DESIGN OF BATTERY SUPPLEMENTED MICRO-STATCOM AND DEVELOPMENT OF ASSOCIATED CONTROL ALGORITHMS TO MITIGATE POWER QUALITY ISSUES IN LOW VOLTAGE NETWORKS

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DECLARATION

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ABSTRACT

Power Distribution Networks are evolving with the rapid penetration of distributed generators and introduction of concepts such as *micro grid based Smart Girds*. Distribution automation devices and solar PV generators in the present-day power systems makes power distribution networks more and more active. Assurance of a power supply with better power quality for a distribution customer is becoming a challenging task with the penetration of various loads inspired by power electronic concepts. And also, with the enormous penetration of solar PV generators to power distribution networks, bi-directional power flow makes it more challenging. As most of the planning studies carried out to improve Medium Voltage (MV) Networks to address these challenges, less attention has paid for the monitoring of power qualities at Low Voltage (LV) Distribution Networks.

This research identifies a vital requirement to improve power quality at the leaf level of LV distribution network and presents a combined solution for most predominant power quality issues exist in LV distribution network. This thesis presents a Micro-STATCOM based solution to address power quality issues by under voltage regulation, over voltage regulation, harmonic mitigation and improving system power factor in LV distribution system. Development of Micro-STATCOM based model with DC power source is presented in order to mitigate major power quality issues exists in the modern LV distribution systems. Performance of the Micro-STATCOM model has evaluated with response time for voltage regulation, resolution of voltage regulation and level of reduction in Total Harmonic Distortion (THD%).

Developed Micro-STATCOM was then integrated into modified IEEE 13 Distribution Bus System in order to observe the mitigation of power quality issues. Results obtained by mitigation of each power quality issues in the distribution network are discussed in this thesis. Potential applicability of developed Micro-STATCOM in the practical low voltage distribution networks and other areas are discussed and recommendations are made for the selection criteria to integrate Micro-STATCOMs in LV distribution Systems.

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LIST OF ABBREVIATIONS

BESS	:	Battery Energy Storage System
DG	:	Distributed Generators
PV	:	Photovoltaic
SCADA	:	Supervisory Control and Data Acquisition
GPS	:	Geographical Positioning Systems
PMU	:	Phasor Measurement Unit
WAMS	:	Wide Area Measurement System
DAS	:	Distribution Automation System
DRMS	:	Demand Response Management Systems
LV	:	Low Voltage
MV	:	Medium Voltage
THD	:	Total Harmonic Distortion
PCC	:	Point of Common Coupling
STATCOM	:	Static Synchronous Compensator
SPWM	:	Sinusoidal Pulse Width Modulator
CEB	:	Ceylon Electricity Board
AC	:	Alternating Current
DC	:	Direct Current
RMS	:	Root Mean Square
PQ	:	Power Quality
FACTS	:	Flexible AC transmission system
OLTC	:	On Load Tap Changer
TCSR	:	Thyristor Controlled Series Reactor
SVC	:	Static VAR Compensator
VOC	:	Voltage Oriented Control
MPPT	:	Maximum Power Point Tracking
IGBT	:	Insulated Gate Bipolar Transistor
IEEE	:	Institute of Electrical and Electronics Engineers
FFT	:	Fast Fourier Transform

1. INTRODUCTION

1.1 Introduction

Global Power distribution systems are evolving rapidly and transforming significantly with the emerging technological enablers. Renewable energy resources are becoming increasingly available around the world and the financially feasible technological approaches for these renewable energy resources has started to dominate modern power systems. With the advancement in electronic devices and the penetration of distributed energy resources has made power systems more flexible. All these drivers in power sector has accelerated the evolution of power systems.

Evolution of power systems identifies opportunities as well as challenges to achieve system flexibility and rapid growth of power system. A luxury of experimented strategies, practices and evolved digitalized instruments to support power system flexibility can be directly integrated and adopted to power systems. Variety of application areas and assets can be identified in order to provide power system flexibility.

- Power plants operating with conventional energy resource are the major source that can be used and applied many strategies in order to achieve power system flexibility.

- Variable renewable energy sources, such as solar power, wind power are emerging as a resources having great potential for system flexibility. Most countries are now focusing on the aggregation of renewable power generators in to their power systems by making necessary changes for their polices on power sector. Specially in Sri Lankan energy mix and power context, renewable energy resources have already succeeded to divert the direction of power systems growth and the Government is also making necessary changes to enable the penetration of renewable resources to the power system.

- Transmission and distribution networks in power system remain as a vital factor of system flexibility.

- New concepts and cost competitive developments such as battery energy storage systems (BESS) are becoming catalysts for power systems flexibility. Distributed energy resources with the concept of smart grid has provided greater potential for the power distribution system transformation.

1.1.1 Evolution of Low Voltage Distribution Systems

The Low Voltage distribution network is the interface to deliver electrical energy to customer after the generation and transmission. Low voltage distribution systems in power sector have been evolved significantly in last decade with the penetration of residential and commercial distributed generators [17].

Traditional Distribution Systems

In traditional power systems, the electric energy is generated centrally and transmit one-way to the customer loads. Conventional distribution networks are hierarchical and contain radially operated structure. Alternative supply was met by arranging open ring connections. Due to this hierarchical structure in traditional distribution network with passive components, measurement of consumed energy, monitoring of network and control of loads are straightforward for the utility providers.

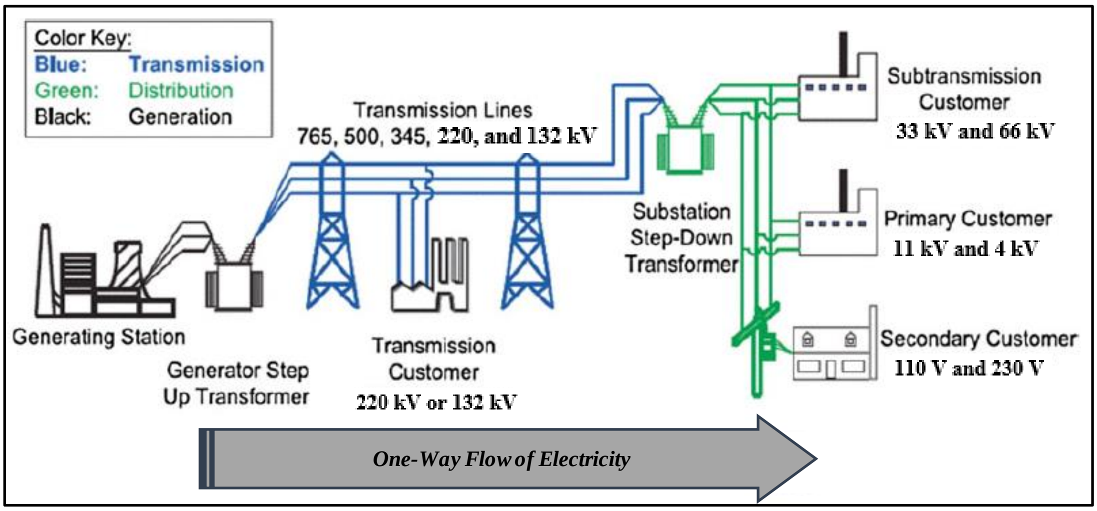


Figure 1: Uni-directional flow of electricity in a Traditional Power System
Source: Evolution of Power Systems into Smarter Networks [01]

The main events that occurs in traditional distribution network are monitoring of major electrical parameters such as voltage, current and power quality at distribution transformer, measurement of energy consumption via energy meters, basic protection including short-circuit and overcurrent protection through fusible devices, generation of supply outage alarms for the utility provider.

Present Day Distribution Systems

Traditional distribution system is evolved with the penetration of distributed generators (DGs) and distribution automation devices on active network elements. Small scale and micro level localized generation has increased in present day distribution networks allowing self-sufficient energy generation for the customers. Types of local micro-generations are mainly Solar Photovoltaic (PV) generation and wind power generation. Penetration of large amount of grid connected DGs, home automation for the energy management and voltage monitoring at utility level has increased noticeably. Aggregation of DG units has increased the requirement of monitoring and real-time regulation of voltage in distribution network.

Most common low voltage distribution networks at present are falling on to this category. With the penetration of DGs, traditional distribution networks are becoming more and more active with bi-directional power flow.

Future of Distribution System – "Smart Grid"

Present power distribution systems gradually transforming to micro grid based *Smart Girds* with the development peer technologies and convergence of these technologies with the digitalization. Major driving forces for the evolution of power systems in the recent past are, [05]

- Advancement of power electronic devices and solid-state devices
- Intelligent Electronic Devices, smart sensors and closed loop measurement principles
- Real-time control and monitoring systems such as SCADA
- phasor measurement units (PMUs), GPS technology and wide area measurement systems (WAMS)

These catalysts have given greater potential to emerge ground breaking concepts such as “smart grid”.

Lot of attention as made on the distribution system recently due to the rapid change of technology. Distribution automation system (DAS) attributes such as auto-reclosing (self-healing), used of SCADA systems, automation of substations, smart metering, and remote operation of have drawn a big interest. Integration of novel concepts such as smart grid technologies will increase the flexibility of absorbing potential benefits of customer demand response management systems (DRMS) and distributed renewable energy generation. With the roadmap to “smart grid” customers may adopt to a more interactive role in power distribution system due to the ability to actively participate for energy management through these DASs.

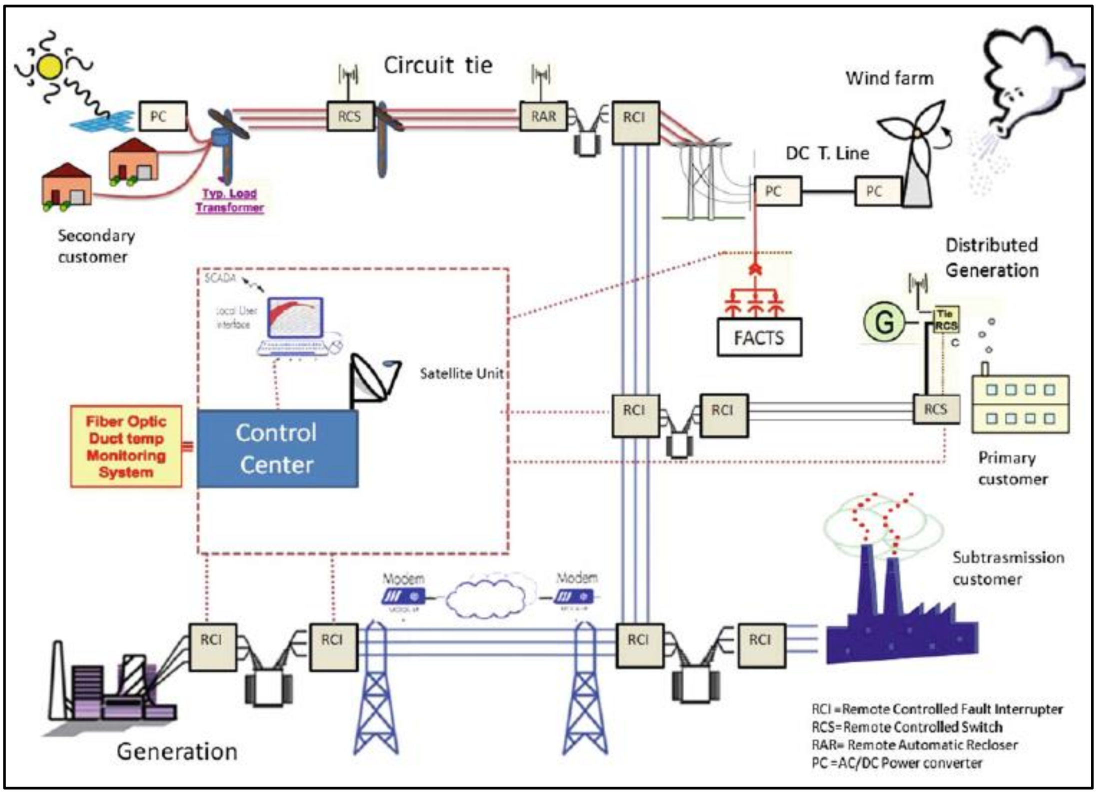


Figure 2: Bi-directional communication in a Smart grid
Source: Evolution of Power Systems into Smarter Networks [01]

1.1.2 Penetration of Solar PV Generators and other DGs

In the last decade or so, there has been a significant growth in the penetration of residential and commercial solar PV systems into the LV and MV distribution networks due to the global concern about climate change and increase in electrical energy demand. Renewable energy technologies such as Solar PV system, wind power generators and their applications into the electric power system are a viable solution to reduce CO_2 emission.

The solar PV system is the most promising renewable energy technology because its primary resources are readily available and enormous in varying intensity globally. Embedded generation popularly known as Distributed Generation is the integration of renewable technologies like PV system and a wind turbine into the MV and LV power distribution networks. The application of solar PV system as DG is gaining popularity globally, most especially in countries like the United States (US), PR China, Germany, Spain, Netherland, Italy, Japan, Australia, South Africa, Kenya, Sri Lanka etc. In recent years, some power system grids around the world are experiencing increasing installation of solar PV system in the LV and MV distribution network. These networks will experience increasing penetration by local, commercial and utility companies in the near future due to the falling price of solar PV modules, government subsidies, and policy incentives. The state incentive schemes are the predominant root cause for the exponential use and development of PV technology worldwide. The most commonly used incentive mechanisms are feed-in tariff and quota system.

The feed-in tariff scheme has been practiced in many countries in the last two-decades including Sri Lanka, and it has increased the integration of PV system in the LV distribution network around the world.

1.2 Power Quality Issues in Active Low Voltage Networks

The Institute of Electrical and Electronic Engineers Standard (IEEE Std 1100) [6] has defined power quality as "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment". A basic and simple definition of power quality is, "Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy" [6]. Performance and the life expectancy are the major impacts of poor power quality on an electrical device.

In an ideal scenario current and voltage in a distribution system have pure sinusoidal waveforms of fundamental frequency [16]. And the system voltage sustains within pre-defined range. But present-day low voltage distribution networks are becoming increasingly active. This is mainly due to the widespread penetration of distributed generators such as solar PV systems.

Integration and frequent operation of single-phase, three-phase large reactive loads with motive power, power electronic equipment such as inverters with high switching frequencies, increased switching of inductors and capacitors, transformers and distributed generators with variable renewable generation characteristics are the major contributors for the presence of different types of power quality issues in low voltage distribution systems.

1.2.1 Types of Power Quality Issues Exist in LV Network

LV distribution networks has led to cause power quality issues in low voltage power systems such as,

- Voltage Variation (Over Voltage and Under Voltage situations)
- Increase of Potential Harmonic Aggregation
- Inefficient Power Delivery due to Poor Power Factor
- Voltage Unbalance
- Overcurrent Issues
- Over voltage Protection Issues

- Increase Network Losses
- Reverse Power Flow in the Distribution Network

The deployment of PV systems provide sufficient technology and environmental benefits of the LV distribution networks under the deregulated market [2]. However, the negative impact of high PV integration tends to affect the operation, voltage profile level and security of the traditional LV distribution network. The uncontrolled penetration (high PV system) of single-phase PV inverter may cause voltage unbalanced, which may result in an increased harmonic level in a three-phase system and this may violate the condition of equal magnitude of the phases [16].

The voltage rise issue which is accompanied by a reverse power flow has been an intensive burden for utility providers and it has led to the development of different voltage rise mitigation strategies. Some of the dominant power quality issues exist in low voltage distribution network can be defined as in below.

Voltage Variation

Voltage variation sometimes called as voltage disturbance sustained less than on minute (voltage swell, sag or interruption) called as short time voltage variation. A voltage disturbance sustained longer than one minute (over voltage, under voltage or interruption) are called as long-time voltage variation [6]. Voltage variations can cause harmful effect on connected sensitive loads and can be a roof cause of lot of other power quality problems.

Power Factor and Reactive Power

Power injection at unity power factor is the IEEE Recommended Practice for integrating PV Systems in a utility network. [6]. Connection of PV system to a power system will increases the voltage at that particular point causing non-linearity of the system. However, with the available options to control reactive power in modern PV systems, voltage at point of integration can be controlled. Ideally reactive power should generate closed to load to fee up the capacity of conductors and transformer.

1.2.2 Statutory Power Quality Requirements

Even though operation of various types of loads and DGs lead to cause different power quality issues in low voltage network, utility providers have to maintain the quality of the power supply within a tolerable level which are imposed by governing regulatory bodies. Range of allowed supply voltage variations, allowed maximum amount of Total Harmonic Distortion (THD) and allowed maximum supply frequency variation are some of the power quality measures monitored by regulatory institution.

Some of the major power quality measures regulated by Public Utility Commission of Sri Lanka for their utility provides are as below,

- *Maximum Allowed Voltage Variation in LV Network is* ±6%
- *Maximum Allowed THD in LV Network is 5%*

1.2.3 Utility Practices on Monitoring Distribution Networks

Distribution power system mainly consist with Medium Voltage (MV) network and Low Voltage (LV) network. Most of the distribution network operators or utility providers closely monitors MV network. Monitoring and active compensation to real time power quality issues are carried out for the MV distribution network. Planning studies also carried out periodically in order to strengthen the medium voltage network.

Less attention is paying for the monitoring of power quality issues arises in LV network. Most of the utility providers stops their planning studies at MV level allowing LV distribution network to grow anonymously. Hence, LV level records are generally poor at the hands of utility providers. As there are no real-time monitoring of voltage variations at LV leaf level, LV feeder end voltage levels are invisible to them [19].

But, with the evolution of power distribution networks, customer is becoming more and more active and aware about the quality of receiving power supply. Statutory bodies also implementing maximum allowable ranges for different types of power quality measures as explained above. Hence, utility providers have to pay close attention on the power quality of low voltage distribution network also. As various reasons causing power quality issues in LV network, utility providers seek combined solutions for major power quality issues.

Some utility providers try to address power quality issues exist at leaf level of LV network by providing solutions to MV level. This is mainly due to availability of planning studies and records at MV level and availability of solutions at MV level for the same power quality issues. But the solution provided at MV level is much muted by the fact that R/X value at LV network is much higher (~1.0 -5.0) [7] than MV level. Hence the applied solutions at MV level doesn't properly reflect at the LV leaf level. Hence, utility providers are seeking for LV level power quality improving technologies in order to improve the quality of LV power supply [18].

High R/X ratio is leads to strong coupling between active power and voltage.

Typical X/R ratios

Plant item	X/R ratio
33 kV overhead line	1.4
132 kV overhead line	2.4
275 kV overhead line	8.5
400 kV overhead line	15.0
132/33 kV 90 MVA transformer	15.0
275/33 kV 240 MVA transformer	50.0
400/275 kV 1000 MVA transformer	130.0
660 MW generator	100.0

Figure 3 Typical X/R ratios of Over Head Power Lines
Source: Reactive Power and Voltage Control [7]

Presently, various solutions are available to address there LV power quality issues and these solutions have their own disadvantages on both customer and utility provider perspectives.

1.3 Research Motivation

Onsite inspection on supply power quality has carried out in low voltage power distribution network in Sri Lanka and measured the values of some critical power quality parameters. It was observed that it is required carryout some improvements actions at the point of common coupling (PCC) in order to provide better LV power supply to the customer.

A power quality analyzer has used to measure the power quality parameters of low voltage 3-phase power supply to the customer. Customer use this supply for his timber workshop which contain 3-phse motors and power electronic devices. It is clear that operation of such large loads with motive power and power electronic switches will have impact on the LV power supply. Presence of power quality concerns can be due to the customer end devices as well as utility supplier network end devices.

Detail and setup to observe power quality measurement at customer location are shown in Figure 4.

Type of Supply	:	400 V, 3-Phase, 60 A Supply
Substation	:	160 kVA, 33 kV/400V Stepdown Transformer
Distance from Customer Location to Transformer	:	~ 500 meters

Figure 4: Power Quality Measurement Setup for 3-phase, 400V Supply

Observed power quality issues are depicted in Figure 5 and Figure 6.

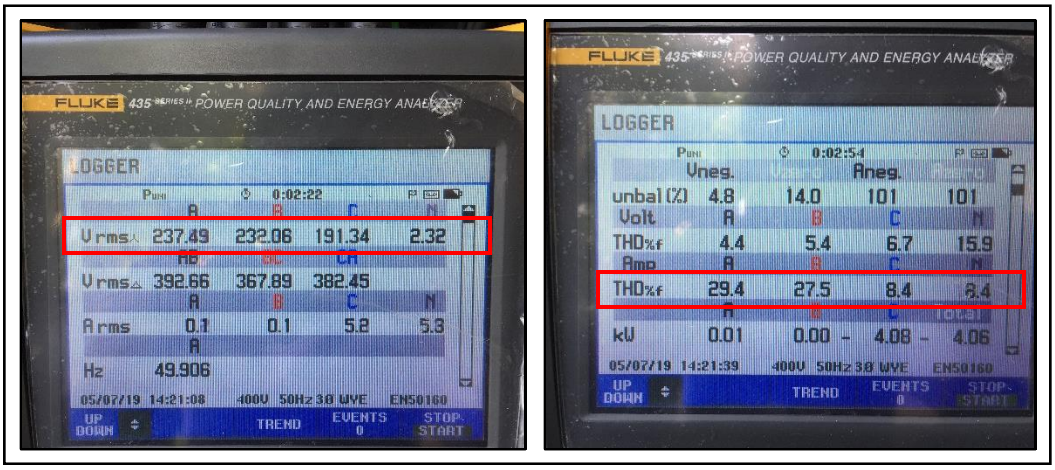


Figure 5: Voltage Variation and Presence of Harmonic

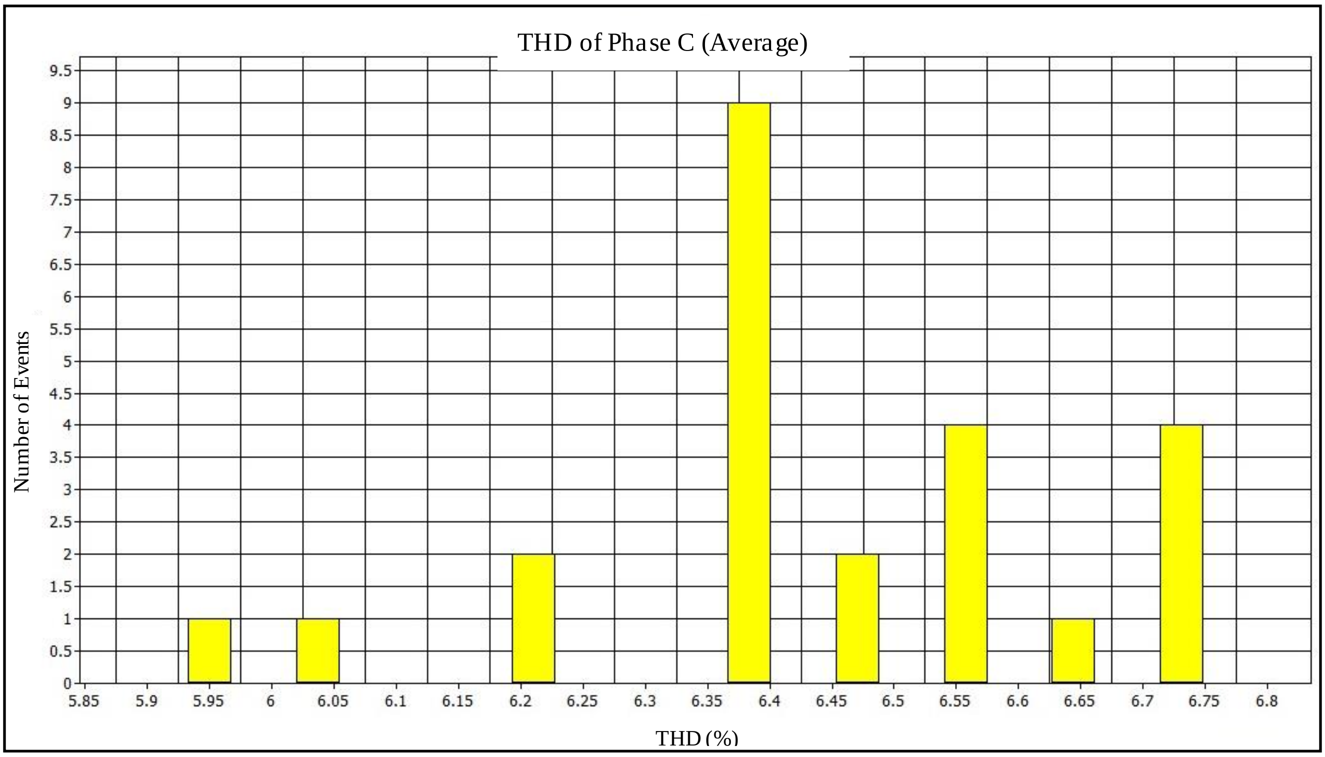


Figure 6: Total Harmonic Distortion (%) in Phase C of 3-Phase Supply

From the quantified details observed from Figure 5 and Figure 6 it can be decided that the LV 3-Phase supply experience *voltage variation* and *presence of harmonics* beyond the statutory allowed limits.

There is a clear requirement for low voltage level solution for the voltage variation and harmonics at the leaf level of the network where utilities have lowest visibility

1.3.1 Objectives

The main objective of this research is design and development of Battery Supplemented Micro-STATCOM model to be integrated in LV distribution network with reactive power processing based on voltage to address power quality issues by,

- Voltage regulation
- Harmonic mitigation and
- Power factor correction

1.3.2 Methodology

In this research a mathematical model was derived in order develop a control methodology for a Micro-STATCOM controller to drive Micro-STATCOM to resolve LV distribution system voltage variation issues dynamically. Developed mathematical model was then adopted to a control sequence in order to operate control mechanism in proper order. Harmonic mitigation algorithm also integrated in to the control sequence to obtain comprehensive control mechanism to resolve voltage variation and harmonic mitigation.

Design and development of Micro-STATCOM controller based on derived mathematical model was done in Matlab^{TM} environment. Design and development of Micro-STATCOM itself and Sinusoidal Pulse Width Modulator (SPWM) also carried out in Matlab^{TM} environment. Developed model was simulated with 2-bus system to test the functionality of the model.

IEEE 13 Distribution Bus System was modified to apply the developed comprehensive Micro-STATCOM model to resolve desired power quality issues. Matlab^{TM} Simulink model was developed for modified IEEE 13 distribution Bus System and desired results were obtained in Matlab^{TM} environment by applying Micro-STATCOM model to modified IEEE 13 Distribution Bus System. Results obtained from simulations in regulating voltage variations, harmonic mitigations and power factor improvements were observed and model was evaluated for its performance in this research.

1.4 Outline of the Thesis

Thesis of this research is organized as follows.

Chapter 01 presents the research motivation for the requirement of LV level solution for the mitigation of power quality issues. Objective and methodology of the research also presented. Literature on evolution of distribution power systems, power quality issues in active LV network, statutory power quality requirement and utility practices on monitoring distribution networks are also presented.

Chapter 02 is the literature study conducted which describes the related work carried out prior. Furthermore, it identifies the research gap between the proposed work and literature.

Chapter 03 focus on derivation of mathematical model for proposed Micro-STATCOM solution and implementation of required controllers based on the mathematical model. Design and development of operational sequence of the proposed solution is also presented in this chapter.

Chapter 04 present the implementation of Micro-STATCOM controller model in Matlab™ environment. Development of Matlab™ Simulink models for Micro-STATCOM itself and SPWM are also described. Finally, implementation Simulink model for complete solution in Matlab™ environment and evaluation of the performance of the solution is presented in this chapter.

Chapter 05 present the integration of developed Micro-STATCOM model in distribution networks using modified IEEE 13 Distribution Bus System. Modification and identification of existing power quality issues in modified IEEE 13 Distribution Bus System is described here. Matlab™ simulation results on power quality improvement, Micro-STATCOM model capability and performance are observed in this chapter.

Chapter 06 is about the analysis and discussion on the results obtained from developed Micro-STATCOM model in successfully mitigating PQ issues in active LV network in Contrast with the literature. It further describes about selection criteria for the Micro-STATCOM in LV network, inter-operation of Micro-STATCOM with other LV network compensators and potential areas of application for Micro-STATCOM.

Chapter 07 present the conclusion of the research and successful achievement of the objectives stated in chapter 01. In this chapter it is also stated the recommendations for future works and opens up the potential areas of research available based on this study.

2. LITERATURE REVIEW

This chapter presents the literatures on previous studies conducted for the compensation of power quality issues exist on low voltage networks and presents available solutions for mitigation of LV power quality issues and their effectiveness and shortfalls. Furthermore, it identifies the research gap between the proposed work and literature.

2.1 Introduction

Mitigation of power quality issues exist in low voltage distribution networks are becoming predominant requirement for the utility providers. As low voltage distribution network becoming more active with the penetration of distributed generators in order to maintain voltage profile within tolerable level according to the regulatory limits, utility providers are practicing various voltage regulation techniques in their LV networks.

2.2 Available Mitigation Options for Power Quality Issues in LV Network

Distribution networks are usually under stress due to the connected loads which results reduction of voltage across the loads affecting the performance. Also, in present LV networks voltage variations can be experience in both ways, under voltage as well as over voltage situations. It is a vital requirement to assure power quality in the distribution network to improve the performance of the power system.

2.2.1 Flexible AC transmission system (FACTS) devices

Predominant cause for the voltage variation in distribution networks is reactive power demand variation. Compensation of reactive power assures voltage stability in the network running at high power quality with minimum system loss. To enhance the system performance Flexible AC transmission system (FACTS) are the promising solution [08].

Series and shunt classification are the broad classification for FACTS controllers, modification to natural electrical characteristic has done by this both varieties. transmission or distribution system parameters are modified by series compensation devices, equivalent impedance of the load is changed by shunt compensation divides. Overall performance of the system will be improved by effectively controlling reactive power flow in both cases. Power handling capability enhanced by series controllers while voltage at a particular location improved by shunt controllers. Both improves the voltage and power handling capability.

Example FACTS controllers are [08],

Controllers in series configuration

- TSSR - Thyristor Switched Series Reactor
- TCSR - Thyristor Controlled Series Reactor
- TSSC - Thyristor Switched Series Capacitor
- TCSC - Thyristor Controlled Series Capacitor
- SSSC - Static Synchronous Series Capacitor
- IPFC - Interline Power Flow Controller

Controllers in shunt configuration

- TCR - Thyristor Controlled Reactor
- TSR - Thyristor Switched Reactor
- TSC - Thyristor Switched Capacitor
- STATCOM - Static Synchronous Compensator
- SSG - Static Synchronous Generator
- SVC - Static VAR Compensator
- SVG - Static VAR Generator or absorber
- TCBR - Thyristor Controlled Breaking Resistor
- BESS - Battery Energy Storage System
- SMES - Super conducting Magnetic Energy Storage

Shunt - Series combined controllers

- UPFC - Unified Power Flow Controller
- TCPST - Thyristor Controlled Phase Shifting Transformer
- IPC - Inter Phase Power Controller

2.3 Evolution of Mitigation Solutions for PQ Issues in LV Network

Early days power distribution networks had uni-directional power flow from distribution substation to customer end. Hence, these days utility providers predominantly experienced under voltage power quality issued in their LV distribution networks. In first generation of power distribution network power quality improvements are mainly concentrated on providing quality power supply with regulated voltage profile along the radial distribution feeders.

2.3.1 Traditional LV Voltage Regulation Methods

First generation low voltage distribution networks voltage regulation methods are mainly based on passive compensation method and some of them can be listed as below [35],

- On Load Tap Changer (OLTC)
- Series Voltage Regulators
- Switched Capacitor Banks
- TCSC, TSSR, TCSR, SSSP, IPFC

These voltage regulation methods are direct compensation devices and regulate system voltage accordingly [28]. These devices are comparatively slow in operation and compensate voltage gradually, hence not properly address short time voltage variations. These solutions are practices by LV distribution network providers with various combinations based on the level of impact by power quality issues on their networks. However, these solutions have their own drawbacks also hence, a requirement of a cost reflective solution has much demand on this area.

2.3.2 Present LV Voltage Regulation Methods

Present power distribution networks are more active with the integration of distributed generators to distribution networks. Bi-directional power flow can be observed in modern distribution networks mainly due to the accumulating penetration of solar PV generators. Output form PV generators are highest in the middle of the day when load is lowest. Net Feed-in tariffs schemes encouraged consumers to shift load away from middle of the day [24].

Presence of bi-directional power flow due to penetration of DGs meant much greater voltage swing both steady state & dynamic. This can exacerbate voltage unbalance between phases also. The biggest problem is, utility providers have lowest visibility on LV leaf level to monitor this power quality issues.

In order to address these issues, distribution network providers adopt to below mitigation solutions [25].

- Application of SVCs
- PV Inverters and BESSs
- Unified Power Flow Controller (UPFC)
- Inter Phase Power Controller (IPC)
- Thyristor Controlled Phase Shifting Transformer (TCPST)
- Active Power Curtailment (APC) of DGs

However, even though these mitigation methods are adopted by utility providers, these solutions have their own disadvantages too.

2.3.3 Evaluation of the Existing Conventional Solutions

Conventional voltage regulating methods adopted for the regulation of voltage or to mitigate the under voltage and/or over voltage power quality issues have their own disadvantages as well as advantages. Table 1 summarizes some of these solutions and their effectiveness in resolving power quality issues in LV power distribution network [22].

Table 1: Advantages and disadvantages of conventional PQ mitigation solutions

Solution	Advantage	Disadvantage
Change Tap setting (LTC) [09]	Simple, Low Cost	Does not solve Voltage Variations, Need Power Outage
On-Load Tap Changer	Dynamic Voltage Regulation	OLTC Time Delay ~ 30s, OLTC tap Step = 0.01 pu, Communication delay is high, Can not be used for long radial Distribution Networks
Augmentation [09] (Splitting LV feeders, Bigger Conductor)	Well Understood	Expensive, Requires Outage, Not addressing core issues
Change in Voltage regulation	Low cost	Not addressing the issues
Active Power Curtailment (APC) of distributed renewable energy sources (DRES) [02]	Simple	Loss of green energy, Not Economical for Distributed Renewable Energy Providers
Customer owned "VAR capable" inverters [10]	Customers pay for the solution	Expensive, Need standard VAR control algorithm, No control to suite network needs (Q based on V, P based on Loading)
Micro SVC Applications	Address voltage issue	Can only sink or source Q, Do not have greater resolution, Bulky. Does not address harmonic issues, Slow operation

2.4 Studies Carried out for Mitigation of PQ Issues in Active LV Network

The following reactive power-based studies have been carried out for the regulation of voltage in active low voltage distribution networks.

01. Y. Hoseynpoor and T. PirzadehAshraf [10] introduces a reactive power enable PV inverter-based voltage control method in low voltage distribution networks. In their study, inverter at PV unit is used for the voltage regulation in the connected LV feeder. In order to source/sink reactive power to/from connected LV network, solar PV generator units operates in Voltage Oriented Control (VOC) mode instead of Maximum Power Point Tracking (MPPT) mode [23].

    In their research, heavy PV populated LV distribution network has taken as their target system. Use of reactive power processing capability in order to source and sink by inverters integrated with solar PV devices are the main compensation method to regulate voltage variations of LV distribution network. Capability of operating along a droop which is configured at customer owned PV system is taken as primary source of control in order to regulate voltage.

PV inverter operated based on pre-configured droop curve. They have come up with an algorithm for PV inverter to operate along the droop curve to regulate LV network voltage by monitoring the voltage at Point of Common Coupling (PCC).

$$Q_{PV}^{ref} = \begin{cases} Q_{max} & U_{sim} < U_1 \\ \frac{Q_{max}}{U_2 - U_1}(U_2 - U_{sim}) & U_1 \leq U_{sim} < U_2 \\ 0 & U_2 \leq U_{sim} < U_3 \\ -\frac{Q_{max}}{U_4 - U_3}(U_{sim} - U_3) & U_3 \leq U_{sim} < U_4 \\ -Q_{max} & U_4 \leq U_{sim} \end{cases} \quad (2)$$

The reactive power reference is calculated using the value of

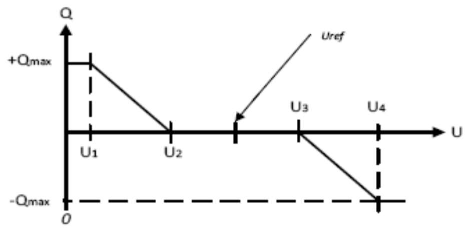


Fig. 1: Standard reactive power method- $Q(U)$.

Figure 7: Droop Curve used by PV Inverter to Regulate Voltage
Source: Reactive Power Control for LV Distribution Networks Voltage Management [10]

Drawbacks of this study are, there is very limited range of voltage regulation is possible through this reactive power capable PV inverters, operation of PV unit in VOC mode is financially not beneficial for the user and normally users tends to operate their PV units in MPPT mode to get maximum solar generation possible and this method offers no control for the utility provider to control voltage regulation.

02. E. Riva Sanseverino, Leon R. Roose, Staci T. Sadoyama, B.V.Doan, N.H.Nguyen[11] in their study proposed a method of optimal placement of SVC devices in Low Voltage network with high penetration of PV systems in order to regulate system voltage. Objective function of their study is to improve voltage of PV populated distribution network by source/sink reactive power via SVCs to the feeders experiencing under/over voltage situations during most of the time in daily loading. Optimal placement of SVC studied under 2 different scenarios, one at low load and high penetration of solar PV generation and one at high load and no solar PV generation.

They have developed an objective function to minimize the number of SVC devices installed and voltage deviation index. Then apply SVCs on feeders having highest voltage deviation index and thereby regulate distribution network voltage.

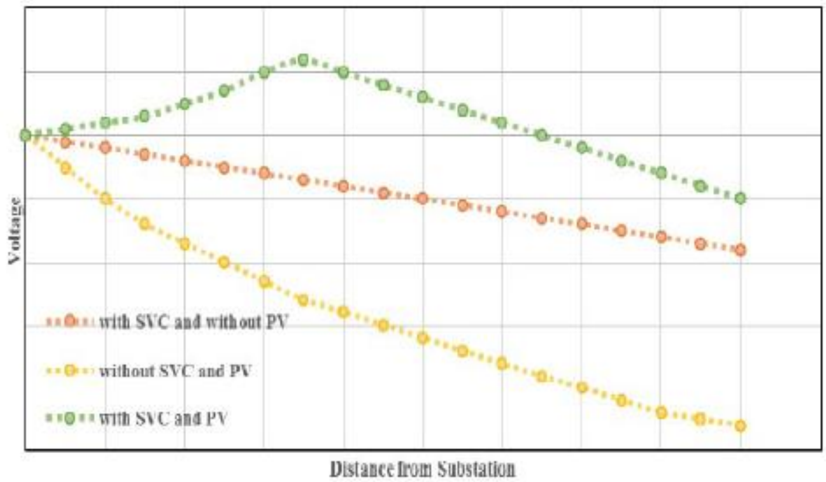


Figure 8 : Profile of voltage along LV feeder with and without SVC & Solar PV
Source: Optimal placement of SVC devices in LV network with high penetration of PV systems [11]

2.5 SVC and STATCOM

In this research Micro-STATCOM is used to resolve low voltage power quality issues as defined in the objectives. SVCs are most common voltage regulation devices that uses in present LV networks to process reactive power in order to compensate over voltage and under voltage issues.

2.5.1 Operational Characteristics of SVC and STATCOM

STATCOMs can be choose over SVCs as a voltage regulation device to effectively process reactive power in LV distribution networks to regulated voltage. Availability of large range of operation at various under voltage or over voltage situations is the predominant advantage in STATCOMs over SVCs. Apart from that, STATCOMs are possess with fast switching capability hence, STATCOMs are well capable of regulating LV voltage variation in a shorter period of time (with in ~50 ms range) [27].

Even though, SVCs have limited voltage regulation range as system voltage goes down, STATCOMs can continue regulating voltage variation via reactive power support even at 0.2 p.u. system voltage levels. Comparison of operating characteristic is shown in figure 9 [20], [21].

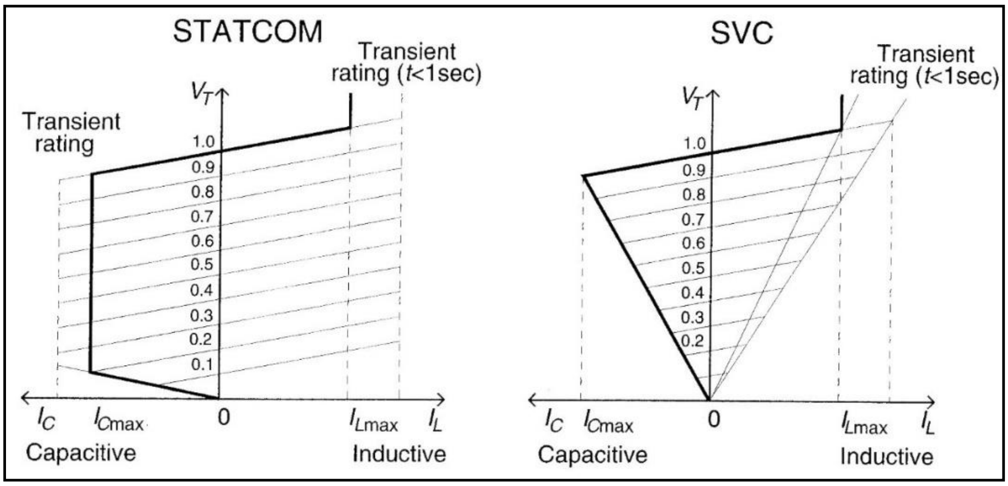


Figure 9: Operating Characteristics of STATCOM and SVC
Source: Reactive power and voltage control [07]

2.5.2 Comparison Between SVC and STATCOM

Technical comparison between SVC and STATCOM based on their operation has tabulated in Table2 below [20].

Table 2: Advantages of STATCOM over SVC

Static Synchronous Compensator (STATCOM)	**Static VAR Compensator (SVC)**
Faster in operation	Slower than STATCOM
Better operating resolution (Large droop)	Not good as STATCOM
Constant current characteristics, Can be operated over its full output current range even at very low (typically 0.2 pu) system voltage levels	Capacitive reactive current drops linearly
Interfaced with real power sources like battery, fuel cell or Solar PV	Can not interfaced with them
Smaller in size (Compact)	Lager in size
Controllable voltage source	Dynamically controlled reactance

2.6 Application of STATCOMs in MV Distribution Network

Distribution-STATCOMs (D-STATCOMs) are widely used in present MV distribution networks. Powe Network utility providers are installing D-STATCOMs in their network in order to improve the distribution network reliability.

Various DGs are integrated in to MV network and voltage variations are expected to be present in MV network. D-STATCOMs continuously provide variable reactive power to in response to MV network voltage variations. Inherent characteristics of D-STATCOMs are best suits to regulate MV voltage and improves system stability. D-STATCOMs are generally in MVar range and faster in response and smooth in operation (switching capability in milliseconds range ~30 ms) [31]. D-STATCOMs are bulky in size and consumes considerable amount of power during its operation. However, D-STATCOMs are very popular in regulating MV network voltage than capacitor banks and other available solutions [36].

2.6.1 Studies Carried out on D-STATCOMs in Voltage Regulation

B. Bakhshideh Zad, J. Lobry and F. Vallee [12] have worked on coordinated actions of OLTC and D-STATCOM for voltage regulation of distributed generators populated medium voltage network.

In their study, they are proposing coordinated operation of D-STATCOM together with OLTC in sequence method. When there is under voltage or over voltage situation occurred within pre-defined window, first D-STATCOM starts to regulated voltage because D-STATCOM is faster and continuous in operation than OLTC. When there is a situation occurs beyond pre-defined window, OLTC also start to regulate the voltage by reducing stress on D-STATCOM. Once voltage came back to pre-defined limits OLTC stops its operation and let D-STATCOM to do the rest. They have introduced this coordinated operation to improve voltage by considering the voltage variation of all feeders in the network [26].

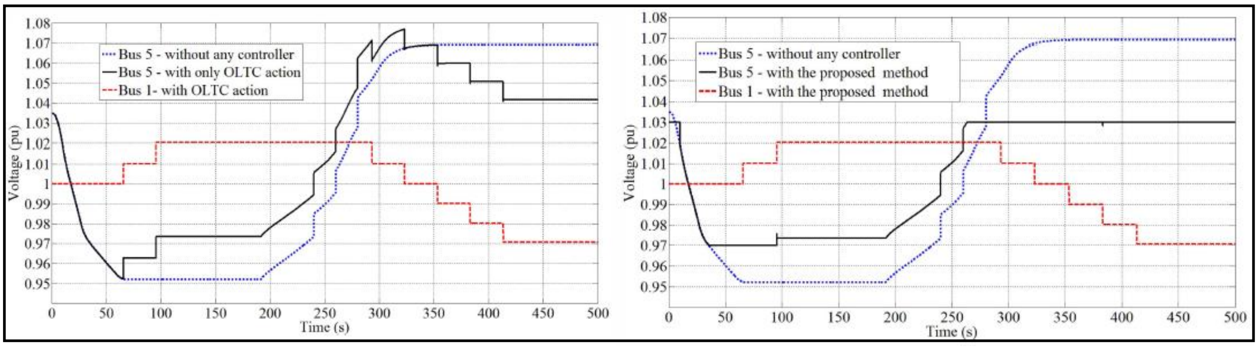


Figure 10: Regulation of system voltage with and without coordinated operation
Source: Coordinated Control of On-Load Tap Changer and D-STATCOM for Voltage Regulation of Radial Distribution Systems with DO Units

2.7 Conclusion

Mitigation of power quality issues exist in LV distribution networks are becoming vital requirement as emerging power electronic devices are mor sensitive for small changes in power quality of electricity supply. Important power quality parameters are well defined and quantified in order to understand the optimal values that need to maintain for these parameters. Predominant pawer quality issues exist in LV distribution network are,

- Voltage Variation & Unbalance
- Aggregation of Harmonics
- Poor Power Factor

Various regulation methods are adopted by utility providers in their LV networks in order to resolve power quality with cumulative integration of DGs. But these solutions have their own disadvantages.

STATCOMs are very efficient in regulating voltage variation issue and presently used in MV network. Application of STATCOMs in low voltage level is new area of research which will certainly replace traditional solutions like SVCs/ TCSR/ OLTC/ Capacitor Banks etc. [32]. Faster response to the LV network voltage variation, low power consumption, low maintenance and high efficiency will make micro level STATCOM very suitable for resolving power quality issues in low voltage network. In this research Micro-STATCOM is developed to be integrated with LV network in order to successfully address power quality issues [29].

3. MODELING OF MICRO-STATCOM

This chapter focus on derivation of mathematical model for proposed Micro-STATCOM solution and implementation of required controllers based on the mathematical model. Design and development of operational sequence of the proposed solution is also presented in this chapter.

3.1 Introduction

In this research Micro-STATCOM based solution is proposed to mitigate power quality issues in active LV distribution networks. Objective function of this research is to dynamically decide quadrature and in phase currents demand that need to be injected by Micro-STATCOM module to PCC in order to compensate voltage variation, mitigate harmonics present in system and to improve power factor of the LV network by taking system parameters as dynamic inputs.

3.2 Conceptual Design on Operation of Proposed Micro-STATCOM

Conceptual operational arrangement of the proposed Micro-STATCOM is depicted in Figure 11. STATCOM controller, driver of the control signals, DC power source and STATCOM itself are the major functional arrangement of this Micro-STATCOM model. This system is integrated to the PPC of LV power system in parallel.

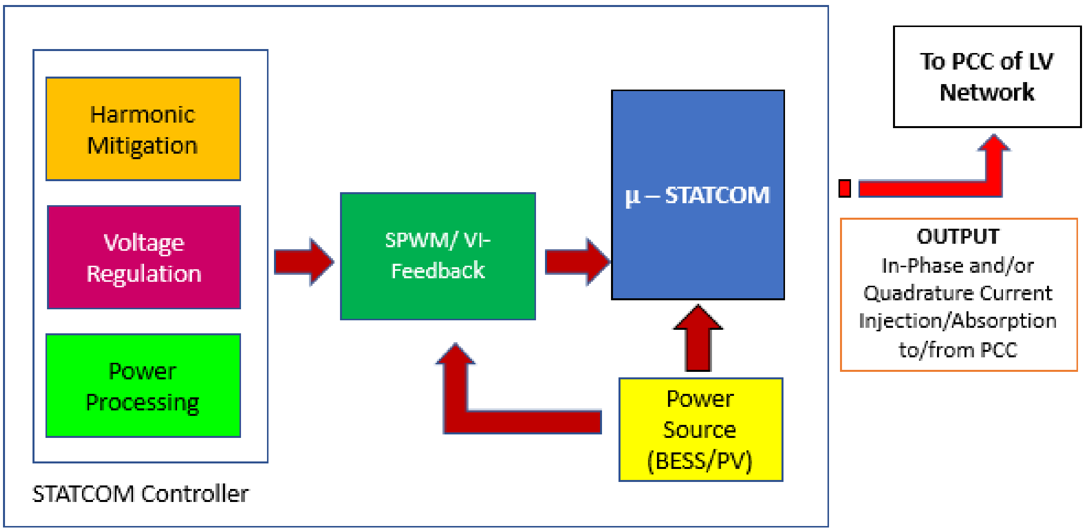


Figure 11: Conceptual Control Block of Micro-STATCOM Connecting to PCC

3.3 Mathematical Modeling of Micro-STATCOM Controller

Predominant function of STATCOM controller is to provide required control signals to Micro-STATCOM to process reactive power in order to compensate dynamic voltage variation of the LV power system. Derivation of mathematical model to evaluate required amount of compensation by taking system current status as input is presented under this section.

3.3.1 Integration of Micro-STATCOM to Distribution System

Integration of Micro-STATCOM model to LV distribution system through PPC is depicted in Figure 12. Three phase connection from STATCOM parallelly connected to PCC.

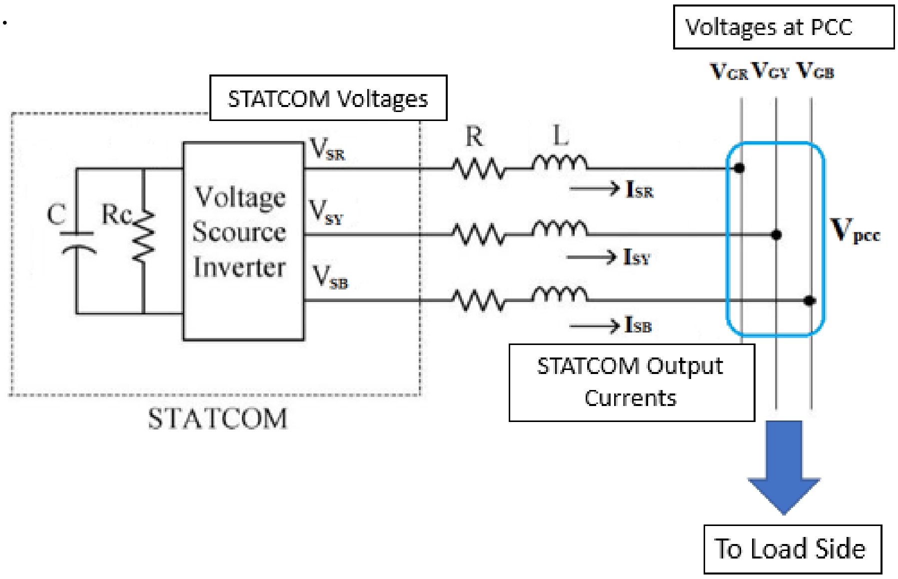


Figure 12: Parallel Connection of Micro-STATCOM to PCC

3.3.2 Phasor Equation for Micro-STATCOM

Phasor equations for the three phase STATCOM shown in Figure 12 can be written as below,

$$V_{SR} - RI_{SR} - L\frac{dI_{SR}}{dt} = V_{GR} \tag{3.1}$$

$$V_{SY} - RI_{SY} - L\frac{dI_{SY}}{dt} = V_{GY} \tag{3.2}$$

$$V_{SB} - RI_{SB} - L\frac{dI_{SB}}{dt} = V_{GB} \tag{3.3}$$

Where,

V_{SR}, V_{SY}, V_{SB} = STATCOM Voltages

V_{GR}, V_{GY}, V_{GB} = System Voltages

I_{SR}, I_{SY}, I_{SB} = STATCOM Current Output

3.3.3 Derivation of Mathematical Model for Micro-STATCOM Controller

Starting from the basic phasor equations, this section elaborates the derivation of governing mathematical model for the Micro-STATCOM Controller.

(R, Y, B) Plane phasor equations (3.1), (3.2) and (3.3) can be convert in to (α,β) stationary reference plane equations using *Clarke Transformation.*[13] Using Clarke transformation current space vectors and voltage space vectors can be expressed as,

$\overline{I_s} = (I_\alpha + jI_\beta)$, $\overline{V_S} = (V_\alpha + jV_\beta)$

Accordingly, system expressed by (3.1), (3.2) and (3.3) equations can be expressed in (α, β) plane as,

$$V_{S\alpha} = RI_{S\alpha} + L\frac{dI_{S\alpha}}{dt} + V_{G\alpha} \tag{3.4}$$

$$V_{S\beta} = RI_{S\beta} + L\frac{dI_{S\beta}}{dt} + V_{G\beta} \tag{3.5}$$

Then the general vector equation can be expressed as,

$$V_{S\alpha} + jV_{S\beta} = R\left(I_{S\alpha} + jI_{S\beta}\right) + L\frac{d}{dt}\left(I_{S\alpha} + jI_{S\beta}\right) + \left(V_{G\alpha} + jV_{G\beta}\right) \tag{3.6}$$

Derived (α,β) stationary reference plane equations can be converted in to (d, q) rotating plane using *Park Transformation.* [13]

<u>Park Transformation Matrix</u>

Transformation from (α,β) to (d,q) is done by

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \times \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

or, $\begin{bmatrix} d \\ q \end{bmatrix} = \left[Park\,Matrix\right] \times \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$

Unit Vectors,

$$Sin\theta = \frac{V_{g\beta}}{\sqrt{V_{g\alpha}^2 + V_{g\beta}^2}}$$

$$Cos\theta = \frac{V_{g\alpha}}{\sqrt{V_{g\alpha}^2 + V_{g\beta}^2}}$$

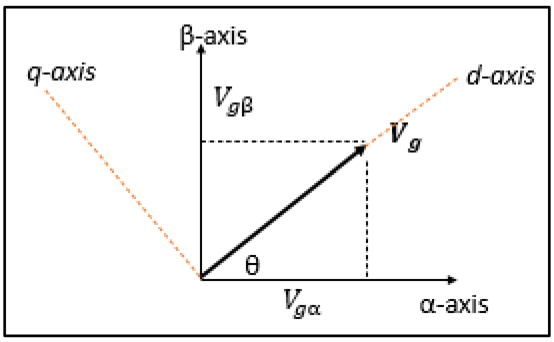


Figure 13: (α,β) stationary plane and (d, q) rotating plane

Where, $\frac{d\theta}{dt} = \omega$

Hence, currents or voltages in (α, β) can be converted in to (d, q) plane as,

$$I_{Sd} = I_{S\alpha} Cos\theta + I_{S\beta} Sin\theta$$
$$I_{Sq} = -I_{S\alpha} Sin\theta + I_{S\beta} Cos\theta$$

Therefore, Micro-STATCOM currents in (d, q)form,

$$I_{Sd} + jI_{Sq} = (I_{S\alpha} + jI_{S\beta})e^{-j\theta} \quad (3.7)$$
$$I_{S\alpha} + jI_{S\beta} = (I_{Sd} + jI_{Sq})e^{j\theta} \quad (3.8)$$

Micro-STATCOM voltages in (d, q)form,

$$V_{S\alpha} + jV_{S\beta} = (V_{Sd} + jV_{Sq})e^{j\theta} \quad (3.9)$$
$$V_{G\alpha} + jV_{G\beta} = (V_{Gd} + jV_{Gq})e^{j\theta} \quad (3.10)$$

After applying equations (3.7), (3.8), (3.9) and (3.10) in equation (3.6),

$$V_{Sd} + jV_{sq} = RI_{Sd} + jRI_{Sq} + L\left(j\omega I_{Sd} - \omega I_{Sq} + \frac{dI_{Sd}}{dt} + j\frac{dI_{Sq}}{dt}\right) + V_G \quad (3.11)$$

Where,

$\frac{d\theta}{dt} = \omega\ ; System\ frequency$

$V_{Gd} = V_G\ ;\ d - axis\ aligned\ with\ V_{Gd}\ \therefore\ V_{Gq} = 0$

So, the (d, q) plane equations for STATCOM are,

Alone $d - axis,$

$$\boldsymbol{V_{Sd} = RI_{Sd} + L\frac{dI_{Sd}}{dt} - \omega LI_{Sq} + V_G} \quad (3.12)$$

Alone $q - axis,$

$$\boldsymbol{V_{Sq} = RI_{Sq} + L\frac{dI_{Sq}}{dt} + \omega LI_{Sd}} \quad (3.13)$$

Deriving transfer function $H(S)$ for the PI-Controller of Micro-STATCOM controller, Equations (3.12) and (3.13) can be re-arranged as below,

$$V_{Sd} - V_G + \omega LI_{Sq} = RI_{Sd} + L\frac{dI_{Sd}}{dt}$$

$$V_{Sq} - \omega LI_{Sd} = RI_{Sq} + L\frac{dI_{Sq}}{dt}$$

V'_{Sd} and V'_{Sq} can be defined as,

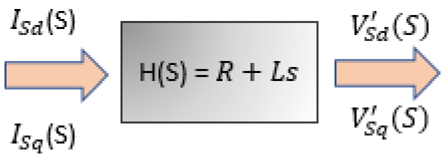
$$V'_{Sd} = RI_{Sd} + L\frac{dI_{Sd}}{dt} \tag{3.14}$$

$$V'_{Sq} = RI_{Sq} + L\frac{dI_{Sq}}{dt} \tag{3.15}$$

Taking Laplace transfer functions for equations (3.14) and (3.15),

$$V'_{Sd}(S) = (\mathrm{R} + LS)\, I_{Sd}(\mathrm{S})$$

$$V'_{Sq}(S) = (\mathrm{R} + LS)\, I_{Sq}(\mathrm{S})$$



Micro-STATCOM output voltages in (d, q) form can then be modeled as below,

$$\boxed{V_{Sd} = V'_{Sd} - \omega L I_{Sq} + V_G} \tag{3.16}$$

$$\boxed{V_{Sq} = V'_{Sq} + \omega L I_{Sd}} \tag{3.17}$$

3.3.4 Active Filtering of Harmonic Currents by the Mathematical Model

Input load current reference (with harmonic components) to the Micro-STATCOM controller can be expressed as (3.18),

$$I = \underbrace{I_0 Cos(\omega t + \emptyset_0)}_{\text{Fundamental}} + \underbrace{I_1 Cos(2\omega t + \emptyset_1) + I_2 Cos(3\omega t + \emptyset_2) + ..}_{\text{Harmonic Components}} \tag{3.18}$$

(d, q) reference frame currents were obtained by Clarke and Park space vector transformation method starting from (R, Y, B) phasor system. The (R, Y, B) phasor system is stationary and (d, q) system is a rotating reference frame with fundamental angular frequency (ω).

In (d, q) frame, the fundamental currents are appearing as dc component and harmonics are appearing as ac components. To assure the synchronism, unit vectors representing angular deviation (θ) in the (d, q) frame were derived with respect to the voltage phasors of (R, Y, B) orthogonal system.

(d, q) Method Control Strategy of Active Filtering of Harmonics

According to the Clarke + Park transformation, the relation between phasor currents and (d, q) frame currents can be mathematically expressed as equation (3.19),

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & \cos\,(\theta - \frac{2\pi}{3}) & \cos\,(\theta + \frac{2\pi}{3}) \\ -sin\theta & -\sin\,(\theta - \frac{2\pi}{3}) & -\sin\,(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} I_R \\ I_Y \\ I_B \end{bmatrix} \tag{3.19}$$

Where, as mentioned in figure:13, θ is the angular deviation of the synchronous reference frame from the stationary reference frame which is a liner function of the fundamental frequency of the system voltage phasors.

Output of the transformation can be expressed as below,

$$I_d = \overline{I_d} + \widetilde{I_d} \tag{3.20}$$

$$I_q = \overline{I_q} + \widetilde{I_q} \tag{3.21}$$

Where, $\overline{I_d}\ and\ \overline{I_q}$ are the dc components of the current in (d, q) frame (fundamental current components). $\widetilde{I_d}\ and\ \widetilde{I_q}$ are the alternating current components in (d, q) frame (harmonic current components). The harmonic reference current can be obtained from the load current using simple low-pass filter (LPF).

After filtering, the dc current components of Clarke + Park transformation output are suppressed and alternating terms are appearing in the output of the LPF (harmonic extraction point) which are responsible for the harmonic population in the power system.

Output from the LPF then will be used for the mitigation purpose of the harmonics in the system. In order to get the filtered currents in three phase system which cancel out the harmonic component form the source side, inverse Clarke + Park transformation is used as expressed in equation (3.21).

$$\begin{bmatrix} I_R^* \\ I_Y^* \\ I_B^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & -sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} \tag{3.22}$$

Figure:14 flow chart represents the active filtering of harmonics by Clarke+Park transformation and use on inverse Clerk+park transformation after active filtering for the harmonic mitigation.

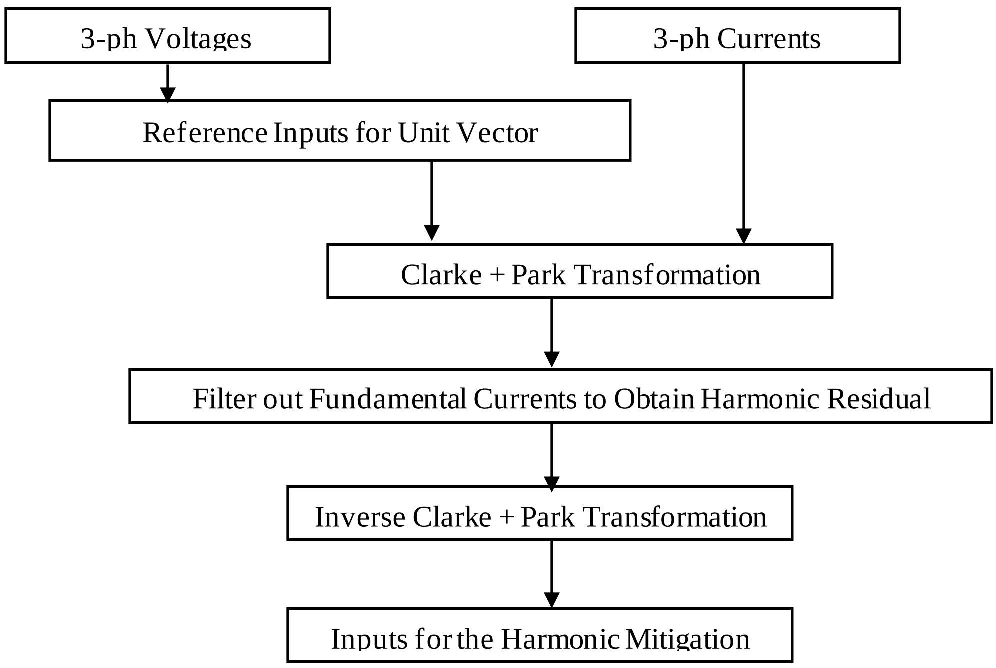


Figure 14: Control Strategy for Active Harmonic Filtering and Mitigation

3.4 Operation of PI-Controller

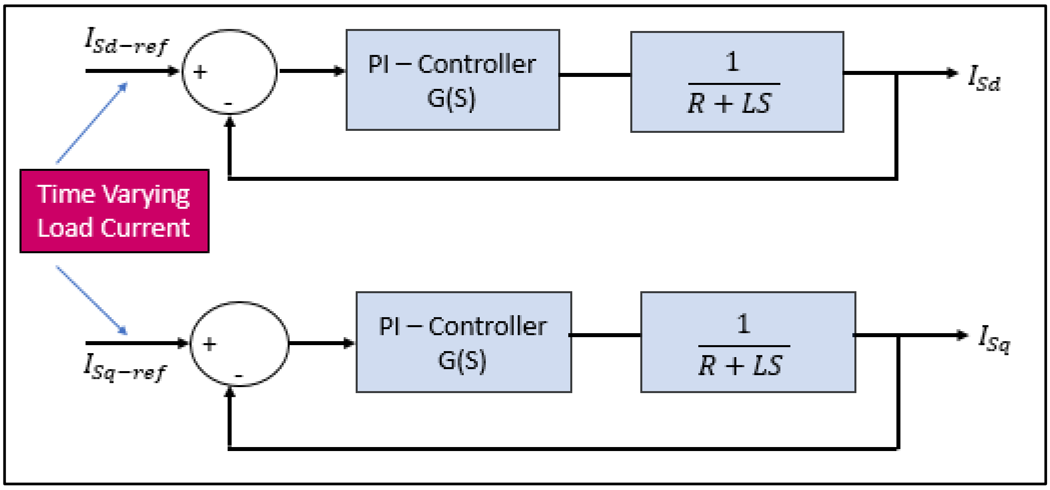


Figure 15: Operation of the PI-Controller

Micro-STATCOM voltage source inverter will behave as a first order low pass filter with f_c cut-off frequency with $f_c = 0.1 f_s$, where f_s is the STATCOM switching frequency. Hence, in order to eliminate higher harmonics, we have to increase switching frequency.

$$\frac{G(s) * \frac{1}{R+LS}}{1 + \frac{G(s)}{R+LS}} = \frac{1}{1+ST} \quad ; Where\ T = \frac{1}{f_c}$$ first order filter,

$$\frac{G(s)}{R+LS} = \frac{1}{ST}$$

$$G(s) = \frac{L}{T} + \frac{\left(\frac{R}{T}\right)}{S} \quad \boxed{K_p + \frac{K_i}{S}}$$ PI-Controller (3.18)

Micro-STATCOM controller takes instantaneous load currents as input reference currents for the PI-Controller and current output from Micro-STATCOM will feed back to PI-controller in order to compute error current such a way that STATCOM controller current output dynamically adopt to regulate voltage at point of common coupling and to eliminate harmonic components in the System. System voltages at point of common coupling also taken as an input to Micro-STATCOM controller in order to improve the system power factor.

3.5 Operation of the Micro-STATCOM Controller

Micro-STATCOM Controller accepts instantaneous load currents, system voltages at point of common coupling and STATCOM current outputs as inputs to the controller and these components are converted in to (α, β) or (d, q) form for the generation of control signals to the sinusoidal pulse width modulator in order to generate required switching signals for the IGBTs in STATCOM. Operation of PI-Controller is explained in sub sections 3.3.3 and 3.3.4 above. PI-Controller generates required quadrature and in phase current components dynamically in order to regulate voltage at point of common coupling and to eliminate harmonics at PCC. Unit vectors required for the generation of control signals are derived from voltage signals at PCC, hence this will improve system power factor also. Integrated external DC (Solar PV or BESS) power source with the coupling capacitor provides required DC voltage support to the Micro-STATCOM module.

Micro-STATCOM Controller Operation Sequence Block Diagram

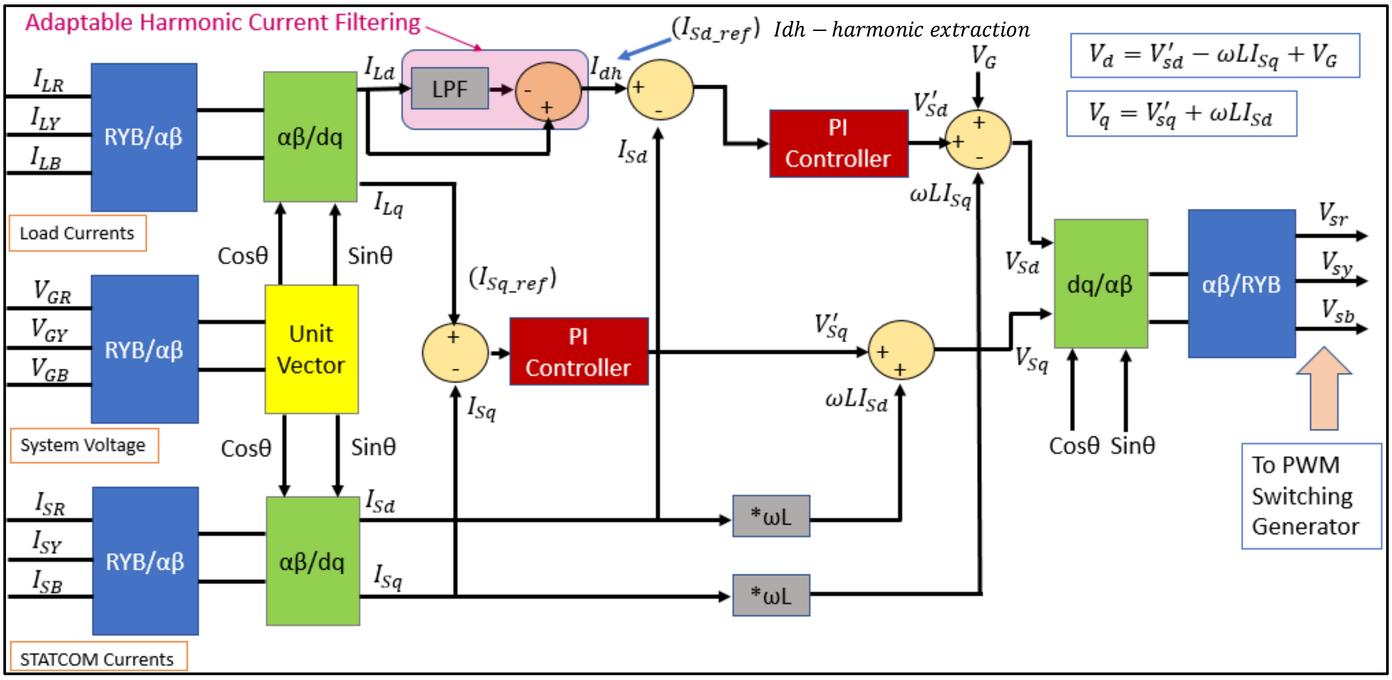


Figure 16: Micro-STATCOM Controller Operation Sequence

4. DEVELOPMENT OF SIMULATION MODEL

4.1 Introduction

Implementation of Micro-STATCOM model in Matlab^{TM} Simulink environment consist of three main sub modules. Micro-STATCOM module, Controller Module and Sinusoidal Pulse Width Modulation Module are the three major components of the comprehensive Micro-STATCOM model. This chapter focus on development of each modules in Matlab Environment and testing of the complete module for its proper operation and inter-working between each model.

4.2 Main Components of the Micro-STATCOM Model

4.2.1 Micro-STATCOM Controller Module

Mathematically derived controller was implemented in Matlab Simulink according to the operational sequence illustrated in Figure 16. Load currents, system voltages and currents feedback from Micro-STATCOM taken as input to the controller and outputs voltage phasor signals to sinusoidal pulse width modulator as shown in Figure 17.

Input current and voltage phasors were transformed in to (α, β) plane using a sub-module developed according to the Clarke transformation matrix. [13]

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} i_R \\ i_Y \\ i_B \end{bmatrix}$$; Clarke transformation matrix

Park transformation matrix [13] is used by the sub-module developed to transform (α, β) plane values of currents and voltages in to (d, q) plane in this controller. Unit vectors are derived using (α, β) components of the system voltage as elaborated in section 3.3.3. PI-Controller tunned using derived equation (3.18) for its transfer function. Low-pass *butterworth* filter was used with system fundamental frequency (50 Hz) as cut-off frequency to filter harmonic components [30].

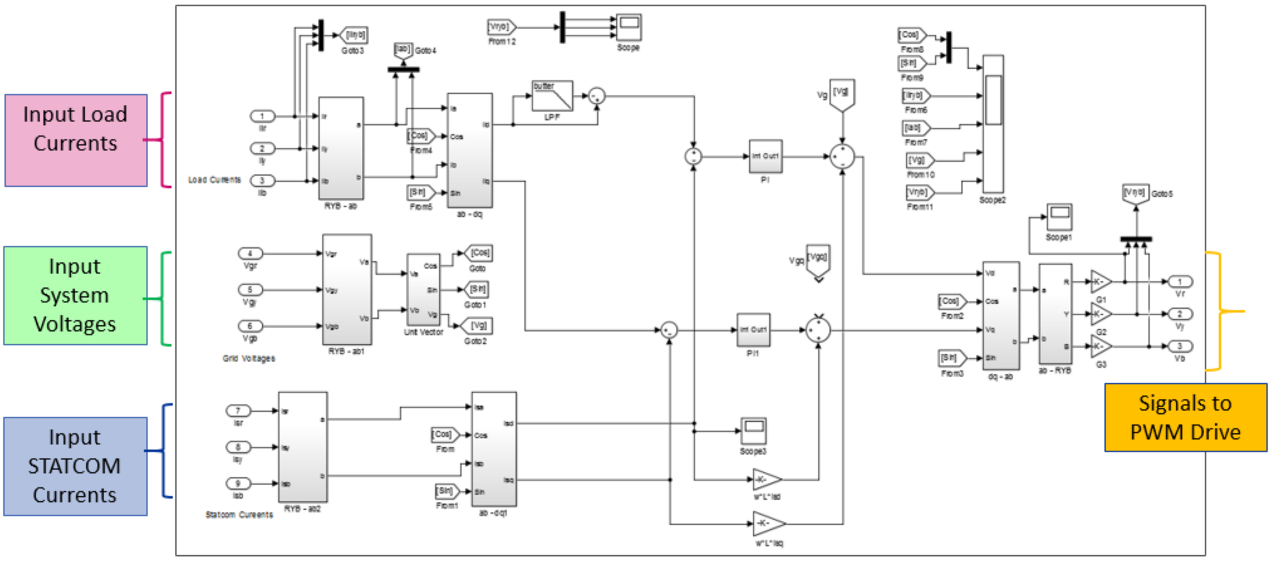


Figure 17: Matlab Simulink Model for Micro-STATCOM Controller

4.2.2 Sinusoidal Pulse Width Modulator (SPWM) Module

This module accepts control signals form Micro-STATCOM controller and generate required driver signals to switch on and off STATCOM, IGBT transistors. The switching frequency used in this modulator is 20 kHz.

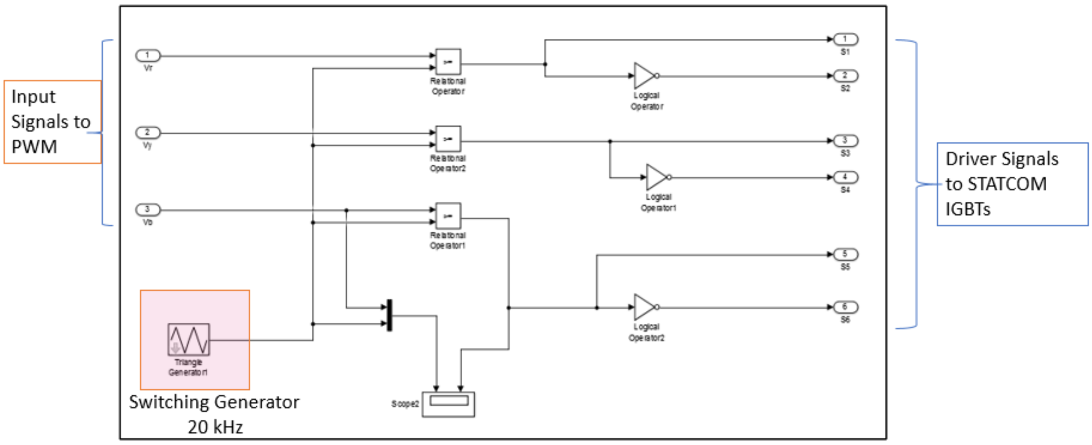


Figure 18: Matlab Simulink Model for SPWM

SPWM drives the IGBT transistor switches in STATCOM by controlling their ON & OFF states such a way that controlled AC voltage waveform generate at the output of STATCOM.

4.2.3 Micro-STATCOM Voltage Source Inverter Module

Micro-STATCOM voltage source inverter was developed in parallel connection with coupling capacitor and DC voltage source of 1000 V in Matlab Simulink to generate required voltages at Micro-STATCOM output in order to source/sink quadrature and in phase currents to/from PCC.

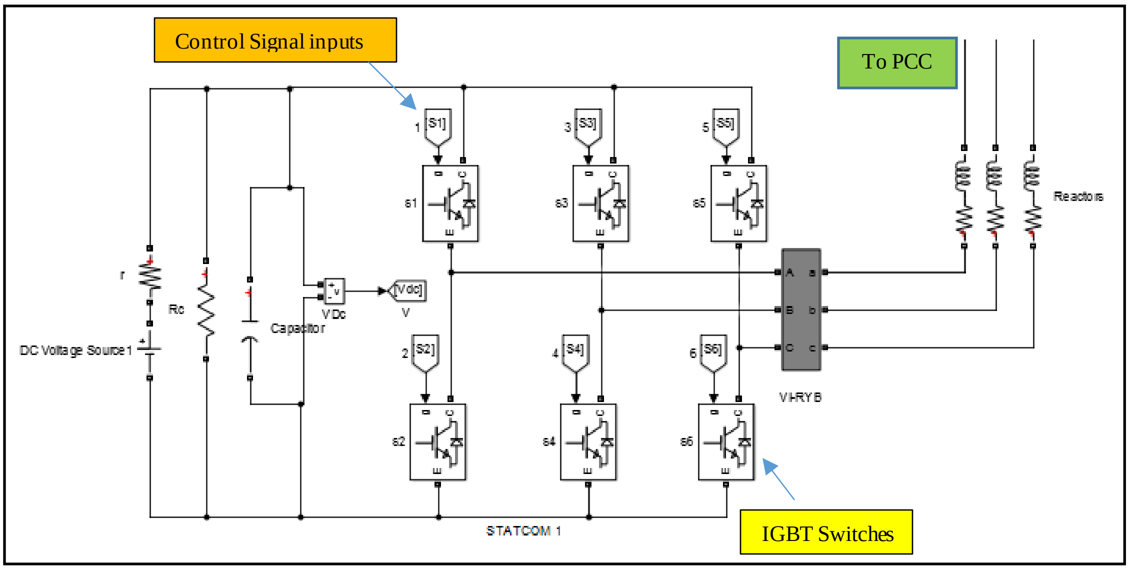


Figure 19: Matlab Simulink Model for Micro-STATCOM

4.3 Validation of Micro-STATCOM Model on Its Operation

Complete model for proposed Micro-STATCOM was developed in Matlab Simulink environment to address power quality issues in low voltage distribution networks by under voltage/ over voltage regulation, harmonic mitigation and system power factor improvement. Developed Micro-STATCOM module was initially applied in to a simple 2-Bus system in order to test and validate the operation of the model.

Expected results were also observed on the 2-Bus setup with the presence of harmonic load.

4.3.1 2-Bus System Test Setup to Validate the Functionality of the Model

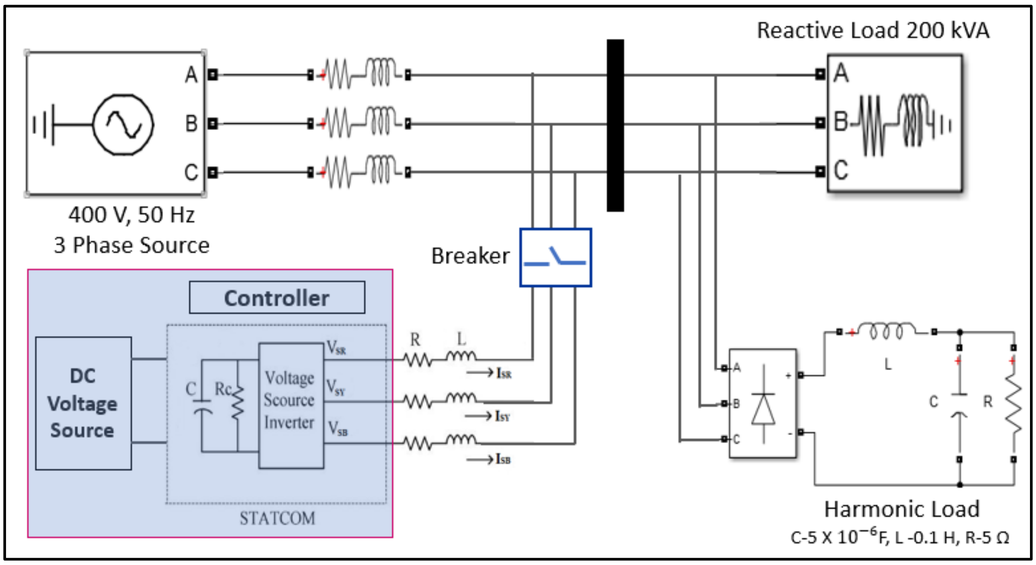


Figure 20: 2-Bus System to test the Functionality of Micro-STATCOM

Operation of Micro-STATCOM model was tested using 2-Bus system under two scenarios. One is when 2-Bus system is in under volage situation with the presence of harmonic loads and the other scenario is 2-Bus system is in over voltage situation with the presence of harmonic load.

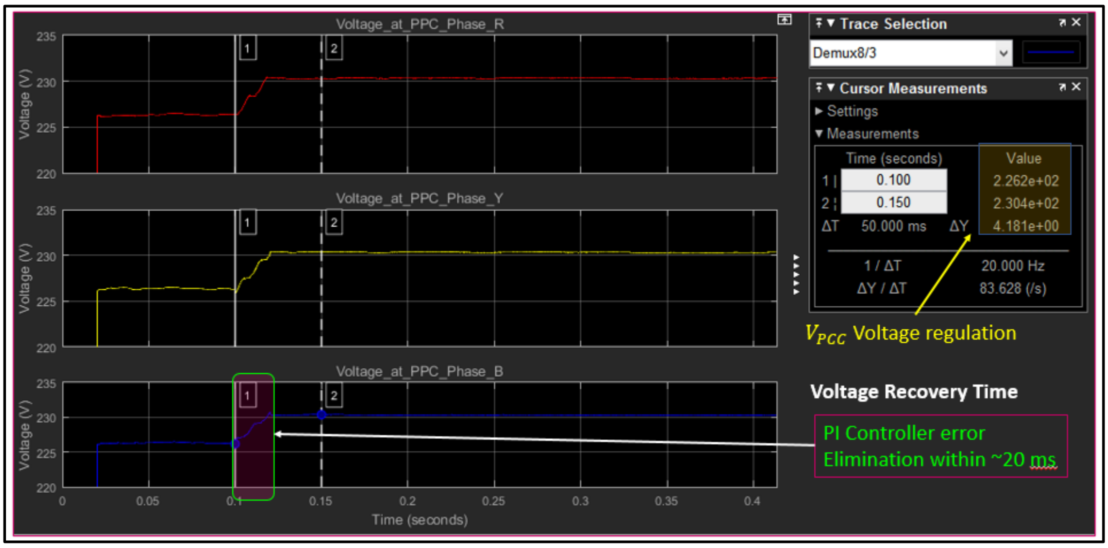
It was observed that developed Micro-STATCOM model was successfully regulated the 2-Bus system voltage variation less than 20 ms of time. It was also observed that the developed model has a potential to eliminated high level of harmonics and system THD % level was brough back to considerable low value (1.1%). System power factor improvement also verified using the phase difference between system voltage and current waveforms after applying Micro-STATCOM.

Hence, the proposed Micro-STATCOM showed successful results in power quality improvement in 2-Bus system test setup on,

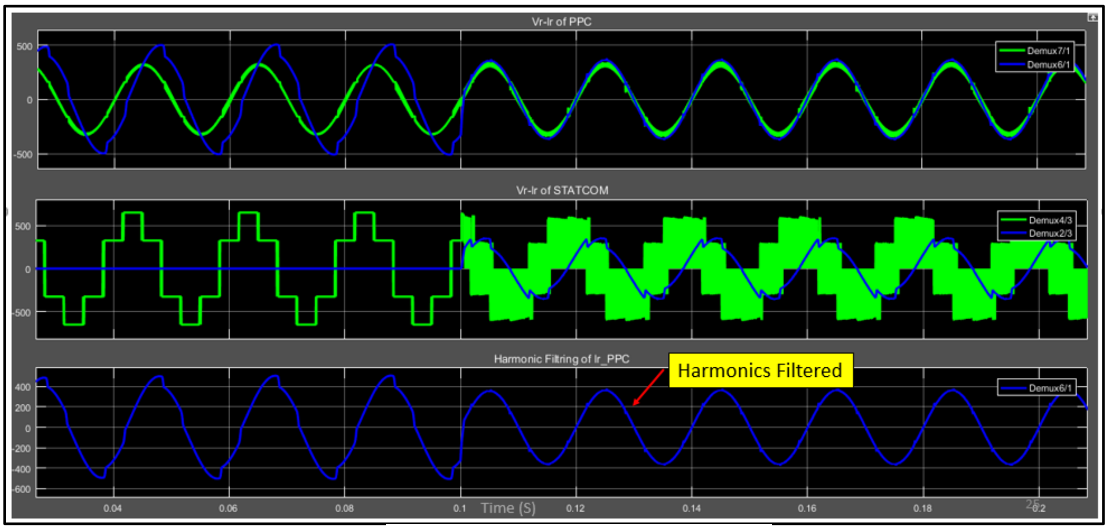
- Voltage Regulation
- Harmonic Mitigation
- System Power Factor improvement

4.3.2 Test Results Obtained from Micro-STATCOM Model Validation

Below are some of the Micro-STATCOM model validation results obtained form 2-Bus system setup,



Under Voltage Regulation



Harmonic Mitigation & pf Improvement

Figure 21: Results on Micro-STATCOM Model Validation

It was observed that Developed Micro-STATCOM model has given desired results on validation and ready for the integration with LV distribution system in order to mitigate power quality issued exist in the LV distribution System.

5. APPLICATION OF MICRO-STATCOM IN LV DISTRIBUTION NETWORK

5.1 Introduction

This chapter focus on integration of developed Micro-STATCOM model in to LV distribution networks. Mitigation capability of power quality issues and performance of the model is analyzed in detail with the results obtained under various scenarios of the LV distribution network.

5.2 Integration of Micro-STATCOM on IEEE 13 Distribution Bus System

5.2.1 Standard IEEE 13 Distribution Bus System

IEEE 13 Distribution Bus system was selected to apply the Micro-STATCOM model to evaluate the power quality issues mitigation capability. Standard IEEE 13 Distribution Bus System has 13 radial bus arrangement with MV and LV feeders. Grid voltage level is 4.16 kV, which is stepped-down in to 480 V LV distribution system. Unbalanced spot and distributed loads are connected to MV and LV systems via 13 buses in the IEEE 13 Bus arrangement. Grid transformer is Δ-Y 115/4.16 kV and it consist of one in-line Y-Y connected 4.16 kV/ 480 V transformer.

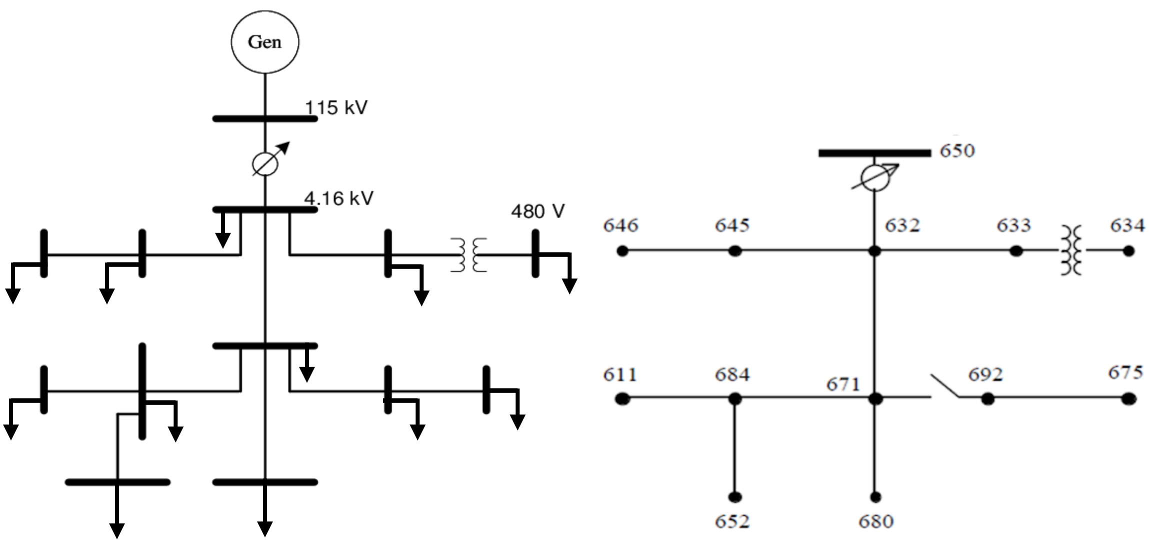


Figure 22: Single Line Diagram of IEEE 13 Distribution Bus System

5.2.2 Modified IEEE 13 Distribution Bus System

Standard IEEE 13 Distribution Bus System has modified through bus number 633-634 in order to expand the low voltage radial networks with more 3-phase, 1-phase reactive loads and 3-phase harmonic loads. And also, 3-phase and 1-phase Solar PV distributed generators were integrated in to the LV network of IEEE 13 bus system to demonstrate more practical LV distribution network from IEEE 13 Bus System. Thereby, is expected to demonstrate various scenarios of low voltage radial network having power quality issues. LV distribution network having under voltage situation, over voltage situation, presence of high level of THD percentage, voltage unbalance and low system power factor are the predominant power quality issues that exist in modified IEEE 13 Bus System. Connected in-line distribution transformer was modified from Y-Y connected 4.16 kV/ 480 V to Y-Y connected 4.16 kV/ 400 V with 500 kVA capacity in modified IEEE 13 Distribution Bus System.

Micro-STATCOM model is expected to integrated in to the Modified IEEE 13 Distribution Bus System in order to mitigate these power quality issues. Mitigation process of various power quality issues are expected to observed by changing the reactive loads and connected solar PV generators under two main case studies.

Case Study 01 -: LV distribution system of modified IEEE 13 Bus System experiencing under voltage situation with the presence of harmonic loads.

Case Study 02 -: LV distribution system of modified IEEE 13 Bus System experiencing over voltage situation with the presence of harmonic loads.

Connected load values and DGs are changed accordingly to obtain LV system from modified IEEE 13 Bus System in order to demonstrate the power quality mitigation capability of developed Micro-STATCOM for the case study 01 and 02.

Existing power quality issues were observed for both LV systems derived from modified IEEE 13 Bus System before integrating with developed Micro-STATCOM model.

Single line diagram of LV system for Case Study 01 is shown in Figure 23.

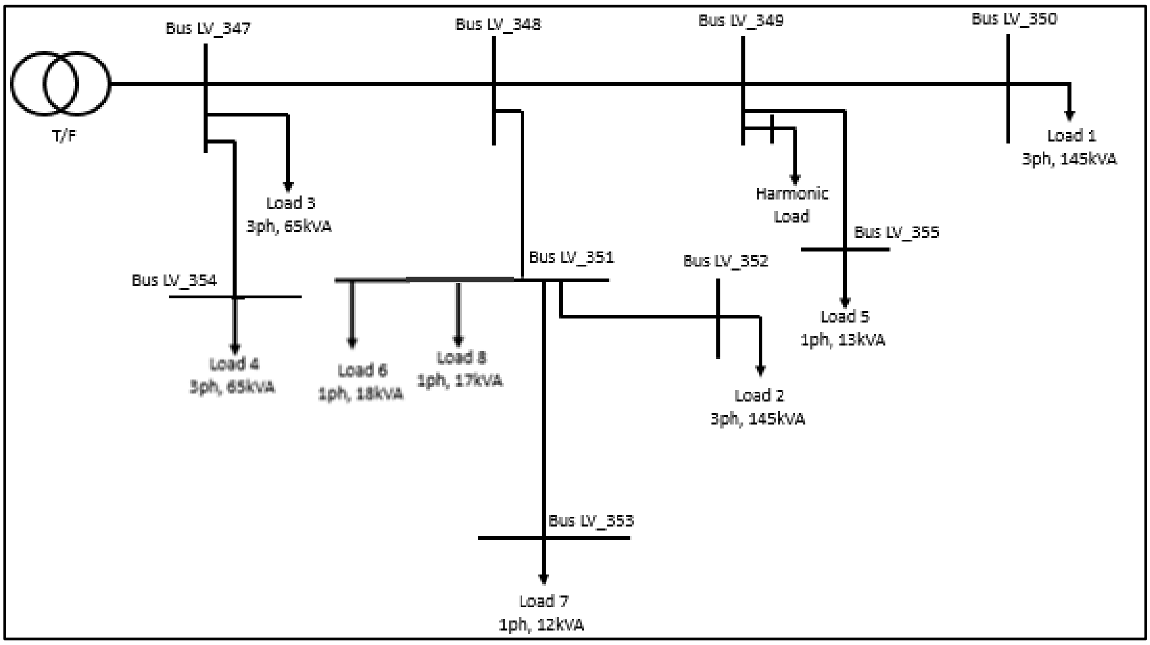


Figure 23: Single Line Diagram of Under Voltage LV System

Single line diagram of LV system for Case Study 02 is shown in Figure 24.

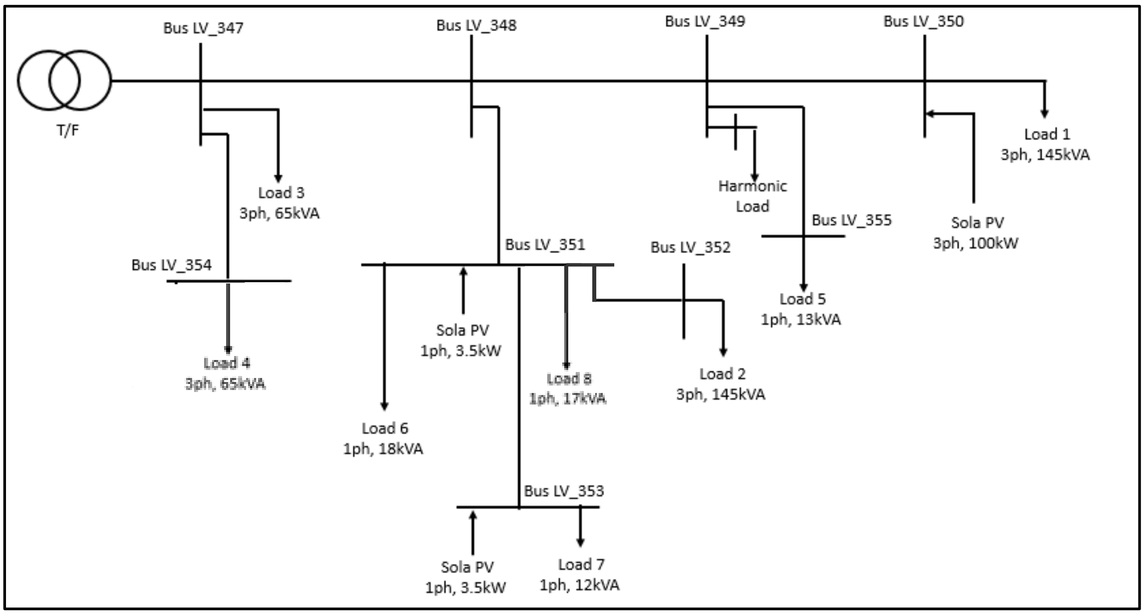


Figure 24:Single-Line Diagram of Over Voltage LV System

Matlab Simulink models for both LV Systems were developed in order to observe the existing power quality issues and also to integrate Micro-STATCOM model to observe the mitigation of power quality issues.

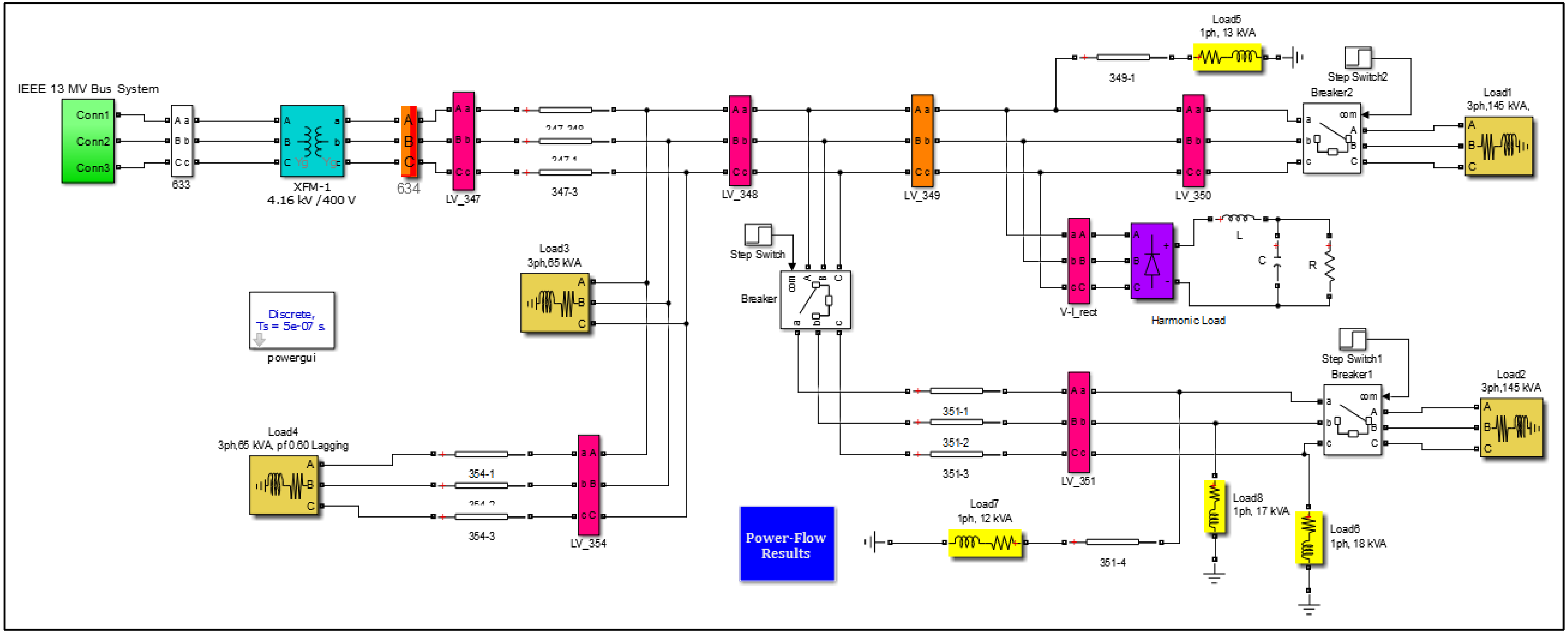


Figure 25: Matlab Simulink Model of LV Distribution System

5.2.3 Load Flow Analysis and Identification of LV Power Quality Issues in Modified IEEE 13 Distribution Bus System

Existing power quality issues in LV system of modified IEEE 13 distribution bus system were identified by a load flow analysis on developed Simulink model. Bus voltages at LV_348, LV_349, LV_350, LV_351 and LV_354 low voltage buses (as indicated in Figure:25) were obtained at steady stated after running a load flow analysis. Total harmonic distortion at the LV_348 bus was measured at the same time, as harmonic load is connected in LV_348 – LV_350 feeder section. Obtained results are shown in Figure: 26 below.

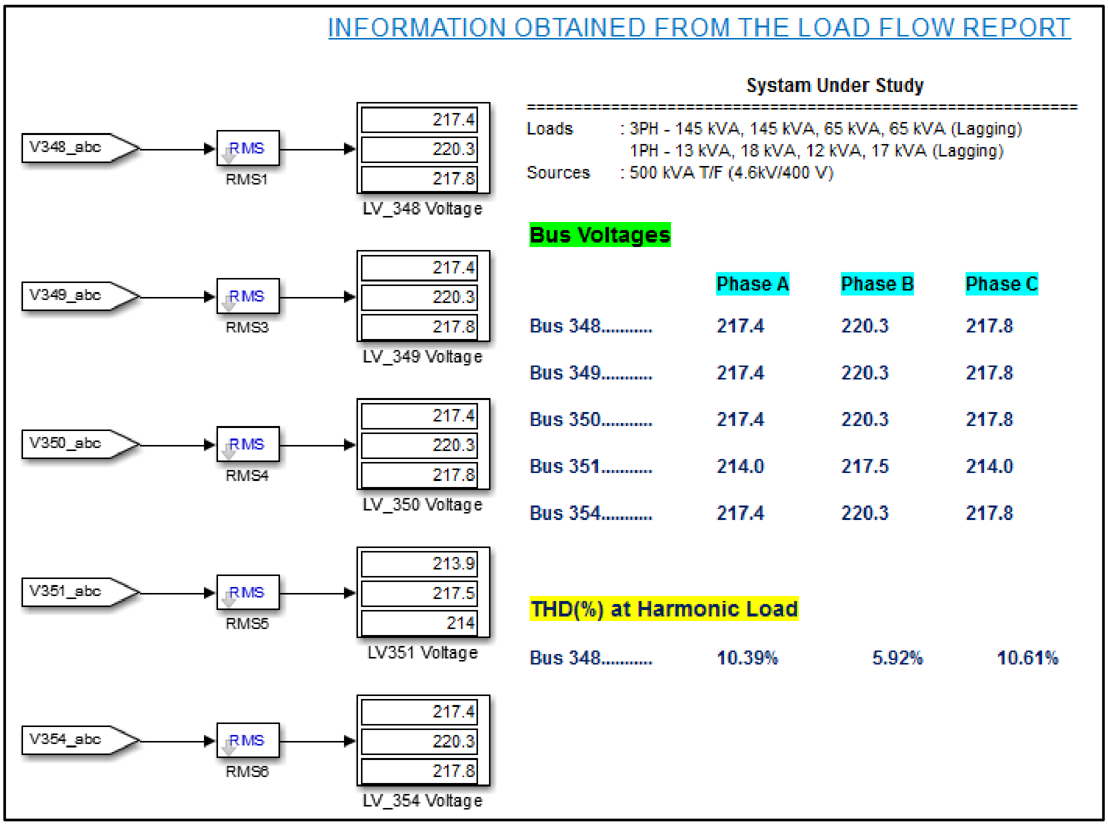


Figure 26: Load Flow Report on LV System Experiencing Under Voltage Issue

From the load flow report, it can be clearly seen that all LV Bus V_{L-N} voltages were below 230 V and hence, it can be decided that LV distribution network under study is experiencing under voltage situation. Percentage of Total Harmonic Distortion (THD%) measurements at LV_348 are also high (>5%) hence, there is a presence of harmonics at LV distribution system.

This was further confirmed by performing a Fast Fourier Transform Analysis (FFT) on phase R, at LV bus LV_348 as depicted in Figure 27.

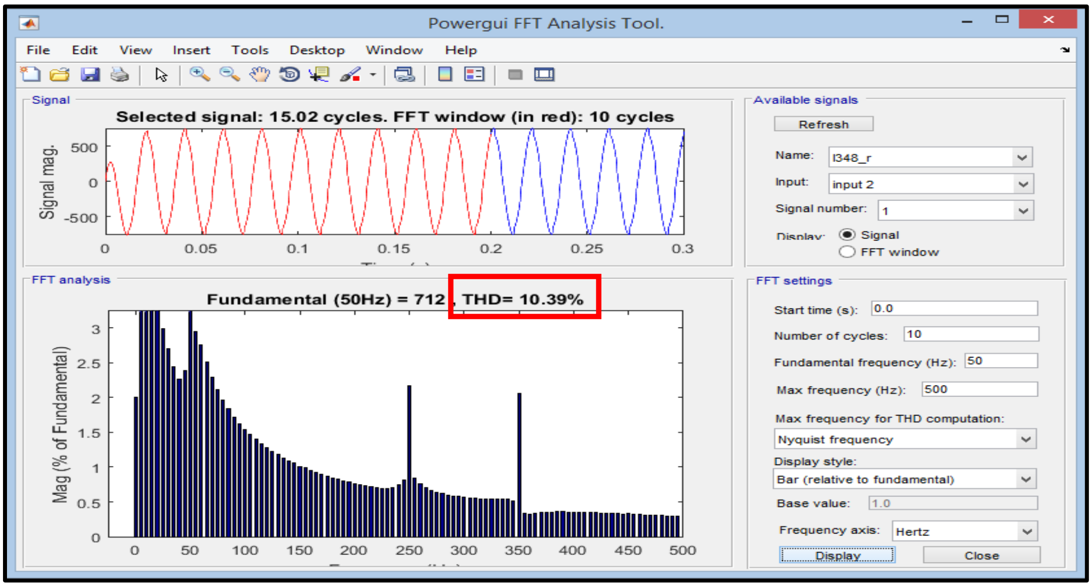


Figure 27: FFT Analysis on Phase R at LV Bus LV_348

Phase voltages at LV_351 LV bus are shown in Figure 28 and the voltage levels in all three phases are well below the nominal system voltage of 230 V, experiencing under voltage condition.

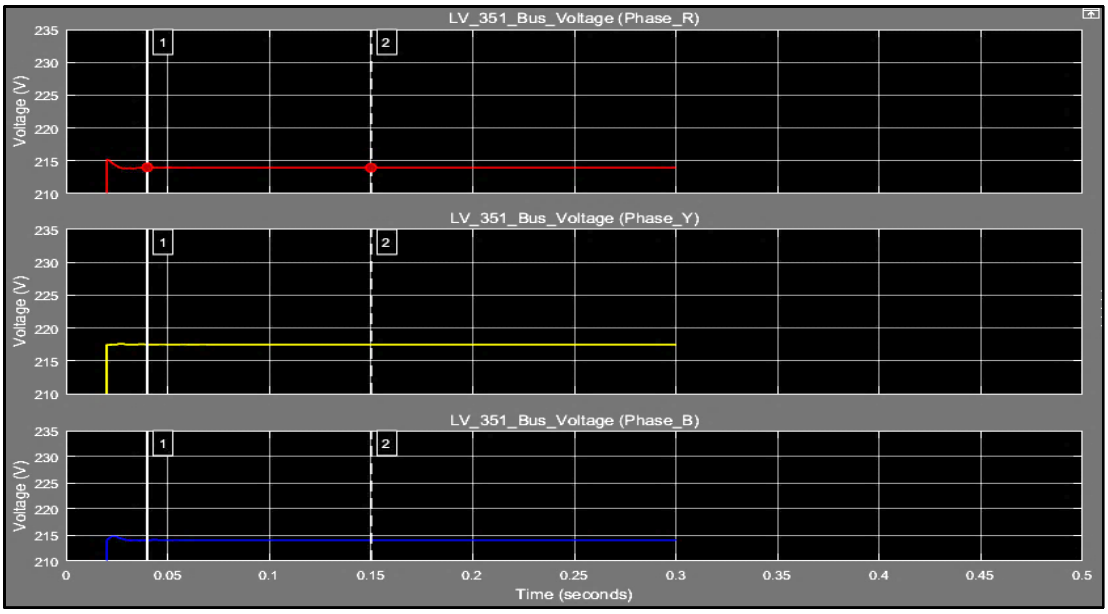


Figure 28: Phase voltages at LV_351 low voltage bus

From all above power quality measurements, it was observed that the LV distribution system was experiencing below power quality issues,

- Under voltage condition
- Presence of aggregated high level of harmonics at LV system
- Poor Power Factor (lagging) in LV system

5.3 Integration of Micro-STATCOM in LV Distribution Network

Power quality issues were identified in the LV system of modified IEEE 13 Distribution Bus System. Developed Micro-STATCOM model was plan to be integrated to mitigate these power quality issues exist in LV system. Application of Micro-STATCOM was studied under two different case studies, one at LV system experiencing under voltage condition and other at LV system experiencing over voltage conditions.

5.4 CASE STUDY 1 - Micro-STATCOM Operation in Under Voltage Regulation

According to the load flow analysis report obtained in section 5.2.3, LV system under study (Figure: 25) can be evaluated according to the impact of power quality issues.

Most Voltage Sensitive Feeder Section

- From the load flow analysis, it can be seen that the most sensitive feeder section of the LV system is LV_348 – LV_351 feeder section as it shows the highest voltage drop. Hence, one Micro-STATCOM was integrated to LV_351 low voltage bus in order to improve the voltage level in that feeder section.

Harmonic rich & Voltage sensitive Feeder

- As LV_348 – LV_350 feeder section contains a 3-phase harmonic load and LV_348 – LV_350 feeder section also shows considerable voltage drop. Hence, another Micro-STATCOM was integrated to the LV system at LV_348 bus to mitigate harmonic aggregation and to improve voltage level.

Power Factor improvement also expected to achieve through this solution

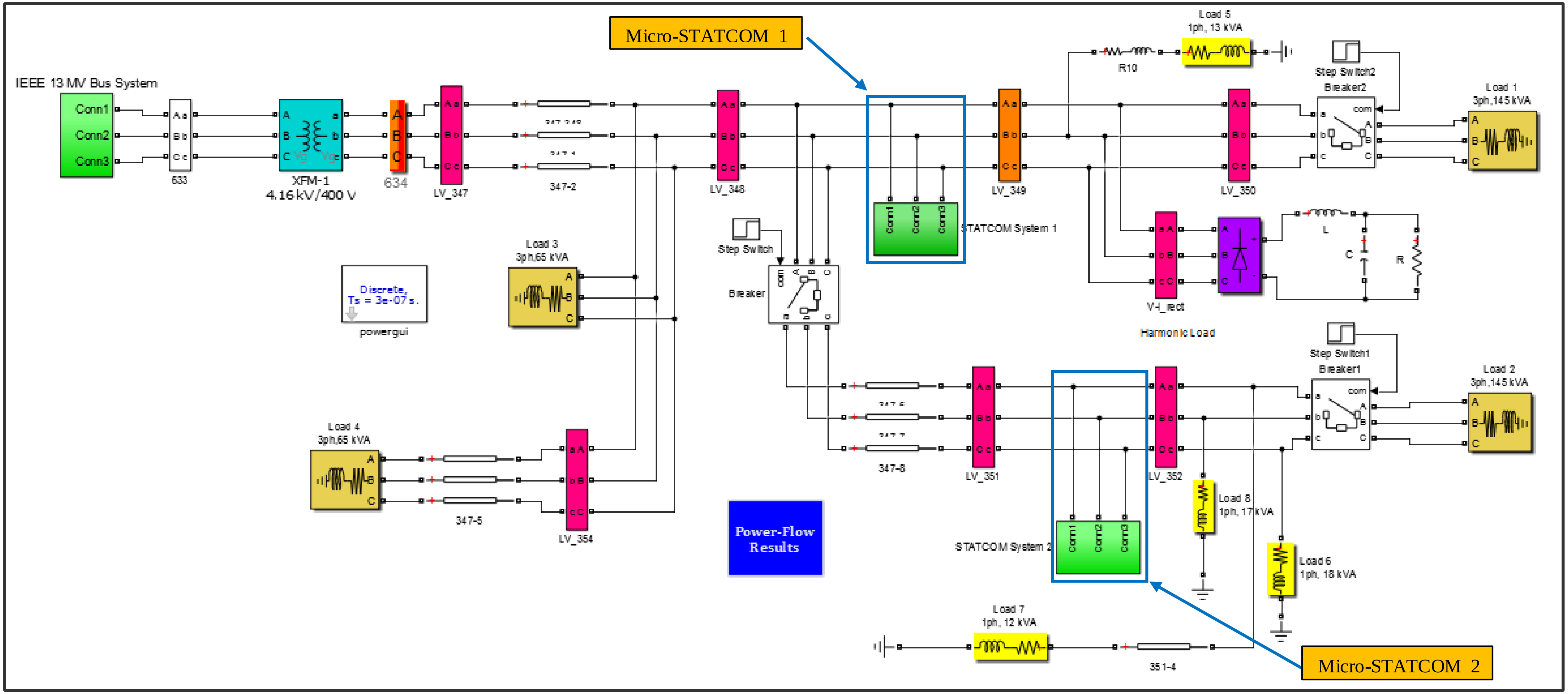


Figure 29: Case Study 1 - LV System with Integrated Micro-STATCOMs

According to the quantification and evaluation of the presence of power quality issues in LV feeders of modified IEEE 13 Distribution LV System, two numbers of Micro-STATCOMs were integrate in order to mitigate these power quality issues in the system. Matlab Simulink model of the LV system with two numbers of Micro-STATCOMs is depicted in Figure: 29.

5.4.1 Scenarios of Micro-STATCOM Operation in Under Voltage Regulation

Application of Micro-STATCOM in LV distribution system which is experiencing under voltage issue was the first case study which elaborates the capability of Micro-STATCOM in mitigating power quality issues. Case Study 1 has performed under two different scenarios to observe the performance of Micro-STATCOM under different loadings conditions of LV distribution system.

Scenario 01

Micro-STATCOM models were applied to LV distribution network which is already experiencing under voltage situation. Voltage regulation, harmonic mitigation and power factor improvement of the LV network by Micro-STATCOMs were evaluated.

Scenario 02

Micro-STATCOMs were connected to dynamically load changing LV distribution network. Micro-STATCOMs were connected to Lightly loaded LV network initially, then lagging loads were connected gradually to LV feeders with time setting.

This simulates practical LV feeders with dynamic change of loads and dynamic behaviour of Micro-STATCOMs were observed in regulating bus voltages by injecting different levels of reactive powers. Dynamic power factor improvement was also observed.

5.4.2 Under Voltage Regulation - Scenario 01

Details of the loads and STATCOMs connected at each feeder sections of the LV distribution system used in scenario 1 is summarized in Table: 3. Matlab Simulink model of the LV distribution network is shown in Figure: 30

Table 3: Load Distribution in Feeders of LV System

<table>
<tr><th>Feeder Section</th><th>3-phase Loads</th><th>1-phase Loads</th><th>Other Loads</th><th>Micro-STATCOMs</th></tr>
<tr><td>LV_348 – LV_350</td><td>Load 1
145 kVA, pf 0.68 lagging</td><td>Load 5
13 kVA, pf 0.72 lagging</td><td>Harmonic Load (C-5 X 10^{-6}F, L -0.1 H, R-5 Ω)</td><td>STATCOM 1
175 kVA</td></tr>
<tr><td rowspan="3">LV_348 – LV_352</td><td rowspan="3">Load 2
145 kVA, pf 0.68 lagging</td><td>Load 6
18 kVA, pf 0.67 lagging</td><td rowspan="3"></td><td rowspan="3">STATCOM 2
175 kVA</td></tr>
<tr><td>Load 7
12 kVA, pf 0.67 lagging</td></tr>
<tr><td>Load 8
17 kVA, pf 0.59 lagging</td></tr>
<tr><td rowspan="2">LV_347 – LV_340</td><td>Load 3
65 kVA, pf 0.60 lagging</td><td rowspan="2"></td><td></td><td></td></tr>
<tr><td>Load 4
65 kVA, pf 0.60 lagging</td><td></td><td></td></tr>
</table>

Model was applied to LV network having loads with low power factors. Intention was to observe the power factor improvement of the LV network together with voltage regulation and harmonic mitigation by Micro-STATCOMs.

LV_348 and LV_351 LV buses were selected in the LV distribution system in order to observe the power quality improvement in the LV system with the operation of Micro-STATCOMs. To clearly observe the of LV distribution system power quality parameters before and after the application of Micro-STATCOMs, operation of Micro-STATCOMs were delayed by predefined time gap in the Matlab simulation model.

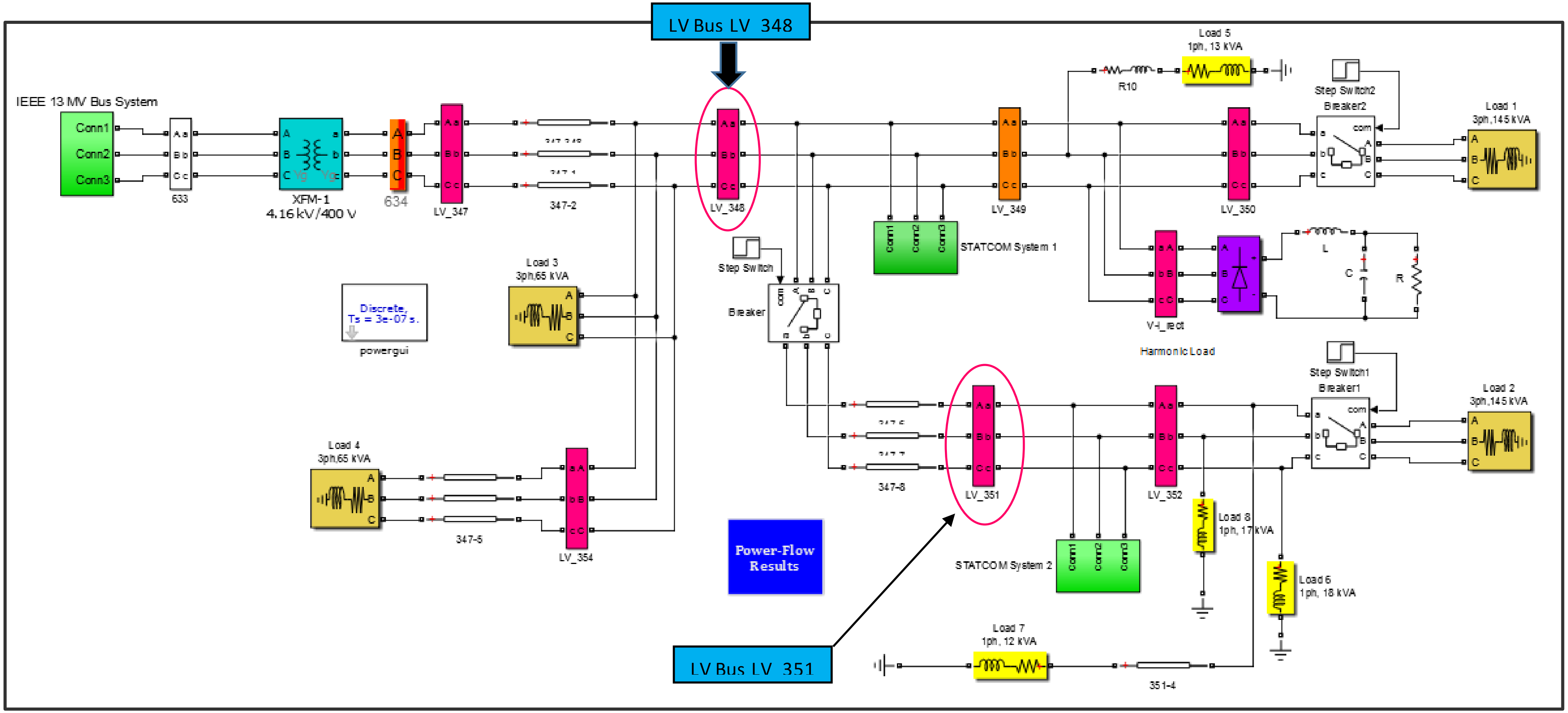


Figure 30: Power Quality Measurement of LV System with Micro-STATCOMs

5.4.3 Simulation Results of Scenario 01 – Under Voltage Regulation

Application of Micro-STATCOM compensation was delayed by 0.1 Seconds in the Matlab simulation model in order to comparatively observe the power quality improvement.

Under Voltage Regulation

Simulation results on under voltage regulation of Micro-STATCOM at LV_351 and LV_348 are showed in Figure: 31 and Figure: 32.

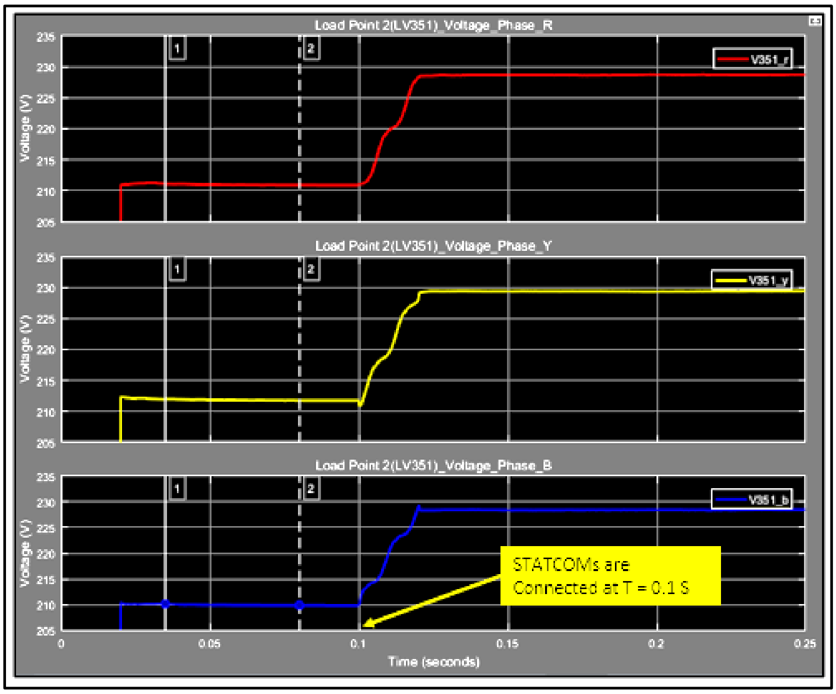


Figure 31: Under Voltage Regulation at LV_351 Bus

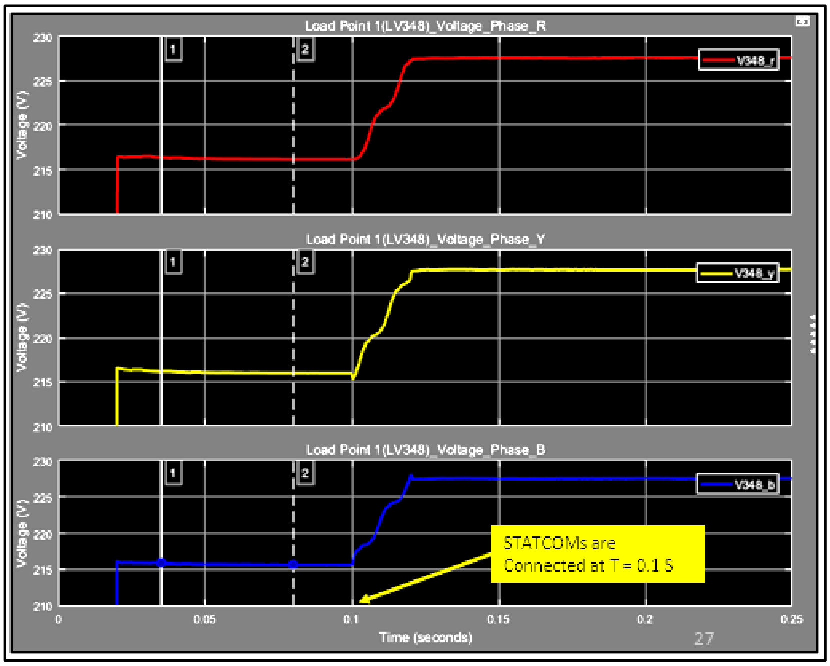


Figure 32: Under Voltage Regulation at LV_348 Bus

From Figure: 31 and Figure: 32 it was observed that phase voltages of all 3 phases has improved with the compensation action of connected Micro-STATCOMs.

Same can be verified by the load flow report shown in Figure: 33. From the load flow report it was observed that 10%-15% level of voltage regulation has done by the combination of two STATCOMs. Apart from the voltage regulation it was observed that THD(%) at LV_348 bus where the harmonic load was connected, was also improved by considerable level. Hence, the mutual operation of both Micro-STATCOMs has regulated bus voltages of the LV distribution system and filtered out the major portion of harmonics in the system.

Amount of reactive power sourced by both Micro-STATCOMs to regulate the voltage of LV network was also observed in the report.

INFORMATION OBTAINED FROM THE LOAD FLOW REPORT

System Under Study

Loads : 3PH - 145 kVA, 145 kVA, 65 kVA, 65 kVA (Lagging)
1PH - 13 kVA, 18 kVA, 12 kVA, 17 kVA (Lagging)

Sources : 500 kVA T/F (4.6kV/400 V), STATCOM1 - 175 kVA, STATCOM2- 175 kVA

	Load Point 1 (Node LV_348)	Load Point 2 (Node LV_351)		Load Point 1 (Node LV_348)	Load Point 2 (Node LV_351)
Without STATCOM Voltage Regulation			**With STATCOM Voltage Regulation**		
Voltage			**Voltage**		
Phase A.................	216.3	211.1	Phase A.................	227.6	228.7
Phase B.................	216.1	211.9	Phase B.................	227.7	229.5
Phase C.................	215.8	210.0	Phase C.................	227.5	228.5
THD(%)			**THD(%)**		
Phase A.................	12.27%	-null-	Phase A.................	01.05%	-null-
Phase B.................	6.08%	-null-	Phase B.................	01.55%	-null-
Phase C.................	10.75%	-null-	Phase C.................	01.07%	-null-
Power Output STATCOM1			**Power Output STATCOM1**		
Reactive (kVar) : 0.00			Reactive (kVar) : 149.5, (+)ve		
Real (kW) : 0.00			Real (kW) : 10.37		
Power Output STATCOM2			**Power Output STATCOM2**		
Reactive (kVar) : 0.00			Reactive (kVar) : 163.1, (+-)ve		
Real (kW) : 0.00			Real (kW) : 13.21		

Figure 33: Load Flow Report on Under Voltage Regulation by Micro-STATCOM

Improvement of system power factor after the injection of reactive power by Micro-STATCOMs can be observed by analysing a V-I waveform at a LV bus. It was observed that the phase-shift between phase current and phase voltage has reduced by a considerable level for a particular phase after the application of Micro-STATCOMs.

V-I waveforms of phase R at LV_348 bus was analysed to observe the power factor improvement and harmonic filtering of the with the operation of STATCOMs. From the Figure: 34 first V-I graph, it was confirmed the improvement of system power factor. After 0.1 S, where the Micro-STATCOMs started their operation, the phase-shift between voltage and current waveform of phase R has reduced considerably. This was due to the improvement of system power factor. From the last graph of Figure: 34, it was also visible that current waveform of phase R at LV bus LV_348, was much smoother and less from distortions after 0.1 S. This also a rough confirmation for the mitigation of harmonic in the system by Micro-STATCOMs.

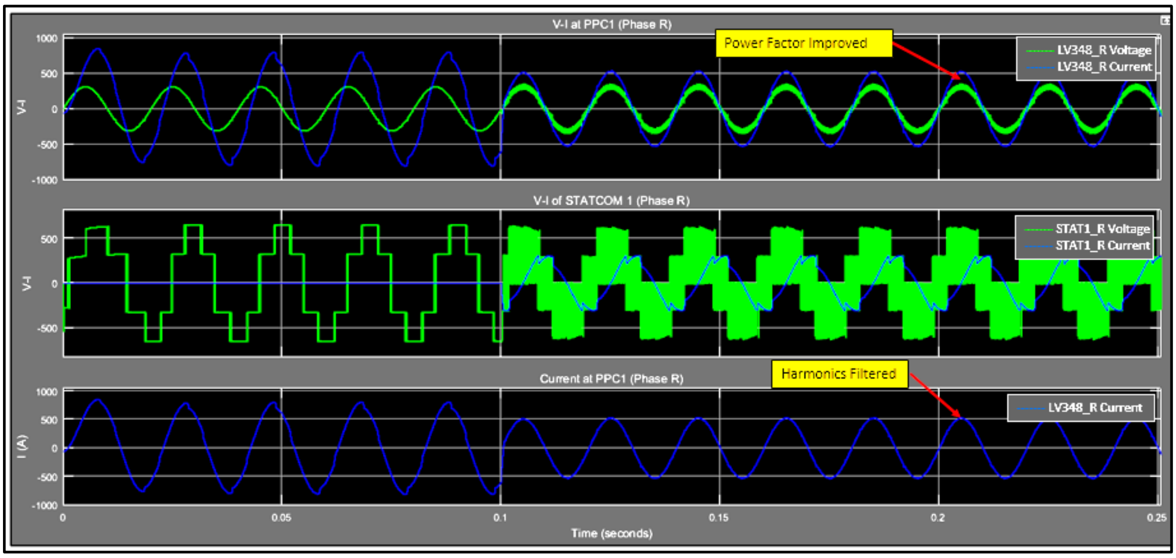


Figure 34: Case Study 1, V-I Graphs of Phase R at LV_348 Bus

In order to get quantified confirmation on reduction of THD (%), fast fourier transform (FFT) analysis has carried out for the phase R current at LV_348 bus where harmonic load was connected. From the FFT analysis in Matlab, it was observed that considerable improvement of THD(%) has obtained by the harmonic mitigation operation of the Micro-STATOM.

Figure: 35 indicate the level of THD(%) in phase R current waveform at LV_348 bus without Micro-STATCOMs in operation and with Micro-STATCOMs in operation. It was clearly observed that after 0.1 S the THD was improved and the presence of harmonic components also reduced. This shows the capability of Micro-STATCOM in mitigation harmonics in the LV distribution system.

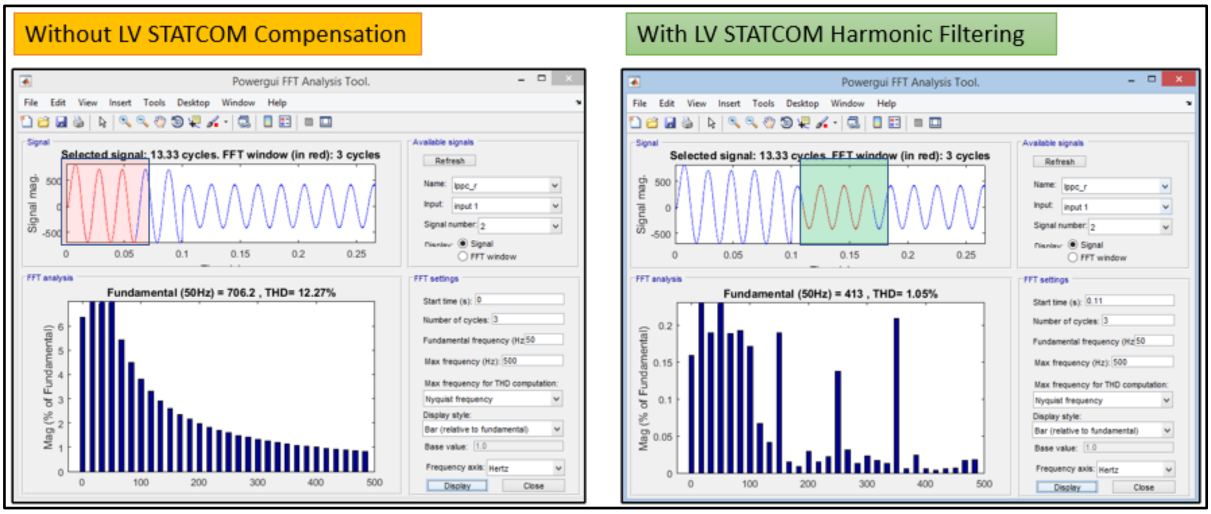


Figure 35: Case Study 1, FFT analysis on Phase R at LV bus LV_348

Power output of both Micro-STATCOMs are shown in Figure: 36. Analyzing the power output of both STATCOMs, it was confirmed that both STATOMs were contributed for the under-voltage regulation of the LV distribution system under study. And this confirms the successful application of Micro-STATCOMs in the LV distribution network.

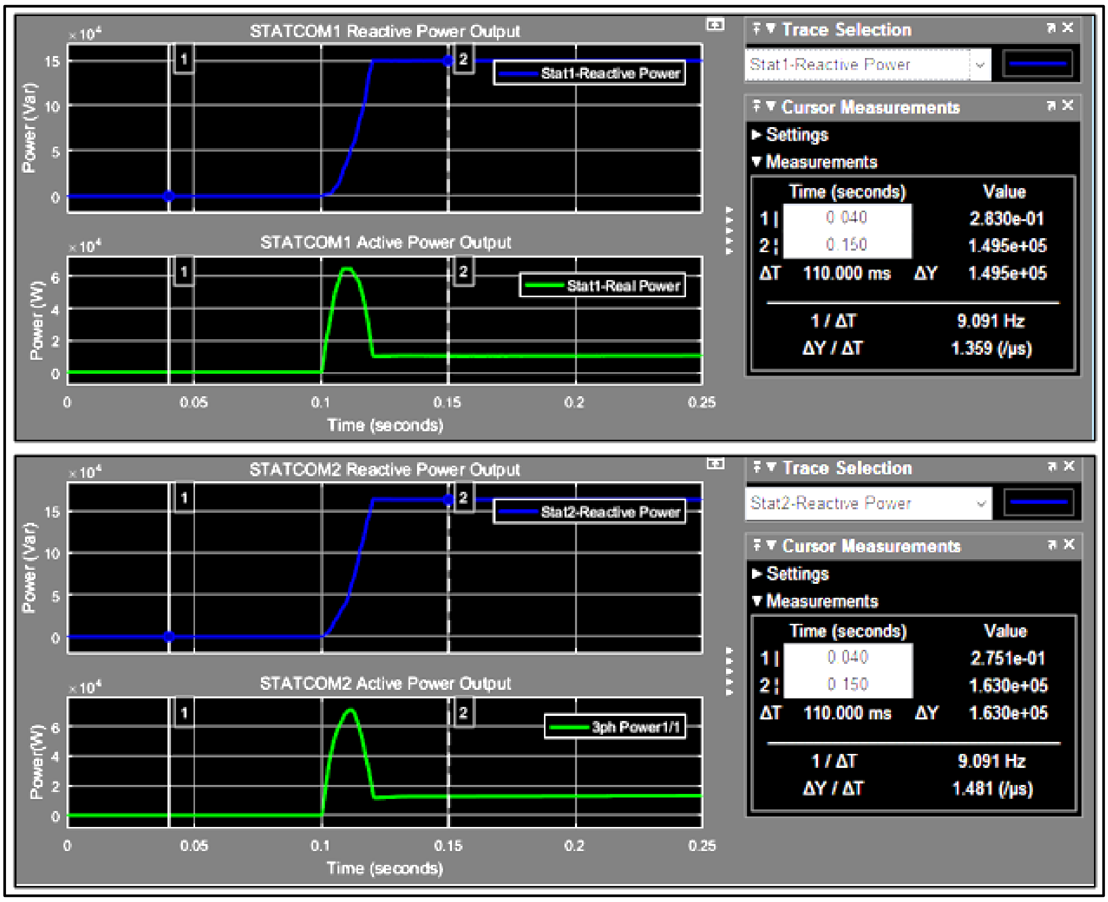


Figure 36: Power Output of Micro-STATCOMs in Under Voltage Regulation

It was observed that, at the steady state Micro-STATCOM 1 has sourced 149.5 kVAr amount of reactive power to the LV distribution system and Micro-STATCOM 2 has sourced 163.0 kVAr amount of reactive power to the LV system.

From above results, it can be decided that Micro-STATCOM has successfully regulated the under-voltage issue of the LV system and also successful performed the mitigation of harmonics from the system. System power factor improvement also achieved by the proper application of Micro-STATCOMs to the LV system.

Resolution of the Micro-STATCOM

Micro-STATCOM is capable of regulating 10% - 15% of reduction of system nominal voltage which can also be increased with higher DC power source connected to STATCOM. Figure: 37 shows the resolution of under voltage regulation with 10%-15% improvement of system voltage.

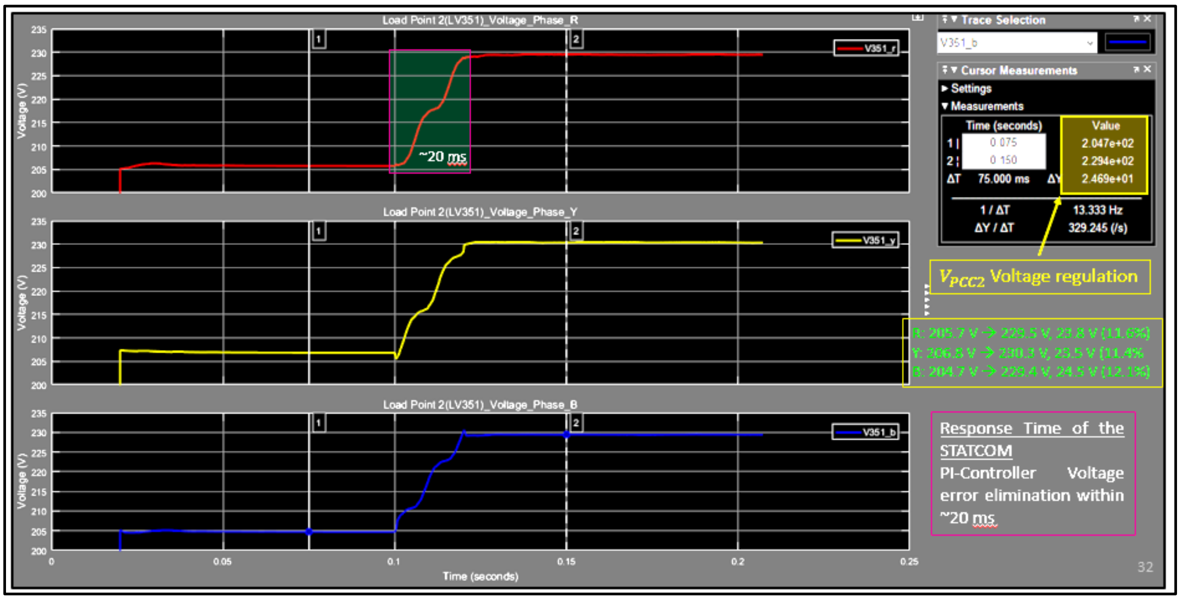


Figure 37: Resolution of Voltage Regulation by Micro-STATCOM

Connected Micro-STATCOM to LV distribution system is capable of regulating under voltage situation with in 20 ms of time. Hence the response time of the developed Micro-STATCOM was in the rage of 20 ms which is one cycle time of the 50 Hz sinusoidal signal.

5.4.4 Under Voltage Regulation - Scenario 02

Micro-STATCOM was then tested in dynamically load changing LV system in Matlab Simulink setup to observe the dynamic behaviour of the operation of Micro-STATCOM. Lagging loads were added dynamically to LV system via a set of breakers having predefined time setting.

This was simulated a practical dynamic LV distribution system with changing loads and the under-voltage impact also changed with the time. Micro-STATCOMs have to adopt by sourcing required instantaneous reactive power demand to the system in order to regulate LV system voltage. Proposed setup is shown in Figure: 38.

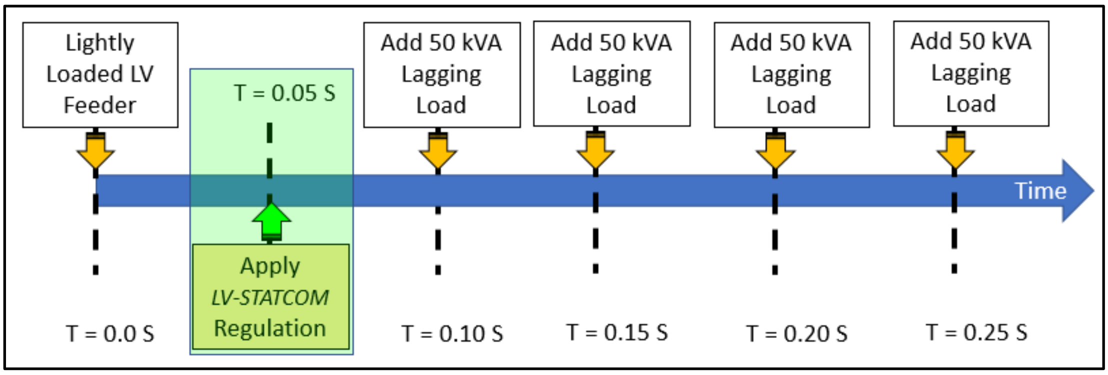


Figure 38: Case Study 1, Setup for Dynamic Load Change

5.4.5 Simulation Results of Scenario 02 – Under Voltage Regulation

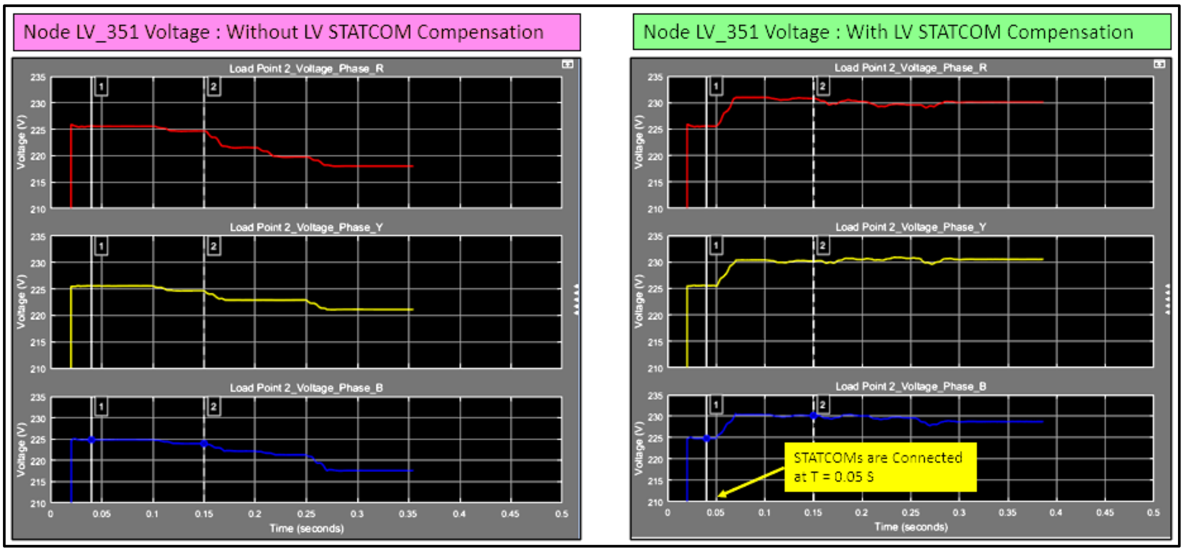


Figure 39: Dynamic Under Voltage Regulation of Micro-STATCOM

As shown in Figure: 39 in absence of Micro-STATCOM compensation the LV_351 bus voltage of LV system under study was continues to drop with the addition of lagging loads with time. But with the compensation facility of Micro-STATCOMs in LV system, it was able to sustain the system voltage around nominal 230V level even with the addition of loads with the time. Operation of Micro-STATCOMs were started after 0.05 seconds.

Dynamic behavior of reactive power output of Micro-STATCOMs are showed in Figure: 40. Power output of the Micro-STATCOMs were increased with the time to compensate the reactive power demand increased with the time due the addition of lagging loads.

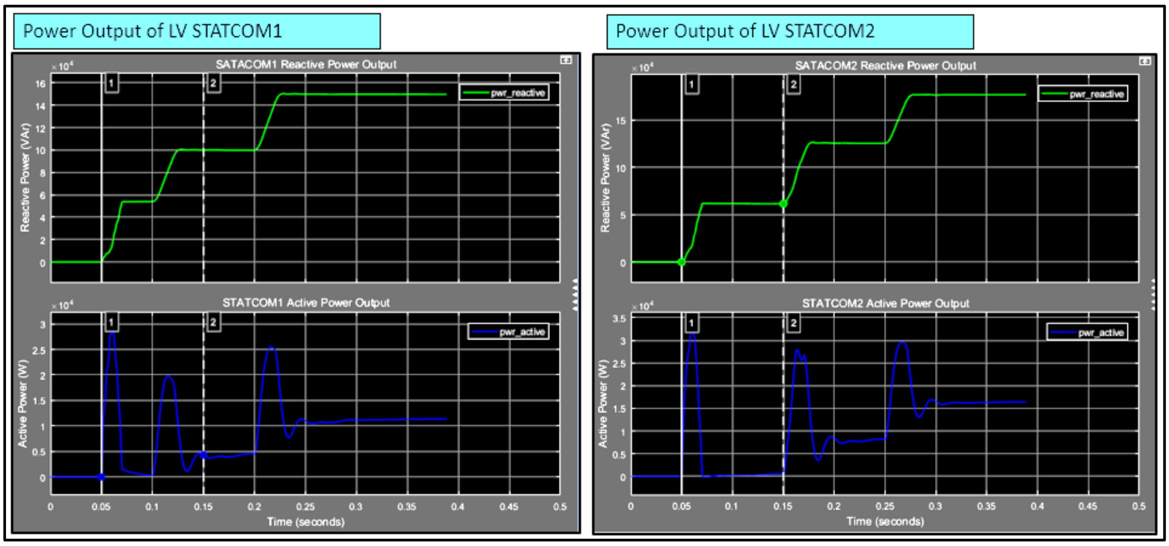


Figure 40: Power Output in Dynamic Under Voltage Regulation

5.5 CASE STUDY 2 – Micro-STATCOM Operation in Over Voltage Regulation

Developed Micro-STATCOM module was applied to LV distribution system of modified IEEE 13 Bus System experiencing over voltage condition in order to observe the over voltage regulation capability. Matlab Simulink model of LV distribution system of modified IEEE 13 Bus System experiencing over voltage situation with the presence of harmonic loads is shown in Figure: 41 and the single line diagram of LV system for Case Study 02 is shown in Figure 24.

Same as in Case Study 1, over voltage regulation was also analyzed based on two scenarios. One is Micro-STATCOM models were applied to LV distribution network which is already experiencing under voltage situation. Scenario 2 was, Micro-STATCOMs were connected to dynamically load changing LV distribution network. Micro-STATCOMs were connected to Lightly loaded LV network initially, then leading loads were connected gradually to LV feeders with time setting.

5.5.1 Over Voltage Regulation - Scenario 01

Details of the loads, DGs and STATCOMs connected at each feeder sections of the LV distribution system used in scenario 1 is summarized in Table: 4.

Table 4: Loads, DGs and STATCOMs Distribution in Feeders of LV System

<table>
<tr><th>Feeder Section</th><th>3-phase Loads</th><th>1-phase Loads</th><th>Other Loads</th><th>Micro-STATCOMs</th></tr>
<tr><td>LV_348 – LV_350</td><td>Load 1
145 kVA, pf 0.68 leading</td><td>Load 5
13 kVA, pf 0.72 leading</td><td>Harmonic Load
(C-5 X 10^{-6}F, L - 0.1 H, R-5 Ω)</td><td>STATCOM 1
175 kVA</td></tr>
<tr><td rowspan="3">LV_348 – LV_352</td><td rowspan="3">Load 2
145 kVA, pf 0.68 leading</td><td>Load 6
18 kVA, pf 0.67 leading</td><td rowspan="3">1 no. of 3phase, 100 kW solar PV system

2 nos. of 1phase 3.5kW Solar PV System</td><td rowspan="3">STATCOM 2
175 kVA</td></tr>
<tr><td>12 kVA, pf 0.67 leading</td></tr>
<tr><td>Load 8
17 kVA, pf 0.59 leading</td></tr>
<tr><td rowspan="2">LV_347 – LV_340</td><td>Load 3
65 kVA, pf 0.60 leading</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Load 4
65 kVA, pf 0.60 leading</td></tr>
</table>

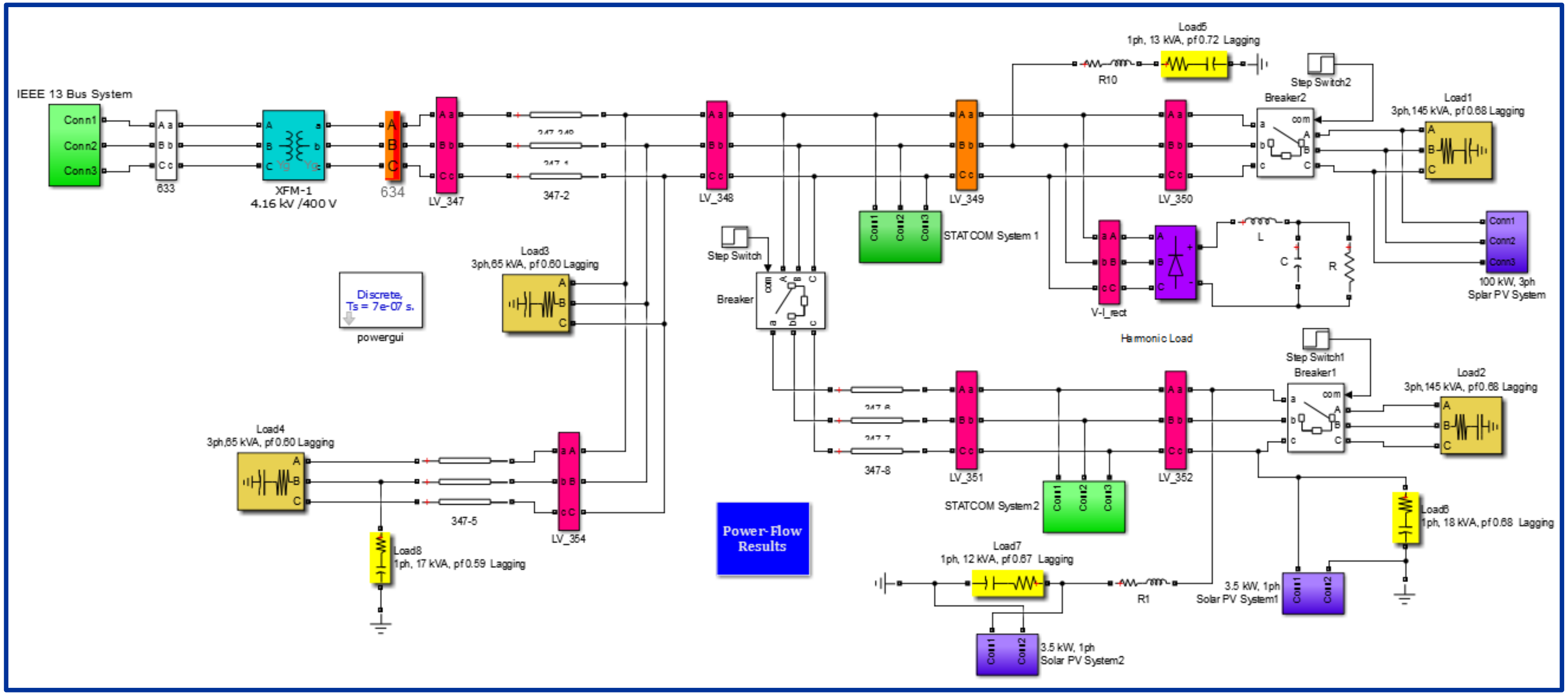


Figure 41: Case Study 2 - LV System with Integrated Micro-STATCOMs

5.5.2 Simulation Results of Scenario 01 – Over Voltage Regulation

Application of Micro-STATCOM compensation was delayed by 0.1 Seconds in the Matlab simulation model in order to comparatively observe the power quality improvement.

Over Voltage Regulation

Simulation results on over voltage regulation of Micro-STATCOM at LV_351 and LV_348 are showed in Figure: 42 and Figure: 43.

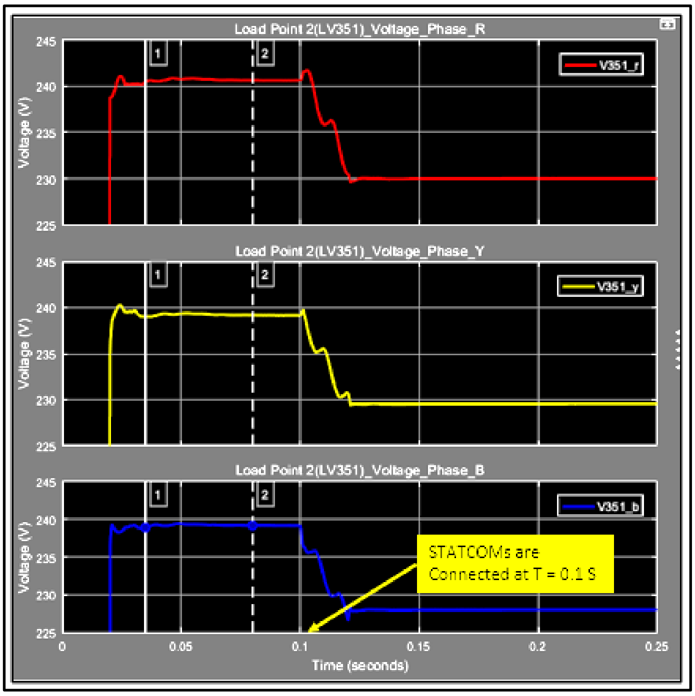


Figure 42: Over Voltage Regulation at LV_351 Bus

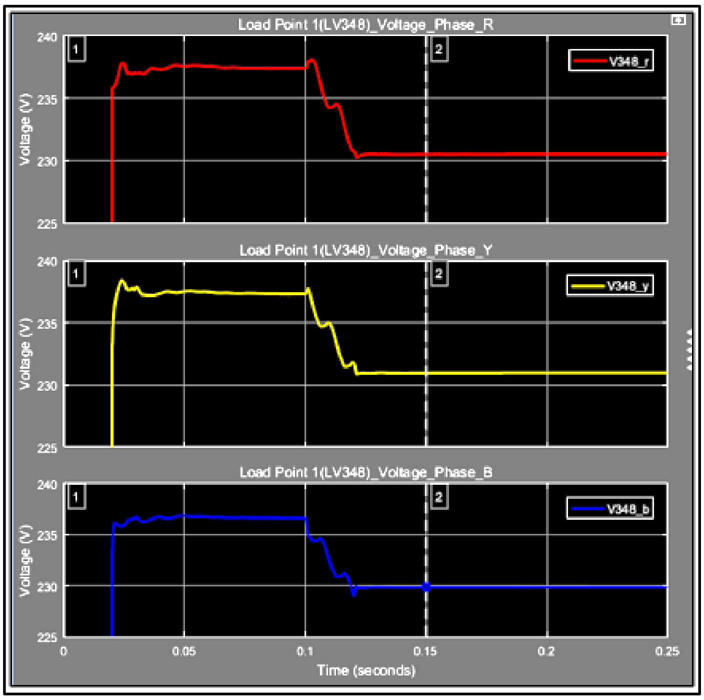


Figure 43: Over Voltage Regulation at LV_348 Bus

As per the simulation results shown in Figure: 42 and Figure: 43, it was observed that phase voltages of all 3 phases in LV bus LV_351 and LV_348 were regulated back close to system nominal phase to neutral voltage with the compensation action of connected Micro-STATCOMs.

By the load flow report show in Figure: 44 it can be further verified that the regulation of over voltage LV distribution system by the connected Micro-STATCOMs. Apart from over voltage regulation, THD(%) value at LV_348 bus where the harmonic load was connected also reduced down to low value (<5%) due to the mitigation actions of the Micro-STATCOMs.

INFORMATION OBTAINED FROM THE LOAD FLOW REPORT

System Under Study

Loads : 3PH - 145 kVA, 145 kVA, 65 kVA, 65 kVA (Leading)
1PH - 13 kVA, 18 kVA, 12 kVA (Lagging), 17 kVA (Leading)
1 No. of 100 kW 3ph Solar PV, 02 Nos. of 3.5 kW 1ph Solar PV
Sources : 500 kVA T/F (4.6kV/400 V), STATCOM1 - 175 kVA, STATCOM2- 175 kVA

Without STATCOM Voltage Regulation	Load Point 1 (Node LV_348)	Load Point 2 (Node LV_351)
Voltage		
Phase A..................	237.6	240.8
Phase B..................	237.5	239.4
Phase C..................	236.8	239.3
THD(%)		
Phase A..................	11.89%	-null-
Phase B..................	6.99%	-null-
Phase C..................	12.75%	-null-

Power Output STATCOM1

Reactive (kVar) : 0.00
Real (kW) : 0.00

Power Output STATCOM2

Reactive (kVar) : 0.00
Real (kW) : 0.00

With STATCOM Voltage Regulation	Load Point 1 (Node LV_348)	Load Point 2 (Node LV_351)
Voltage		
Phase A..................	230.5	230.0
Phase B..................	231.0	229.6
Phase C..................	229.9	228.0
THD(%)		
Phase A..................	1.10%	-null-
Phase B..................	1.55%	-null-
Phase C..................	1.07%	-null-

Power Output STATCOM1

Reactive (kVar) : 106.60 (-)ve
Real (kW) : 5.54

Power Output STATCOM2

Reactive (kVar) : 120.10, (-)ve
Real (kW) : 9.32

Figure 44: Load Flow Report on Over Voltage Regulation by Micro-STATCOMs

The mutual operation of both Micro-STATCOMs have regulated bus voltages of the LV distribution system and filtered out the major portion of harmonics in the system. In this case, Micro-STATCOMs has sunk the excess reactive power in the LV distribution system which led the system into over voltage situation. Amount of reactive power sunk by both Micro-STATCOMs to regulate the voltage of LV network were also observed in the report. Negative sign was to indicate consumption of reactive power by the Mico-STATCOMS.

As elaborated in Case Study 1, here also V-I graph of phase R of LV_348 bus was observed to confirm the system power factor improvement and harmonic filtration. Related V-I graphs are shown in Figure: 45.

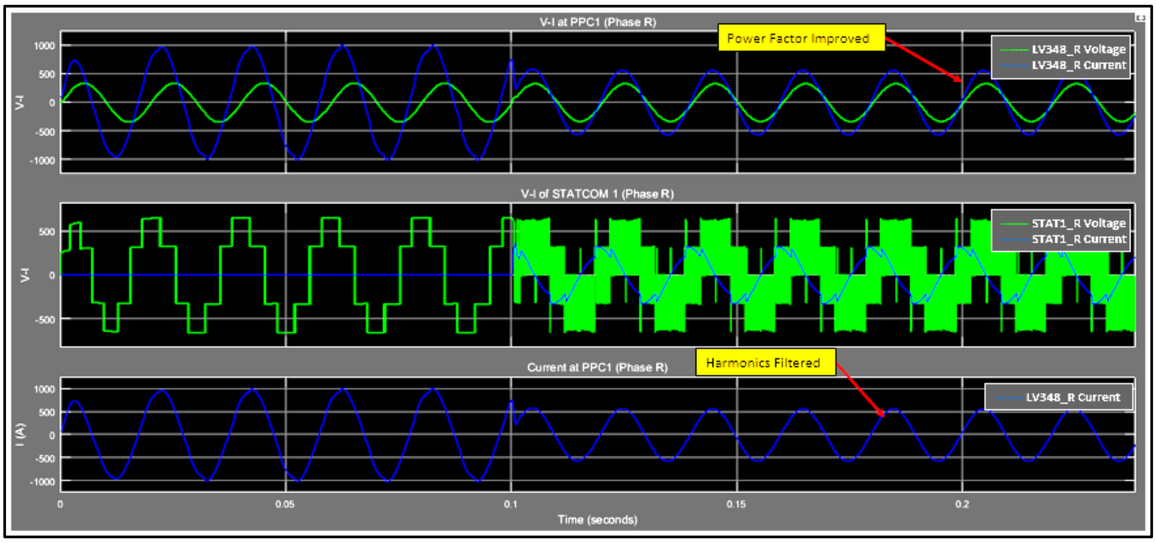


Figure 45: Case Study 2, V-I Graphs of Phase R at LV_348

In order to get quantified observation on harmonic mitigation, FFT analysis also ran on phase R of current at LV-348 bus in LV system under over voltage issue. From the FFT analysis it was confirmed that there was a considerable improvement of THD(%) level on phase R of current at LV_348 bus. FFT analysis on mitigation of harmonic shown in Figure: 46.

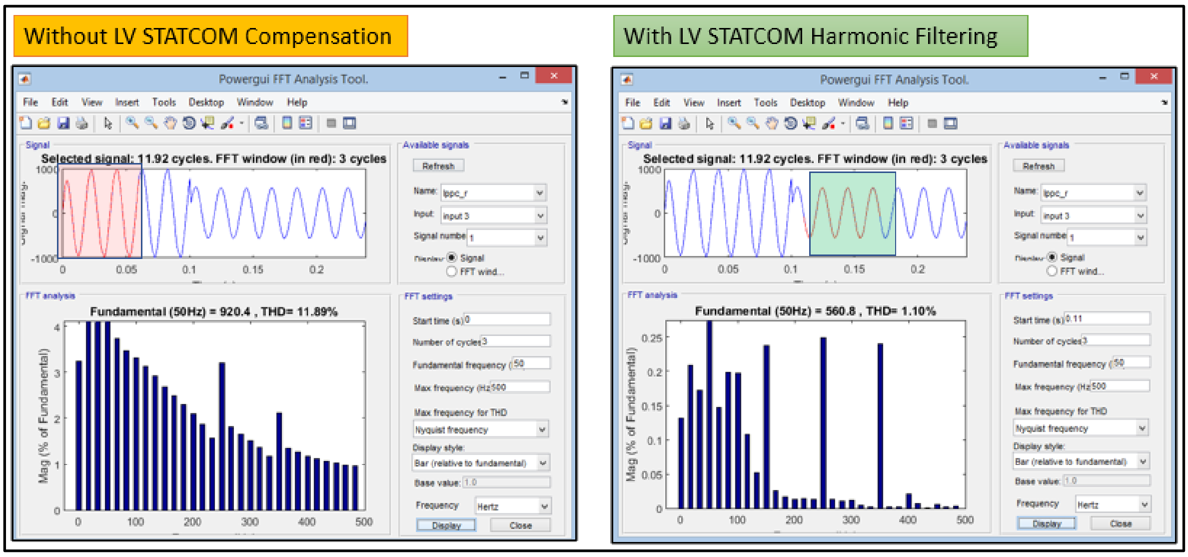


Figure 46: Case Study 2, FFT analysis on Phase R at LV bus LV_348

Power output of the Micro-STATCOMs in regulating over voltage LV network is shown in Figure: 47. Negative reactive power output was observed from both Micro-STATCOMs as the reactive power has been consumed by STATCOMs in order to regulated the voltage of LV distribution system which was in over voltage condition. As per the results shown in Figure: 47, Micro-STATCOM 1 has consumed 106.6 kVAr and Micro-STATCOM 2 has consumed 120.1 kVAr of reactive power from the LV network in order to brought the system voltage down to nominal voltage of 230V.

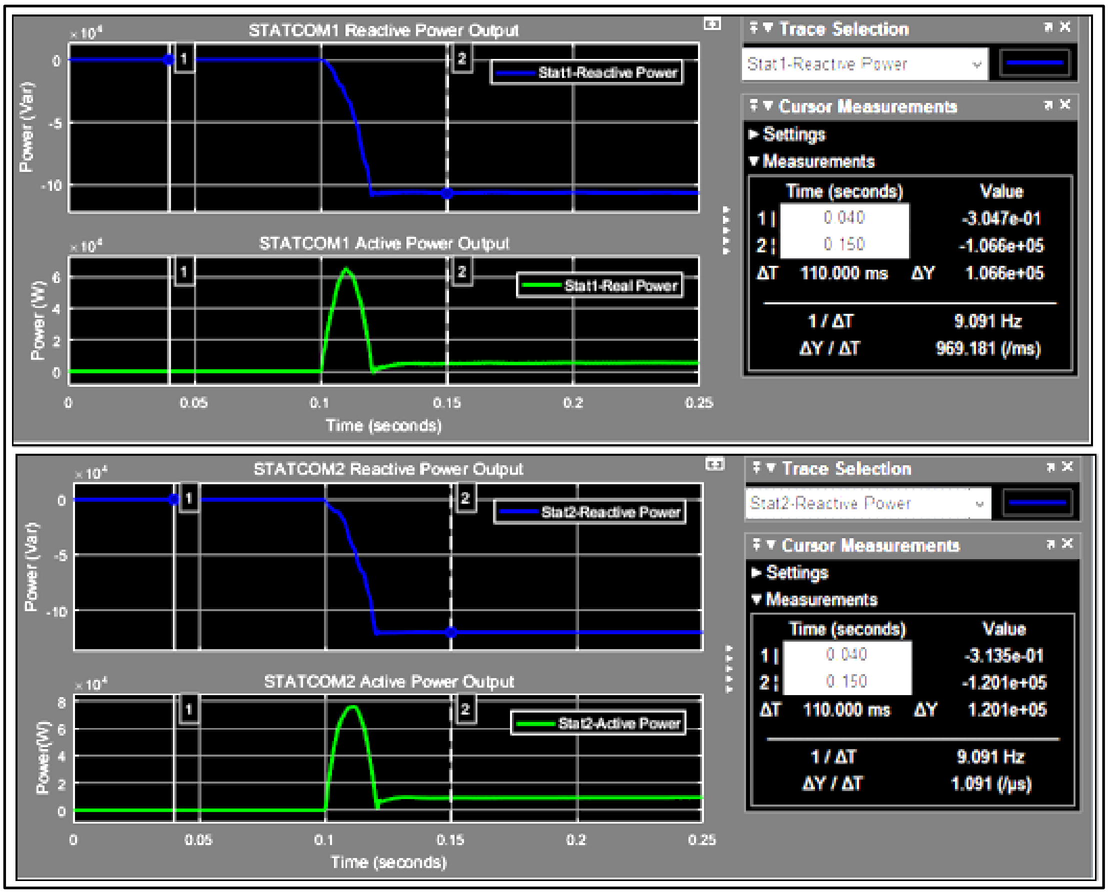


Figure 47: Power Output of Micro-STATCOMs in Over Voltage Regulation

5.5.3 Over Voltage Regulation - Scenario 02

As elaborated in Case Study 1, here also Micro-STATCOMs were analyzed for their dynamic behavior in regulating over voltage power quality issue. Figure: 48 shows the proposed setup to analyze dynamic over voltage regulation of Micro-STATCOMs in LV distribution network.

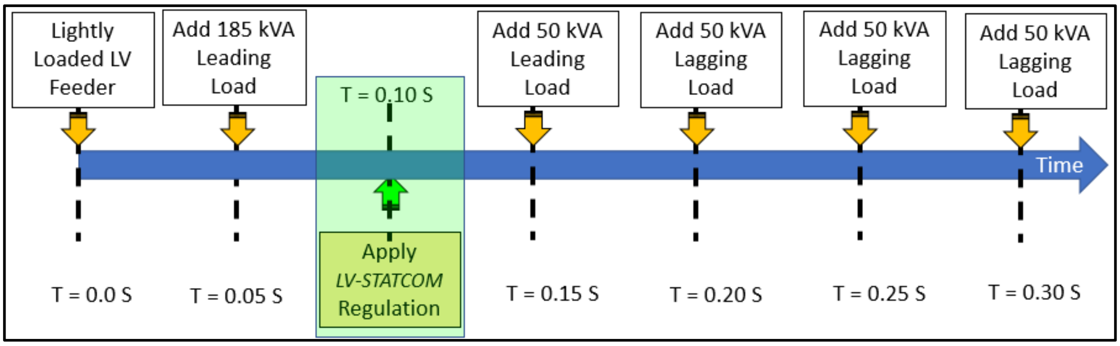


Figure 48: Case Study 2, Setup for Dynamic Load Change

5.5.4 Simulation Results of Scenario 02 – Over Voltage Regulation

Dynamic leading loads were added with time setting and the voltage regulation at LV_351 bus was observed. With the Micro-STATCOMs in operation LV system voltage was sustained around system nominal voltage even with the addition of leading loads with the time. Without Micro-STATCOM compensation LV system voltage was raises with the addition of leading loads.

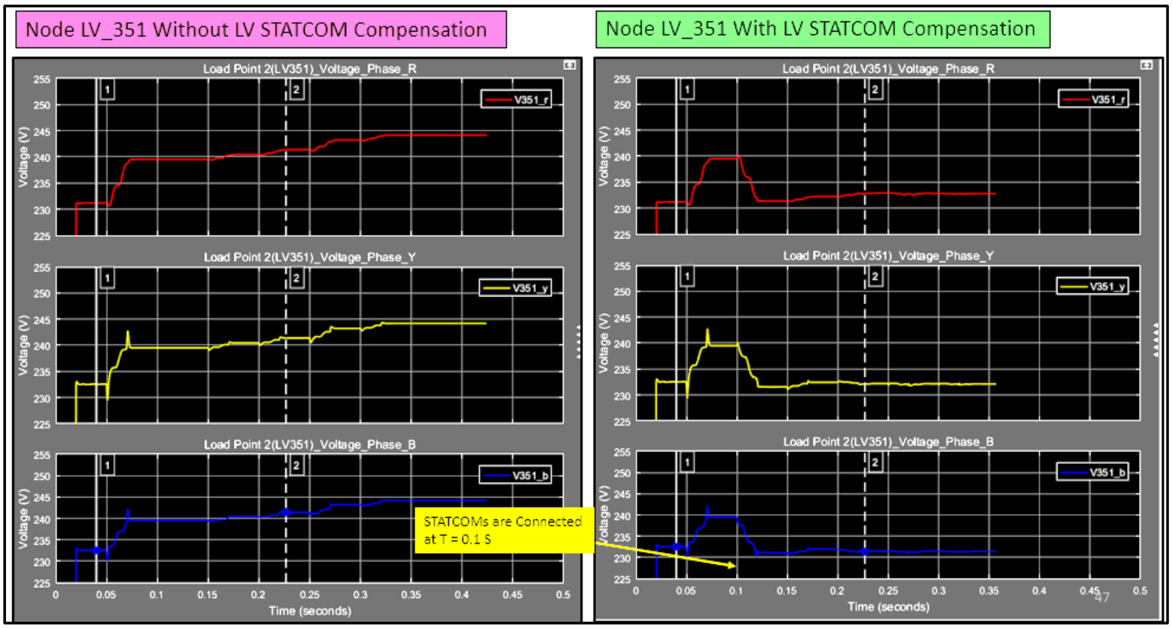


Figure 49: Dynamic Over Voltage Regulation of Micro-STATCOM

Micro-STATCOMs has dynamically sunk reactive power with the addition of capacitive loads in order to maintain LV system voltage around nominal voltage. Power output of both Micro-STATCOMs shown in Figure: 50.

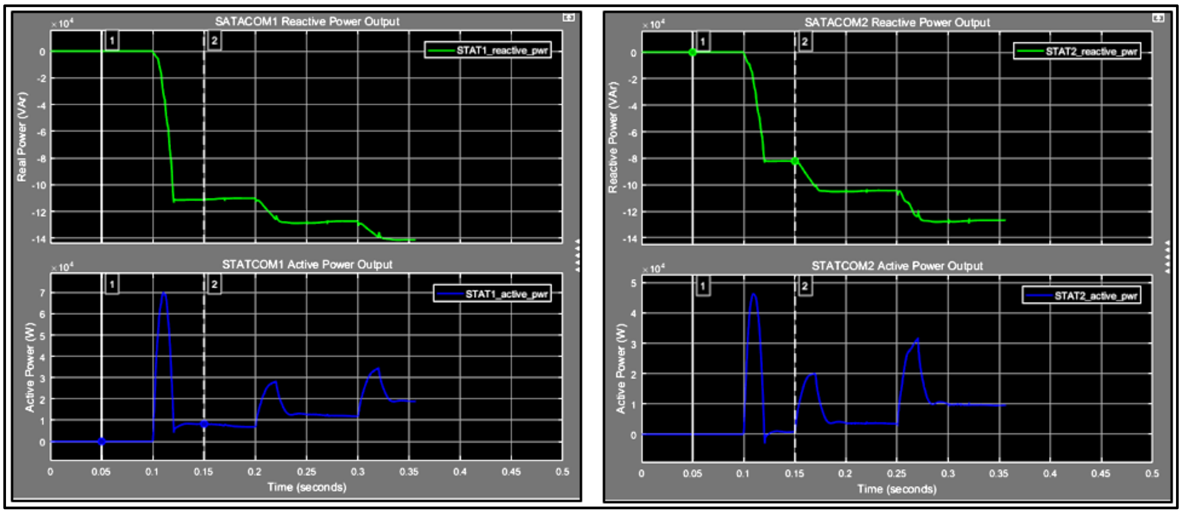


Figure 50: Power Output in Dynamic Over Voltage Regulation

From the simulation results and observations elaborated in this chapter with the Micro-STATCOM integrated LV system in modified IEEE 13 distribution Bus System, it can be confirmed that developed Micro-STATCOM module in this research was successfully abled to mitigate low voltage distribution systems power quality issues by,

- Under voltage regulation
- Over voltage regulation
- Mitigating aggregated harmonics in the LV system
- And, improving system power factor.

Voltage regulation response time of the Micro-STATCOM was around one cycle of 50 Hz sinusoidal signal, that is around 20 ms.

5.6 System Power Losses due to the Integration of Micro-STATCOMs

It is crucial to analyze the behavior of the of the system power delivery to LV network through distribution transformer before and after the integration of Micro-STATCOMs to the LV system. There by it can be observed the level of power loss introduced to the LV system due to the power quality issues mitigation process of the Micro-STATCOMs.

5.6.1 Behavior of Active and Reactive Power delivery form Distribution Transformer

Scenario 1 of the Case Study 1 above was selected to observe the change of active and reactive power output form distribution transformer to LV system during the absence of Micro-STATCOM and with the presence of Micro-STATCOM for power quality issues mitigation in LV network. Under voltage regulation and mitigation of harmonics were happened during the operation of Micro-STATCOMs in Scenario 1 of Case Study 1.

Figure: 51 shows the active and reactive power output from distribution transformer to the LV system of modified IEEE 13 distribution bus system during the absence of Micro-STATCOMs. It can be observed that at the steady state, active power output from transformer is 264.6 kW.

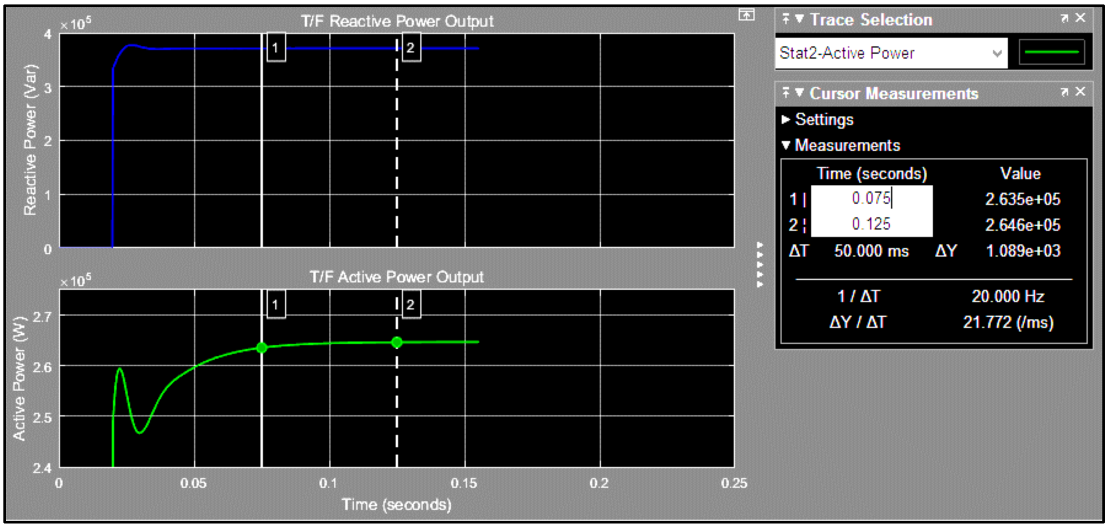


Figure 51: T/F Power Output to LV Network without Micro-STATCOMs

Figure: 52 shows the active and reactive power output from the distribution transformer during the operation of 2 nos. of Micro-STATCOMs in LV network. There are two noticiable changes can be observed once the operation of Micro-STATCOMs stsrted after 0.05 seconds.

1. Once the steady state contitions reached with the operation of Micro-STATCOMs, reactive power output from the distibution transformer has reduced by a considerable amount. This is due to the reactive power support provided by the integrated Micro-STATCOMs during the under voltage regulation. Hence the system power factor has improved and under voltage regulation happened. Figure: 31, Figure: 32, Figure: 33 and Figure: 34 shows the related power qulity improvement and Figure: 36 showes the power output of two Micro-STATCOMs.

2. Second observation is variation of active power output at steady state from ditribution transformer to the LV system. Active power output of the transformer during Micro-STATCOMs are in operation to LV network is around 269.0 kW.

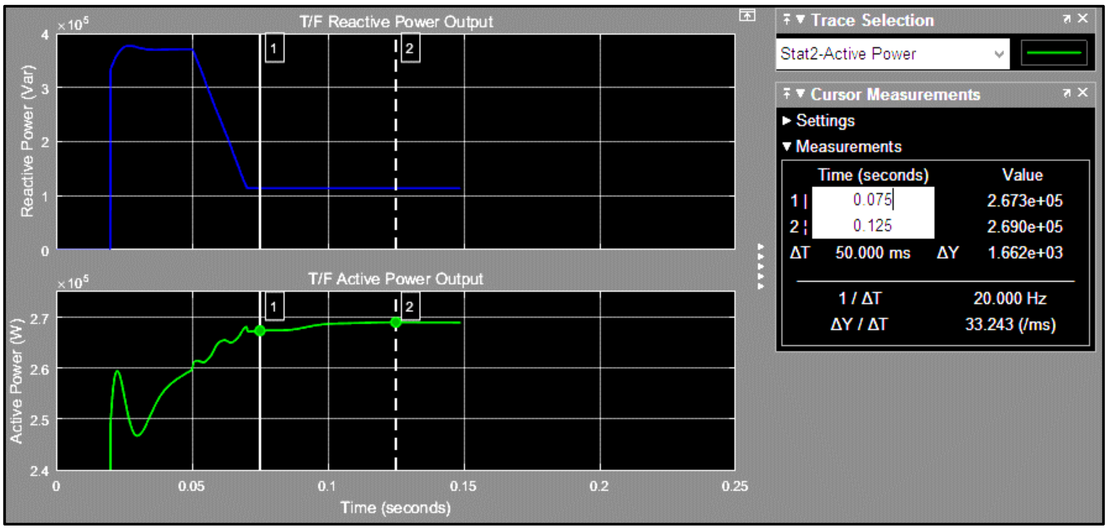


Figure 52: T/F Power Output to LV Network with Micro-STATCOMs

5.6.2 Active Power Consumption by Coupling Reactors of Micro-STATCOM

Coupling reactor is used to integrated Micro-STATCOM to the Point of Common Coupling of the LV feeder. Impedance of the coupling reactor is majorly contributed to the active power loss of the power sourcing from battery supported Micro-STATCOM. Minor loss of active power is due to the active harmonic compensation current injected by Micro-STATCOMS to the LV system. This can be minimized by careful selecting of coupling parameters for the coupling reactor.

Coupling reactor active power loss in Scenario 1 of Case Study 1 can be minimized by optimizing the impedance. Optimizing values for R and L components while ensuring that required reactive power is sourced to the LV network for under voltage regulation, power output of both Micro-STATCOMs can be obtained as in Figure: 53.

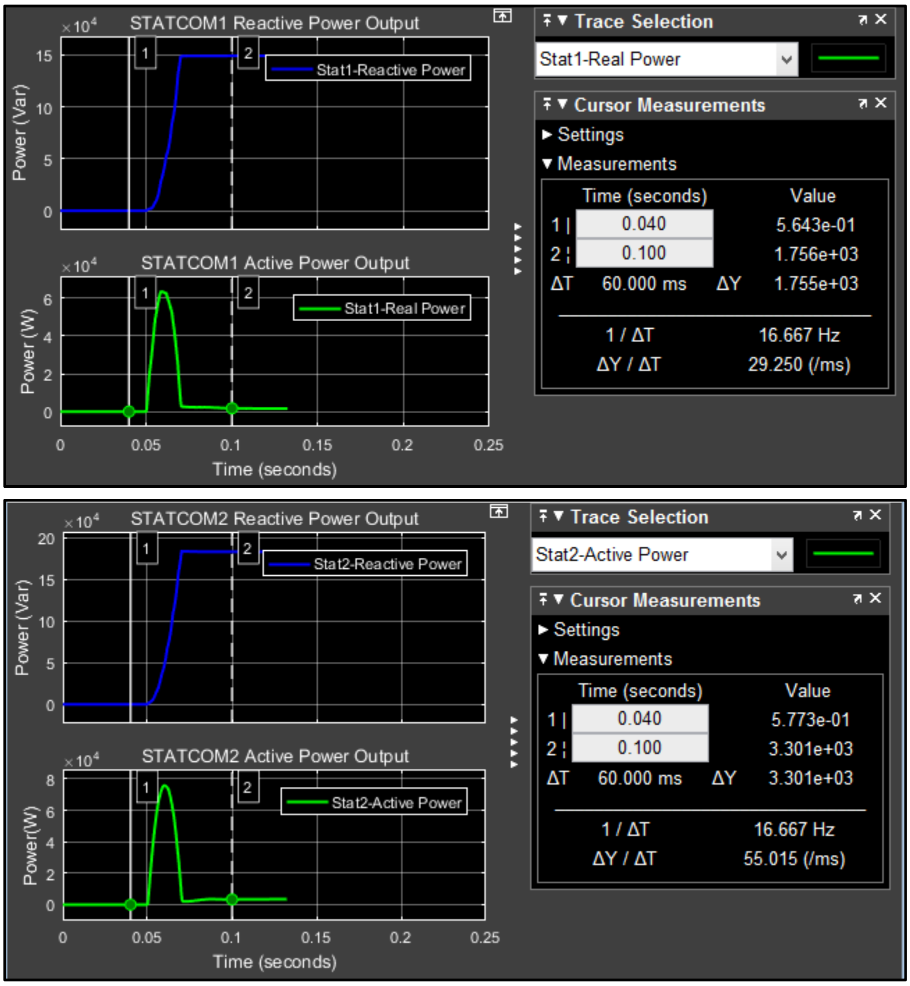


Figure 53: Power Output of Micro-STATCOMs after Optimization

5.6.3 Total Active Power Loss in the System

It can be observed form the results obtained in section 5.6.1 that the increase of active power output from the distribution transformer to the LV system due to the integration of Micro-STATCOMs is considerably small which can be encountered as an appreciation of power loss due to the operation of Micro-STATCOMs. Quantitative value of the power loss from the grid power due to the integration of Micro-STATCOMs is around 1.66%.

Coupling reactors used for the integration of Micro-STATCOMs to the PCC of LV system also consume some amount of active power from Micro-STATCOM and that can be treated as an active power loss from Micro-STATCOM setup itself. It can be quantified by the results obtained in section 5.6.2 above, active power loss due to coupling reactors is in the range of 1.91%.

This can be well and truly justified by the performance of voltage regulation, harmonic mitigation and power factor improvement capabilities of the Miro-STATCOMs. Regulation of system voltage variation around 10% - 15% amount from the system nominal voltage within 20 ms, improvement of THD levels from 12% to 1%, power factor improvement and increase of effective of real power delivery in the LV system by releasing system reactive power demand by a large margin are predominant improvements done by Micro-STATCOMs. Hence, aforesaid overhead for the system losses is justifiable.

6. DISCUSSION

6.1 Introduction

In this chapter, a discussion is presented about the performance and the results obtained on Micro-STATCOM module in mitigating power quality issues in active low voltage distribution networks. Further, the selection criteria of an optimum location to integrate Micro-STATCOMs also discussed in this chapter. Inter-operation of Micro-STATCOM with other network compensators and other potential areas of application for Micro-STATCOM are also discussed in this chapter.

6.2 Performance of Micro-STATCOM in Contrast with the Results Obtained

From the Matlab simulation of Micro-STATCOM connected LV distribution network of modified IEEE 13 Distribution Bus System under different scenarios of power quality issues, it was observed that Micro-STATCOM has functioned satisfactory in mitigating power quality issues in the LV networks.

With a connection of DC voltage source, Micro-STATCOM was successfully regulated under-voltage & over-voltage power quality issues by 10% -15% percent of system nominal voltage. The response time of the Micro-STATCOM was 20 ms which is one cycle time of the 50 Hz sinusoidal signal. In contrast with the time duration considered for under voltage and over voltage power quality issues, response time taken by Micro-STATCOM in compensating under voltage or over voltage issue is in the scale of 10^{-3}. This is mainly due to the capability of dynamically adaptable PI-controller error elimination function built in the Micro-STATCOM. Response times of other available compensation devices are greater than 100 ms (SVCs, OLTCs and Var capable inverters etc.).

Apart from the under voltage and over voltage regulation, Micro-STATCOM was successfully filtered system harmonic reducing total harmonic distortion (THD) level to acceptable level in a LV distribution network (<5%). With the presence of harmonic loads like AC drivers, AC-DC drivers, and other electronic switching devices, LV systems experience presence of heavy harmonic levels.

This was acceptably controlled and filtered out by Micro-STATCOM harmonic mitigation process. It was able to improve THD% levels from 12% to ~1% in the LV system.

System power factor also improved with the integration of Micro-STATCOMs to LV distribution system. This is mainly due to the amount of reactive power sourced/sunk by Micro-STATCOM depending on the LV system reactive power demand. This provided a release to the LV system and hence system power factor at PPC has also improved by increasing the efficiency of power delivery.

6.3 Selection Criteria to Integrate Micro-STATCOMs in LV System

6.3.1 Factors to be Considered in LV Network

This research was mainly focused on the development of Micro-STATCOM module that can be used in LV distribution systems in order to mitigate power quality issues. Observing the results obtained by applying Micro-STATCOM in LV system, it can be decided that the mitigation capability of the Micro-STATCOM is acceptable.

Even though the developed Micro-STATCOM was able to mitigate power quality issues in LV network, proper integration of Micro-STATCOM in LV distribution system is important in order to mitigate prevailing power quality issues in the LV system in efficient manner.

Integration of one or more Micro-STATCOMs developed in this research in an active LV network require below factors to be considered.
Location of integration depends on the, LV network Characteristics such as,

- LV feeder length
- Load density
- Connected transformer capacity
- Behaviour of other connected DGs
- Operation of other compensation devices in the LV network

These factors need to be taken in to account when deciding on the location of integration and also in the number of Micro-STATCOMs required to compensate PQ issues in the network [33].

6.3.2 Voltage Sensitivity Index Based Evaluation Method

Voltage sensitivity index, based evaluation using $\frac{\partial V}{\partial Q}$ for LV feeders is recommended to identify most voltage sensitive LV feeder. Dynamic behaviour of LV feeders with the connected loads can be evaluated using this method. Evaluation can be led to decide required capacity and required number of Micro-STATCOMs for the compensation of PQ issues in LV distribution network [34].

6.3.3 Inter-Operation of Micro-STATCOMs with Other Network Compensators

Inter-operation of Micro-STATCOM with other network compensators is very important factor to be considered when integrating to the LV system. Rang of operation (Resolution) of other PQ compensators such as SVCs, OLTCs, localized inverters and SVC should not be overlapped with the region of operation of Micro-STATCOM.

6.3.4 Introduction of Dead-Band

A dead-band can be easily imposed on the operation of Micro-STATCOMs in order to allow compensation operation of other localized compensators such as inverters built in solar PVs. Localized compensators can be effectively used for the compensation of small-scale voltage fluctuations in the LV system. But as they do not possess enough reactive power to compensate sustained under voltage or over voltage conditions in the LV system, operation of Micro-STATCOM need to be started.

As the response time of some compensators like OLTCs and even in some SVCs are not small as Micro-STATCOMs, coordinated operation between each compensator is required for the efficient compensation process in the LV network which is recommended as a future study.

6.4 Potential Areas of Application of Micro-STATCOM

Study of this research was predominantly focused on the application of Micro-STATCOM module to mitigate power quality issues in LV distribution systems as a utility level solution. But the application of Micro-STATCOM is not limited to mitigation of power quality in LV distribution system, but it can also be used as a consumer level solution in order to regulate voltage, filter out harmonics and to improve power factor of industrial level plants.

Some of the potential areas of applications are listed in as below,

- Rural power grid
- Residential Solar PV Systems
- Rail transit
- Hospital
- Heating industry
- Cigarette Factory
- Offshore oil production
- Radiator factory
- Construction machinery factory
- Airport
- Shipyard
- Water plant
- Sewage treatment plant

Application of Micro-STATCOM in industrial facilities as mentioned above, will eventually lead to reduce kVA consumption by the factory/facility by improving it's power factor. As the utility provider charged from the bulk customers based on KVA consumption, integration of compensator like Micro-STATCOM in their LV system will reduce kVA consumption from the utility power supply. Hence, it will reduce the KVA charge form the customer.

7. CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

Study of this research was carried out to address the predominant power quality issues in low voltage distribution networks where customers are connected to. Under Voltage issue, over voltage issue, presence of high level of harmonics in the system and poor power factor are among the major PQ issues. Powe regulatory bodies are imposing certain power quality level to be assured by the utility providers in the electricity supply provided to their customers. In order to meet these requirements in highly vulnerable LV distribution network environment with various loads connected to is a challenge.

As per the objectives of this study, providing utility level solution at the leaf level of LV distribution network to mitigate power quality issues was a burning requirement as already existing compensators are not performing up to the satisfactory level. Implementation of Micro-STATCOM with DC power source was successfully mitigated the power quality issues with a low response time. Developed Micro-STATCOM successfully mitigated the power quality issues by performing,

- Under voltage regulation
- Over voltage regulation
- Harmonic filtration
- Improving system power factor,

within 20ms of operation time and the resolution of the voltage regulation of the Micro-STATCOM is in 10%-15% of the system nominal voltage.

Developed Micro-STATCOM was integrated in to modified IEEE 13 Distribution Bus System and satisfactory observed the result in mitigating power quality issues prevailed in the LV system. Level of mitigation of harmonic were in considerably high level which obtained results from 12% THD to 1.2% THD. Power factor correction was also observed from the results obtained in integrating two numbers of Micro-STATCOMs in to modified IEEE 13 Distribution Bus System.

7.2 Recommendations for Future Works

Micro-STATCOM developed in this study was a standalone solution which is to be integrated with LV distribution network with proper evaluation. During the integration of Micro-STATCOMs for the mitigation of power quality issues in LV network, it is required to avoid over shadowing of the operation of existing localized and other major compensation devices. And also, when there are more than one Micro-STATCOMs are in operation in the LV network, coordinated operation with each compensator will provide optimal operation in mitigating power quality issues. Implementation of such coordinated operation can be recommended as a future research work.

- Coordinated operation of multi Micro-STATCOM system in active low voltage networks can be implemented with real-time communication of reactive current demand at each feeder section among Micro-STATCOMs to dynamically regulate voltage level.

Developed Micro-STATCOM in this study is a 3-phase device. There is a research opportunity to expand the capabilities of this Micro-STATCOM by implementing 1-phase device. Then the voltage unbalance power quality issue can also be addressed.

- Development of single-phase Micro-STATCOM Models having voltage regulation and harmonic mitigation capability can be improved further to address voltage unbalance power quality issue in the active LV distribution network.

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