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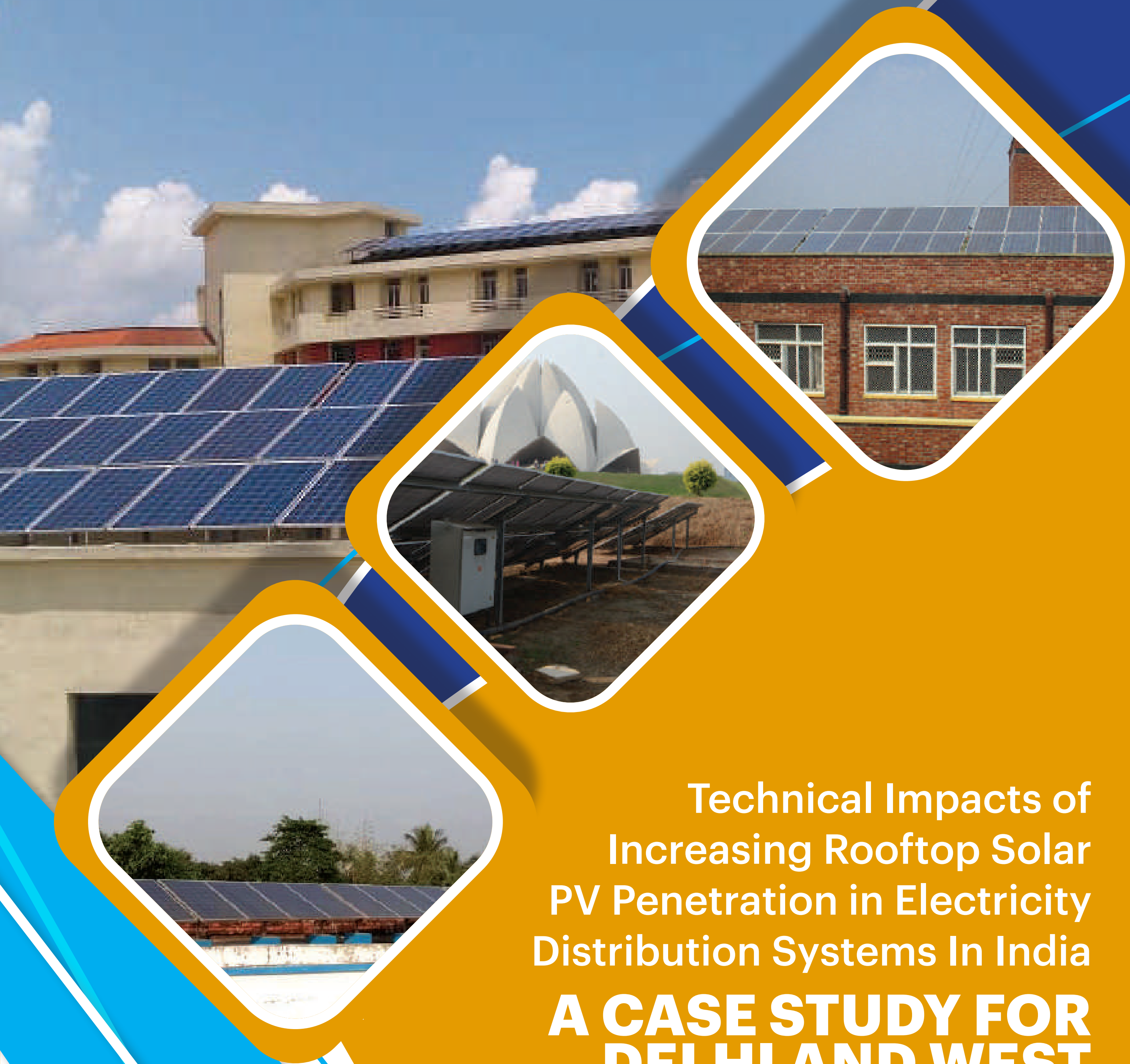

Technical Impacts of Increasing Rooftop Solar PV Penetration in Electricity Distribution Systems In India

A CASE STUDY FOR DELHI AND WEST BENGAL

Technical Impacts of Increasing Rooftop Solar PV Penetration in Electricity Distribution Systems in India

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Foreword

Utility-scale solar is already the cheapest source of electricity in India when the sun is shining. With the advent of energy storage, solar plus storage is set to beat coal-based electricity. Recent developments, like the Solar Energy Corporation of India (SECI) tender in February 2020 for solar and energy storage to provide power for both peak and off-peak times provide us more reasons to consider this source seriously. Certainly, these are exciting times to push solar energy further and bring it into the mainstream. Rooftop Solar is another opportunity waiting to be unlocked. The commercial and industrial consumer segments in India have already started adopting rooftop solar systems, and it is now important to develop technical configurations and business models so as to enable scale up at the residential level.

Rooftop Solar (RTS) is beyond doubt one of the key technology interventions to meet the growing challenges on the energy front both globally and at the national and subnational levels. In countries like India it assumes added importance in the context of rapidly growing demand and the vision to provide 24X7 reliable power supply to all at affordable rates, reduce urban air pollution, increase the share of renewable electricity, enable e-mobility, etc. The government is committed to activities related to development of solar energy, and particularly, expanding the RTS segment.

Being a country lying in the tropics, India is blessed with high insolation for 7-8 hours per day, and almost round the year in most locations. With significant fall in solar tariffs during the last couple of years, solar power has become a potent alternative to fossil fuel-based power, especially supported by strong policy push of the government. The National Institute of Solar Energy (NISE) has estimated about 750 GWp of solar power potential in the country. Out of a total RE capacity installation target of 175 GW by end of 2022, the target for solar PV based capacity is 100 GW, out of which 40 GW is to be achieved through rooftop solar. In the overall capacity installation of 368.68 GW as on 31st January 2020, solar contributed over 34 GW capacity, including rooftop solar of about 2.37 GW, which has been set up during the last ten years after launch of the National Solar Mission in 2010 by the Union Government. In addition, large capacities are under development including those that are under tendering by SECI and the respective state nodal agencies. The pace of RTS installation needs to be accelerated, not only to achieve the target but also in view of its capability to serve the local demand and help distribution utilities in managing their peak loads. It is heartening to note that at many places, the capacity addition is also being driven through comprehensive demand aggregation exercises.

At the same moment, it is important to acknowledge that policy and regulatory pushes are needed for distribution networks to achieve higher penetration levels of RTS. This requires an assessment of the likely technical impacts of RTS so as to safely accommodate solar power without adversely impacting system operation. Detailed power system modeling and simulation studies on the likely technical impacts of RTS and their possible mitigation techniques, are essential to establish the framework within which the power distribution companies can integrate RTS further.

This report presents such assessments carried out by TERI for the West Bengal State Electricity Distribution Company Limited (WBSEDCL) and BSES Rajdhani Power Limited (BRPL) which serves a major portion in NCT of Delhi. This has been made possible with funding support from theMacarthur Foundation. The reported work is based on extensive modeling of representative typical feeders in both the utilities and related power system simulation studies, carried out in close association with stakeholders and senior officials of both WBSEDCL and BRPL.

The recommendations of the study provide a framework for the integration of RTS into these two distribution companies , and support the efforts of policy makers, regulators, utility officials, other power utilities in West Bengal and Delhi as well as in other states to incorporate RTS into their expansion plans in a technically sound manner.

Dr. Ajay Mathur
Director General, TERI

Preface

Transformation of the power sector is regarded crucial to India for achieving its Nationally Determined Contributions (NDCs). Apart from large-scale mega solar parks, rooftop solar is seen as an important segment that would help the power sector in moving towards a low carbon pathway, by serving the local demand. This is especially so in developing economies like India where the electricity demand is rapidly growing and there is a pressing need to look at all possible ways to augment the power supply through adoption of clean energy sources. Since 2016, MacArthur Foundation's key focus in India has been to support mitigation interventions that seek sustainable solutions to challenges India faces from climate change. As 80% of projected emissions are likely to come from sources not yet built, it provides a huge opportunity for India to make long-term beneficial decisions now. In order to facilitate this decision making, the Foundation supports established civil society organisations with expertise in climate change mitigation to undertake projects that help reduce greenhouse gas emissions and build public demand for climate solutions.

As an organisation working to prevent global climate change by supporting policy, regulatory and technological interventions to curb Greenhouse Gas (GHG) emissions, renewable energy and energy efficiency are key focus areas for us. Through adoption of rooftop solar, the Indian electricity distribution sector offers ample opportunities for improvement in the operational indices of DISCOMs. It is well-accepted that electric utilities have the potential to serve the demand of their consumers through localized sources. Therefore, feeder-level rooftop solar energy becomes a very vital resource. In this direction, TERI has performed a set of comprehensive studies for the states of Andhra Pradesh, West Bengal and the National Capital Territory (NCT) of Delhi. The study performed for Andhra Pradesh was published previously, having been released at the World Sustainable Development Summit (WSDS) in January 2020. This report now presents the findings for West Bengal and the NCT of Delhi for which TERI partnered with West Bengal Electricity Distribution Company Limited (WBSEDCL) and BSES Rajdhani Power Limited (BRPL). The study looks into the likely technical impacts of increasing penetration levels of rooftop solar power into the distribution network in the states, and has identified various mitigation measures for each type of impact. On behalf of MacArthur Foundation, I would like to compliment TERI, WBSEDCL and BRPL for coming together and undertaking such a detailed study, which can also serve as a broad framework for other utilities and regulatory commissions to plan for integration of rooftop solar power capacities into their system and for smooth running of their networks.

Moutushi Sengupta
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This study was made possible by the research grant provided by MacArthur Foundation. The project team at TERI is grateful to Ms Moutushi Sengupta, MacArthur Foundation, for supporting the present work on impact assessment of rooftop solar generation for two distribution utilities: BSES Rajdhani Power Limited (BRPL) and West Bengal State Electricity Distribution Company Limited (WBSEDCL) This modeling and simulation study was carried out for two feeders, one for each utility, to identify, understand and analyze the technical impacts of rising solar photovoltaic power on distribution feeder operation and to suggest possible mitigation measures for the same.

The team wishes to put on record their appreciation and gratitude to the CEO, BRPL and the CMD, WBSEDCL for their valuable guidance and the encouragement provided during the course of the study. The team also acknowledges the respective nodal persons from BRPL and WBSEDCL and their team officials at various levels for facilitating the study through in-depth discussions and inputs including datasets, maps, diagrams and providing access to sites.

The support of all stakeholders like the Central Electricity Authority (CEA), Distribution Utilities Forum (DUF) and the Hon’ble Commissions of both the states, with whom the team interacted during the tenure of this study, is also gratefully appreciated and sincerely acknowledged.

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ACSR	Aluminium Core with Steel Reinforced
AMR	Automatic Metering Reading
ANSI	American National Standards Institute
BESS	Battery Energy Storage System
BRPL	BSES Rajdhani Power Limited
CAGR	Compounded Annual Growth Rate
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
DER	Distributed Energy Resource
DERC	Delhi Electricity Regulatory Commission
DISCOM	Distribution Company
DER	Distributed Renewable Energy
DT	Distribution Transformer
EV	Electric Vehicle
FoR	Forum of Regulators
GW	Giga Watt
HT	High Tension
IDMT	Inverse Definite Minimum Time
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
INDC	Intended Nationally Determined Contribution
kV	Kilo Volt
kVA	Kilo Volt Ampere
KWp	Kilo Watt peak
KUSUM	Kisan Urja Suraksha evam Utthaan Mahabhiyan
LT	Low Tension
MNRE	Ministry of New and Renewable Energy
MWp	Mega Watt Peak
NEMA	National Electrical Manufacturers Association
PV	Photovoltaic
PCC	Point of Common Coupling
PQ	Power Quality
OLTC	On Load Tap Changer
OCR	Over Current Relay
RMS	Root Mean Square

RMU	Ring Main Unit
RTS	Rooftop Solar
SLD	Single-line Diagram
THD	Total Harmonic Distortion
TDD	Total Demand Distortion
WBERC	West Bengal Electricity Regulatory Commission
WBSEDCL	West Bengal State Electricity Distribution Company Limited

Executive **Summary**

Rooftop solar (RTS) systems are expected to witness significant growth in India owing to increasing economic viability and a facilitating policy and regulatory framework across the country. Such distributed renewable energy (DRE) resources could provide various system benefits in terms of improved power reliability, deferment of grid-related investments and reduction in transmission and distribution losses, etc. However, since the electricity distribution grid in India was not designed keeping in mind the potential for high penetration levels of DREs such as RTS, there are valid concerns on the technical side from distribution companies about impacts of rising RTS levels on the low-tension (LT) distributionnetwork . Acknowledging the same, TERI with support from the MacArthur Foundation, carried out modelling and simulation studies to understand these impacts and suggest possible mitigation measures. The studies were performed for three distribution utilities – Andhra Pradesh Southern Power Distribution Company Limited (APSPDCL), West Bengal State Electricity Distribution Company Limited (WBSEDCL), and BSES Rajdhani Power Limited (BRPL). The findings of the studies performed for APSPDCL were published previously in a report. This report is in continuation to the previous report launched for APSPDCL and documents the major findings of the studies done for BRPL and WBSEDCL including the set of recommendations pertinent to specific issues

To address the anticipated concerns among distribution utilities regarding increasing penetration of RTS, this report begins with an exhaustive review of the existing technical standards and practices applicable to distribution networks in India, including a review of state-level policies and regulations. Further, the study outlines potential solutions and proposes a possible way forward for a structured and effective integration of distributed RTS systems with distribution networks in the country .

The analysis and results are expected to bring forward the technical challenges of and the potential solutions to a large-scale integration of distributed RTS with the distribution networks. A greater common understanding of the key issues would help facilitate faster deployment of distributed RTS in India.

1. Introduction

Solar Energy Landscape in India

With an objective to decarbonize the power sector, the Government of India has set an ambitious target of installing 175 GW of Renewable Energy (RE) by the end of 2022[1]. This capacity is projected to increase to 275 GW as per the National Electricity Plan, 2018[2]. Also, at the recently concluded UN Climate Action Summit, the Hon'ble Prime Minister of India announced increasing the share of RE based capacity to 450 GW[3] in due course. As on December 31, 2019, the installed RE capacity in India touched 86 GW. According to the 2019 year end review of the Ministry of New and Renewable Energy (MNRE), the total RE capacity installed or in the pipeline is approximately 150 GW[4], which is almost close to the 2022 target.

Major thrust is also being given to promote Distributed Renewable Energy (DRE) sources with many recently launched schemes giving impetus to the same. The Kisan Urja Suraksha evam Utthaan Mahabhiyan (KUSUM) scheme for setting up of 25,750 MW additional decentralized solar capacity (including decentralized ground-mounted and solar pumps) and Phase II of the grid-connected rooftop solar (RTS) programme of MNRE, with a target of achieving cumulative capacity of 40,000 MW by 2022, are among them. To facilitate deployment of RTS, most of the state governments have already come out with their state-specific solar or RTS policies. Along with that, all the State Electricity Regulatory Commissions (SERCs) as well as the Joint Electricity Regulatory Commission (JERC) for Union Territories (UTs) and Goa have till date notified their regulations relating to RTS projects. Most of the states adopted net-metering regulations as per the 'Draft Model Regulation for Rooftop Solar Grid Interactive Systems based on Net Metering' notified by the Forum of Regulators[5].

Falling prices of solar Photovoltaic (PV) modules[6] as well as those of lithium-ion-based battery storage systems are likely to make solar power much cheaper or, even at par with conventional grid-electricity in coming years, as shown in Figure 1. Rapid technological advancements and falling costs are thus among the prime factors behind increased integration of distributed solar power at the distribution network level. The enabling policy and regulatory landscape in India has also played a pivotal role in the rise in adoption of rooftop solar systems by all set of consumer cateogories viz. institutional, commercial, industrial, residential and agricultural. However, it is important to plan for an increased RTS uptake in view of the distribution network's power handling capacity and operational health. This is required to ensure hassle-free integration of increasing solar power considering future growth in load and RTS capacity. High penetration of RTS may have adverse technical impacts[7] that have been explained in detail later. However, acknowleding the possibility

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[1] Ministry of New and Renewable Energy. Tentative state-wise break-up of renewable power target to be achieved by the year 2022. Details available at https://mnre.gov.in/file-manager/UserFiles/Tentative-State-wise-break-up-of-Renewable-Power-by-2022.pdf

[2] Central Electricity Authority. 2018. National Electricity Plan. Details available at http://www.cea.nic.in/reports/committee/nep/nep_jan_2018.pdf

[3] PMIndia. 2019. PM Modi addresses Climate Action Summit. Details available at https://www.pmindia.gov.in/en/news_updates/pm-modi-addresses-climate-action-summit/

[4] PIB. 2020. Renewable energy sector makes rapid strides in 2019: Installed RE capacity crosses 84 GW; nearly 10 GW RE capacity added in 2019. Details available at https://pib.nic.in/PressReleseDetailm.aspx?PRID=1598948

[5] Forum of regulators. Model regulations. Details available at http://www.forumofregulators.gov.in/Model_Regulation.aspx

[6] MNRE. 2019. MNRE benchmark costs for grid connected rooftop solar power plants for the year 2019–20. Details available at https://solarrooftop.gov.in/notification/Notification-17072019-100623.pdf

[7] Forum of Regulators. 2019. Report on metering regulation and accounting framework for grid connected rooftop solar PV in India. Details available at http://www.forumofregulators.gov.in/Data/Reports/REPORT-METERING-ROOFTOP-08-05-19.pdf

of such impacts on the system, the RTS grid-connectivity regulations in many states have put a limit of 1 MWp on the maximum individual capacity that can be connected to the utility network. Different limits have also been imposed on individual RTS capacities with reference to sanctioned load of the consumer and cumulative capacity of the distributed RTS. Although, the Model Net-Metering Regulations of 2013 have not prescribed any limit based on sanctioned load, state regulations have imposed additional restrictions based on sanctioned load, which vary from state to state. Overall, the range for this limit is from 40% to 100% of the sanctioned load, and the limit on installed capacity of RTS with reference to Distribution Transformer (DT) capacity ranges from 15% to 75% in different states, as shown in Figure 2. The Central Electricity Authority (CEA) has also notified ‘Technical Standards for Connectivity of the Distributed Generation Resources, 2013 ’ and its amendment regulations in 2019.

Keeping these aspects, including the different connectivity limits precribed in various state regulations in view, TERI took up studies on likely technical impacts under different scenarios of RTS penetration levels and load growth for a few selected feeders in three distribution utilities in India, with funding support from the MacArthur Foundation. This report presents analysis and results for power system studies carried out on two feeders, one each from the BRPL and WBSEDCL license areas, identified in consultation with the utility. The report presenting case study for Andhra Pradesh has already been published, as mentioned previously.

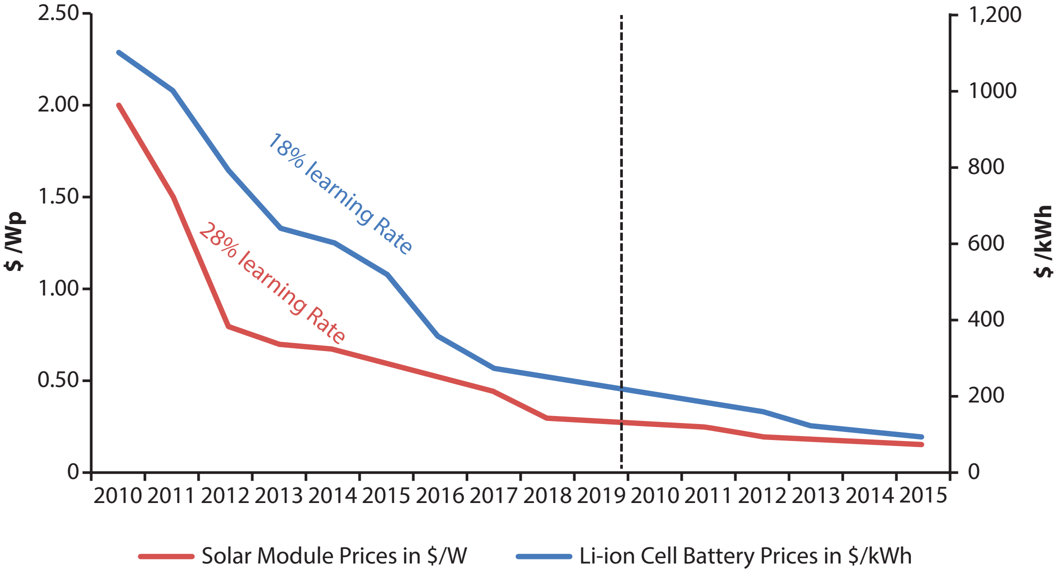

Figure 1: Falling prices trend/projection for solar module and battery energy storage

(Source: TERI and Bloomberg New Energy Finance)

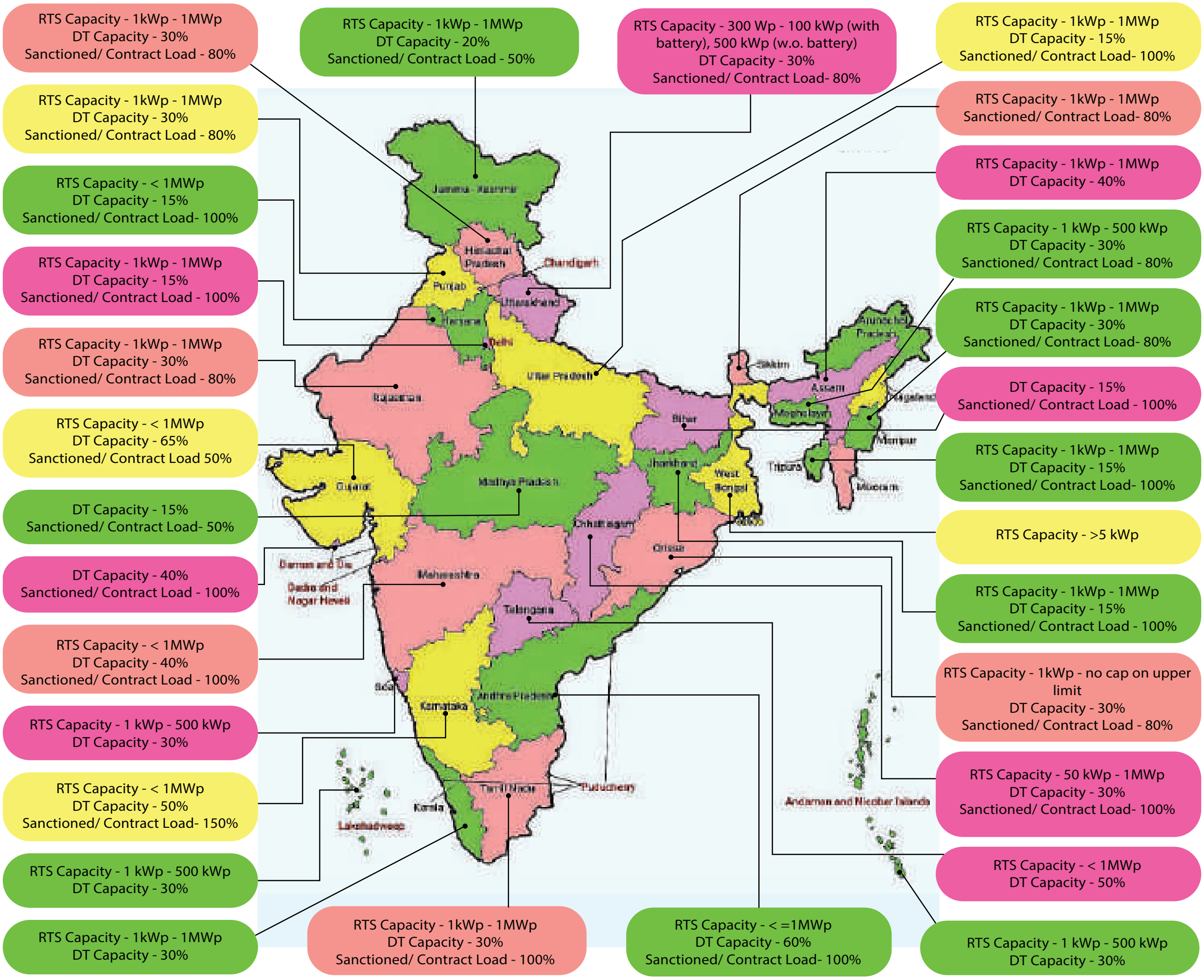

Figure 2: Grid-connectivity regulations on rooftop solar system's size and limits on distribution transformer capacity in different states as on April 2019

Source: TERI analysis based on data from state regulations)

The report is organized into seven chapters:

Chapter 2 describes the anticipated impacts of rising penetration levels of RTS and elaborates the importance of power system modelling and simulation studies to understand such impacts and their mitigation measures. Chapter 3 describes the characteristics of the feeders selected for the study and explains the different types of studies perfomed and impacts investigated. Chapter 4 presents the modeling details and the results and analysis for the power flow studies. Chapter 5 presents the results of the harmonic measurement studies. Chapter 6 gives an account of the power-system protection-related aspects based on analysis of actual feeders. Chapter 7 concludes the report and provides recommendtions and way-forward.

2. Technical Impacts of RTS in Distribution Systems

Considering the current pace of technological development coupled with fast changing demand pattern, increasing participation of intermittent solar power, and proliferation of electric vehicles as a rising form of DREs, electricity Distribution Companies (DISCOMs) foresee significant operational issues at the low-voltage distribution network level. This chapter describes some of these impacts, both in steady-state and in the condition of a short-circuit fault on the distribution system, on various power system parameters. The importance of power system studies, in view of understanding these impacts, has also been brought out at the end of the chapter.

Impacts of RTS on a Distribution System

Grid-connected RTS is a form of DRE source whose impact on the distribution network it is connected to depends on its location, line parameters and the load on the system apart from sudden chnages in solar irradiance, which have an independent absolute impact. Since a solar PV array is essentially a current source, the magnitude of the output current of a RTS mostly influences the various impacts such as reverse power flow (which also depends on load) that are reported to occur with its integration. The extent of impact that an RTS might have on a distribution network is often studied through a term called penetration level, which defines the amount of PV generation capacity (in terms of installed peak capacity) relative to a) Maximum/ minimum feeder load b) DT capacity, as the usual parameters. The different ways of defining penetration level are given in [1]. Most commonly, it is defined as the ratio of the RTS capacity to the DT capacity, as mentioned above, however, other definitions also exist where DT capacity is replaced by the minimum line loading among others. The different ways of defining penetration level are given in [1]. Aproperly structured power system study can provide a framework to develop a good understanding of the technical impacts considering generation and load levels and choosing the most representative parameter corresponding to the feeder and its characteristics for expressing the RTS hosting level for the feeder.

In steady state, solar PV systems have been reported to cause over-voltages at the local buses on the network. This can be explained by the reduction in the substation current that leads to reduced voltage drop in the netwok conductors, thus causing a reatively higher voltage magnitude at the buses compared to the situtation when no RTS is present in the system. However, this also depends on the location of the RTS relative to the loads. Such an impact might lead to an improved voltage profile along the line, however, very high voltage magnitudes, beyond the prescribed limits, may impact the life of overhead insulators and may also affect consumer equipment. On the other hand, reverse power flow due to very high injection of power from the connected RTS can also lead to mal-operation of the substation on-load tap changer (OLTC) [2]. These voltage-control equipment are also found at many 33/11 kV substations on distribution networks of BRPL and WBSEDCL and hence this aspect may be relevant to consider in this study. Intermittent generation from RTS can also lead to voltage fluctuations due to frequent operation of tap changers. Thus, voltage magnitude deviations are an important impact..

Similarly, power quality parameters, usually measured in terms of total harmonic distortion (THD) of voltage and current on the feeder and at the RTS terminals and by the total demand distortion (TDD) of current in the feeder, also get affected by increasing penetration levels of RTS. The power electronic circuitry inside PV inverters in an RTS system (which operates on pulse switching mode) adds to the harmonic content in the supply thus leading to an increase in the THD. Though, most of the modern commercial grid-tied inverters comply with the stringent IEEE 519 standard, increasing penetration of RTS (and number of inverters) could raise the level of system harmonics and the associated THD beyond the specified limits. Existing non-linear loads in the system may further add to the harmonic content. The THD at the load and RTS terminals can be measured, however, the values for the line are estimated by harmonic power flow. This study has focussed on on-site measurements of power quality parameters measured at various RTS sites in BRPL and WBSEDCL license areas that have been presented in the report. However, the set of measurements taken as part of this study, and the network-level parameters already available, are adequate to perform a harmonic power-flow study that can provide additional insights into distortion levels in the distribution line power flows alongwith the analysis of cumulative impact of RTS inverters and non-linear loads and the impact of change in their locations.

The voltage distortion in a power system is a function of the current distortion and the system impedance at various frequencies. The current distortion is also dependent upon the system impedance, in addition to the load. The short-circuit level of a power system is a practical way to define the impedance of a power system and hence the IEEE 519 standard defines current distortion limits in terms of the ratio of short-circuit current (I_{sc}) to the maximum demand current (I_L). The IEEE-519 (2014) specifies the voltage Total Harmonic Distortion (THD) limits for various power system voltage levels as given in Table 1.

Table 1: Voltage distortion limits under IEEE 519-2014

Bus V_{PCC}	**Individual harmonic (%)**	**THD (%)**
$V_{PCC} \leq 1$ kV	5.0	8.0
1 kV ≤ V ≤ 69 kV	3.0	5.0
69 kV ≤ V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

PCC: Point of common coupling; THD: Total harmonic distortion; V_{PCC}: Voltage at point of common coupling.

The standard also defines current harmonic distortion limits in terms of Total Demand Distortion (TDD) which is the ratio of RMS of harmonic currents to the maximum demand current at fundamental frequency. These limits are defined at various ratios of I_{sc}/I_L as given in Table 2.

Table 2: Current total demand distortion limits under IEEE 519-2014

I_{SC}/I_L	**TDD (%)**
<20	5.0
20 < 50	8.0
50–100	12.0
100–1000	15.0
>1000	20.0

TDD: Total demand distortion.

It is thus essential to know the short-circuit capacity of a power system to identify the correct current distortion limit for the system, as per the IEEE 519-2014 standard. It is a widely accepted standard and in India too, the Central Electricity Authority (Technical Standards for Connectivity of the Distributed Generation Resources) (Amendment) Regulations, 2019 have referred to it. Limits for curent harmonic injection at the PCC and the method of harmonic measurement have been set in accordance with the IEEE 519-2914, as amended from time to time. An increase in harmonics could lead to increased I^2R losses resulting in overheating of the lines and the equipment besides large load currents in the neutral wires of a three-phase system and high neutral-to-ground voltages, communication errors etc.

Under a short-circuit fault on a line or a feeder section, the presence of RTS systems is likely to impact the flow and distribution of fault current magnitudes and directions. This may have potential impacts on the reach or sensitivity of over-current relays that are typically found at the DT level and the existing scheme of protection coordination between various fuses at the LT downstream level and between these LT fuses and the DT over-current relay. Apart from short-circuit faults, there may be problems of earth fault relay mal-operation due to phase imbalances induced by high RTS penetration. Unintentional islanding also remains a remote possibility. Various possible issues that might emerge in the system have also been reported in chapter 6 on protection-related aspects.

Importance of Power System Modelling and Simulation Studies

Rising penetration levels of RTS could contribute to increasing skewness in demand pattern that affects system operation. There are also chances of voltage variations and changes in power flows. Harmonics and other power quality issues, and certain protection equipment maloperation are also among the most likely impacts of large-scale RTS penetration. Addressing these set of operational challenges at the distribution level of the power system is a task in itself since the network was originally designed to allow unidirectional power flows. Hence a changing paradigm of localized, bi-directional power flows because of the presence of RTS calls for extensive power system studies during the planning phase as well as during the operational phase to accurately understand the behavior of such distributed RE systems integrated at the distribution network level. Accordingly, it becomes imperative to analyze the anticipated technical impacts in order to improve the overall operational efficiency of distribution utilities, manage load on distribution transformers, and ensure 24x7 quality power supply. Accurate models of distribution feeders, RTS, and the loads (duly considering the phase-wise unbalance) for distribution power-flow studies are important to study, and possibly quantify such impacts. Grid integration studies usually cover the study of impacts – both in steady state and in dynamic/transient state, due to integration of RTS as discussed above. These also include study of possible measures for DISCOMs to mitigate such impacts. Deviations in steady-state voltage magnitudes at each bus, power quality impacts, distribution of fault currents in a system having deployment of RTS, and protection-coordination issues are generally studied as possible technical impacts. Once the technical impacts can be quantified and understood, it is equally important to model various mitigation techniques to address these issues and study their effectiveness through similar power system simulation studies. This would help the distribution utilities to plan the operations of their network accordingly. Similarly, incorporation of models for OLTCs, smart solar PV inverters with appropriate droop characteristics, and other such measures would help in understanding their feasibility as mitigation measures. In similar fashion, sizing, rating of protection devices required to be added, and modelling of new protection coordination schemes must be carried out to study the impact and mitigation in case of faults. The degree of impacts that a particular distribution network can withstand, without experiencing deviations in various parameters, outside their prescribed limits, often provides the DISCOMs with an idea of the allowable penetration level for each distributed energy resource

(DER). Therefore, one of the major outcomes of such intensive power system studies through modelling and simulation is the quantification of the RTS hosting capacity of a particular feeder.

For perfoming the power flow studies, use of annual time-series datasets of feeder and DT loading , including modelling of Low Tension (LT) feeders of a distribution network was felt necessary; whereas for studying impacts of harmonics, on-site measurements were made. The overall objectives of this study are: to assess the technical impacts due to high penetration of RTS; suggest possible mitigation measures for the DISCOMs; and to present a systematic study-based approach that can be applied for determining the aggregated capacity of RTS power plants that can be safely connected to the existing distribution network without adversly impacting system operation and grid-security. The studies cover not only the present scenario but also different possible future scenarios of RTS penetration and load growth duly considering diurnal and seasonal variations in load and solar generation, RTS penetration based on technical potential and state's project pipeline, location of RTS in the feeder and size of individual RTS systems, improvements in inverter power factor, voltage-control capabilities, etc.

Similar studies on integration of distributed PV in the Indian Electricity Distribution System have been undertaken previoulsy in which generally distribution assets upto DT level were modelled. The present study by TERI models the distribution system at a more granular level, to develop deeper insight at the LT level (415 V downstream network) since most of the distributed RTS systems are currently connected at LT feeder level, either as three-phase or single-phase connections. Moreover, a three-phase distribution power-flow approach modeling the phase-wise imbalance present in the load has adopted. Power quality measurements at various locations on the feeder have been done to capture the actual impact of RTS generation alongode non-linear loads and a review of various protection-related phneomenon has been made so as to provide a ready-reference and a practical account of the various impacts possible on the protection-system and possible mitigation measures.

The next chapter describes the rationale behind selection of states and distribution utilities for undertaking this illustrative study. The feeders identified in consultation with the utilities and their characteristics have also been mentioned. Lastly, a snapshot of the data collected, modelling approach adopted, and the list of studies carried out with key outcomes targeted have been provided.

3. Feeders Selected and Studies Carried Out

State-selection Criteria

In order to undertake a detailed utility-level simulation study, the state of West Bengal and the national capital territory (NCT) of Delhi were identified primarily in view of the salient features of their rooftop solar (RTS) policies and regulations. State geography, electricity demand growth rate, consumer mix, and ownership of DISCOMs (one publicly owned and one privately owned) were also among the major considerations for selection of one DISCOM each from both the states. In West Bengal, the West Bengal Electricity Regulatory Commission (WBERC) notified 'West Bengal Electricity Regulatory Commission (Cogeneration and Generation of Electricity from Renewable Sources of Energy) Regulations, 2013' to specify connectivity rules. The Government of West Bengal also launched an ambitious programme, namely, 'Alosree', with an objective to install RTS systems on all government buildings and buildings of local bodies. As per the state regulations, RTS system capacity shall not be less than 5 kWp, and injection from such sources shall not be more than 90% of the consumption in a year[1]. Hence, with a policy and regulatory framework that is evolving with a comprehensive outlook, West Bengal was identified as one of the states to undertake such an analysis. The state-owned utility WBSEDCL was selected based on the wide portfolio that it has in RTS segment and the availability of data and ease of access to its sites for survey.

In the NCT of Delhi, the Delhi Electricity Regulatory Commission (DERC) has notified 'Delhi Electricity Regulatory Commission (Net-Metering for Renewable Energy) Regulations, 2014'; the Government of NCT of Delhi (GNCTD) subsequently launched the 'Delhi Solar Energy Policy' for the period from 2016 to 2020. As per the net-metering regulations of NCT of Delhi, DT-level capping to be offered for connecting renewable energy system for net metering by the distribution licensee shall not be less than 20% (at least) of the rated capacity of respective distribution transformer.[2] There is no capping on RTS-installed capacity in terms of the sanctioned/contract load of the consumer, and a minimum 1 kWp of RTS size is allowed on one-phase connection. Recently, to promote RTS projects further, the DERC notified 'Delhi Electricity Regulatory Commission (Group Net Metering and Virtual Net Metering for Renewable Energy) Guidelines, 2019 so that the benefits of clean energy from RTS reach even those who do not own a roof, given the typical residential high-rise apartments that exist in Delhi. The BSES Rajdhani Power Limited (BRPL) has majority of privately-owned stake and serves the Southern and Western parts of Delhi. The utility also maintains feeder and DT-level datasets including the LT network details efficiently. Hence, the studies were performed in consultation with them.

As per MNRE, the proposed target for installation of grid-connected rooftop solar systems in West Bengal and NCT of Delhi is 2100 MWp and 1100 MWp respectively by 2022[3] (out of the total pan-India target of 40,000 MWp of RTS). As per SARAL – State Rooftop Solar Attractiveness Index, NCT of Delhi and West Bengal have been assigned with A+ and B grades respectively,[4] for 2018/19.

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[1] In the net-metering facility provided in the state of West Bengal, injection from RTS plants of eligible consumer can be adjusted with maximum 90% of the energy consumption of that consumer annually.

[2] Guidelines under DERC (Net Metering for Renewable Energy) Regulations, 2014. Details available at http://www.derc.gov.in/Regulations/DercGuidelines/Net%20Metering%20Guidelines/Guidelines.pdf

[3] MNRE. 2015. State wise and year wise targets for installation of 40,000 MWp grid-connected solar rooftop systems. Details available at https://mnre.gov.in/sites/default/files/webform/notices/State-wise-and-year-wise-target-for-installation-of-40000MWp-GCRT-systems_0.pdf

[4] MNRE. SARAL: State rooftop solar attractiveness index – for the financial year 2018/19. Details available at https://solarrooftop.gov.in/notification/Notification-30082019-161516.pdf

Typical Characteristics of Feeders Selected

One urban and one semi-urban feeder was selected and modelled under this study. The urban feeder was from BSES Rajdhani Power Limited (BRPL), while the semi-urban feeder belongs to West Bengal State Electricity Distribution Company Limited (WBSEDCL). The following technical criteria were considered to choose these feeders:

- **Type of feeders**: Open ring and underground in NCT of Delhi and overhead, long and radial in West Bengal
- **Length of feeders**: Long in case of WBSEDCL and short feeders in BRPL area
- **Consumer mix**: Residential, commercial, and institutional
- **Transformer capacity**: Upto 990 kVA for BRPL while for WBSEDCL, the capacity is usually of the order of 315/200/100/63-kVA
- **Existing penetration of RTS**: Approximately 350 kWp of RTS already exists in WBSEDCL feeder and approximately 25 kWp of RTS in case of BRPL feeder
- Load and RTS growth possibility

BRPL feeder

The feeder selected for this study is an urban feeder that mainly supplies to residential premises and a few commercial customers. It is located in a locality of South Delhi, in the NCT of Delhi, India. The 11 kV feeder operates in an open-ring configuration and there are eleven distribution transformers on the feeder. These 11 DTs are fed from the utility upstream supply through Ring Main Units (RMUs), some individually while some are grouped together and are connected through an RMU. The rated capacities of DTs on the feeder are 400 kVA (one), 630 kVA (four), and 990 kVA (six) while each of them is rated as 11 kV/415 V. Each of the DTs is housed inside a DT substation that is a characteristic of the network in this license area of the utility. Although 415 V is the standard recommended LT voltage level at the consumer side, the DTs are usually operated at a tap setting of 1.05 per unit so that 433 V is obtained at the secondary terminals to compensate for the drop along the downstream till the service points. The feeder has majority of the underground 11 kV sections made up of 30 sqmm Aluminium Core with Steel Reinforecd (ACSR) cables. Figure 3 shows a single-line diagram of the BRPL feeder.

WBSEDCL feeder

The 11 kV feeder is a dedicated feeder that serves an institutional premises in the Narendrapur area of the Garia division of the DISCOM. It is one of the 11 kV feeders that emanates from the 33/11 kV Narendrapur substation. The feeder is a radial one with no point of alternative in-feed from any other substation. All conductors are in the form of overhead lines and there are seven DTs on the feeder with the following capacities: 63 kVA (one), 100 kVA (four), 250 kVA (one), and 315 kVA (one).

The institutional premises houses many buildings such as hostel blocks, a school, a bank, a college, an administration block, and a kitchen. The electrical load on the network physically corresponds to the equipment or appliances inside these buildings that are connected to the network at 415 V and are individually metered. There are a total of five distributed solar PV plants installed on the rooftops of some of these buildings that have net-metered connections. Single-line diagram of the selected feeder namely RK Mission feeder is presented in figure 4.

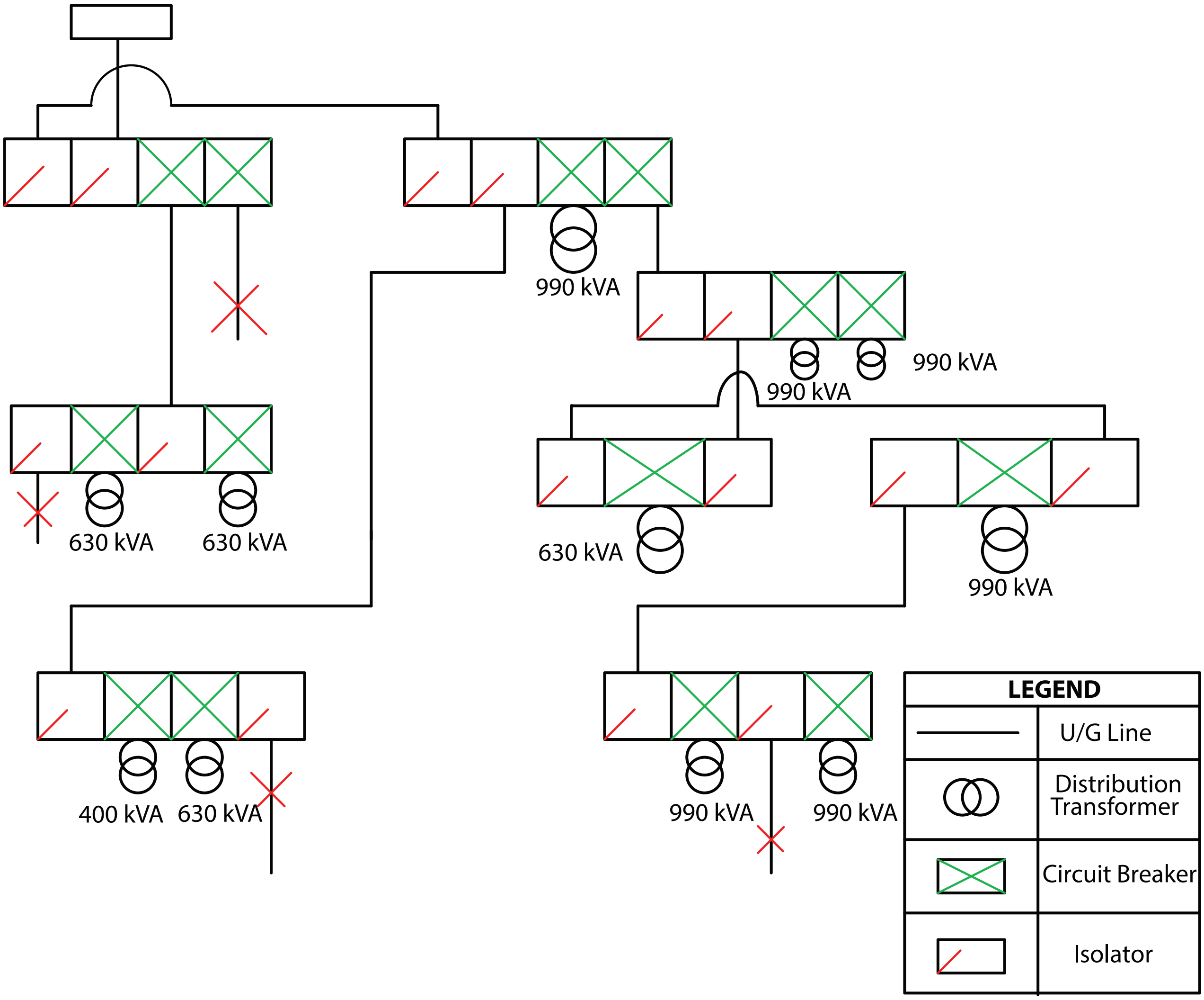

Figure 3: Single-line diagram of the BRPL feeder

Simulation Studies

To study the anticipated impacts of increasing RTS penetration on the distribution feeders selected, detailed modelling, as mentioned in the previous section, was required for carrying out the simulation studies for which the following datasets were collected from the respective DISCOMs:

1. Single-line diagrams of the feeders showing DT capacities including transformer tap positions, conductor types and line lengths
2. Transformer impedance parameters, short-circuit capacity of the substation, and line parameters of the different cables and conductors used

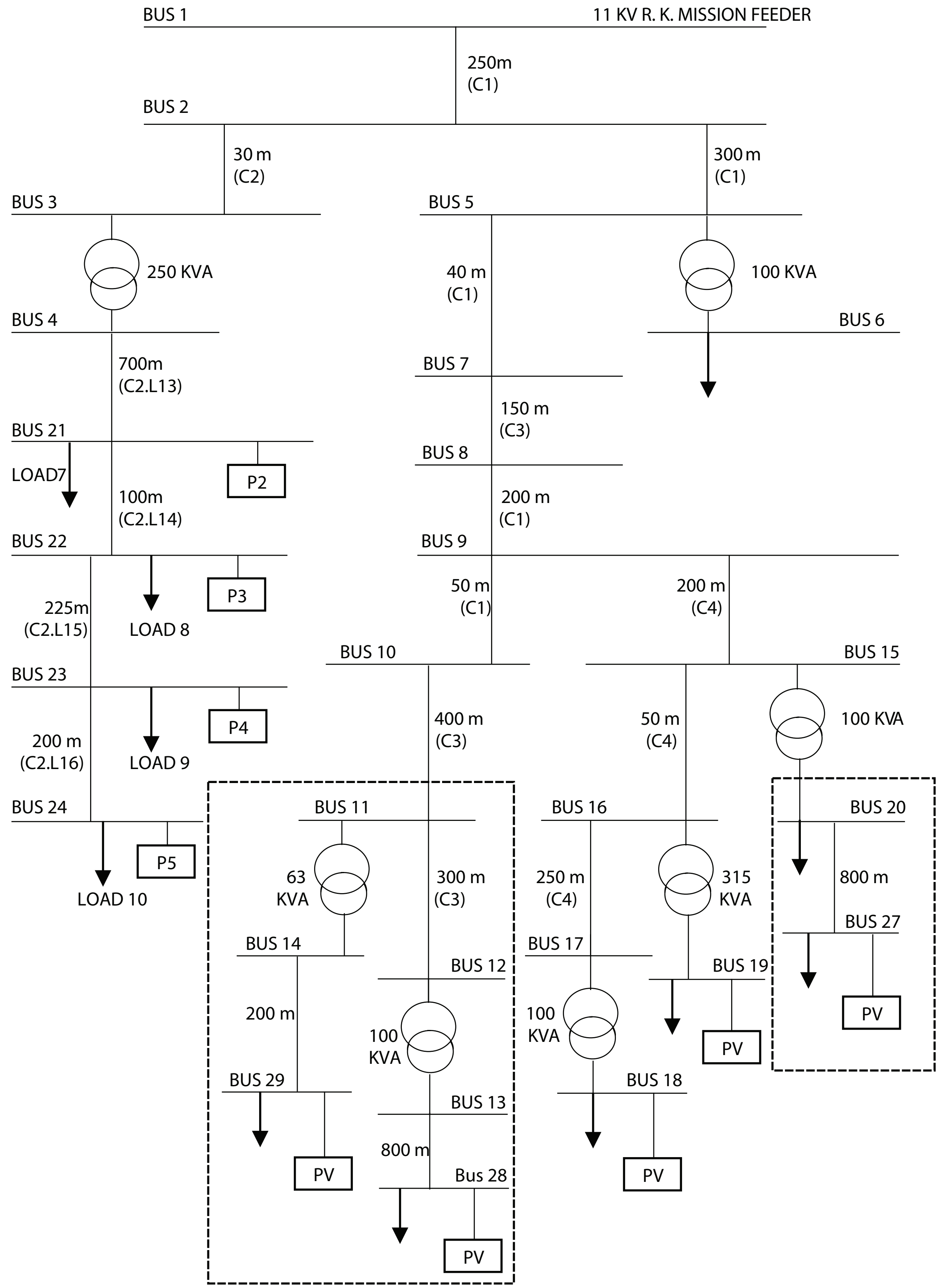

Figure 4: Single-line diagram of the WBSEDCL feeder

3. Geographical information systems files of the feeder to calculate technical RTS potential and model the network
4. Time series loading data of the automatic metering reading (AMR) for the 11 kV feeders and all the DTs for the past 3 years, wherever available from DT meters. The utillty projected load growth was also considered to model the load-growth scenarios.
5. Monthly energy bills of certain net-metered consumers on the WBSEDCL feeder (in absence of DT metering), the detailed procedure being given in respective section
6. Solar generation data of RTS (for one year for the feeder location in Delhi) from remote-monitoring portals to cross check and validate solar PV models used in the OpenDSS program
7. Protective device ratings, settings, and specifications

Weather data for Delhi and Kolkata was collected for appropriately modelling solar generation profiles. The single-line diagrams of the shortlisted 11 kV feeders were collected from the concerned DISCOM team and the networks were modelled in Open Distribution System Simulator (OpenDSS), which is a standard power system modelling and simulation package and an open source. OpenDSS was preferred due to the ease in debugging of code and the modularity of editing the model file through custom, user-defined model parameters and flexibility in modelling approach. Both the feeders were surveyed to understand the network configuration and note finer details such as conductor spacing, conductor types etc. that aided in exactly and realistically modelling the feeders. The LT network beyond a DT was also surveyed for both the feeders so as to capture the LT side distribution, starting from the DT secondary to the LT feeder mains to the feeder pole/pillar box upto the service connection of the consumer.

In order to study and analyze various anticipated impacts of RTS on the distribution networks selected, the following power system studies were performed:

1. **Load-flow studies**: Three-phase distribution power flow was performed for both the feeders for different scenarios of load and RTS growth in order to estimate the voltage levels at different points on the network and understand the power flows to identify reverse flow, if any.
2. **Harmonic Measurements**: Total harmonic distortion (THD) of voltage and current were measured at the DT secondary and the RTS terminals to estimate the level of power quality distortions affected by RTS and non-linear loads combined, for different times in a day.
3. **Study of protection-related aspects**: The existing scheme of protective devices on both the feeders was reviewed. The ratings, settings, and scheme of co-ordination between fuses and over current relays on different sections of the feeders were studied (site surveys were undertaken) and possible issues that can come up due to rising RTS penetration levels were discussed with the utilities. Some important observations and recommendations have been made regarding upgrading the existing protection systems, importance of inverter testing and other aspects, based on extensive field visits and study of operational characteristics of protective devices.

The next three chapters describe the results of the load-flow studies, the harmonic measurement studies, and the important observations regarding system protection, respectively.

4. Load-Flow Studies: Modeling Details and Study Results

Modeling Approach for Delhi

The characteristics of the selected feeder from the BRPL license area were described in the previous section. Acknowledging the fact that most of the rooftop solar (RTS) photovoltaic (PV) installations will be at the consumer premises that are connected at the 415 V low tention (LT) level, it is important to model the feeder exactly till the LT feeder portion. Hence, to more realistically estimate the voltage magnitude so as to understand the potential impacts at the consumer premises, with reference to the supply code, the feeder was extensively surveyed and conductor types and lengths from distribution transformer (DT) till downstream end at feeder pillar box or overhead pole to consumer service connection/meter were noted. Accordingly, extensive effort was made to realistically model the feeder till the downstream. Scenarios were designed to take into account present PV and load levels and future growths and possible connection points of PV. Three-phase unbalanced power-flow program was then run.

The electrical characteristics of the conductors and other relevant data on short circuit capacity, X/R ratios, and DT parameters were used to model the feeder in OpenDSS, an open-source distribution modelling and analysis software. The DT has digital meters installed on its secondary terminals with logging of loading data for every half-hour interval. This dataset was made available by the utility for three consecutive years and the dataset for the base year (FY 2016/17) was used to prepare the net load data file. Three-phase loads were modelled to incorporate the unbalance in the system. The 'load buses' were modelled at a certain physical distance from the DT secondary sides (the cable lengths were ascertained by the utility) so as to obtain realistic values of nodal voltages at these LT buses, a step-forwad from the approach of lumping the load at the DT secondary.

PV modelling

The feeder, at the time of modelling, had a cumulative solar PV capacity of 25 kWp, split into two rooftop plants of capacities 20 kW and 5 kW, and joined with nodes that connect to two DTs, respectively. Accordingly, the solar PV generation in the system was modelled to incorporate the physical characteristics including annual solar irradiation profile at the location, module characteristics, and inverter efficiency. For the feeder base-case scenario, two solar PV generation systems were modelled and connected to the 'load buses'. The actual physical distance of the rooftop from the local DT was obtained through geographical information system (GIS) mapping. Hence, the solar PV generation systems were incorporated into the model as single lumped sources of generation at the 'load bus', affecting the 'net load' on that bus for the power-flow program. Also, the DT meter loading data represented net load on the DT since the solar PV generation had been accounted for. Since the solar PV systems were individually modelled as independent generators connected to a bus, the 'load bus' characteristic of each of such buses (the '433 V-rated' node in the power-flow program) having an RTS system connected to it was kept intact by adding the time series of the modelled solar PV systems to the time series of the net load. Thus, an extensive exercise of adding corrected solar PV generation (since there were irregularities in recorded actual generation) to the DT meter net loading data was done to represent the gross load in the load data file in the script. Helioscope software tool was used to estimate the generation corresponding to the modelled RTS plants so as to correct the gaps in the recorded generation values (obtained through remote monitoring access to the inverter meter).

Scenario design

The base-case scenario represents the feeder 'as it is' in the base year considered, that is, 2016/17. The cumulative solar PV capacity on the feeder stood as 25 kWp, distributed over two 433 V buses in the sizes of 20 kWp and 5 kWp. The loading values on the LT load buses as obtained for the base year were used. The three-phase load-flow program was then run for the base-case dataset used in the model and the nodal voltages at each LT bus were obtained and analysed.

Design of load-growth scenarios

The feeder load growth scenarios were meticulously designed to represent realistic future year DT-wise loading. A clustering approach was implemented to group ring main units (RMUs); with one or more DTs, based on their proximity to each other. Three such clusters were created. Accordingly, the sum of current peak loading of each DT (corresponding to the base year 2017) in a particular cluster was computed. The peak load was observed to be occurring mostly during night hours in the summer months of June. In consultation with the utility, it was agreed that the sum of current/ base-year peak loading can be taken as an appropriate parameter to estimate the increase in loading for the future year scenario for each of the three clusters. Based on peak loading values for the past 3 years (from the base year) and the future plans of the utility, the feeder peak-load compounded annual growth rate (CAGR) was noted to be 6%. RMU clusters with a higher peak capacity were assumed to proportionally have a higher growth rate. Since all DTs in any RMU are in proximity of each other, load distribution on these DTs would be determined by their existing loading, that is, future addition of load would take place on the lightly loaded DT, in accordance with the present utility practice. There are 11 DTs on the feeder of capacities 400 kVA, 630 kVA, and 990 kVA. There are eight RMUs to which the DTs are connected. Leaving three, each RMU has two DTs connected to it while one RMU does not have any DT connected to it. Accordingly, three clusters were formed. The current cluster-wise peak and the increased peak in the fourth year were then taken to find the new peak load on a DT and this approach was verified with the utility team. Consequently, this increased peak loading over the current peak load was used as the scaling factor for individual phase-wise loading values for each DT. The gross loading on each DT, in a future year scenario after adding the corresponding solar PV generation values, was obtained in this manner.

Design of solar PV capacity growth scenarios

As the first step, the technical potential of solar PV for the feeder was estimated by GIS-based modelling. The physical extent of the feeder was mapped on a GIS tool and the rooftops of individual buildings near each RMU were identified in the digital terrain map. The usable area for installing RTS plants was then estimated. Considering 30% of the total area of a rooftop as available for installing an RTS plant and taking 15 m^2/kWp as the area requirement, the total potential of RTS PV for the feeder was estimated to be 1071.84 kWp. Based on certain paramters viz. the number of years (from the base year) in which the total potential can be achieved, the proportion of total rooftop area available for an RTS plant's installation, the rate of growth curve, and the load growth CAGR, the scenarios for solar PV capacity growth were designed. For designing the scenarios, few of the parameters, mentioned above, were kept constant while the remaining were varied in a range. Considering the technical potential estimated, it was assumed that the total RTS potential could be achieved in the fifth year from the base year. Hence, 5 was taken as the number of years to achieve the total potential. It was considered that the annual growth followed a cubic curve hence 3 was taken as the growth-rate number. The feeder growth CAGR was kept as 6% and hence the numeral 6 was used. The usable area (proportion of rooftop area for RTS PV) was varied as 30%, 40%, and 50%. Year-on-Year (YoY) capacity additions were considered for the third and the fourth years. In total, six such scenarios were designed (Table 3). Each one of them were uniquely named to distinguish one from another. For example, a scenario wherein the RTS addition was considered for the fourth year at 50% usable area was named as 4YO50536. Figure 5 explains the nomenclature of scenarios. Among all the RTS capacity growth scenarios, this particular scenario was chosen (considering that it has the highest possible RTS capacity relaltive to the load which is also highest in this scenario) and the load flow was run to observe the nodal voltages without any mitigation technique and after applying each one of the three techniques.

Table 3: Power-flow scenarios for the BRPL feeder

S.No.	Scenario Name
1	3YO30536
2	3YO40536
3	3YO50536
4	4YO30536
5	4YO40536
6	4YO50536

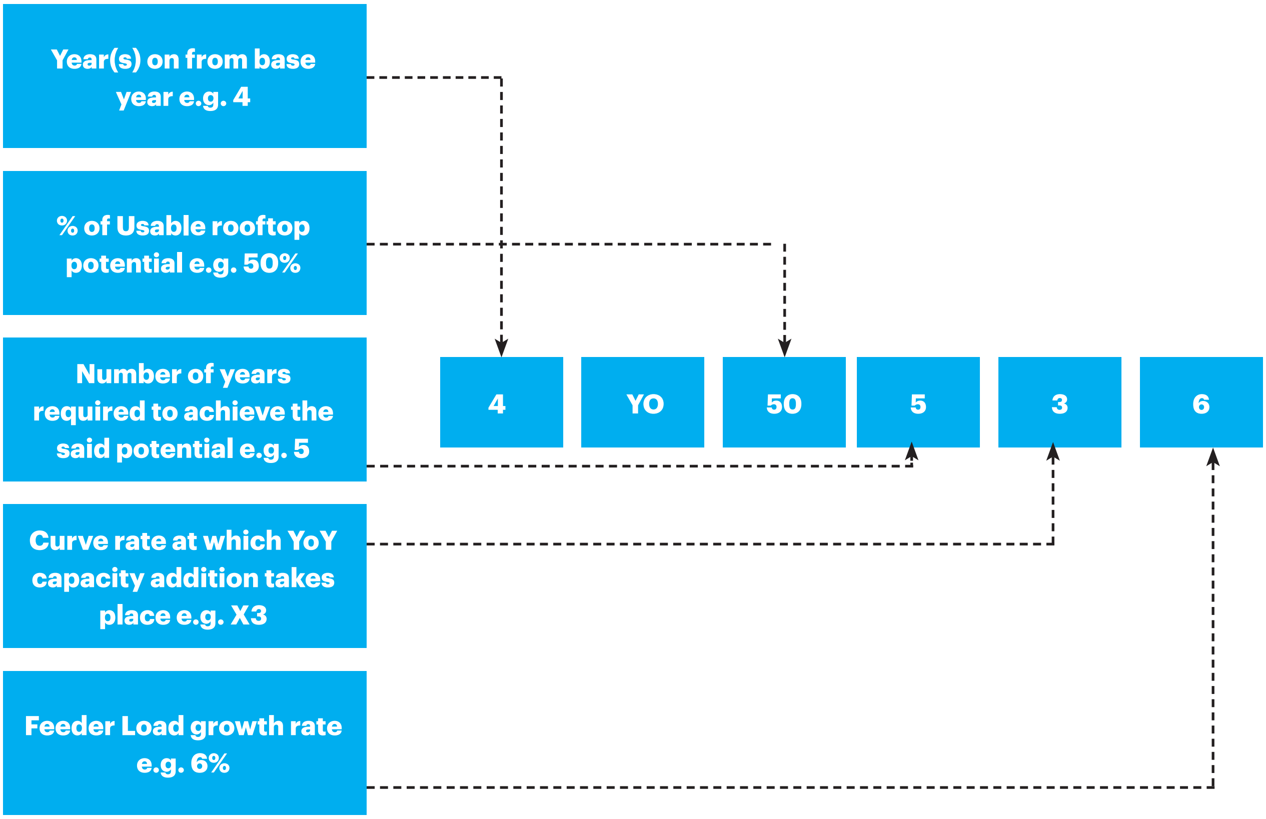

Figure 5: Explanation of the design of power flow scenarios for the BRPL feeder

Load Flow Results for Delhi

The 'gross-loading' values for each load bus and the estimated solar PV generation values, for different scenarios, were included in the OPenDSS model. Three-phase distribution load flow was programmed in OpenDSS and run for each scenario studied. The load-flow program was a variant of the forward–backward sweep algorithm in which a nodal admittance-based matrix analysis was used to calculate the node voltages. The voltages at the 'load buses', modelled at a physical distance from each DT secondary, were observed and have been reported below for different scenarios. Yearly load-flow simulations were run and voltage magnitudes at all buses where loads were modelled to be connected have been reported in phase-neutral values. Phase-wise voltage values were observed and 0.94–1.06 per unit (p.u.) was selected as the operating voltage range as per the DERC supply code, 2006.

The base case, reference case, and the cases modelled to study mitigation techniques are summarized in Figure 6. The base-case results are important to show the present power flow conditions in the feeder under the very low levels of current RTS penetration (base year 2016-17).

Base Case:
Current Load & No Solar PV Systems (Existing penetration too low to be considered)

Reference Case:
Load growth at 6% CAGR and 4th year solar PV capacity, at 50% usable area. No mitigation techniques like OLTC, smart inverters and BESS

Mitigation Test Cases:
Load growth at 6% CAGR and 4th year solar PV capacity, at 50% usable area. Various mitigation techniques at selected buses for voltage control.

Figure 6: Overview of cases created to show results for the BRPL feeder

Base Case Results

There are 11 DTs on the feeder. However, since the loads were not lumped on the DT secondary side, 'load buses' were created for the power-flow program as described earlier. Therefore, the number assigned to each load bus does not correspond to the serial number of the DT (used to identify the sequential location of the DTs on the feeder). Figure 7 shows the power flow along the feeder in the base-case scenario, for the base year. The phase-wise active power (in the above portion of the graph) and the reactive power magnitudes and direction indicate that there is no reverse power flow at the present RTS penetration level, which is too small to cause such reversal of power. All power flows being in the positive direction, it is apparent that there is no reverse power flow which is, generally,also a reason for voltage deviations [3]. However, in the subsequent subsections, a few load buses where voltage deviations were outside the prescribed limits for the 4YO50536 scenario (reference case) have been presented for analysis.

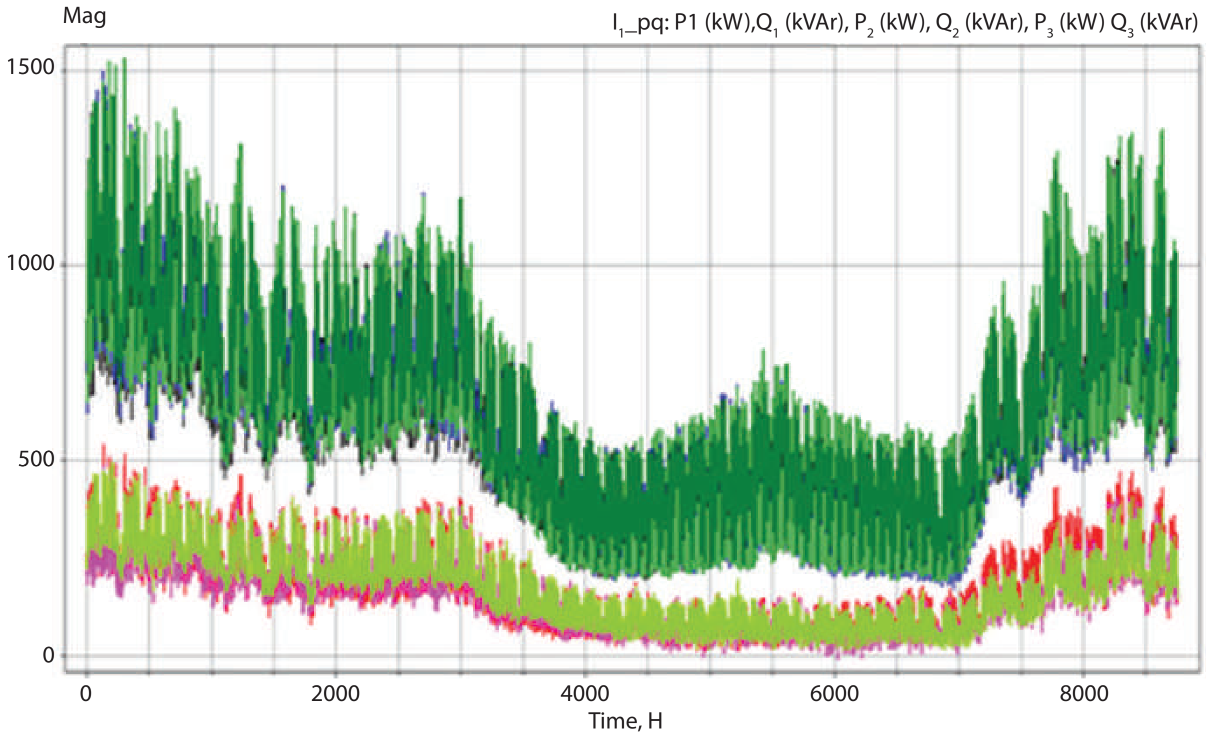

Figure 7: Base-case power flow for BRPL feeder

The next set of results corresponds to a future year, fourth year from the base-year, as defined for the reference case scenario (4YO50536), having the corresponding RTS capacity following the cubic growth rate curve and load growth at 6% per annum.

Reference Case Results: Impact on DT Loading

Based on the RMU clsutering approach and the projections of RTS capacity over the future years, each of the 11 DTs was allocated a certain RTS capacity. Figure 8 shows the RTS capacities relative to the DT capacities, in a way representing the distribution of PV penetration levels on the 11 DTs. The primary axis shows the RTS capacity in kWp while the secondary axis shows the PV penetration level on the DTs in percentage terms. It can be seen that DT number 3 has the highest capacity of RTS installed relative to its own capacity and consequently has the highest PV penetration among all the 11 DTs. Also, DT 1 and DT2 are seen to practically have no RTS penetration in the 4th year (counted from the base year 2017)

Analyzing the impact of RTS generation on DT loading throughout a day brings out some interesting observations. Figure 9 shows the daily load factor for a peak summer day for all the DTs vis-à-vis the same when RTS is connected to each one of them for the same period. It can be seen that DT3, which has the highest RTS penetration, has a slighly improved load factor compared to when no RTS was connecetd to it, for the same period. DT 7 shows highest improvement in load factor. This is apparently due to the fact that for DT 7, the maximum loading coincides with the solar generation hours and hence both average loading and peak loading seemed to have reduced drastically. For DT 3, there may not be an effective reduction in average loading throughout the day relative to the peak load reduction and hence the load factor remains more or less the same, even after having the highest PV penetration among all DTs. For all other DTs, the average loading was not found to be significantly lower than the reduced peak loading. This is appropriate since most of the DTs are residential and commercial whose loading peaks duering night time in summers because of air-conditioning. Figure 8 however protrays how RTS systems can actaully help in asset management for the DISCOM by reducing the loading during peak afternnon hours although the evening power requirments may suddenly ramp up when the solar hours vanish and this would require careful planning for peak-power procurement and network load management.

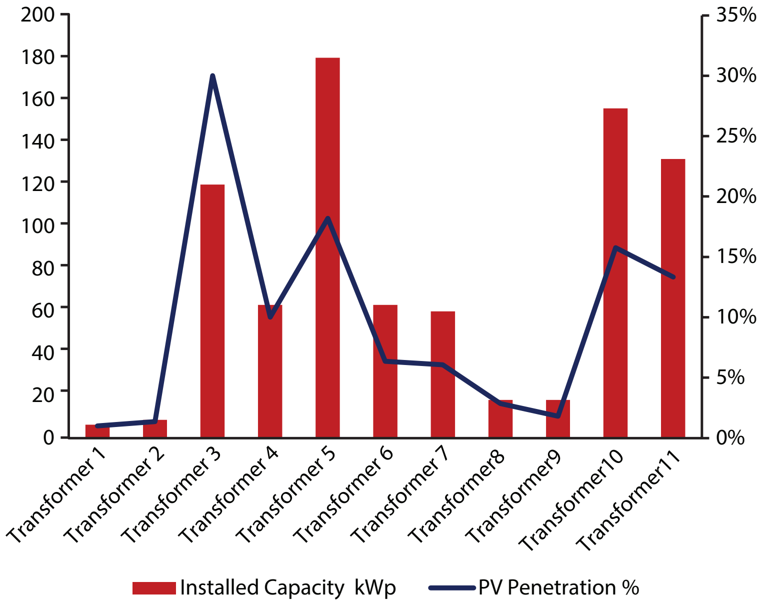

Figure 8: Rooftop solar capacity relative to distribution transformer capacities on the BRPL feeder

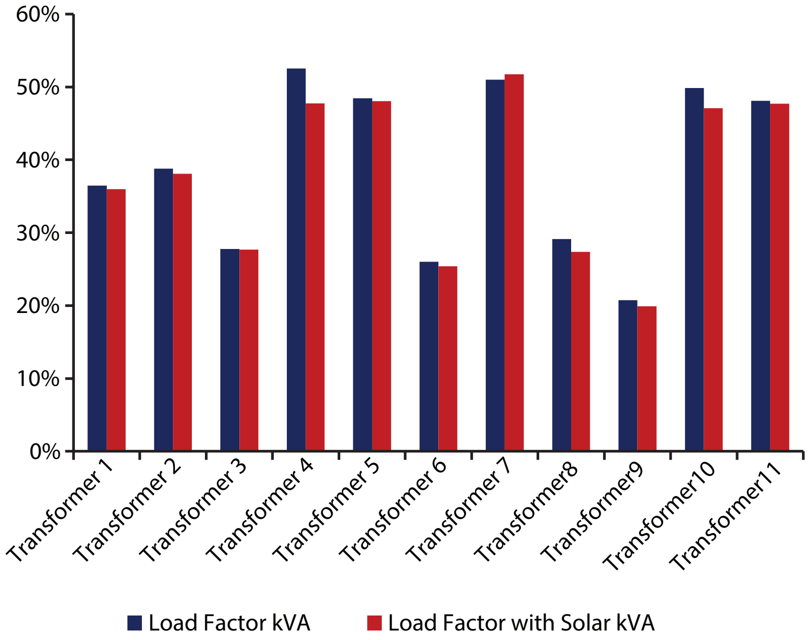

Figure 9: Load factor on distribution transformers on the BRPL feeder

As per the results of the mitigation techniques scenario, shown later, even a small amount of storage could significantly improve the absolute load factor.

In the 4YO50536 scenario, the impact of RTS on peak load reduction on the DTs is interesting to note and is shown in Figure 10.

It can be seen that the reduction in peak loading is seen to be maximum for DT 8 and DT 9 since the RTS systems are directly connected to these. The reduction in peak loading on the distribution lines was also noted and is shown in Figure 11.

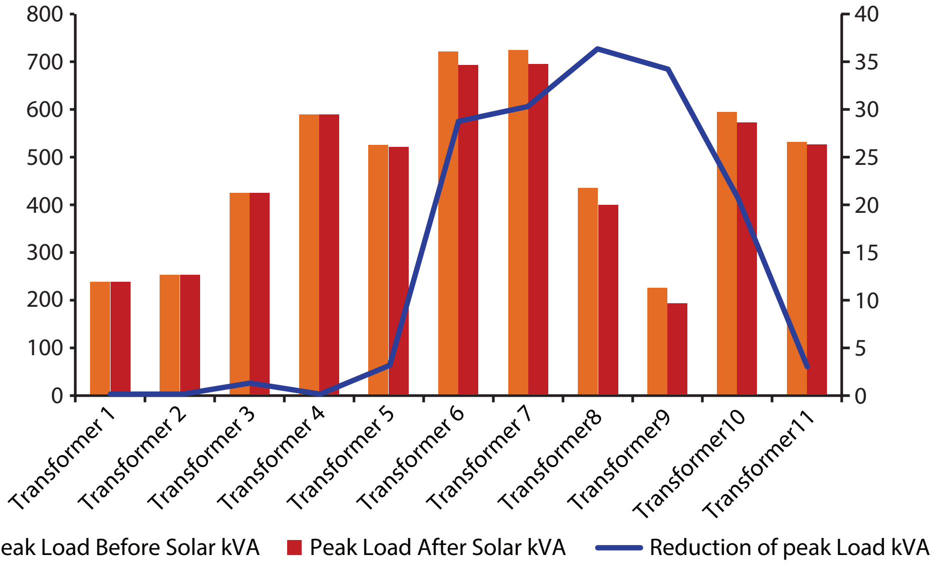

Figure 10: Peak load reduction on distribution transformers on BRPL feeder as a result of rooftop solar integration in a future year

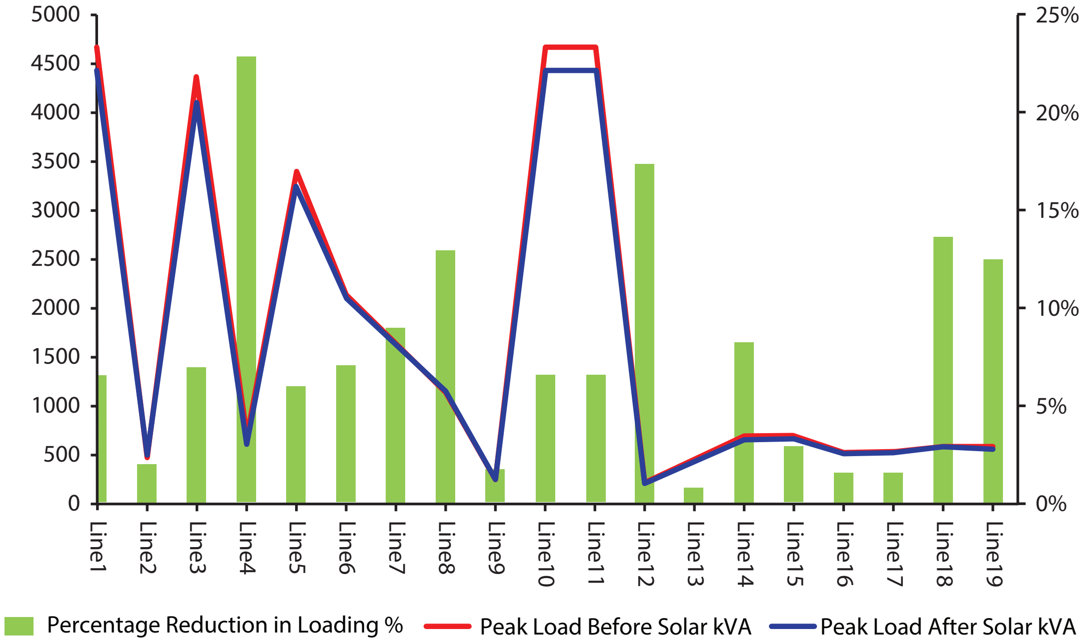

Figure 11: Reduction in peak loading of different line segments on the BRPL feeder

The impact of penetration of RTS in different scenarios on the voltage magnitudes at different buses is an important outcome to note in power-flow studies. It also acts as a factor for selecting candidate buses to apply mitigation techniques to and check their effectiveness. As the focus of this study is more towards LT network side parameters, the phase-neutral voltages for individual phases of each 'load bus' were determined. It is more important to find out which buses tend to experience instances of voltage support (voltage levels are maintained as per the supply code regulations) and where all do we note instances of voltage rise, since lowering of voltage is not a property generally associated with RTS systems.

The base voltage considered was 239.6 V phase-neutral. An RTS system could help improve the voltage profile if its peak generation coincides with the peak load or in any manner contributes to peak time generation, and location of the 'load bus' is relatively closer to the end of the feeder. On the other hand, an RTS system could cause a voltage rise if its peak generation does not coincide with the peak load or in any manner contributes to peak generation, and location of the 'load bus' is relatively closer to the DT. Figure 12 depicts the number of instances where voltage-rise tendency can be observed at each bus throughout the year alongside the number of instances where voltage levels remain within the regulatory limits. This analysis assisted in identifying the candidate buses where various mitigation techniques were required to be modelled and applied to in order to check their effectiveness.

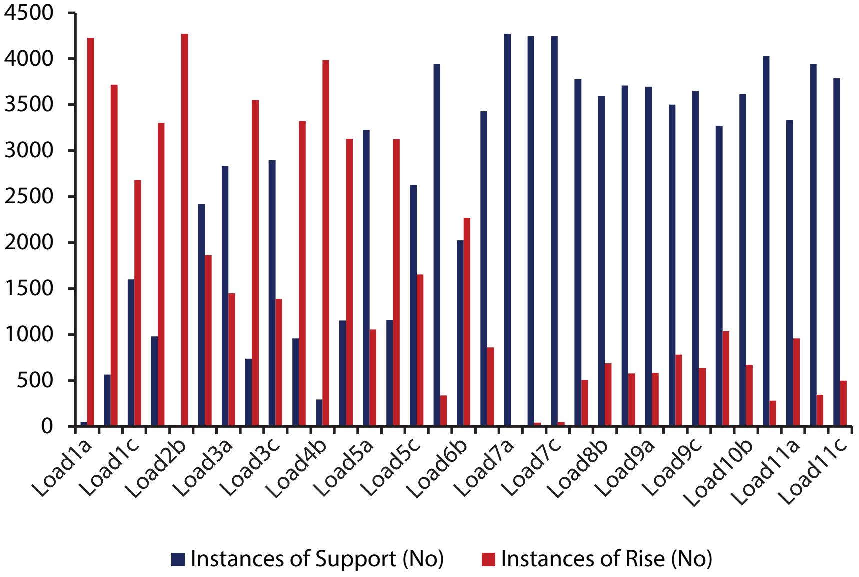

Figure 12: Phase-neutral voltage magnitudes at different buses in the reference case for the BRPL feeder

Selection of Candidate Buses for Applying Mitigation Techniques

On the basis of number and magnitude of voltage deviations observed throughout the year in the 4th year scenario, the buses that require certain interventions to restore voltage levels within the prescribed regulatory limits were selected. Different voltage-rise mitigation techniques like voltage control through smart solar inverters, on-load tap changer (OLTC) at DTs, and battery energy storage system (BESS) were modelled and applied to these buses. The effectiveness of these techniques was then assessed based on the power-flow results. The phase-neutral voltage magnitudes for each load bus in the reference case are plotted in Figure 13 in absolute Volts. These values represent the maximum voltage observed at each bus throughout the year, with RTS and without RTS connected to them. It was found that the highest voltages are found in the case when RTS is connected to a bus and among these buses, the ones with highest duration of occurrence of these voltage magnitudes (mainly during low load and high solar generation hourse) were selected. The tap position for all DTs was kept constant at 1.05 p.u., that is, 435.75 V L-L although the supply code allows upto 6% deviation on the upper side. The buses where the voltage limits are exceeded can be observed. The buses encircled red in the plot observe instances of reverse power flow due to very low load. Based on the results obtained, load Bus 3b, 6b, 4a, 4b, 4c, 11a, 11b, and 11c were selected to test various mitigation measures. Here, a, b, and c refer to individual phases.

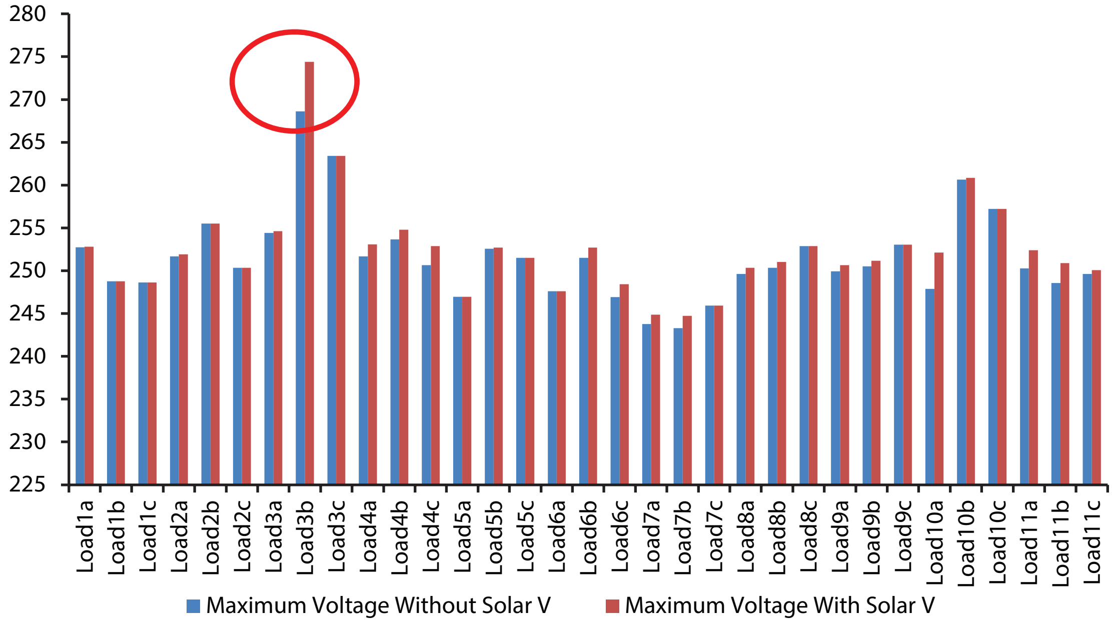

Figure 13: Phase-neutral voltage magnitudes at different buses in the reference case for the BRPL feeder

Voltage-deviation Mitigation Techniques and Power-flow Results

Changes in voltage magnitude at the load buses were reported from the load-flow results for the 4YO50536 scenario. To control the voltage excursions, three mitigation techniques were proposed in the study. The voltage values, without any mitigation technique and with each of the three mitigation techniques in the future scenario, considered for selected buses (having significant over voltages), have been presented subsequently.

Smart Solar Inverters with Voltage-control Capabilities

The solar PV generation system model in OpenDSS, incorporating the physical characteristics, was modified by including the Volt-VAr and Volt-Watt capability of an RTS inverter. The reactive power-based voltage control functionality can modulate the inverter's output power according to the utility grid conditions. Injection/absorption of reactive power based on the grid voltage (bus voltage precisely) is one of the methods to provide voltage control. This feature is analogous to the Q-V droop characteristics of synchronous generators and is a very useful and an effective localized method for voltage control.

The Volt-VAr (VVAr) characteristics used inside the smart solar PV inverter modelled in this study are shown in Figure 14. The parameters on both Y and X axes are given in per unit. It was provisioned that the active power can be curtailed, if adequate excess capacity from the power conditioning unit is not available for VAr support. The direct current (DC)/alternate current (AC) ratio was assumed to be 1 and no restriction was put on VAr support. Figure 15 shows the Volt-Watt characteristics modelled inside the smart solar PV inverter. In this also, the DC/AC ratio was kept unity and no restriction was put on active power curtailment. The active power was modelled to curtail in terms of percentage of generation.

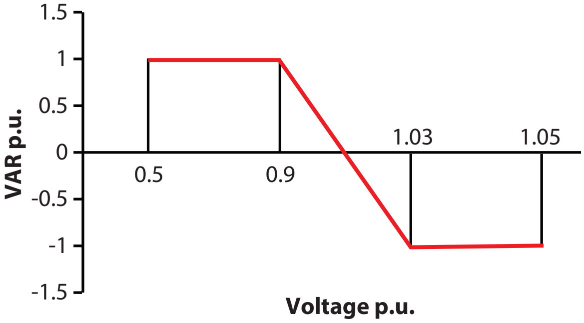

Figure 14: Volt-VAr characteristics of rooftop solar inverter modelled for the BRPL feeder

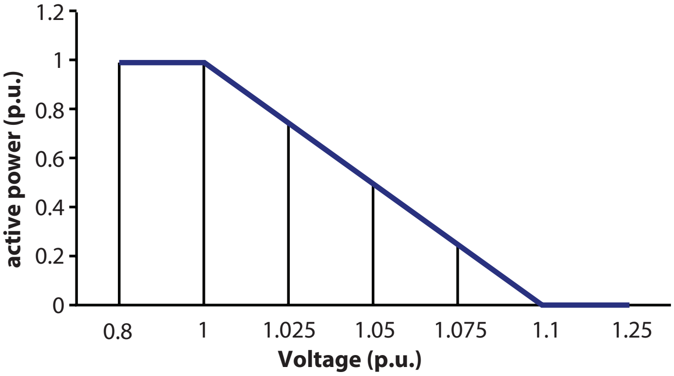

Figure 15: Volt-Watt characteristics of rooftop solar inverter modelled for the BRPL feeder

The effectiveness of VVAr smart inverter technique is shown in Figures 16 and 17. The maximum and minimum voltages obtained at all the critical or candidate buses throughout the year for the scenario having Volt-VAr control versus the maximum voltages obtained without any mitigation technique are shown in Figure 16.

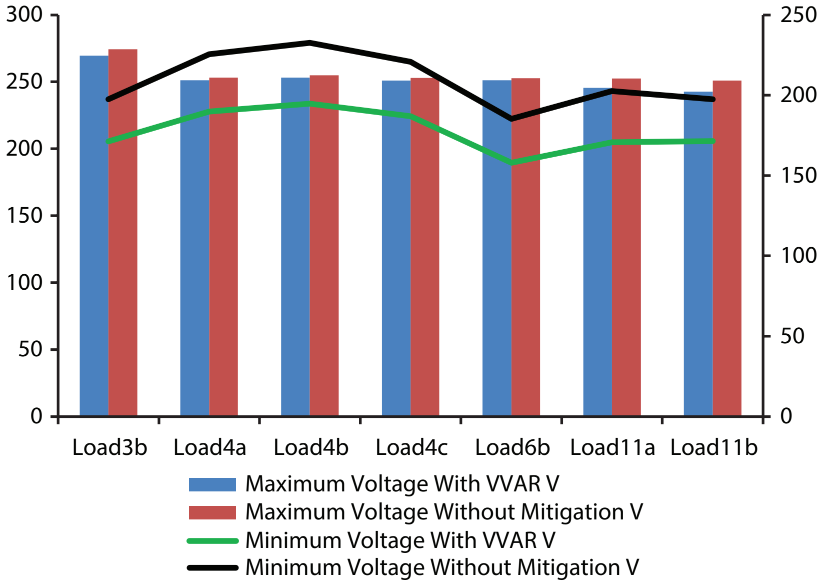

Figure 16: Effectiveness of Volt-VAr smart inverter technique in terms of maximum bus voltages for the BRPL feeder

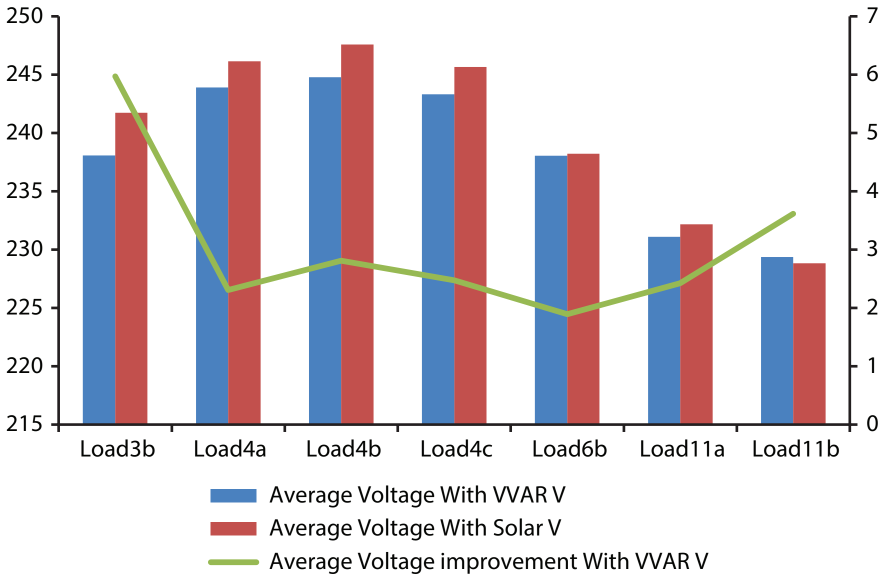

Figure 17: Improvement in average bus voltages due to Volt-VAr smart inverter technique for the BRPL feeder

Figure 17 shows average voltage obtained at all the candidate buses throughout the year for the scenario having VVAr control versus the average voltage observed without any mitigation technique. It also shows the average improvement in voltage at these buses due to VVAr method.

VVAr control has some bearing on the active power output of the RTS inverter since some amount of it has to be compromised to allow more reactive power from a given rating in kilo-Volt-Ampere. Figure 18 shows the relative reduction in active power (for different PV generation units modelled for this scenario) due to use of Volt-VAr control and it can be seen that the reduction in active generation is not much significant over an annual basis and some amount of headroom can thus be provided in RTS inverters to allow for flexible usage of such smart inverter schemes.

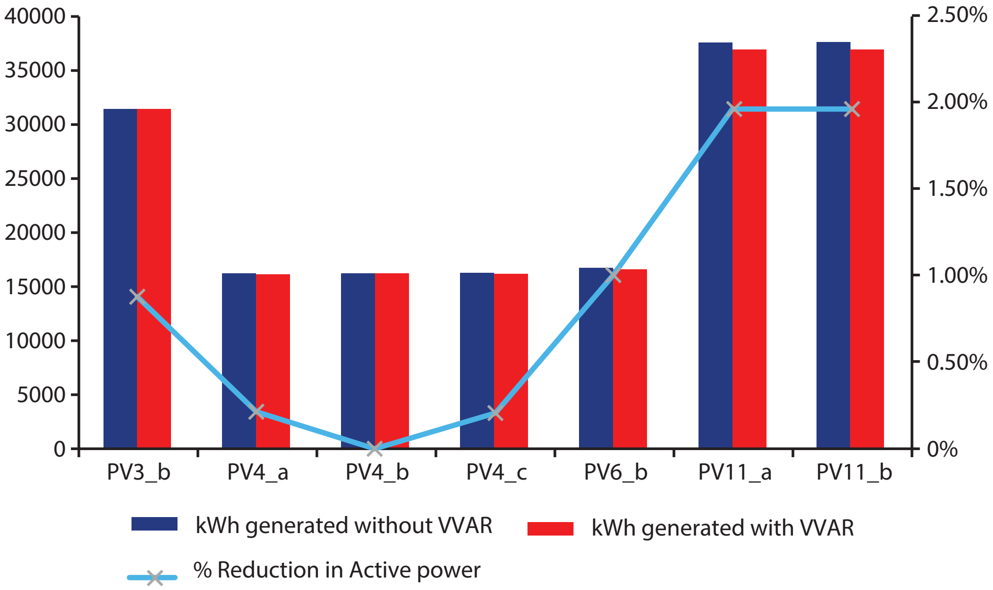

Figure 18: Rooftop solar active power reduction due to use of Volt-VAr technique for the BRPL feeder

Figure 19 shows the maximum voltage obtained at all the candidate buses throughout the year for the scenario having Volt-Watt control versus the maximum voltages obtained without any mitigation technique.

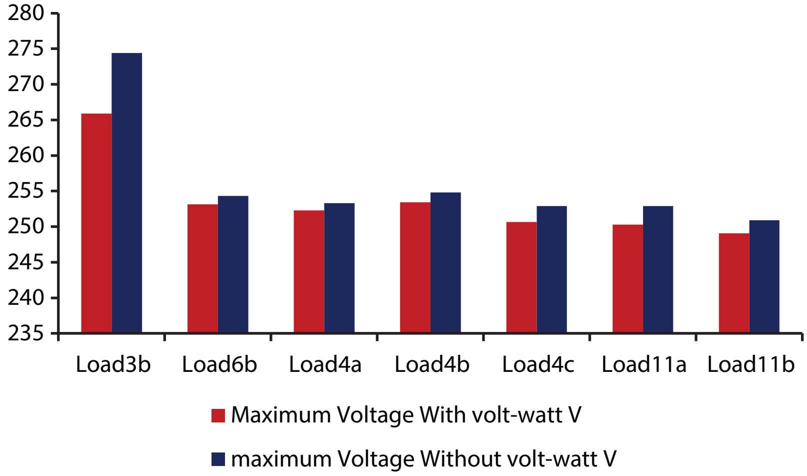

Figure 19: Maximum voltage at critical buses with and without Volt-Watt smart inverter technique for the BRPL feeder

For the Volt-Watt control method, the loss of active power generation could severely be reduced, if no cap is applied on kilo Watt curtailment. Figure 20 shows the effectiveness as well as the risk of using kilo Watt curtailment as a measure for voltage control. It can be seen that the maximum loss in active power generation is 69% for load bus 3b. Feasibility of the same in these cases is questionable. A slight variation in the operational characteristics could change the effectiveness of this mitigation measure since reduction of active power may not be entirely appropriate although a techno-economic analysis is required to study the two smart-inverter based voltage-control techniques for providing a cost-effecctive and reliable volatge mitigation approach.

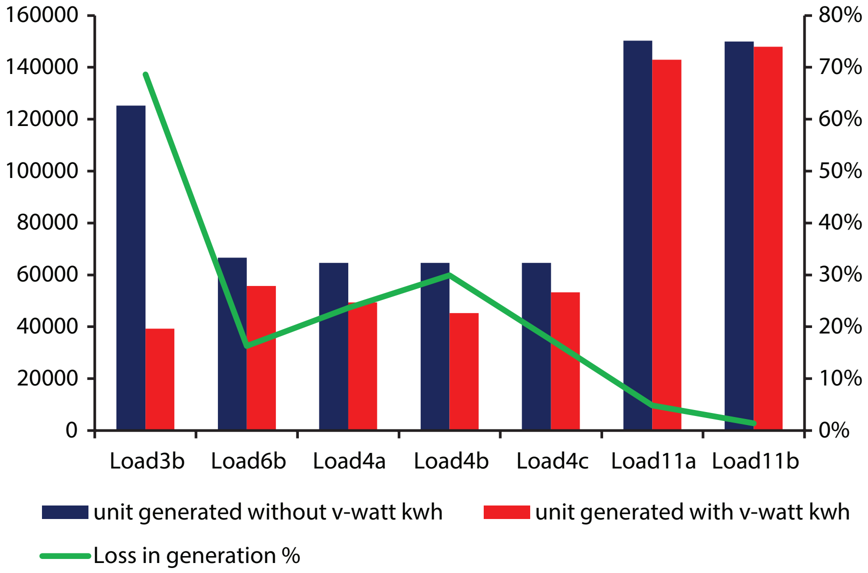

Figure 20: Loss in active power generation due to use of Volt-Watt control technique for the BRPL feeder

On-Load Tap Changers at DTs

One of the effective methods of voltage control is from the utility side through the supply-side voltage transformation ratio. OLTC control is one such method for regulating downstream voltage. Three-phase OLTC in the form of three one-phase transformers was modelled in OpenDSS for the selected buses. The control/regulation set point was accordingly modelled to run the three-phase load flow. An illustration of the modelled OLTC scheme is shown in Figure 21.

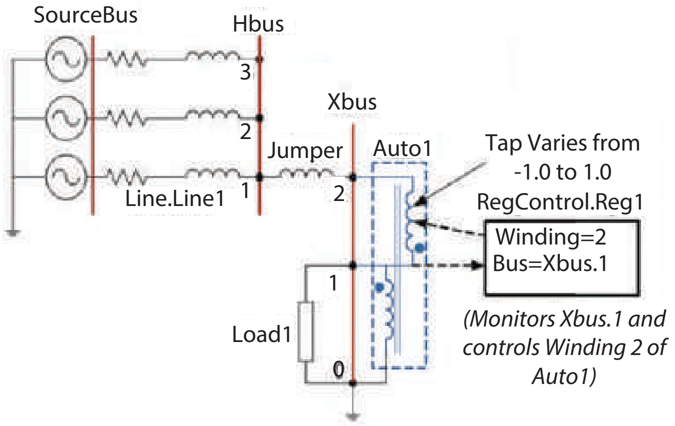

Figure 21: On-load tap changer model for the BRPL feeder

The DT is assumed to have 32 auto taps. The OLTC was modelled as single-phase auto transformers having +/- 10% step voltage regulators. Two operating bands were considered:- operating band 1: +/- 8 V and operating band 2: +/- 4 V. The R and X parameters were set for voltage control at the load end. It must be noted that the number of tap changes severely affects the life of an OLTC distribution transformer [4].

Figures 22 and 23 show the maximum and minimum voltage obtained at all the candidate buses throughout the year for the scenario having OLTC band 2 control (2 V step control) and OLTC band 1 control (4 V step control), respectively, versus the maximum and minimum voltages obtained without any mitigation technique.

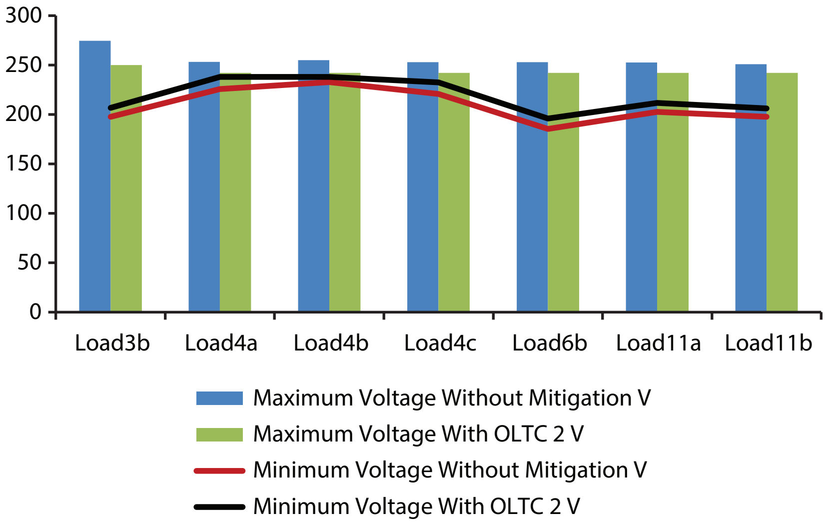

Figure 22: Minimum and maximum voltage at critical buses with and without 2 V on-load tap changer control for the BRPL feeder

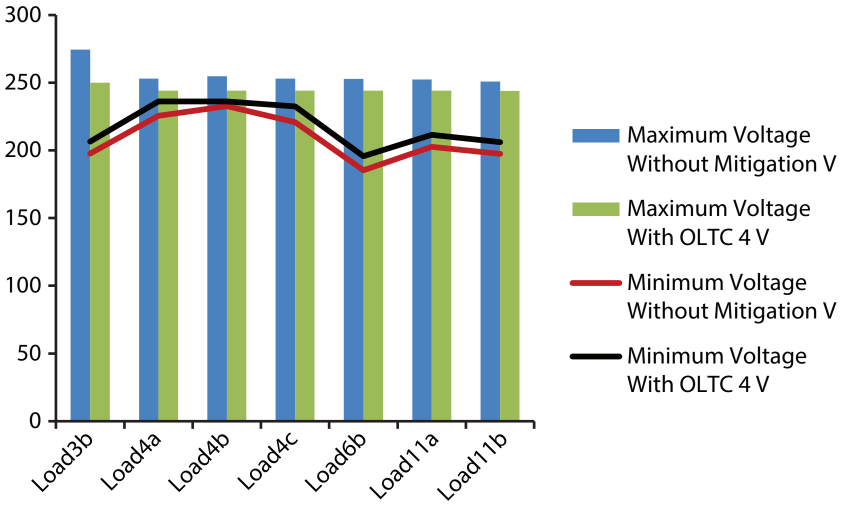

Figure 23: Minimum and maximum voltage at critical buses with and without 4 V on-load tap changer control for the BRPL feeder

Figures 24 and 25 show average voltage obtained at all the candidate buses throughout the year for the scenario having OLTC band 2 operation control and OLTC band 1 operation control, respectively, versus the average voltage observed without any mitigation technique. It also shows the average improvement in voltage at these buses due to Volt-VAr method.

Although OLTC can be used to effectively regulate the voltage but the control point or setting that is used to compensate for the line loss requires the control point to be properly defined. In reality there are multiple control points (so a compromise has to be reached) or end points, however, in this case there was only one control point per phase per DT. The cost of installing an OLTC per DT is significant, speaking for the Indian setup.

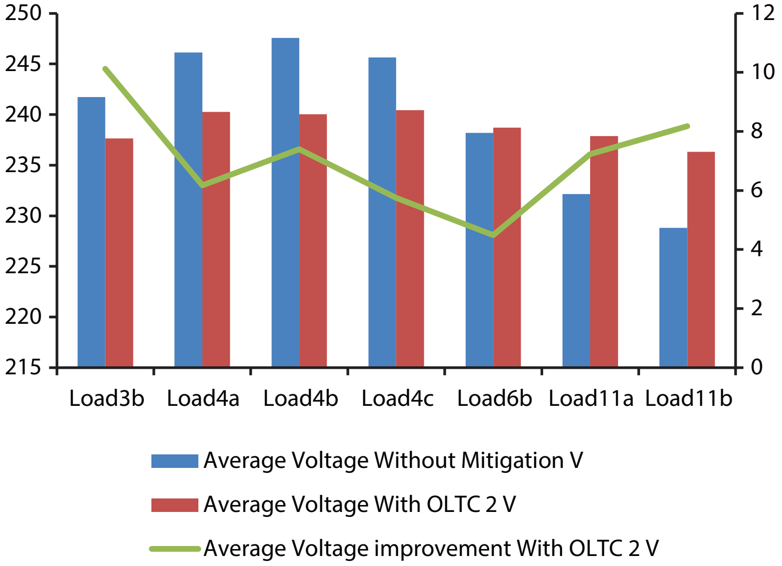

Figure 24: Improvement in average bus voltages due to on-load tap changer2 V step control technique for the BRPL feeder

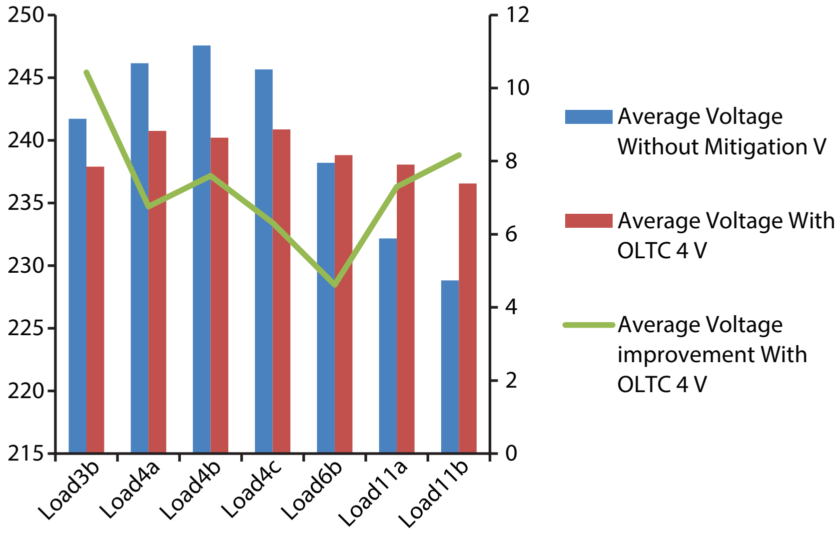

Figure 25: Improvement in average bus voltages due to on-load tap changer 4 V step control technique for the BRPL feeder

BESS for Localized Voltage Control

A BESS was modelled to examine its capability as a voltage control technique. The sizing of the battery for this application was based on finding a correlation between the voltage magnitudes at the 'critical' buses and the power flows along the lines connecting those buses. Based on the maximum amount of power flow observed in relation to a significant voltage excursion, an appropriate kWh and kW capacity was decided for a BESS to be installed at the 'critical' buses.

A small battery of size 50 kWh was modelled. The BESS was assumed to provide only active power. A battery logic was developed, analysing load and voltage profile. The logic for the BESS units kept at load bus 4, 11, and 6 is shown in Figure 26.

The impact of BESS on voltage improvement depends on

I. Size in kWh and maximum C-rate.

II. Battery charge and discharge logic.

III. Current voltage profile

The percentage charge and the percentage discharge values were decided arbitrarily from the voltage profile and the net-load curve. Figures 27 shows the maximum and minimum voltage obtained at all the candidate buses throughout the year for the future year (4th year from base) scenario with BESS-based voltage control and without BESS-based voltage control.

Figure 28 shows a plot for a typical day in the 4th year scenario where voltage profile throughout the day for a particular bus, with and without BESS and having no mitigation technique in place can be seen. Also, the battery parameters like state of charge (SoC) and rate of charge/discharge in kW can be seen varying throughout the day.

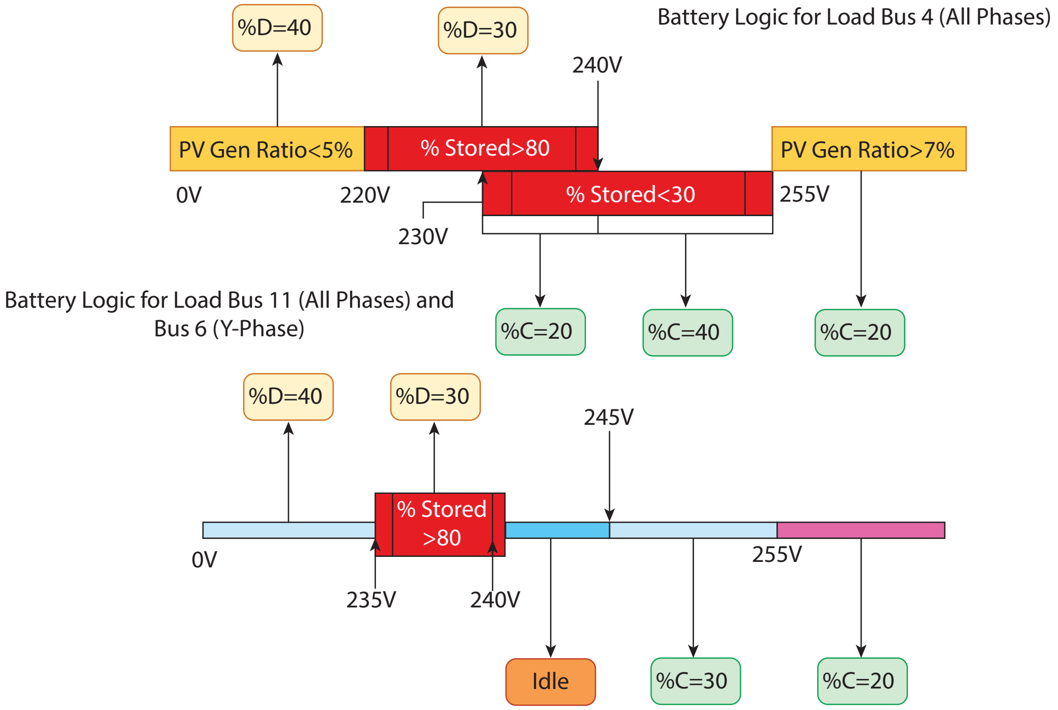

Figure 26: BESS control logic for bus voltage improvement for the BRPL feeder

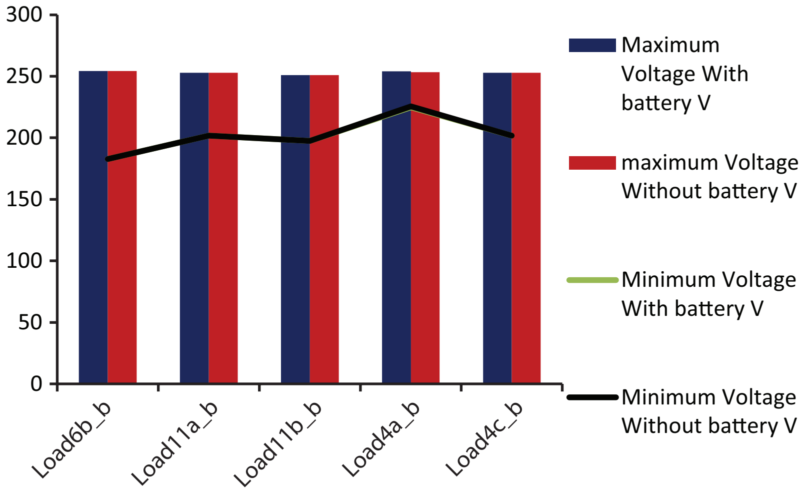

Figure 27: Minimum and maximum voltage at critical buses with and without battery energy storage system-based voltage control for the BRPL feeder for the 4th year scenario

It can be seen that there is no significant increase in the average bus voltage and a very marginal reduction/increase in maximum and minimum voltage. This may be due to lack of sufficient slots to charge/discharge that may not be available according to the defined logic. The SoC range of above 20% or below 100% makes the BESS non-operational, which leads to it poor effectiveness.

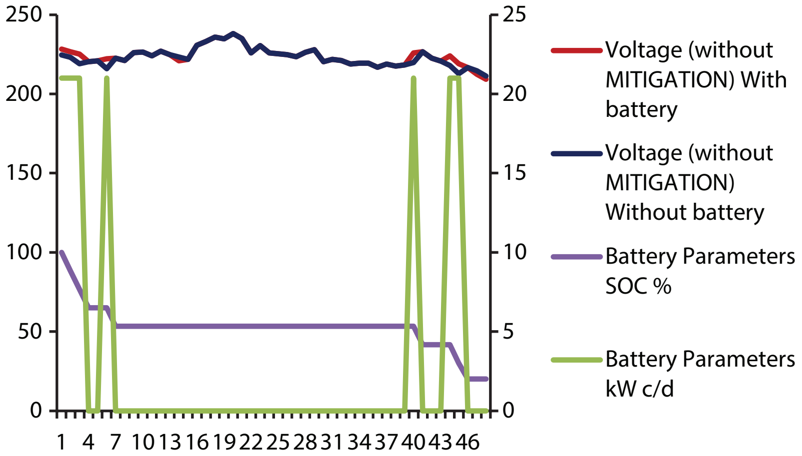

Figure 28: Voltage (without any mitigation technique) with and without battery energy storage system at a particular battery energy storage system and its parameters for a typical day in the 4th year scenario for BRPL feeder

Concluding Remarks

Based on the exhaustive simulation studies presented above, the following observations can be made regarding the effectiveness of the three mitigation measures modelled for controlling the volatge-related issues:

- Volt-Watt control was found to be useful in some cases
- However, if sufficient kVA rating is available, then Volt-VAr control is more effective however a techno-economic option needs to be worked out for selecting the most appropriate smart-inverter based voltage control option
- BESS was not found to be much effective in voltage control
- OLTC is a mitigation technique whose costs will have to be seriously considered over the benefits, if they are able to be quantified

Modeling Approach for West Bengal

The typical characteristics of the WBSEDCL feeder including the Single-Line Diagram (SLD) were presented in the previous chapter. To undertake the power-flow studies, the following steps were taken as part of the modelling approach used in OpenDSS:

1. Building a library of the equipment used in the feeder: An equipment library was created based on the data provided by the DISCOM and some approximations.

2. Creating the network model.

3. Creating the load and PV model

The conductor lengths and types were indicated in the SLD provided by the DISCOM. The electrical parameters corresponding to the conductors were found out from the manufacturer's manuals and put in the openDSS program to model the overhead lines. As mentioned above, a library of overhead conductors was first created, as is the approach in OpenDSS scripting. Then, by defining the buses as per the SLD, the overhead lines were drawn between the respective buses to model the conductor or line segments. Similarly, transformers were added in the network model by first creating a library of the transformer model, available inside OpenDSS, for different capacities of the DTs and then adding the DTs to their respective buses. The tap settings of each DT were kept as per the field practice so as to have a secondary side voltage of 433 V. The institutional premises houses many buildings such as hostel blocks, a school, a bank, a college, an administration block, and a kitchen. The electrical load on the network physically corresponds to the equipment or appliances inside these buildings that are connected to the network at 415 V and are individually metered. There are five net-metered-distributed RTS connections installed on the rooftops of some of these buildings, as mentioned in the previous chapter. The conductor length to these loads on some of the buildings, beyond the secondary of the DT serving them, was given in the SLD. For some of the other such loads, some conductors' length extending beyond the secondary of the DT serving them was judiciously assumed based on site survey results. Since the RTS PV systems are actually connected on the 415 V network, more realistic impacts of their integration could not have been observed if the loads on these buildings would have been lumped at the DT secondary bus. Hence, the distribution network was modelled to the best extent possible till the low voltage side, extending till the loads.

Load Modelling

Many studies have aggregated both solar PV and load at the DT level thus simplifying the model as the data available with the distribution utility is usually aggregated at a DT level. However, this approach fails to estimate the voltage profile obtained at the distributed load end. To identify the over-voltage/under-voltage issues pertaining to large-scale RTS penetration, it is important to model the secondary side of the DT [8]. Aggregating loads could also lead to overestimating voltage

magnitudes at buses resulting in conservative estimates on the hosting capacity. To ensure that realistic voltage profiles are observed and to show the necessity of modelling distributed load (secondary side of the DT) at various distances from the DT, the secondary side of one such DT in the feeder was accurately modelled from the data obtained from site survey.

Since the loading values were available in the form of net feeder load, the gross feeder load was obtained as $P_{\text{gross feeder}} = P_{\text{net}}$ + corrected estimated P_{solar}. The gross feeder load was then distributed among the seven DTs based on the typical loading pattern for the DTs, as provided by the utility. For one DT (on bus 3), its share (of the gross feeder load) was further divided into four values to model loads on the low voltage network emanating from its secondary. Furthermore, for two consumers (building loads), net-metered bill for 1 month was also provided. The estimated solar PV generation (for that month) was added to the net values (for respective DTs) to get the 'actual gross load' (DT side loads). Since, for these two DTs, the values of actual gross load, estimate gross load, and percentage estimate gross load (proportion of gross feeder load, estimated) were available, a generalized relation could be devised to find out the actual gross load for each DT by re-adjusting the proportion of 'estimate gross feeder load' as in Equation 1.

$$\text{Actual} = \frac{\text{Actual (\%)}}{\text{Estimate Value}} \times \text{Estimate (\%)} \qquad \text{(Equation 1)}$$

These data were available at 1-hour interval and was obtained using log sheets maintained by the DISCOM. The allocation of load to each DT based on the feeder load was done for each time interval, as explained above. The category/subcategory of consumers present on this network is as follows:

1. Educational institute
2. Hostel blocks
3. Bank
4. Commercial complex

Since the load data was available only at 11 kV feeder level, the allocation of the load to each DT and subsequently, each low voltage-side consumer had to be done. A spreadsheet based tool was built and used for allocating load to each DT. For the DTs for which the secondary side could not be modelled in detail, the load was lumped at a distance from the DT. This average distance from the DT to a load was obtained from a map created after site survey. Using the above-mentioned spreadsheet tool, load pattern for each category was estimated considering the consumption pattern for each DT in consultation with DISCOM officials. This was done while ensuring that the respective monthly consumption is almost the same as that obtained from the electricity bill. It was also cross-checked that the peak demand, as seen in the load curve given in Figure 29 is lower than that mentioned in the electricity bill of the respective month. Modeled loads represent buildings on the campus such as hostel blocks, a kitchen, a school, and a college.

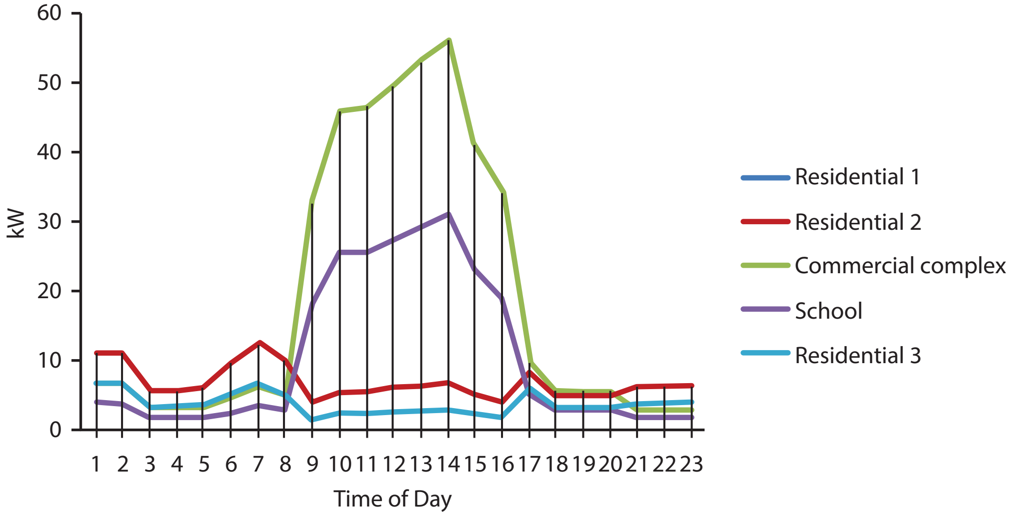

Figure 29: Load profile for different consumers for a typical summer day for the WBSEDCLfeeder

Solar PV Modelling

The solar PV two-diode-equivalent model as available in OpenDSS was used. However, the temperature irradiation-based variant was employed. The major aspect of PV modelling in this exercise focused upon estimating the 1-hour interval power generation values for the RTS PV power plants. Actual generation data (through remote monitoring) of 15-min interval (for the same time period of 1-year duration as that for the load) for four out of five existing plants was downloaded from the remote monitoring portal. There were substantial missing values in this dataset. All the PV systems were then modelled in HelioScope and using the actual generation data, the error in HelioScope generated data was reduced.

Solar generation data correction: Δ = Actual generation - HelioScope value. Mean (Δ) was used to adjust each individual row having missing actual values to get an approximate number. This dataset was extrapolated to 1-hour interval data to be used for simulation using linear interpolation.

Load-flow Analysis: Approach and Scenarios

After the rigorous exercise of modelling the loads and the solar PV and incorporating them in the detailed network model, the load-flow simulations were run to analyze the voltages at all the buses and the line power flows. Considering the evident unbalance in load values and the extensive detailed modelling of the feeder, distribution load flow was adopted. An iterative power flow based on the forward–backward sweep algorithm was run in OpenDSS.

The power-flow program was run for the base case wherein the network was analyzed with the present scenario's data, that is, for the network 'as it stands'. Load data and solar PV capacity for 1-year period from May 2016 to June 2017 was used in the base-case scenario and a yearly time series load-flow simulation was run. Hence, the current load and the existing solar PV systems scenario gave the baseline results to benchmark against. However, growth in load on a distribution feeder is inevitable. Similarly, PV systems capacity addition is also foreseen for the feeder studied. With increasing penetration of solar PV systems in different scenarios, some impacts would be observed and hence a technology option to mitigate the same must be modelled as well. Accordingly, three more scenarios were designed to capture the load and PV growths and the impact of changing the solar PV inverters to smart inverters, at selected buses. The various scenarios modelled for this study have been described in Table 4. The load growth scenarios were based on assuming a CAGR of 6%–8%, in discussion with the utility. Hence the current DT loading was scaled up by this growth factor to find out the loading for the subsequent year in order to create the scenarios that follow the base case. For estimating the growth in solar PV capacity installed on the feeder, the total technical potential of RTS PV that can be installed in the premises was estimated. For this, the approach of GIS mapping of building rooftop area was used to calculate the effective area available for installation of solar PV systems. Based on the standard factor of area required per kilo Watt peak of solar PV capacity, a total available potential of 537 kWp was found out for the feeder. For simulating PV growth, 200 kWp of this capacity was added to the current installed capacity since the resulting PV capacity was less than the available potential. Accordingly, the Cases 2 and 3 were designed having these amounts of load and solar PV growth as common for both, use of smart solar PV inverters being the only point of difference.

Table 4: Power-flow scenarios for the WBSEDCL feeder

Case	Load	RTS Capacity	Smart Inverter
Base Case	Current load	Existing capacity	No
Case 1	Current load	Existing capacity	At selected LT buses
Case 2	6%–8% CAGR load growth	Addition of 200 kWp of distributed capacity	No
Case 3	6%–8% CAGR load growth	Addition of 200 kWp of distributed capacity	Additional smart inverters at selected buses

CAGR: Compounded annual growth rate; LT: Low tension; RTS: Rooftop solar.

The time series load-flow program gave 8760 values of voltage magnitudes for 8760 continuous instances in a year or the scenario year considered for all the buses modelled. For this study, the lower and upper limits of bus voltages considered were 0.95 p.u. and 1.05 p.u., respectively. The WBERC (State Electricity Grid-code) Regulations, 2017 specifies the voltage to be maintained within the limits of 0.94–1.06 p.u. Therefore, maintaining the bus voltages within the limits considered in this study will ensure compliance with the state grid code. A narrower and more strict operating voltage range was thus selected for the PV inverters, covering practical voltage drop.

Load Flow Results for West Bengal

For the base-case scenario, the power-flow results gave contrasting results for bus voltages, measured at different buses on the feeder. Figure 30 shows the voltage values, over the year, at the bus where load 1 is connected (Bus 6 on the feeder SLD shown in chapter 2). It shows the hourly variations in one-phase voltage magnitude of the bus where load 1 is connected. These are observed to be within the limits considered in this study. However, for the base case only, if we observe the results for voltage magnitudes at the bus where load 7 is connected (Bus21 on the SLD), the story is different. Since this bus was modelled in greater detail on the low-voltage network extending beyond the DT secondary (connected to Bus 4 on the feeder SLD), the voltage magnitudes are on the higher side, as shown in Figure 31. This bus has a considerable amount of solar PV installed and it is observed that the one-phase voltage magnitudes are not within the bounds taken in this study. The effect of detailed modelling of the secondary-side low-voltage network gives a realistic estimate of the voltage on the bus. For the base case, over-voltage issues were observed for buses at which loads 7, 8, 9, and 10 are, respectively, connected. Accordingly, Case 1 was then designed wherein some of the solar PV inverters at some 415 V buses were replaced by smart inverters. After running the power flow for Case 1, all the bus voltages were brought within the limits considered. Thus, the effect of modelling smart inverter functionality and introducing it at some of the 415 V buses could be first observed. The Volt-VAr characteristics modelled in this case are shown in Figure 32.

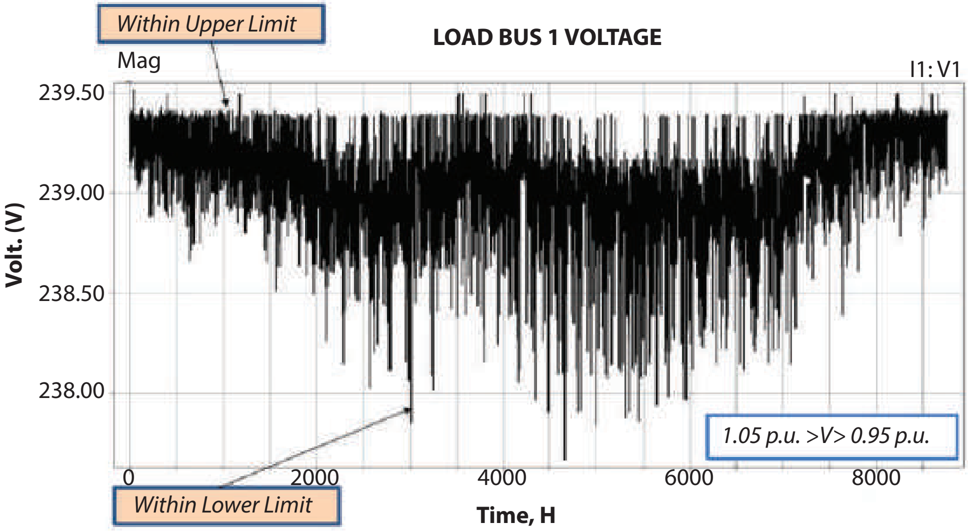

Figure 30: Hourly variations in one-phase voltage at load bus 1 for WBSEDCL base case

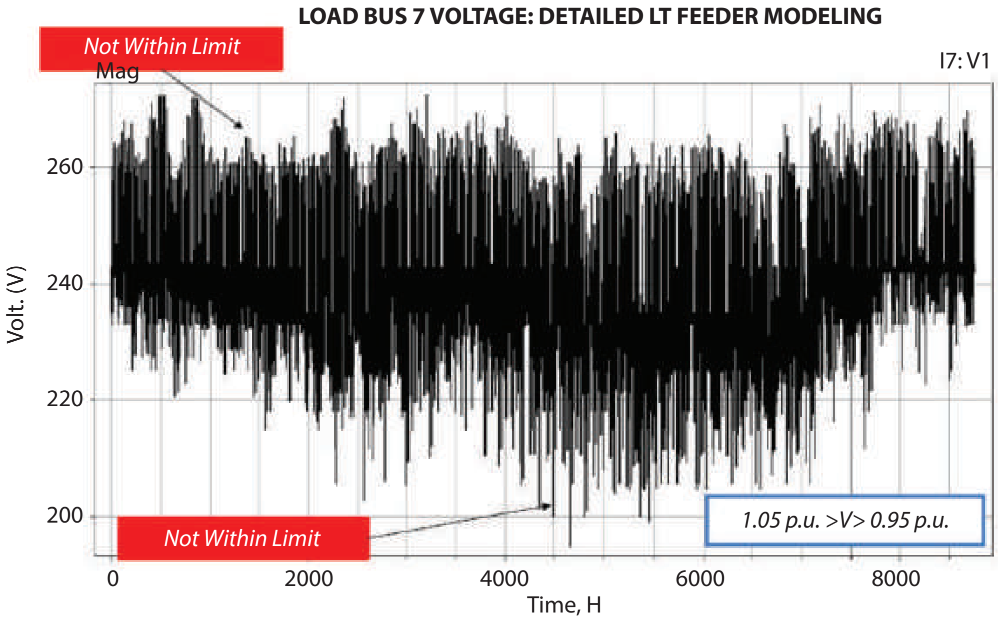

Figure 31: Over voltages observed at a low tension bus for base-case scenario for WBSEDCL feeder

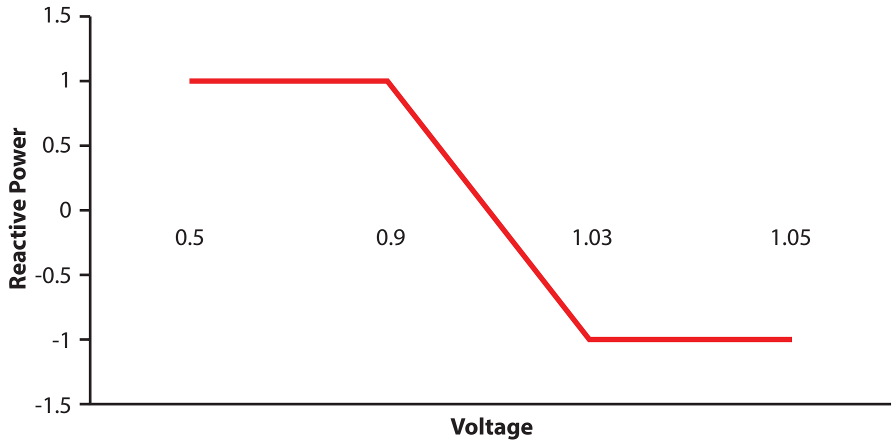

Figure 32: Volt-VAr characteristics of the smart inverter modelled for WBSEDCL feeder study

By keeping the mix of normal solar PV inverters and smart inverters as in Case 1, the DT loading was scaled up and 200 kWp of distributed solar PV capacity was added to create Case 2. The power flow was run and it was found that all the voltage magnitudes, except for the ones observed at bus 27 and bus 28 where load 2 and load 5 are connected, respectively, remain within the limits. This prompted the design of Case 3, which is exactly similar to Case 2, however, some additional smart inverters replaced the normal solar PV inverters at some selected buses. After running the power flow for Case 3, it was found that all the bus voltage magnitudes are within the limits considered in this study.

Since over-voltage issues in Case 2 were observed at buses where load 2 and load 5 are connected (as mentioned above), smart solar PV inverters were introduced at these buses in Case 3. At this stage, the voltage control effect of smart PV inverters could be very well observed. To understand the effect of having some smart solar PV inverters on a distribution feeder on a typical day's operation, a daily load-flow program was also run. The loading pattern of the DTs was observed and representative loading days from summer, winter, and monsoon seasons were chosen. The load flow for each typical summer, winter, and rainy season day was run for Case 2 and the voltage profile over 24 h of a day was observed at two critical buses: Buses 27 and 28 where loads 2 and 5 are connected, respectively. Keeping the smart inverter placement as in Case 3, the daily load-flow program was run again. The daily voltage profile for bus 27 (load 2) and bus 28 (load 5) was observed again. This comparative graph of voltage profiles for the said buses for Case 2 and Case 3 is shown in Figure 33. The blue line and the red line represent the Cases 2 and 3, respectively.

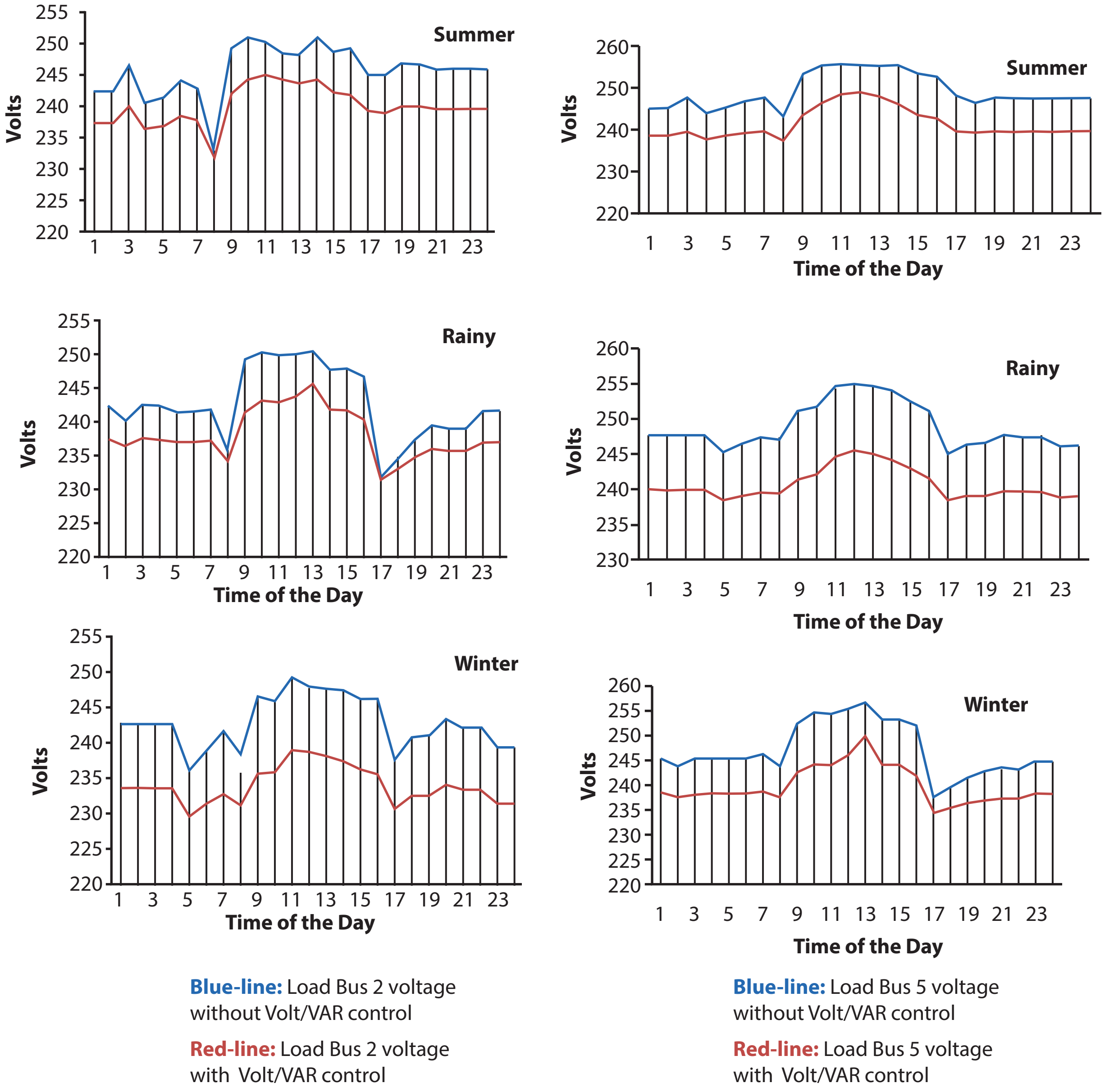

Figure 32: Typical summer, winter, and rainy season days' critical bus voltage profiles for Case 2 and Case 3 for WBSEDCLfeeder

The effect of the Volt-VAr control feature inside the smart inverters can be very well observed. Thus, even for high levels of solar PV penetration, use of smart inverter functionality can enable effective integration into the network by mitigating voltage issues, if any.

The voltage-related impacts of increasing RTS penetration levels were presented in this chapter through illustrative load-flow studies. The next chapter describes the results of on-site harmonic measurements for studying the possible power-quality impacts of RTS on the feeders.

5. Results of Harmonics Measurement Based Analysis

Power quality is one of the important aspects to be considered while integrating distributed renewable energy (DREs) into the distribution network, especially when these sources have intermittent generation. In order to evaluate the impact of solar PV systems on distribution equipment, it is imperative to inspect the harmonic content (voltage and current) in the power flow. With the increasing proliferation of non-linear loads and intermittent and inverter-based generation sources into the distribution system, harmonic injection into the system is expected to rise that might reduce the service life of distribution assets. The power conversion system of a rooftop solar (RTS) system has significant impact on harmonic injection into the network since it produces non-sinusoidal current and voltage waveform. Hence, it is important to measure the system harmonic levels in the presence of RTS systems.

A distribution transformer is one of the most important and expensive components of a distribution network that is generally utilized to interface the load with electricity supply. It is, therefore, essential to examine the impact of harmonic currents and voltages on the service life of a distribution transformer. Harmonic voltage increases the losses in magnetic core whereas harmonic current increases losses in the winding and structure. Direct Current (DC) offset is also another impact that degrades the supply to various equipment due to presence of DC ripple in the output supply. Generally, the pr esence of harmonics in the supply is directly related to heating losses in the winding, eddy current, and stray losses in the magnetic core. With an objective to meet the ambitious target of 40 GW grid-connected RTS power systems under the phase-II of the MNRE programme, the Central Electricity (CEA) amended the regulations related to 'Technical Standards for Connectivity of Distributed Generation Resources' in February, 2019. The standards specify that the limits for injection of current harmonics at the Point of Common Coupling (PCC) by the user, method of harmonic measurement, and other such matters, shall be in accordance with IEEE-519:2014 (limits are given in Tables 1 and 2). The standard also specifies the compliance provision for measurement and metering devices for Power Quality (PQ) parameters measurement as per IEC 61000-4-30 Class-A. Furthermore, voltage unbalance is recommended to be 3% as per American National Standard for Electric Power Systems and Equipment (ANSI) C84.1. Since there are no standards available for current unbalance, as per NEMA MG-1 standard, the maximum standard limit of current unbalance due to 3% of voltage unbalance can be advised as 30%. At this point, it is important to note that different state regulations in India define various allowable levels of harmonic injection at different voltage levels. However, most of these limits are based upon the values guided by internationally accepted standards like those published by the IEEE and IEC.

As the RTS penetration is set to rise, it is important to assess and analyse the levels of harmonic content that will be present in the power flowing in the LT network where most of the RTS systems would come. Accordingly, on-site measurements were done for two sites in the WBSEDCL and BRPL network to gauge the present scenario of power quality. These sites belong to the same feeder for WBSEDCL. However, in the case of BRPL, since the feeder modeled for load-flow studies was under preventive maintenance, another feeder having similar configuration and consumer mix, in the same division, was used for making power quality measurements. It is believed that the results may reflect the characteristics and behaviours of the systems in BRPL license area belonging to that division or area where these feeders are situated.

On-site Measurements for Power Quality Analysis of Solar PV Sites in BRPL Area

Measurement Analysis for 512 kWp Solar PV Plant

In order to study the PQ issues, a grid-connected solar PV plant (512 kWp) at a residential site in Delhi was selected for the analysis. The PV systems are connected at the secondary side of a 630 kVA, 11/415 V distribution transformer, dedicated to feed the PV-generated power to the utility grid. Output of PV plants is subdivided in to three sections, one having total output of 189 kWp and other two having 161 kWp each. There are three meters in place to measure the power flow through these sections individually.

Two highly accurate and precise PQ meters were used to measure the key electrical parameters, which create PQ problems. The Fluke make analyser (Model no. - 435-II) was connected at secondary terminal of the DT having three-phase four-wire configuration and the other PQ meter of HT Italia make (Model no.- PQA 824) was connected at the solar metering point wherein 189 kWp PV plant outputs are adjoined. Some of the measurement parameters selected in the instruments are: voltage/current harmonics (1st to 20th order), voltage/current unbalance, frequency, active power, voltage, current, etc. Integration/sampling time for the data logger of meter was selected as 30 s and the total duration of measurement was 24 h (consists of total 2880 data points).

Observations (PQ meter connected at LT terminal of DT)

Power supply frequency was in the range of 49.7–50.2 Hz, which is within the permissible range of 49.5–50.5 Hz. Voltage unbalance measured in the form of magnitude of negative and zero sequence voltage values was also observed to be within the standard limit (3%) while the maximum value of negative sequence-based unbalance was around 1.6%. On the other hand, current unbalances were very high (up to 300%) for a few instances since the value of neutral current is almost close to phase current in this case, as can be seen in Figure 34, which shows the magnitudes of negative and zero sequence currents measured throughout the day. However, the current unbalance was found to lie within the standard limit (<30%) when phase current is much higher than neutral current.

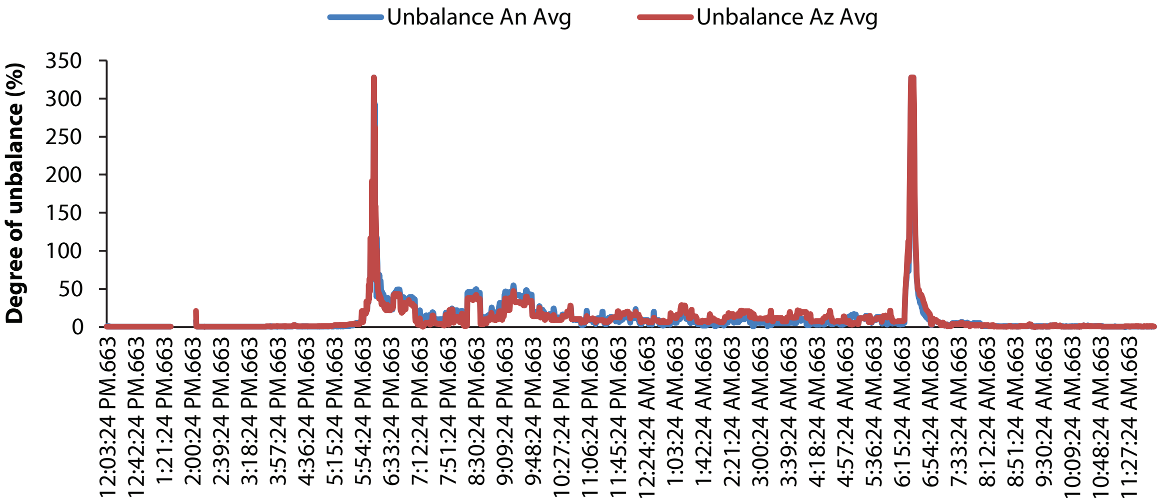

Figure 34: Current unbalance observed at the BRPL site

Further, power flows through individual phases were analysed and it was perceived that some amount of reverse (in contrast to the actual upstream power flow in this case) power (up to 1–2 kW) is flowing to the downstream network (high tension to LT) particularly when solar irradiance was significantly low or negligible. This can be seen in Figure 35 where active power for each phase has been measured throughout the day.

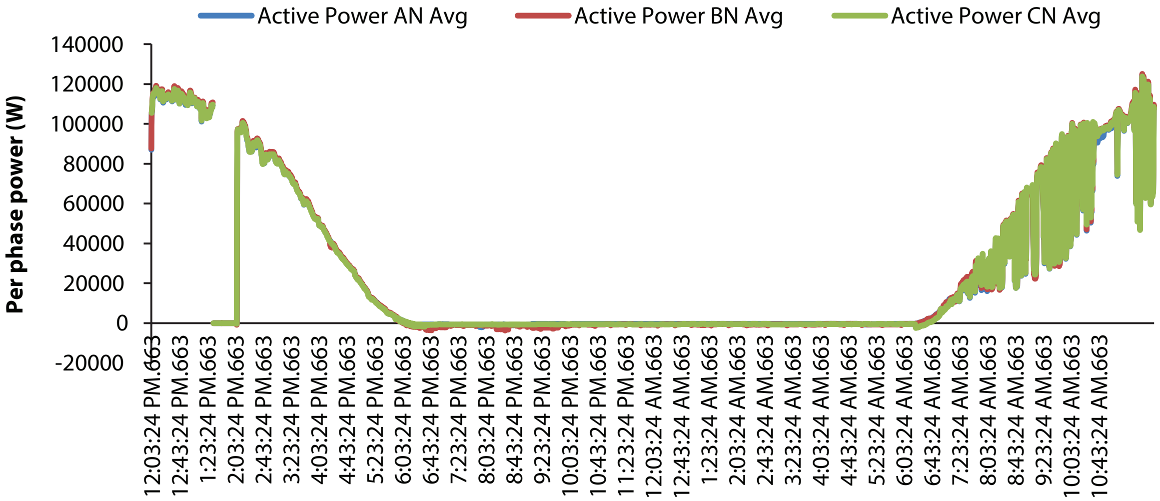

Figure 35: Active power flow through individual phases for the BRPL site

Voltage and Current Harmonics for the BRPL Feeder

Voltage harmonics were observed to be within the permissible range (<5% for individual harmonics and <8% for THD$_v$) while the maximum value was found to be 2%, corresponding to the 5th order harmonic. Current THD$_i$ value exceeded 300% especially when phase currents magnitudes were much lower (<10 A) than maximum demand current at PCC as can be seen in Figure 36.

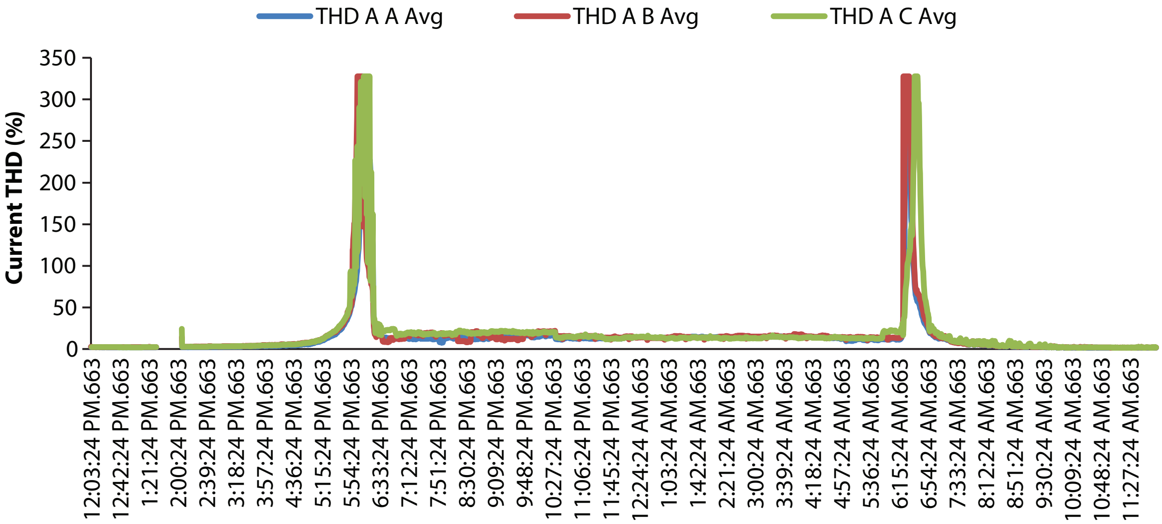

Figure 36: Total harmonic distortion in individual phase current for the BRPL site

Individual current harmonic components were also analysed from recorded data and it was observed that 5th and 11th harmonic contents are out of the standard limit, particularly when current flowing through each phase is lesser than 20 A approximately, as can be seen in Figure 37.

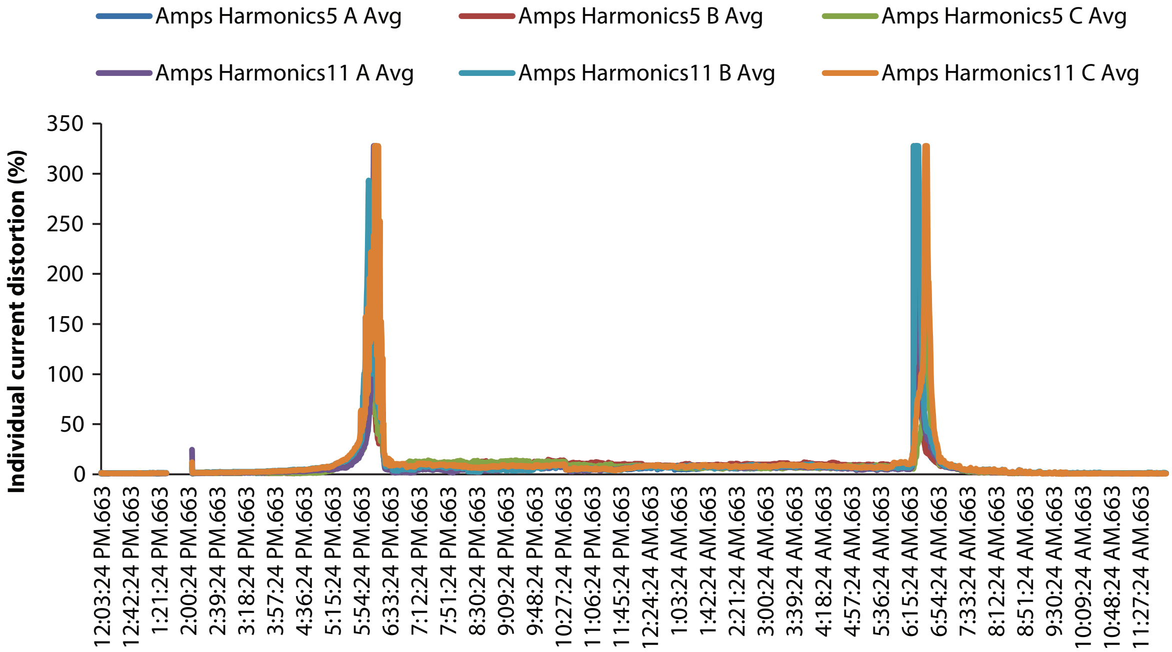

Figure 37: Individual component of current harmonic distortion for the BRPL site

On-site Measurements for Power Quality Analysis for the WBSEDCL Feeder

The WBSEDCL feeder has RTS plants distributed over the rooftops of several buildings on the campus. Accordingly, to analyse the PQ impacts of RTS integration into the distribution network in detail, two of the RTS plants were selected, 90 kWp and 20 kWp plants, and PQ measurements were made for 1-day duration by connecting PQ meters at the RTS inverter terminals and at the DT secondary terminals.

Measurement Analysis of 90 kW RTS PV Plant at Three-phase Inverter Output Point

The measurement device (HT Italia, PQA 824) was connected at the combiner box having three-phase 4-wire arrangement wherein distributed inverters of RTS plants with cumulative capacity of 90 kWp are connected at a common interconnection point. The instrument has a very high accuracy and good resolution with compact size. The key electrical parameters, which lead to PQ problems into distribution system, were selected for recordings. The parameters (voltage and current harmonics up to 20th order, voltage imbalance, voltage and current total harmonic distortion [THD], etc.) were recorded at 30 s time interval for 24 h with an objective to capture the instances of low and high-power generation from RTS plants, particularly when solar irradiance is significantly low and high, respectively. The following observations were made:

It was observed from the recorded data of power flow through individual phase and cumulative power of all the three phases that power flow through phases is almost symmetrical, which indicates a balanced system operation, as seen in Figure 38.

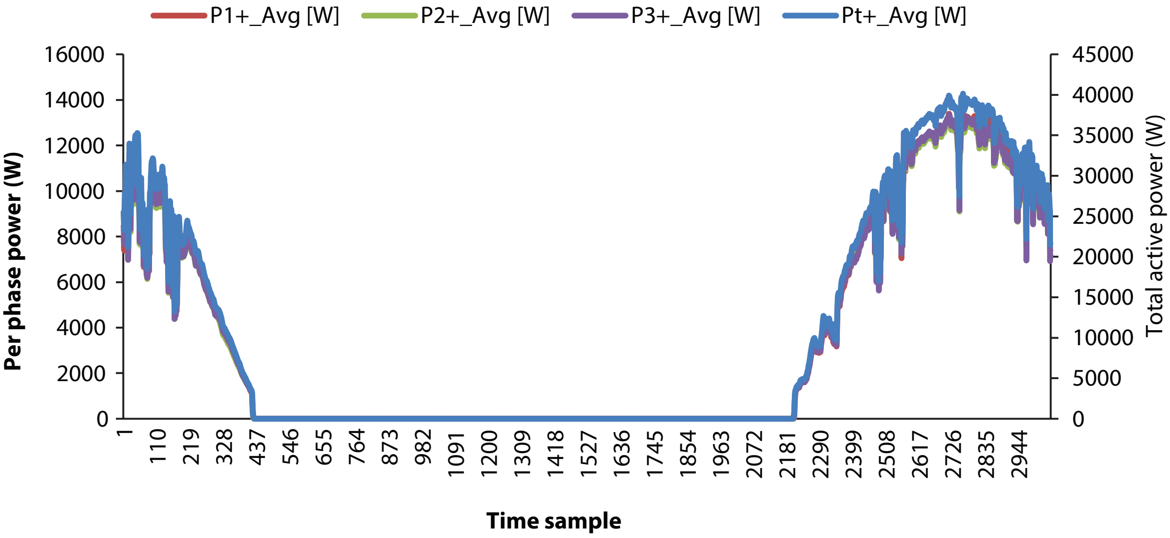

Figure 38: Active power flow through individual phases for the 90 kWp rooftop solar site on WBSEDCL feeder

Further, THD of voltage of each phase was analysed and it was found that the total harmonic distortion (THDv) as well as individual voltage harmonics remain within the standard limit as specified in Table 1. However, only THD for all the three phases has been depicted in Figure 39 since the individual components of voltage harmonics are observed to be 2%–3% approximately, which is below the standard limit (5%).

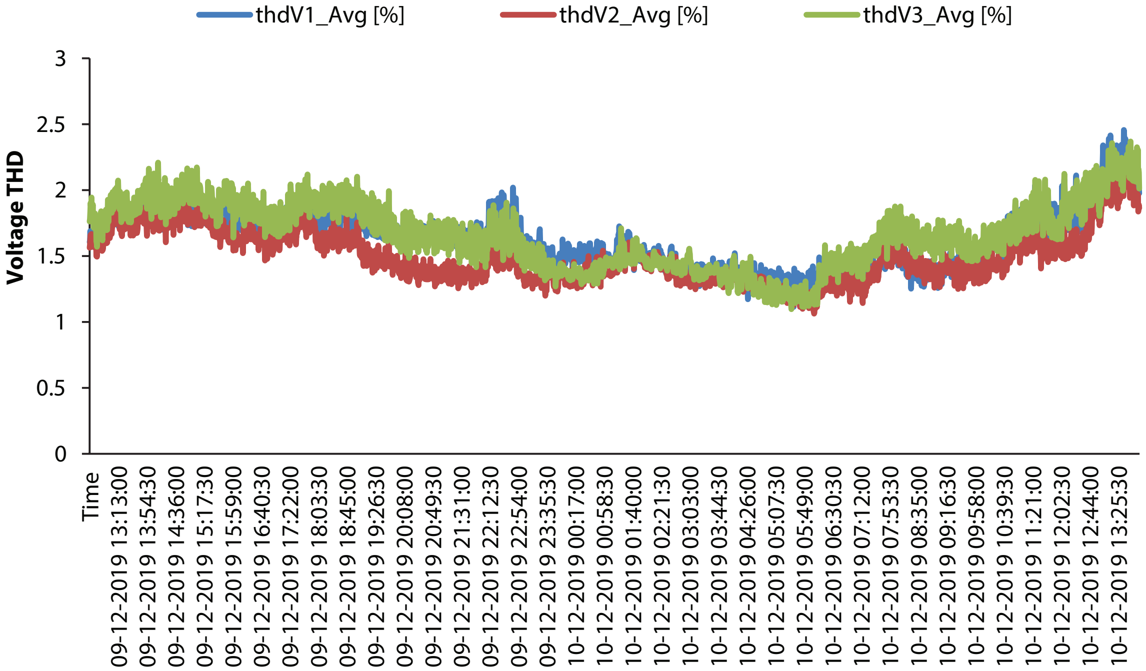

Figure 39: Total harmonic distortion of individual phase voltages at the 90 kWp rooftop solar site on WBSEDCL feeder

The current THD (THD_I) is seen to be much higher (>20%) when power flow through the individual phases is considerably low (approximately 3 kW per phase), and it is because of very low value of the fundamental component (<10 A). The individual harmonic components of current are found to be maximum (>30%) for the 5th harmonic when the current flowing through the phases is lesser than 5 amperes. Figure 40 shows the THD values for each phase current.

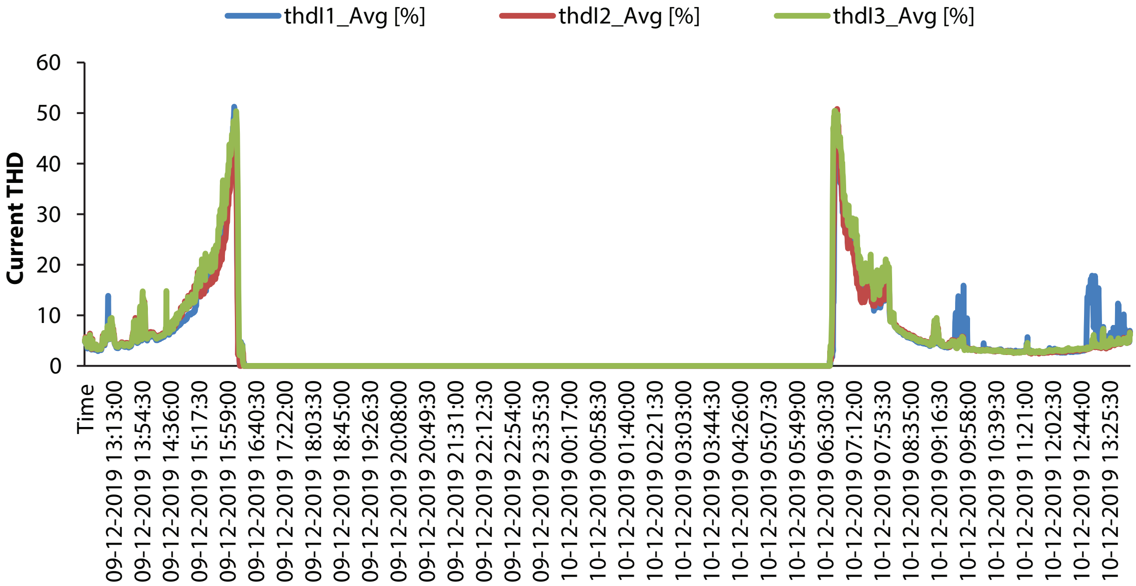

Figure 40: Total harmonic distortion of individual phase current for the 90 kWp rooftop solar site on the WBSEDCL feeder

The unbalance in input voltage measured through the negative and zero sequence component magnitudes was found to be within the prescribed limit of 3%, as recommended in the standards. Figure 41 shows the magnitude of negative and zero sequence components of voltage measured throughout the day to represent the unbalance.

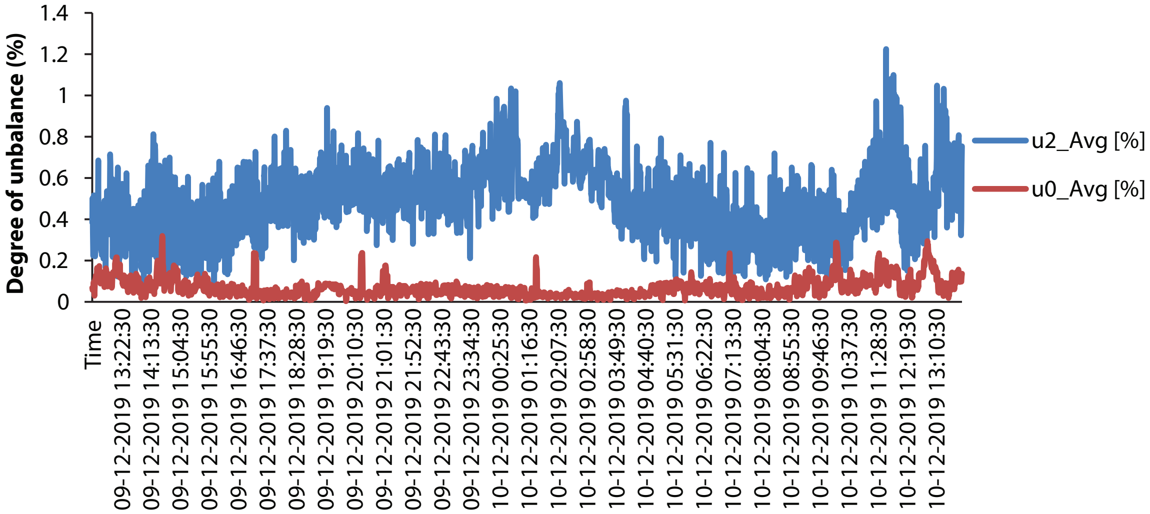

Figure 41: Voltage unbalance for the 90 kWp rooftop solar site on the WBSEDCL feeder

Measurement Analysis for the 90 kW RTS Plant at the DT Secondary Terminal

As one of the measurements for harmonic analysis was done at the solar inverter terminal and it could have lesser impact on DT as compared to harmonics generated at nearest location, it was therefore imperative to measure the PQ parameters at the secondary terminals of the DT. Hence, another PQ meter (Fluke 435-II) was connected at the secondary terminal of the 11 kV/415 V DT. The existing downstream circuitry of DT has three-phase 4-wire configuration wherein PQ meter was connected between the net meter and LT terminal of DT. Several electrical parameters that reflect PQ issues such as voltage and current THD, unbalance, individual harmonic component of voltage and current (up to 20th order), etc., were selected for recording with a 10 s sampling interval for a 24-h period. The following observations were made:

Since the load on this line is generally lower than the solar PV generation capacity and the device is connected after the net-metering point, a bi-directional power flow was observed through the line for the day of recording, as can be seen in Figure 42.

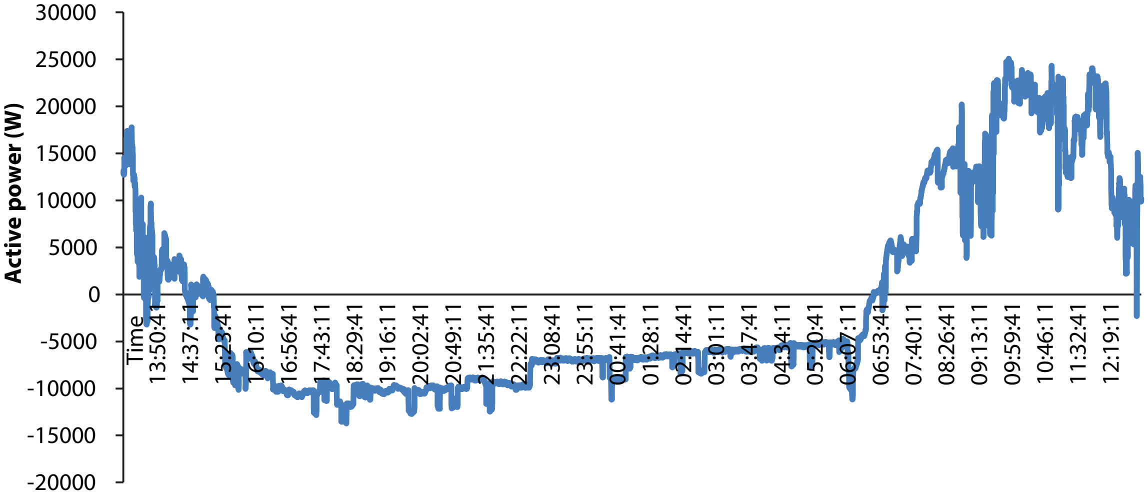

Figure 42: Active power flow through the low tension line from the distribution transformer having 90 kWp rooftop solar on the WBSEDCL feeder

The THD of voltages for each phase along with the individual harmonic components of the phases was analysed and it was found that voltage THDv (Avergage value of RMS phase-neutral voltage) remains within the standard limits as can be seen in Figure 43. The individual harmonics components of voltage also had magnitudes that were found to be within the limits and did not exceed 2%.

The current THD_I values were observed to be very high (>20%) when the current drawn through the phases was lesser than 15 A. It is therefore perceived from the trend shown below in Figure 44 that current THD is significantly higher as compared to the distortion observed when the same was measured at the inverter end, as elaborated in the previous section.

K-factor is an indication of eddy current losses in the network, which ultimately causes the overheating of distribution assets such as DTs. It is the ratio of eddy current losses due to distorted current to the losses for the same amount of fundamental current. This value should not exceed the recommended safe K-factor of

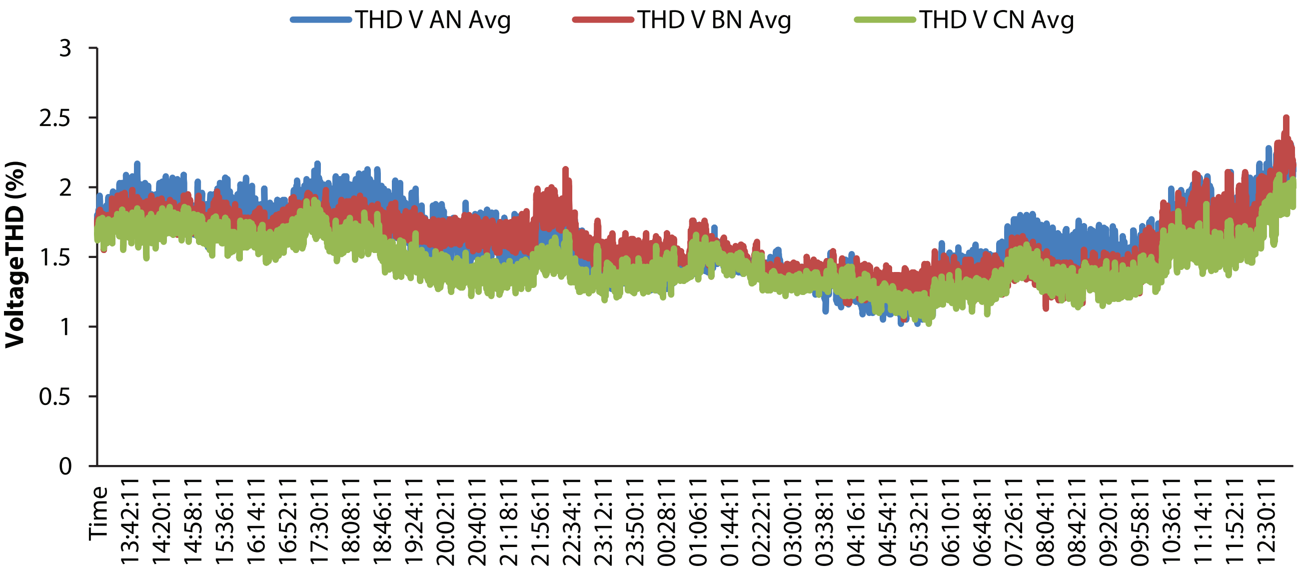

Figure 43: Total harmonic distortion of individual phase voltages measured at the distribution transformer secondary for the 90 kWp rooftop solar site on the WBSEDCL feeder

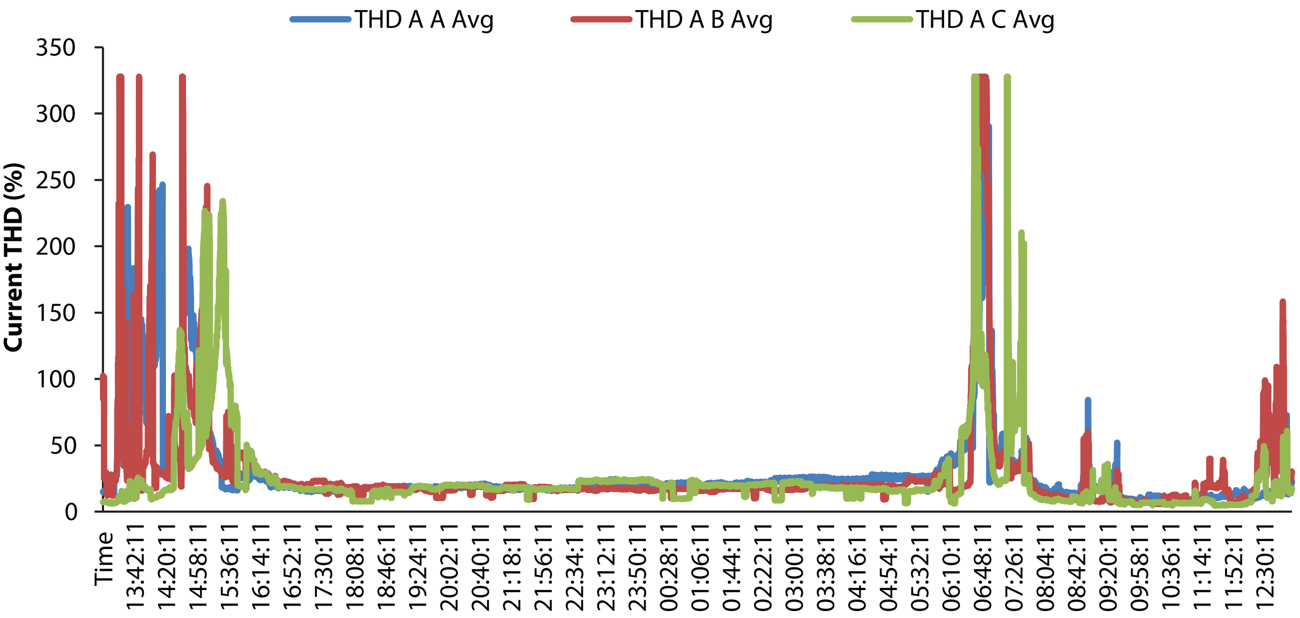

Figure 44: Total harmonic distortion of individual phase currents measured at the direct tension secondary for the 90 kWp rooftop solar site on the WBSEDCL feeder

particular transformer wherein PQ meter has been connected for recording and analysis. Since the lower value of fundamental component contributes to higher K-factor, the values of K-factor were seen to be up to be approximately 120 because of very low current in the phases (approximately 2 A). K-factor is defined as in the equation:

$$K= \sum_{h=1}^{h=\infty} I_h\,(pu)^2\; h^2 \qquad \text{Equation 2}$$

where,

$$I_h\,(pu) = \frac{\text{Distorted current (rms)}}{\text{Fundamental current (rms)}}$$

Figure 45 shows the k-factor for individual phases for measurements made at the DT secondary terminals.

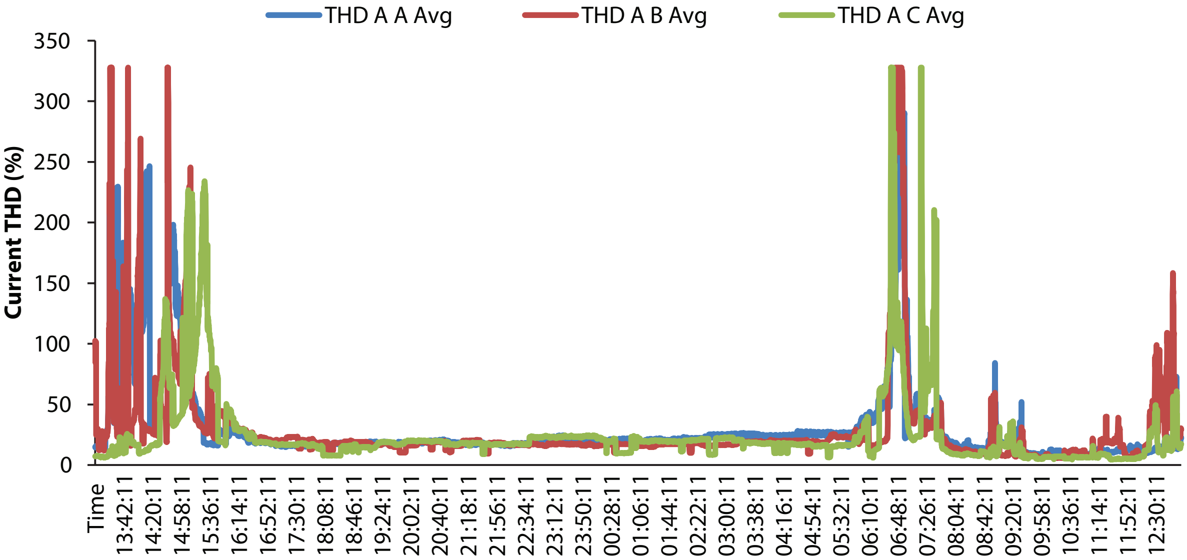

Figure 45: k-factor for individual phases for measurements made at distribution transformer secondary for the 90 kWp rooftop solar site of WBSEDCL feeder

Measurement analysis of 20 kW RTS PV Plant at Net Load Point

Another set of PQ measurements were made for a 20 kWp RTS plant on the feeder. The PQ instrument (HT Italia, Model – PQA 824) was connected at the net-metering point, that is, between gross load and LT side of DT. The PQ parameters were recorded for 1 h with 30 s interval time.

The following observations were made:

The active power flow through the phases is depicted in Figure 46 and it indicates balanced system operation since the load on each phase is almost equal. Further, the demand is very minimal as power flow through the line is uni-directional and thus power is being supplied to the grid since solar generation is higher than the load demand in this case.

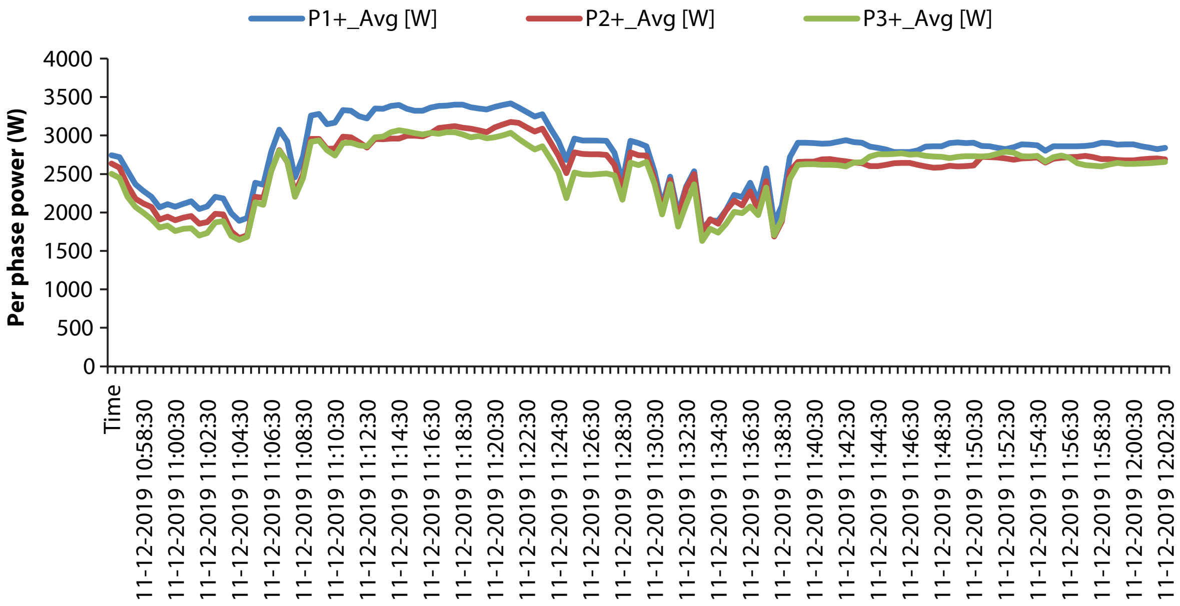

Figure 46: Active power flow for the individual phases at the net-metering point of the 20 kWp rooftop solar site on the WBSEDCL feeder

Voltage THDv for each phase and individual voltage harmonic component distortion were found to be within the standard limits and no excursion was observed throughout the measurement duration. Similarly, current THD_i alongside individual current harmonic component distortion also lied in the limit and no excursion was observed. Figures 47 and 48 show the THD in individual phase voltage and phase current, respectively.

The voltage unbalance measured through the magnitude of zero sequence voltage component (u_0) was observed to be outside the standard limits and it was found to be up to 5% for some instances as depicted in

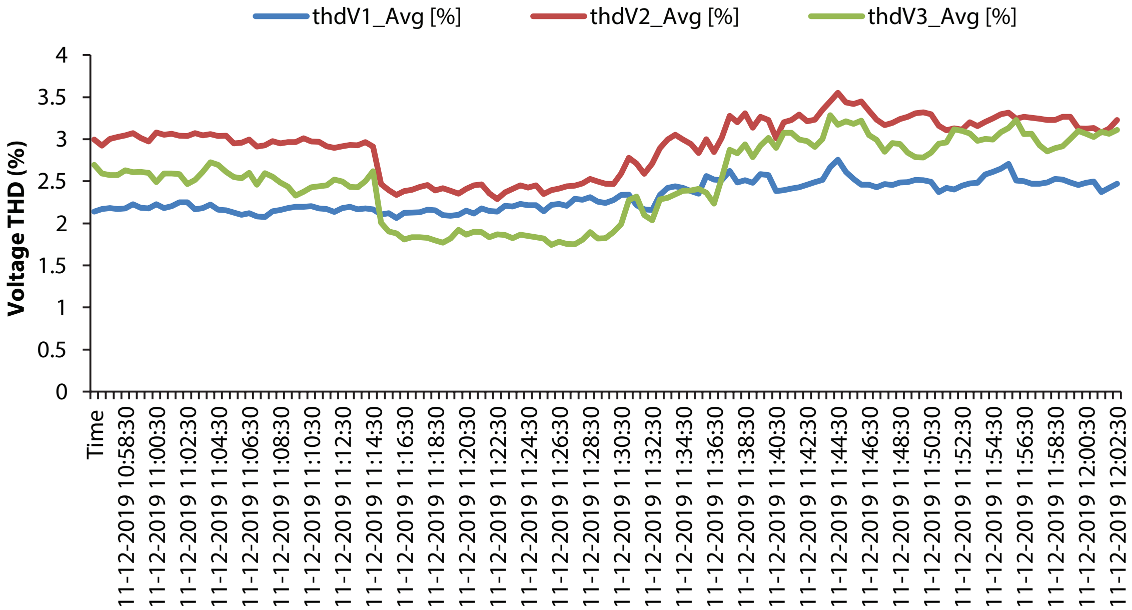

Figure 47: Total harmonic distortion of individual phase voltage measured at the net-metering point for the 20 kWp rooftop solar site on the WBSEDCL feeder

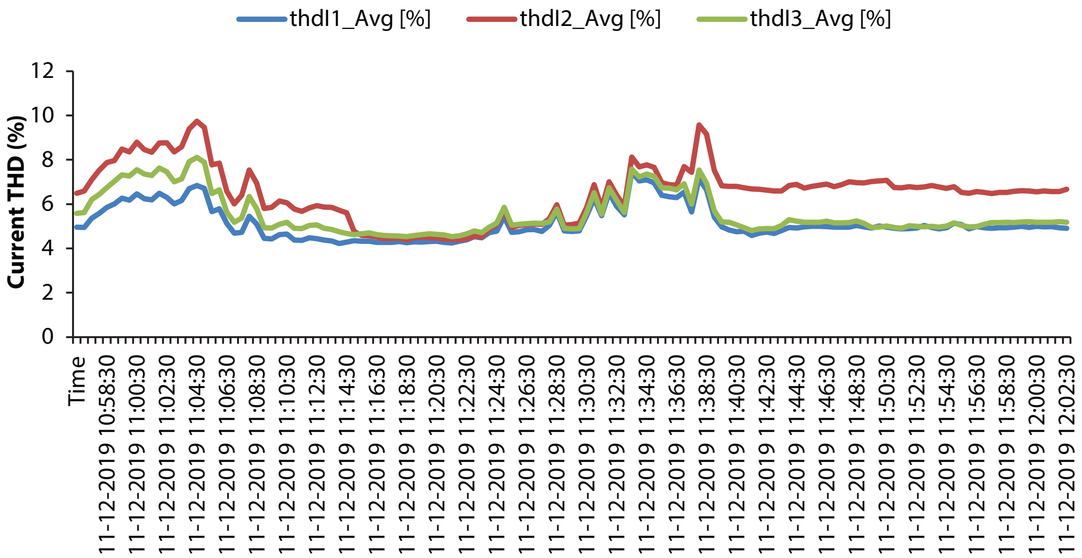

Figure 48: Total harmonic distortion of individual phase current measured at the net-metering point for the 20 kWp rooftop solar site on the WBSEDCL feeder

Figure 49. However, the negative reference unbalance (u2) was within the limits throughout the measurement duration. Any unbalance in the system causes the flow of current through the neutral wire and thus increases the copper loss in the winding. Voltage imbalance also increases the heating loss in the induction machines. For example, a voltage unbalance of 3% increases the heating by 20% for an induction motor and thus reduces the motor efficiency. Accordingly, it is recommended that the utilities periodically measure the THD of voltage and current and total demand distortion of current at different points as per the prescribed standards to check the PQ in their distribution systems.

Harmonics Mitigation Techniques

The harmonic mitigation techniques are categorized into classical and modern approaches. The classical methodology is typically implemented through the use of devices such as Alternating Current (AC) choke line

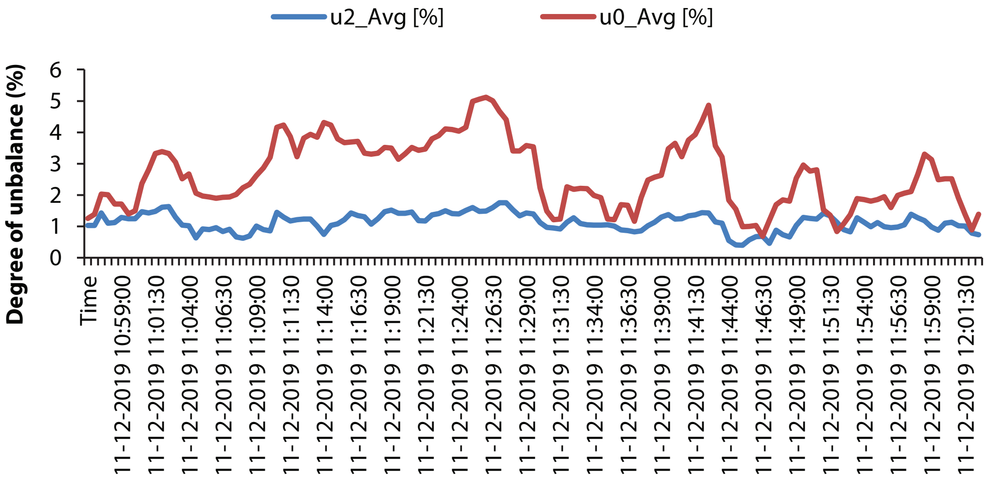

Figure 49: Voltage unbalance measured through zero sequence components at the net-metering point for the 20 kWp rooftop solar site on the WBSEDCL feeder

reactors, K-factor transformers, tuned harmonic filters, low pass harmonic filters, pulse-switched rectifiers, phase shifting transformers, active harmonic filters, and hybrid harmonic filters to limit high harmonics loads. In addition, passive filters are being broadly used to avoid influx of harmonics into the supply by providing low impedance path to harmonic currents and thus reducing the distorted current in main power supply [5]. These are basically designed to operate at individual frequencies to absorb any particular order of harmonics (3rd,5th, 7th etc.), or at a band of frequency and can be tuned for a series of harmonics. Passive filters are capable of reducing current total harmonic distortion (THD_i) up to 50% and also voltage THD_v up to some extent. Further reduction in current THD is possible only when the impedance of the filter is comparatively lesser than the short circuit impedance of mains supply. Additionally, passive filters prevent the flow of circulating harmonic currents into the system. However, passive filter system has some disadvantages as well, which are listed below:

a. They are not adaptable to changes in the system as they cannot be tuned and filter size remains fixed if the filter is designed to operate at a specific frequency.
b. Parallel resonance between grid inductance and filter capacitance may occur if single-tuned passive harmonic filter is off-tuned, which may lead to amplification of source current.
c. Excessive harmonic currents can flow into the passive filter due to voltage distortion caused by possible series resonance with the source.

There may be a case where more than one harmonic component may exceed the limits specified as per IEEE 519-2014. Therefore, it is required to employ a number of shunt filters (passive filters) into the system in order to absorb the multiple order harmonics [6]. However, there is a possibility of resonance occurring due to interaction of filter impedance with source impedance. Hence, the high pass shunt or C-type filter is a preferred option in this case, thereby shunting high order harmonics above certain level to the ground.

Active harmonic filters are utilized to overcome the aforementioned drawbacks of passive filters since active filters are constantly kept tuned by automatically varying the reactance by means of a control system to keep inductance and capacitance voltage equal. These filters monitor the electrical parameters such as load currents/voltage and filter out the fundamental frequency currents/voltages. Consequently, the system injects the appropriate reverse current/voltage by analyzing the individual harmonics content of voltage/current. Contrary to passive filters, active filter systems are able to mitigate both low and high harmonic components, being characterized by dynamic performances, and do not possess the risk of being affected by resonance at mains frequency. Therefore, active filters are utilized for more complicated and critical systems wherein a large number of non-linear loads are connected into the facility, requiring dynamic response from the filter to absorb the disturbances.

6. Study of Protection-Related Aspects

Steady-state power flow for estimating the voltage magnitude levels and measurement and inferences from steady-state power quality parameters were presented in Chapters 3 and 4, respectively. This chapter presents the results and insights from extensive field and site surveys done for both the selected feeders to understand the actual impacts that are likely to occur due to presence and rise of Rooftop Solar (RTS) systems on the feeder and raise the important issues, relating to behaviour of the system in fault conditions and corresponding action of the protective devices.

The insights and analysis done in this chapter broadly apply equally to both BSES Rajdhani Power Limited (BRPL) and West Bengal State Electricity Distribution Company Limited (WBSEDCL) in a sense that the LT-side protection schema is similar for both the utilities. The important considerations of doing such a study for any utility are generally based on the following anticipations:

1. What will be the behaviour of the RTS system in case of short circuit faults?
2. What will be the magnitudes of fault currents in the presence of RTS systems and how will they be distributed?
3. Are the current protective devices adequate enough to withstand the fault currents in the presence of RTS inverters or an upgrade would be required?
4. Can RTS systems lead to any kind of fault in the system?
5. Will the ratings and settings of the over-current relays and fuses on the LT side required to be changed?
6. Is there any requirement for changing the co-ordination among different protective devices as the penetration level of RTS systems rises in the future?

To answer the first two points as listed above, it is important to understand the fault-current characteristics of RTS inverters. A solar PV array is electrically a current source and hence there is a limit to the amount of current that it can provide during the condition of a short circuit. An RTS inverter can only provide a maximum of 1.1 times its rated current during a short circuit fault. However, for higher penetration levels of RTS systems on a feeder section, the absolute contribution from an RTS inverter and the magnitude and direction of fault currents in the system, determined through a short circuit study, are expected to change drastically in such a way that higher total fault currents in the system, at some locations, might be experienced.

To understand the possibilities of such an occurrence, the interactions with utility officials were conducted interacted alongwith multiple site surveys. The following observations were made:

1. The most common types of faults that occur on the system are line-ground short circuit faults that happen due to accidental reasons or during digging of roads.
2. The RTS penetration level is presently low for both the feeders and is set to rise in the future, however, the load growth is also foreseen; at any given instant, the quantum of power exported to the low tension (LT) network due to RTS systems is quite low to significantly influence short circuit currents.

3. Since the state regulations in Delhi also allow for one-phase RTS connection, even for a three-phase customer, phase imbalances are expected to occur. This might cause increased neutral current flow leading to false tripping of an earth-fault relay if adequate and appropriate grounding protection is not provided at the RTS system level.

Another important point of consideration, particularly for short feeders, as in the case of BRPL, is the presence of RTS inverters in the system during a short circuit fault. Since during a short circuit fault at any point on the LT line or cable, the voltage of the system becomes extremely low such that it goes beyond the operational limits of the voltage-band set for the RTS inverters to operate. Hence, the under-voltage protective relay trips and the RTS systems become off-line in which case there is no question of impact of RTS inverters during a short circuit fault. However, the Central Electricity Authority (CEA) notified some provisions relating to Low-Voltage Ride Through (LVRT) in solar PV inverters in the Central Electricity Authority (Technical Standards for Connectivity to the Grid) (Amendment) Regulations, 2019. Even though these directly apply to solar-generating stations for voltages measured at the High-Tension (HT) side of the grid, and not for RTS plants, if the same characteristic curve, as shown in Figure 50, was to apply for RTS inverters, then the contribution of RTS inverters during a short circuit fault would become significant.

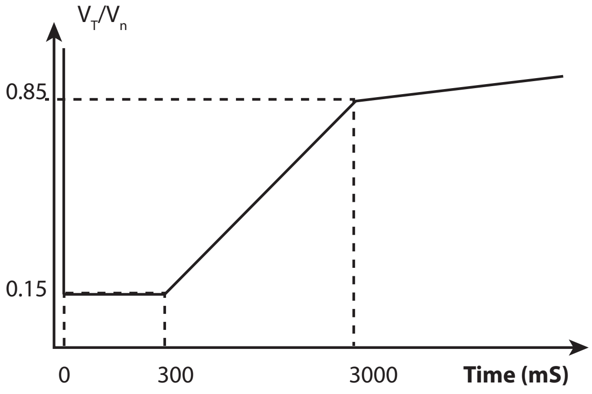

Figure 50: Low-voltage ride through characteristics for rooftop solar systems as proposed in CEA amendments

To understand the actual possible impacts of RTS systems on the protection system of a distribution feeder, it is essential to first understand the existing protection scheme at the LT network level. Typically, each distribution transformer branches into several LT feeders that further emanate from an LT mains bus. The LT feeders emanate from their respective protective devices, usually an Air Circuit Breaker (ACB) and further distribute towards the consumer meters through overhead main and services cables over poles or through feeder pillar boxes. A typical scheme of LT distribution is shown in Figure 51. Most of the short-circuit faults are expected to occur at the DT downstream network, or the 415 V LT-side network. For any short circuit fault that occurs on the network, upstream of the consumer meter, the LT-side protection present on the poles or pillar boxes operates. These are usually High-Rupturing Capacity (HRC) fuses typically of 250 A rating, however, this can be 450 A based on the connected load. In case the fuses fail to operate, the backing is provided by the primary LT feeder protection, which is in the form of an ACB at the LT feeder bus, which is typically of the order of 400 A ratings but is based on the DT capacities to reflect short-circit handling capacity. The last point of protection is an over-current relay at the DT secondary, which is known as the LT mains bus protection.

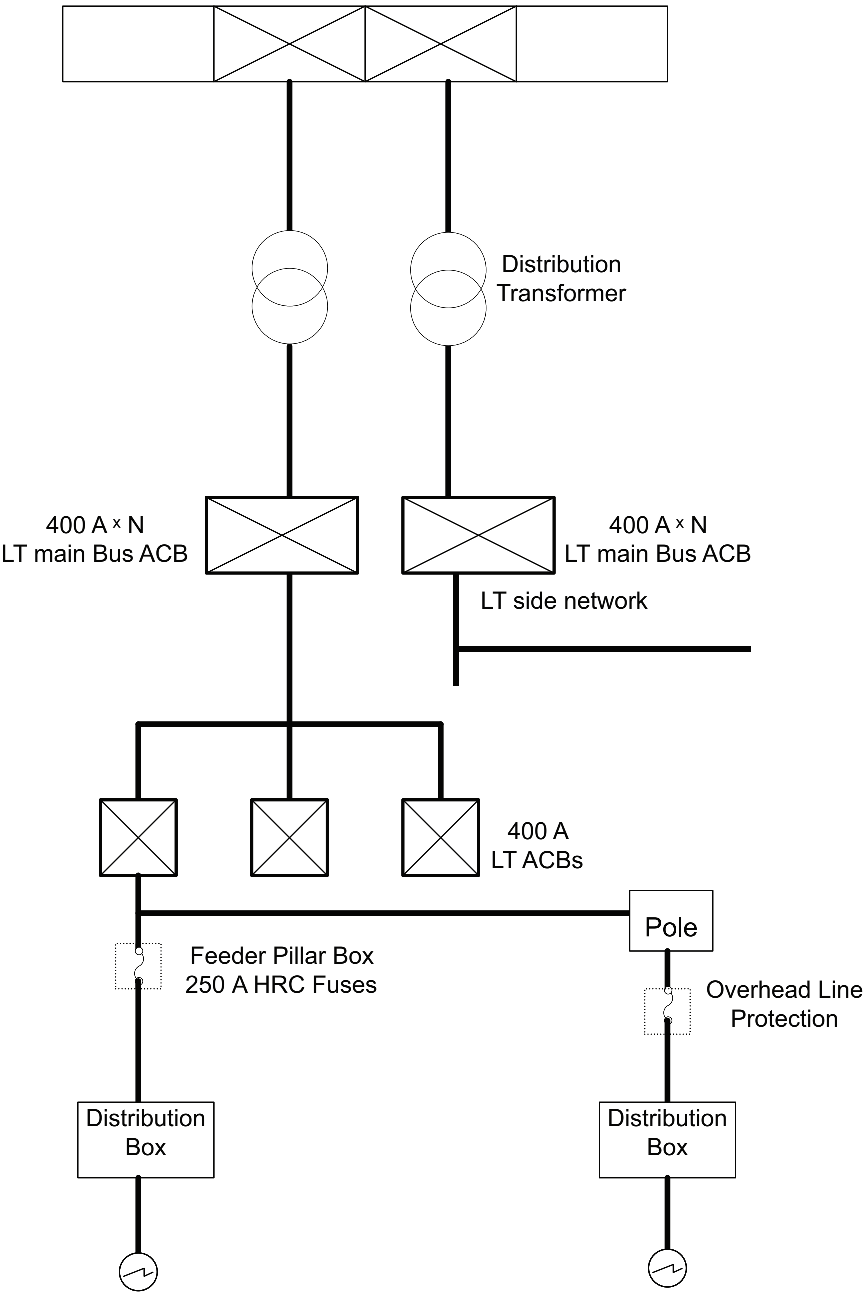

Figure 51: Typical protection schema on a LT network

The rating for this device is based on the number of LT feeders emanating from it, and usually for the BRPL networks, it is a multiple of 400 A, the multiplication factor being the number of LT feeder emanating from the main bus.

For any faults on the blue-colored network, the possibility of tripping of the inverter under-voltage relay does not seem remote especially for short urban feeders such as those in the BRPL network, as explained above. The time-current or I^2-t characteristics of an HRC fuse is almost instantaneous and hence these operate very quickly upon sensing the fault current and clear the fault.

However, due to high instantaneous RTS penetration, if the RTS inverter remains online, the fault currents contributed by the upstream system may reduce. This might lead to the fuse not blowing since the amount of current sensed by it may reduce because of the re-distribution of fault currents caused by RTS inverters' contribution. The over-current relays, which generally have an inverse time-current characteristics, mostly inverse definite minimum time, are expected to operate as backup to the fuses. This standard relay–fuse co-ordination is generally seen in most of the LT-side distribution networks in India. However, due to the above-stated conditions, RTS inverters could reduce the reach and sensitivity of the Over-Current Relays (OCRs) and the ACBs at the LT feeder bus might not operate, failing to clear the fault. This is due to reduction in the upstream fault-current contribution and since these OCRs do not have any directional element, they do not trip.

Anticipating such possibilities, the following general recommendations can be made in view of the analysis of protection-related aspects of RTS inverters through certain guidelines and a few studies to be conducted by DISCOMs:

4. The inverter-operating voltage limits and cut-off characteristics, as mandated by CEA standards, must be validated before field deployment. Hence, the distribution companies (DISCOMs) must be encouraged to test their RTS inverter settings in emulated conditions in certified testing laboratories to assess that the RTS inverter operation occurs as desired on the field. Any mal-operation on the filed during short circuit faults could affect network conditions.

5. DISCOMs must maintain an event book of various types of faults that occur on their system so that a short circuit study can be carried out for their specific network having the exact modelling of the network and the RTS systems.

6. The short-circuit study would give an idea to perform a protection-adequacy study so as to assess whether the existing fuse ratings and the OCR ratings and settings are adequate enough to clear the faults, even in a scenario of rising RTS penetration levels or an upgrade would be required.

7. For anticipating any protection-blinding phenomenon, the I^2–t and the I-t characteristic curves of the fuses and the OCRs must be analysed, respectively. Observing the magnitude of fault currents sensed by these protective devices, a new protection co-ordination scheme, if required, would need determining the new plug-setting multiplier for the OCR or finding a new fuse–relay combination, based on the intersection of the fuse and OCR curves, that gives the least time of operation to the fuse and sufficient backup time to the OCR, for the new fault currents for both fuse and OCR, in case the fuse fails to operate.

Another concern related to protection coordination is in the case of parallel feeders emanating from the same DTR, where a healthy feeder may trip for a fault on the other (faulted) feeder. This phenomenon of 'sympathetic tripping' could occur in feeders with large motor loads following transient faults when the relay in the healthy feeder senses a current higher than its trip rating due to motors in that feeder (that were stalled or running at reduced speeds) that start drawing large current as the voltage starts recovering [7]. The presence of RTS may further aggravate the problem.

7. Conclusion and Recommendations

In view of the rising Rooftop Solar (RTS) penetration levels, as favoured by many states like Delhi and West Bengal, it is important to perform exhaustive technical studies both at the planning and operational levels in order to have a better understanding of the anticipated impacts of RTS systems on operation of distribution feeders.

An illustrative study was performed for representative feeders in the BSES Rajdhani Power Limited (BRPL) and West Bengal State Electricity Distribution Company Limited (WBSEDCL) license areas and the corresponding results were presented in this report. Since major RTS installations are taking place on rooftops of commercial buildings, institutional campuses, and residential premises, it is essential to model the low tension (LT)-side network as many of the industries are consumers at 415 V level also. The study presented an approach of modelling a distribution feeder till the LT-side network so that the impacts of RTS integration can be estimated correctly. Pertinently, record keeping and collection of relevant datasets like distribution transformer (DT) and feeder time series loading and geographical information system datasets of the feeders become all the more important apart from maintaining feeder single-line diagrams and conductor and DT specifications. In this respect, data availability and its adequacy on part of the Distribution Companies (DISCOMs) is essential acknowledging the fact that data constraints are likely to be encountered.

Steady-state voltage magnitude levels at all the LT buses, for different scenarios of load and RTS growth, were estimated using three-phase distribution power flow for a complete year. Based on the voltage levels observed, certain critical buses were identified and various mitigation techniques like OLTC, smart inverter Volt-VAr and Volt-Watt functionalities and battery energy storage system were modeled and their effectiveness tested. Smart inverter control was found to be one of the most effective solutions for localized voltage control. This additional feature comes at a mimimal incremental cost and can be very effective during the solar hours. Accordingly, regulations can also be amended to allow this feature to operate for enhancing localized voltage profile. Therefore, a stronger and more proactive policy push is required to enable provisions so as to encapsulate this extra capital expenditure for effective voltage-control. Seeing the emergence of new technologies like smart PV inverters, such a policy directive is equally essential to build capacity of utility and stakeholders to effectively bring benefits for the greater good. Many utilities like BRPL are also doing pilot trials using this technology so as to control voltage at a localized level

The power quality impacts were assessed based on the on-site measurements of voltage and current total harmonic distortion levels at different points: DT secondary terminals, RTS inverter terminals, and the net-metering point for various RTS plants on the selected feeders of the two utilities. Such measurements must be periodically done by DISCOMs to review the state of power quality in their networks and adopt suitable mitigation or control techniques, some of which were also discussed in this report. Lastly, the feeder protection-related aspects were discussed. Important insights gathered from site surveys and interactions with the DISCOMs' field personnel regarding the practical impacts that might occur on their networks, given the very specific protection schema were adopted. The various types of faults that commonly occur on the LT network and the chances of RTS inverter staying online given the excessive low voltages during a short-circuit fault were mentioned including the possibility of low-voltage ride through and fault ride through that might be adopted by CEA in the future since it has been brought as a draft amendment for the high-tension/ 33 kV level and above. The report tried to flag some of the relevant issues that are of importance considering the impacts of RTS during different types of short circuit faults that can occur on the feeders, other faulty conditions that can develop, and the effects these can have on the existing protection system. A general schema of the LT-side protection followed by most distribution utilities was discussed to understand the types of short circuit faults, their probable points of occurrence and the various impacts that presence of RTS inverters can have on the different protective devices located at their respective positions. The possible approach for performing a protection-adequacy and protection-coordination study was highlighted and a few general recommendations were made in view of the actions or activities the DISCOM should undertake in order to better anticipate the protection-related aspects of high RTS penetration levels.

The importance of standards for facilitating smoother grid integration of RTS emerges out to be paramount through such investigative analyses. It was found that many states have adopted different standards in relation to integration of RTS into the distribution network. Even though they are largely adopted from existing international standards, in many cases they were found to differ. It is important to take note of the fact that harmonization and streamlining of standards and guidelines is essential and the Bureau of Indian Standards (BIS) has undertaken efforts to channelize the same. The BIS has constituted a committee on 'Grid Integration of Renewables' to formalize and publish an Indian standard on the same. The ETD-46 sectional committee constitutes members representing various relevant stakeholders in the country, including TERI, and efforts are underway to harmonize the various guidelines and standards, in alignment to relevant IEEE/IEC standards, across the country so that a national standard can be framed.

References

[1] Aziz T and N Ketjoy. 2017. PV penetration limits in low voltage distribution networks and voltage variations. IEEE Access.

[2] Chandra A. 2016. A review on impacts of grid-connected PV systems on distribution networks. International Journal of Electrical and Computer Engineering 10(1): 129–141

[3] Ding F, A Pratt, T Bialek, *et al.* 2016. Voltage support study of smart PV inverters on a high-photovoltaic penetration utility distribution feeder. Proceedings IEEE 43rd Photovoltaic Specialists Conference (PVSC), 1375–1380

[4] Zaidey Y and Y Ghazali. 2017. Managing on-load tap changer life cycle in Tenaga Nasional Berhad (TNB) distribution power transformer. Proceedings of the 24th International Conference and Exhibition on Electricity Distribution (CIRED), 303–307

[5] Ciufu L, C-L Popescu, and M-O Popescu. 2017. Experimental mitigation techniques to reduce the total harmonic distortion of low voltage non-linear power sources. Proceedings of the 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, 138–141

[6] Bayliss C R and B J Hardy. 2012. Power Quality – Harmonics in Power Systems: Transmission and Distribution Electrical Engineering (Fourth Edition)

[7] GE Multilin, "Distribution Feeder Principles", 2013