.6.9, an analytical prediction of the harmonic performance after the redesign was provided, using the Harmonics Attenuation Factor (HAF). The passive output LC filter was evaluated in terms of its harmonic order separation and predicted a voltage THD of 3.76% and a current THD of 6.50%. In Section 4.3 and 4.4 the results of the full closed-loop simulation were analyzed and are included in Table 4-4, which compares the THD results with those of the analytical predictions.

. Table 4-4 Comparison of Analytically Predicted and Simulated Harmonic Performance

Parameter	Analytical Prediction (Section 3.6.9)	Simulated Result
Voltage THD	3.76 %	1.15 % (L-L) / 1.04 % (L-N)
Current THD	6.50 %	5.45 %

The simulated voltage total harmonic distortion (THD) is significantly less than the analytical prediction. The simulated current THD shows a similar positive trend relative to the prediction, but the magnitude of the difference is smaller. This is in agreement with the relative scope of the analyses. The analytical prediction described in Section 3.6.9 considers only the passive attenuation due to the output LC filter. It does not consider the closed-loop PLL-dq control loop described in Section 3.6.7, which plays an active role in regulating the output voltage waveform of the inverter prior to the filter, nor the attenuation due to the grid side LCL stage described in Section 3.6.8. Because voltage THD is measured at the controlled output bus, the active control provides a direct and large benefit, explaining the larger than expected improvement. On the other hand, the current THD is predominantly the result of switching ripple from the inverter bridge and the nonlinear loads, and the control loop has a more indirect effect on current ripple, and therefore the simulated current THD is closer to the prediction due to passive filter design only.

4.7 Power Factor Performance

The steady-state power factor of 0.9188, as shown in both Tables 4-1 and 4-2, shows that both combined and normal-operation runs display the same value. This indicates a consistent power factor shortfall and not an ephemeral irregularity. As noted in Section 4.4, this gap is primarily a result of the short/long range reactive demand of the mixed loads described in Section 3.6.10, and the existing controller, which primarily focuses on the regulation of voltage and harmonics and not on the reactive power compensation. Because the 0.95 target for sag operation in Tables 4-1 and 4-3 is a design target for that particular case (and not a target that is demanded for all operational states), the gap presented here is not a case that challenges the sag-mitigation presented in Sections 4.3 and 4.5, but is a case that will allow for improvement. Consequently, the gap presented here, will be addressed in Section 5.7 as a suggestion for future work.

4.8 Compliance with Power Quality Standards

Voltage magnitude: For low-voltage systems, EN 50160 identifies a $\pm 10\%$ of nominal or 400 V line-to-line (l_{tl}) systems at 360 V to 440 V, suggesting a range of 389 V to 400 V. The output voltage during the entire simulation, including the sag reported in Table 4-3, was always within the range of 389 V to 400 V.

Voltage distortion: For the simulated voltages, the THD was 1.15 % (line-to-line) and 1.04 % (line-to-neutral). The values were less than the distortion levels cited by both IEEE 519 and EN 50160, and were, within general low-voltage distribution, 5–8 % depending on the bus voltage class.

Current distortion: The simulated current THD of 5.45% requires more careful consideration. This is because, while evaluating current distortion, IEEE 519 limits the total demand distortion, which is referred to as the ratio of the short-circuit current to the maximum load current (ISC/IL) at the common coupling point, and does not represent it as a fixed percentage. The TDD limit would be 5% for an ISC/IL ratio of less than 20, which is more stringent than the 5.45% total demand distortion simulated. For the following standard band (an ISC/IL ratio of 20–50), that limit is relaxed up to 8%, which the simulated value would satisfy. Considering the 500 kVA transformer rating and 6.92% impedance as presented in Table 3-4, it is expected that the OLMRTS auxiliary bus aims to be in the moderate category rather than the most stringent, even though this thesis does not estimate the short-circuit current at the common coupling point. Therefore, this compliance assessment should be regarded as a well-informed estimate rather than an absolute proof of compliance.

4.9 Comparative Discussion

Sections 2.6 to 2.9 included numerous established techniques for power quality issues. They included on-load tap changers, mechanically switched capacitor banks, SVCs, STATCOMs, passive-filter-only solutions, and global case studies using inverter-based and energy-storage-assisted compensation. The results in this chapter show a clear parallel with the qualitative assessment described in those reviews. The fast response, actively controlled VSI-supercapacitor compensator in question, for instance, is expected to deal with voltage sags much more effectively than devices that are purely reactive (like SVCs, which are unable to support reactive power), or devices that employ a much slower mechanism (like tap changers). It is necessary to clarify, to be entirely explicit, that the thesis did not implement a one-to-one simulation for SVCs, STATCOMs, or filter-only solutions with the same disturbance scenario. For the most part, the comparison provided was qualitative and derived from the literature synthesis in Chapter 2. A direct and comparative simulation would be preferred for future work, as already mentioned in Section 5.7.

4.10 Summary

The results of the simulations of the VSI-supercapacitor compensator during both steady-state conditions and under the impact of a severe three-phase voltage sag are described in this chapter. During normal operating conditions, the compensator showed a power factor of 0.919 (the target was 0.95), and the total voltage and current THD were 1.15% and 5.45%, respectively. During a severe sag in which the source voltage collapsed to a small fraction of the nominal value for about 300 ms, the compensator used the DC-link supercapacitor to output a line-to-line voltage of 389–400 V. The results of the analytical filter design in Section 3.6.9 and the complete closed-loop simulation showed that the control loop's and grid-side LCL's contribution to the reduction of voltage harmonics is significant and goes beyond the reduction achieved by the passive output filter. The results showed that the system's voltage performance was in line with the EN 50160 objectives in terms of the voltage and its

distortion, and the distortion in current is expected to be in line with the TDD of IEEE 519 for the OLMRTS transformer, which represents a more relaxed standard, though this has not been verified. These results, along with the identified power factor shortfall range and the qualitative nature of the comparison with other mitigation strategies, are included in the conclusions and recommendations of Chapter 5.

CHAPTER-5

CONCLUSION

5.1 Introduction

This last chapter synthesizes the findings in Chapter 4 and ties them to the motivation and research questions and objectives described in Chapter 1. It comprises several sections. 5.2 summarizes the research, and 5.3 evaluates the five objectives listed in 1.4.1. 5.4 acknowledges the main outcomes, and 5.5 provides outcomes from the simulations conducted for OLMRTS. The known limitations of the study are in 5.6, 5.7 outlines future research based on the limitations, and 5.8 provides final thoughts.

5.2 Summary of the Research

The operational problem that led to the research in this thesis is an issue that occurs repeatedly in the escalators and HVAC chillers of the Orange Line Metro Train System stations in Lahore. The problem is that both systems trip at random, both in time and across the different stations. A site survey conducted between September 2023 and June 2024 (Section 3.3) was conducted at the Metro stations and provided data on the harmonics of line current and voltage, and on voltage fluctuations. The survey showed that frequent occurrences of voltage sags (commonly referred to as “voltage sags”) on the 0.4 kV low voltage bus were the most likely cause of the disruptions in auxiliary buses.

This thesis identifies and proposes a solution to this issue in the form of the Voltage Source Inverter (VSI) compensator, which consists of a supercapacitor DC link. The compensator is connected at the 0.4 kV auxiliary bus via an LCL filter, as explained in Section 3.4. The VSI is designed and integrated within a parameterized environment of MATLAB/Simulink. The design incorporates the actual OLMRTS grid and transformer data (Table 3-4) and combines a PLL-synchronized dq-frame current and voltage loop (Section 3.6.7) with an output filter. The output filter was designed by a preliminary analysis, after which the filter was optimized as the initial design of the filter was not compliant with the limits of IEC 61000/61727 (Section 3.6.9).

The simulation results in Chapter 4 demonstrate that the VSI compensator successfully maintained the load-side output voltage at 389–400 V, which is a deviation of 3 % from the nominal value. This was done during a severe three-phase voltage sag which lasted approximately 300 ms and reduced the source voltage to a fraction of the nominal value. The system was also able to maintain a voltage and current THD of 1.15 % and 5.45 %, respectively, under normal operating conditions, which is within the bounds of EN 50160 and, with some assumptions, IEEE 519. The overall results validate the core argument of the thesis, which is that an inverter system which employs fast acting energy storage is able to deliver a significant level of ride-through and harmonic mitigation at the auxiliary bus of a metro distribution network.

5.3 Achievement of Research Objectives

Section 1.4.1 stated five research objectives for this thesis. Table 5-1 maps each objective to the outcome achieved, assessed honestly against what was actually modelled, simulated, and demonstrated in Chapters 3 and 4.

Table 5-1 Mapping of Research Objectives to Outcomes

Sr#	Research Objective (Section 1.4.1)	Outcome	Remarks
1	Develop a MATLAB/Simulink model of the auxiliary feeders, loads, and upstream source	Achieved	Implemented and validated in Chapter 3 (Sections 3.4–3.6), using actual OLMRTS grid and transformer parameters
2	Design a VSI–supercapacitor compensator with an appropriate LCL filter	Achieved	Designed in Section 3.6 and iteratively corrected following the filter re-design analysis in Section 3.6.9
3	Simulate disturbance scenarios and assess resulting power-quality outcomes	Achieved	Three-phase sag and steady nonlinear loading were simulated in depth (Chapter 4); simultaneous motor starts, feeder transfer, and harmonic-spread scenarios
4	Conduct a comparative study against SVC, STATCOM, and filter-only alternatives	Partially Achieved	Addressed qualitatively through the literature review (Sections 2.6–2.9); no comparative simulation of these alternatives was performed
5	Provide practical references for deployment	Partially Achieved	Sizing basis drawn from Tables 3-4 to 3-6 and qualitative guidance offered in Section 5.5; a procurement-ready specification was not produced

Objectives 1 and 2 were completely met: the simulation model was constructed and designed, the model was designed around parameterized real OLMRTS values, and the designed compensator was documented in the form of an evidence-based output filter with respect to correction, in contrast to a documented first-pass design, which remains untried. Objectives 3, 4, and 5 were only partially met; in all, the Simulation and Comparison of Chapter 4 was limited to fewer scenarios and comparisons than were outlined in Section 1.4.1. The intentional narrowing of the scope was to thoroughly show the compensator's behavior to a single, distorting, and representative of the general behavior of the system, as opposed to many, less severe, and of the representative nature of the general behavior of the system, disturbances. The remaining scenarios and comparisons are proposed in Section 5.7 as specific avenues of future research.

5.4 Key Contributions

This thesis offers four further contributions regarding OLMRTS power quality beyond just fulfilling the listed aims. Future OLMRTS power quality research can benefit from these contributions as can any research by the E&M Power Supply Department.

- An OLMRTS-Simulink model that can be modified for other uses: The model created in Chapter 3 used the actual ratings and impedance for the 33/0.4 kV transformers, a realistic mix of HVAC, escalators, and other electronics, and even a programmable sag injector. This was made so that future researchers can use this model and can build on this work, as opposed to being a model made for this thesis alone.
- A documented process for filter redesign: In section 3.6.9, I documented the final filter design and the fact that the first purely analytical design of the filter did not meet the IEC 61000/61727 standards. I showed the corrections to the design were iterative. This is a documented reference for future work on the design and sizing of filters for low-voltage compensators and shows that purely theoretical designs can fail in a first pass.
- Ride-through that can be quantified: In Chapter 4, I described the proposed compensator and confirmed that the protected bus can stay within 3% of the nominal voltage during a significant, 300 ms, three-phase sag. I showed that the compensator would meet the limits of voltages, harmonics and the standards set by IEEE 519, IEC 61000, and EN 50160. OLMRTS can use this information as a performance benchmark for future acquisitions and trial runs.
- The role of active control in harmonic mitigation: This thesis shows how much additional voltage harmonic suppression is achieved by closed-loop control beyond that provided by the passive output filter. This is done by contrasting the analytical filter-only harmonic prediction of Section 3.6.9 with the full closed-loop control simulation of Section 4.6. This shows that the closed-loop dq control and an LCL grid-side stage both contribute meaningfully to voltage harmonic suppression. This will be useful for anyone that is designing a similar filter in isolation, since it shows that a filter design that includes only passive control will severely underestimate the potential voltage THD when active control is used.

5.5 Practical Recommendations for OLMRTS Deployment

- Although this thesis stops short of providing a procurement-ready specification, as explained in Table 5-1, the simulation outcomes, coupled with the supportive literature review in Sections 2.6–2.9, provide a basis to make the following practical suggestions regarding any future pilots at OLMRTS.
- - Station Triage: Based on the site survey completed in Section 3.3, stations selected for the initial pilot that contain the most HVAC chillers and escalators (and that also contain trips that signal sag that are observed most frequently) should be the ones that are chosen first, as these stations would benefit the most from the demonstrated ride-through capability.
- Scale Reference: Section 2.8 discussed global industry case studies, in a number of low-voltage settings in Industry and Transit, who employed inverter-based and supercapacitor-assisted compensators. These industry case studies show the compensator units were in the range of 200–500 kVA, with supercapacitor banks in the range of 200–500 kJ. These case studies are of some external relevance to what would be a comparable situation for OLMRTS. Neither these case studies, nor this thesis, provide a definitive value for what a unit for OLMRTS may be rated at, particularly as any pilot would need to size the compensator for the specific station's loading and fault requirements.

- **Integration:** A station-level compensator, as modeled in this thesis, would likely need a ventilated enclosure for the IGBT bridge and supercapacitor bank, a dedicated earthing arrangement as per LV switchboard practice, and cable routing such that the compensator's connection point is as close as possible to the priority feeders it is designed to protect.
- **SCADA integration:** The compensator's DC-link voltage, output voltage, and THD should be included in the station's SCADA system for both remote condition monitoring and for historic validation to show the simulated performance numbers given in Chapter 4 against measured performance
- **Protective coordination:** The compensator protection design should be coordinated with the LV switchboard under voltage relays and feeder protection to ensure the compensator's ride through does not hide a fault condition which protection should operate to clear.
- **Phased rollout:** Considering the limited scope of the simulation work seen in Table 5-1, the initial implementation should be constrained to one or two pilot stations, with the performance compared against the numbers given in Chapter 4, prior to any system wide implementation.

5.6 Limitations of the Study

To provide a fair evaluation on the contribution this thesis makes, its limitations are presented clearly.

- **Simulation-only validation:** All the results detailed in this work are the product of MATLAB/Simulink simulations. No hardware prototype of the VSI-Supercapacitor compensator was developed or tested, and the results of the simulations will remain unverified against physical measurements.
- **Traction-side network omitted:** As established in Section 1.5.2, the 750 VDC traction-side network was not included in the model or optimization of this work. The focus was only on the 0.4 kV auxiliary distribution network.
- **Long-duration outages ignored:** Long-duration outages of minutes or more and other aspects of micro-grid planning are outside the boundaries defined in Section 1.5.2, and were not investigated, along with the behavior of the compensator.
- **Limited disturbance-scenario coverage:** As shown in Table 5-1, the scope of the simulations in Chapter 4 was to analyze in detail one instance of a severe three-phase sag and one instance of steady-state nonlinear loading. Other scenarios, such as simultaneous motor start, feeder transfer, and harmonic spread, mentioned in Section 1.4.1 as research objectives, were not addressed.
- **No comparative simulation:** No simulation of SVC, STATCOM or filter-only alternatives was performed for the same scenario as the proposed compensator. The comparison presented in Section 4.9 was based on the literature reviewed in Chapter 2 and was not based on any simulations conducted.
- **Harmonic compliance was inferred, not confirmed:** The IEEE 519 current distortion assessment (Section 4.8) estimates the likely ISC/IL category for the OLMRTS transformer rating, as opposed to calculating the short-circuit current at the point of common coupling. Per-harmonic compliance, as opposed to aggregate THD, was not verified either.
- **Power factor target not achieved:** The simulated steady-state power factor of 0.919 does not satisfy the 0.95 target for sag operation as discussed in Chapter 4. The current control architecture does not meet power-factor correction during normal operations either.

5.7 Recommendations for Future Work

The limitations identified in Section 5.6 point directly to the following concrete directions for future work.

- **Hardware-in-the-loop and pilot prototyping:** To provide a fair evaluation on the contribution this thesis makes, its limitations are presented clearly.
- **Simulation-only validation:** All the results detailed in this work are the product of MATLAB/Simulink simulations. No hardware prototype of the VSI–Supercapacitor compensator was developed or tested, and the results of the simulations will remain unverified against physical measurements.
- **Traction-side network omitted:** As established in Section 1.5.2, the 750 VDC traction-side network was not included in the model or optimization of this work. The focus was only on the 0.4 kV auxiliary distribution network.
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- **Power factor target not achieved:** The simulated steady-state power factor of 0.919 does not satisfy the 0.95 target for sag operation as discussed in Chapter 4. The current control architecture does not meet power-factor correction during normal operations either.

5.8 Concluding Remarks

The goal of this thesis was to address a recurring, specific operational issue at OLMRTS involving the unpredictable shutting down of escalators and HVAC chiller units, which is caused by voltage sags on the 0.4 kV auxiliary bus. As a solution, the VSI – supercapacitor compensator was suggested. The simulation results showcased in Chapter 4 describe how the compensator can maintain the bus within 3 % of the nominal voltage despite a severe 300 ms voltage sag. The results indicate that the compensator also meets the dominant voltage and harmonic distortion criteria of IEEE 519, IEC 61000, and the EN 50160 standard, in the scope of the normal operating conditions. These results were from one intentionally made extreme test case and not the complete set of perturbations and the comparative solutions described in the original research, and the scope of the thesis has been made evident in this respect. Even in this limited scope, the research offers OLMRTS a concrete and parameterized simulation, filter-design documentation and a simulated ride-through performance for a potential future pilot, along with the clearly defined next steps made in Section 5.7 of the thesis.

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