

## **ABSTRACT**

SINGH, SHASHWAT. Cost Benefit Analysis of FREEDM System. (Under the direction of Dr. Mesut Baran.)

In recent past there has been an unprecedented interest in integrating more and more Distributed Renewable Energy Resources (DRER) with the distribution systems. This may entail the upgrading of the conventional system. Hence, a smart distribution system, FREEDM system was developed wherein Solid State Transformers (SST) replace the traditional distribution transformers to facilitate high penetration of DRERs.

In this study, impact of different levels of photovoltaic (PV) penetration on distribution systems has been studied. Furthermore, the benefits of FREEDM system over the conventional counterpart is investigated and identified. Multiple studies were performed on the distribution system to assess and analyze different impacts. The study involved performing case studies on IEEE 34 Nodes Test Feeder where two different systems were considered:

- Base System
- FREEDM System

The identified impacts were quantified & monetized and a basic Cost Benefit Analysis was performed so as to judge the economic viability of the FREEDM System.

The results of the study show that the FREEDM System accommodates PV better than the base system and at the same time has the potential to be economically viable too.

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Cost Benefit Analysis of FREEDM System

by  
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## **DEDICATION**

To my parents  
SriKrishna Singh and Manisha Singh

## **BIOGRAPHY**

Shashwat Singh was born on June 12th 1991 in Varanasi, Uttar Pradesh, India. He received his B.Tech. in Electrical and Electronics Engineering from Uttar Pradesh Technical University in 2013. He joined North Carolina State University to pursue Master of Science in Electrical Engineering in Fall 2014. In 2015, he joined FREEDM Systems Center as a Research Assistant under the guidance of Dr. Mesut E. Baran.

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## CHAPTER

# 1

# INTRODUCTION

Conventionally electrical power is generated using non-renewable energy resources like coal, gas, nuclear fuel etc. These methods of generating are centralized and needs large infrastructure to transport the energy from the generating end to the customer end.

With the advancement of technology, we discovered new methods to harness electrical energy from renewable energy resources such as hydro, biogas, solar power, wind energy and geothermal power. Among these new sources of energy, solar energy (PV) have become very popular in recent past. Persistent development in technology has made it possible for us to convert the solar energy into electrical energy.

These renewable sources of energy are usually not centralized in nature as the conventional power generation. They are distributed in nature and do not produce electrical power in bulk. Thus, they are named as Distributed Energy Resources (DERs).

As DERs do not produce as large electrical power as compared to our conventional system; presently they cannot take over the conventional system. But, they can be surely utilized to reduce the existing pressure on our conventional system. Furthermore, this practice would reduce the rate of consumption of our non-renewable fuels.

In this study we are primarily focusing over the photovoltaic (PV). It has been noticed that although we are able to transform a very little amount of solar energy into electrical energy, it is serving

great returns economically. But this topic is debatable as integrating PVs with the conventional grids surely offers some great benefits but also leads to the cropping up of several issues which needs to be mitigated. Low PV penetration might not create much issues but then they won't provide substantial benefits too and vice-versa.

## 1.1 Impact of PV on a Distribution System

"Technical concerns with integrating higher penetrations of photovoltaic (PV) systems include grid stability, voltage regulation, power quality (voltage rise, sags, flicker, and frequency fluctuations), and protection and coordination. The current utility grid was designed to accommodate power flows from the central generation source to the transmission system and eventually to the distribution feeders. At the distribution level, the system was designed to carry power from the substation toward the load. Renewable distributed generation, particularly solar PV, provides power at the distribution level challenging this classical paradigm. As these resources become more commonplace the nature of the distribution network and its operation is changing to handle power flow in both directions.

A large portion of distribution system components, including voltage regulators and protection systems, were not designed to coordinate with bidirectional power flow and bidirectional fault currents from distributed generation and PV systems in particular. Coordinating these devices in the presence of high penetration PV areas introduces additional challenges to feasibility and system impact studies. Some cases require modification of existing protection schemes, additional distribution equipment, or reactive power requirements on the PV inverters." - [21]

In this thesis, significantly high levels of PV penetration is considered under different scenarios on base system and FREEDM system to identify the impacts and judge the system performances. Several defined metrics were calculated for each scenario and were compared for both systems so as to reach to a conclusion about the better system in terms of accommodating the PV's better.

## 1.2 FREEDM System

There are several challenges associated with the integration of DERs at high penetration levels which are facilitated by FREEDM System - a novel distribution system which uses new power electronics based devices [1][2][3][4]. The intermittent nature of DERs may actually cause unexpected operating conditions, if integrated to a large extent [5].

FREEDM system claims to accommodate more DERs than the conventional system. But being an advanced system it uses high-end devices which are costlier than their counterparts presently being used. Thus, it's debatable whether FREEDM system is cost effective. FREEDM offers great

FREEDM System Features/Functions	Specific Benefits	Benefit Category			
		Economic	Reliability	Societal	Security
<b>Accommodate High PV Penetration</b>					
Value of Solar	Net benefit of PV above 20%				
Plug & Play	Simplify DER integration				
Effective Volt/Var Control	Reduction in power loss				
	Mitigate voltage issues				
Energy Storage + DGI	Mitigate variability of power				
<b>High Reliability &amp; PQ</b>					
Looped Primary	High reliability				
Fault Locating, Isolation					
Service Restoration	Minimize fault impact on components				
Fast Protection with FID	High power quality				
Regulate Service voltage					
<b>Real Time Monitoring &amp; Control (M&amp;C)</b>					
Enhanced System M&C	Reduced O&M				
	Optimal capacity use				
CVR	Load management: peak demand and energy reduction				
<b>System Resiliency</b>					
Enabling micro-grid tech	Micro-grid increases resiliency				
<b>Customer Participation</b>					
DGI- Price Signals DLMP	Customer DSM				
	Peak demand reduction				
	Economic efficiency				
<b>Motivating New Business</b>					
Enhanced DSM	Transactive Energy				

**Figure 1.1** FREEDM System Benefits

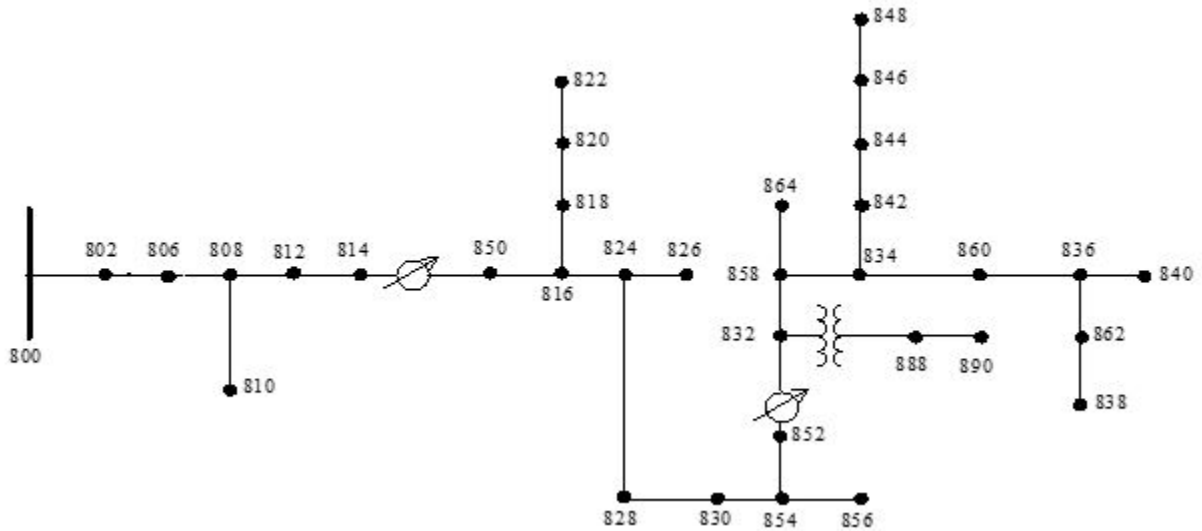
benefits but it might be possible that the value of those benefits are not good enough as compared to the investment needed for the FREEDM system.

From control point of view, PV can impact the system voltages, power quality, operations of control devices and power loss significantly asking for a better Volt/VAR control schemes. One special feature of the FREEDM system is that Solid State Transformers (SSTs) are used instead of conventional distribution transformers, and each SST can work under unity power factor or its reactive power from the feeder can be controlled. Therefore, SST as a VAR compensation device, plays an important role in the Volt/Var control on the FREEDM systems.

Also, the reliability of system gets improved as FREEDM allows the looping of primary. This feature comes up as FREEDM uses Fault Isolation Devices (FIDs) instead of circuit breakers. FIDs are very quick and have the capability to reconfigure the system giving an option for looped primary.

**1.2.1 FREEDM System Benefits**

FREEDM system offers several benefits over the conventional system which are tabulated in figure 1.1. This study aims at quantifying these benefits and check for the system performances with high levels of PV penetration in distribution systems.



**Figure 1.2** IEEE-34 node test feeder

### 1.2.2 Test Feeder

IEEE-34 node test feeder is used for this study and is displayed in figure 1.2. It was assumed that the published results was the peak load condition for the feeder. Thus, the peak load on the feeder is 2058.64 kVA (with 1769.82 kW).

Figure 1.2 displays the prototype system or we call it the conventional system. Reliability study was performed for the base system and the FREEDM system. FREEDM allows the primary to be looped and hence, FREEDM system was developed by looping the IEEE-34 node test feeder as shown in figure 1.4. Furthermore, the looping arm was appended with six equidistant nodes to be more realistic. The nodes on the looping arm were expected to have similar kVA load as the nodes in the major arm and number of customers were decided as per the assumed value of average kVA per customer for the system.

To be consistent with the number of customers, the base case was developed from the prototype feeder. In here, the system was same as the FREEDM system but the looping was absent i.e. the looping arm was not connected to the end of the main feeder as shown in figure 1.3. Furthermore, figures 1.3 and 1.4 also show the placement of circuit breakers (squares in the figures) over the feeder, which was decided previously keeping in mind the recommendations in [12].

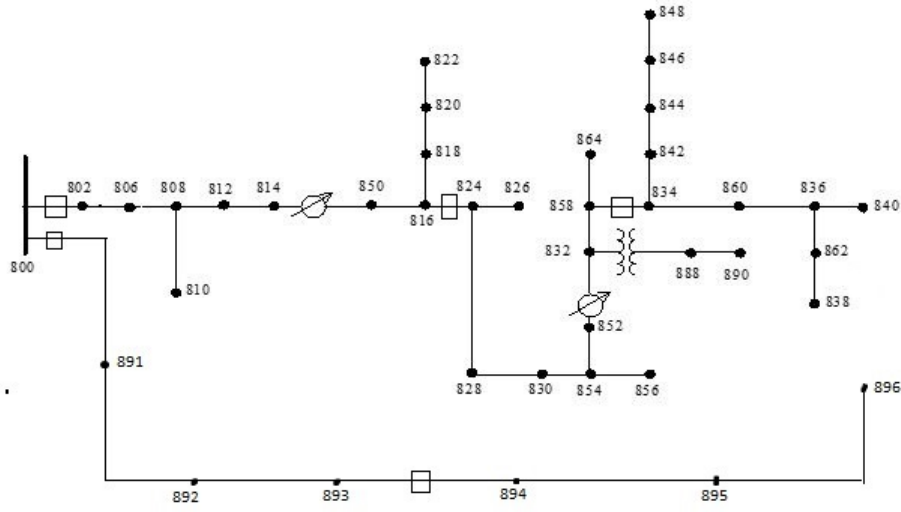


Figure 1.3 Base System

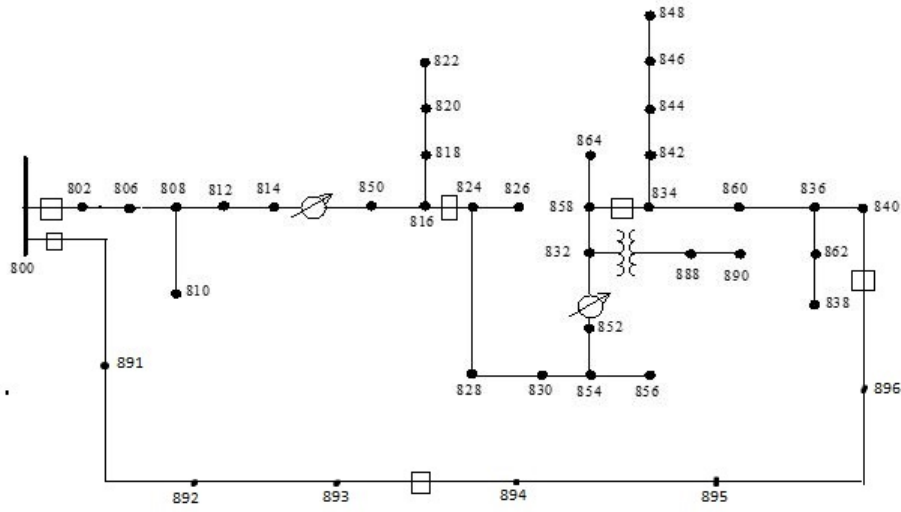


Figure 1.4 FREEDM System

### **1.2.3 Number of Transformers**

According to the data given by Duke Energy, a 25kVA transformer can take up to 4-5 customers and a 50kVA transformer can take a maximum of 6-7 customers. Thus, depending on these values, number of transformers required by the system were calculated.

It came out that, this modified system requires 50, 25kVA transformers and 25, 50kVA transformers. If we count the transformers needed with the looped branch removed, it comes out to be 36,25kVA transformers and 24, 50kVA transformers.

## **1.3 Proposed Work**

It is required to identify the FREEDM benefits and quantify them. After the quantification of benefits, monetization is needed so as to give a dollar value to the benefits. Furthermore, as the costs incurred in FREEDM are more, it is needed to perform a cost - benefit analysis to check for the economic feasibility of FREEDM system. These are the main aspects with which this thesis deals.

Chapter-2 deals with assessment of DER impacts on ditribution systems. In Chapter-2 several impacts were quantified and calculated under different scenarios. Chapter-3 deals with calculation of costs and monetizing the quantified benefits (energy losses) over an year to have an idea about the economic feasibility of the FREEDM system.

## CHAPTER

# 2

# ASSESSMENT OF DER IMPACTS

A handbook describing the method on how to perform impact study of high PV penetration was published by NREL in January 2016. The handbook provides an idea over development of distribution and PV system models required to evaluate the impacts of high PV penetration. Further it identifies key impacts and defines necessary studies needed to be performed and the necessary points (critical points); where the study shall be more detailed to obtain a clear cut picture of the impacts. It also provides with the mitigation measures in terms of implementing advanced PV inverter. Lastly it presented an example to support the methodology, giving us a better understanding [6].

From the above mentioned handbook, it was confirmed that two major studies need to be performed for the purpose of quantifying the impacts.

- Reliability Study
- Volt/VAR Study

Table 2.1 gives some identified impacts of high PV penetration as observed from the literature survey - [6][13][14][15].

<b>Issues</b>	<b>Impacts</b>
Intermittent Nature of PV	Increased no. of operations for Voltage Regulators and LTCs Higher generation ramp rates
High Penetration	Insulation failures and Equipment Damages due to reverse power flow
Unbalanced PV	Causes Voltage Unbalance leading to motor failure Misfunctioning of relay due to higher neutral current Reduced life of equipments

**Table 2.1** Impacts of PV Penetration

## 2.1 Reliability Study

Reliability of the system or a component is an attribute that consistently performs according to its specifications. It is the ability to be relied on or depended on. In power systems, reliability has to do with electric interruptions. Power reliability can be defined as the degree to which the performance of the elements in the bulk system results in electricity being delivered to customers within accepted standards and in the amount desired. The degree of reliability may be measured by the frequency, duration, and magnitude of adverse effects on the electric supply.

Reliability mainly considers sustained outages. As per the definition of sustained outage according to the IEEE standard; sustained outages are the outages having duration more than 5 minutes. To quantify reliability, mainly two metrics are considered universally-[11]. They are defined as follows:

$$SAIFI = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customers Served}}/\text{year} \quad (2.1)$$

$$SAIDI = \frac{\text{Total Customers Interruption Duration}}{\text{Total Number of Customers Served}}/\text{year} \quad (2.2)$$

Reliability study was performed for the base system and then for FREEDM system to calculate SAIFI and SAIDI for both cases and analyze the variations in the same. As discussed earlier FREEDM system uses a smart circuit breaker know as FID which is fast and allows quick reconfiguration of the primary, thus, allowing looping of primary. Because of looping there is an option of backfeeding. After the fault is isolated, certain number of customers can be backfed. This process of isolation of fault and backfeeding takes lesser than 5 minutes and hence, it is not counted as a sustained outage; improving the reliability indices of the system.

The three feeders - prototype system, base system and FREEDM system are hereby again displayed in the figure 2.1-2.3

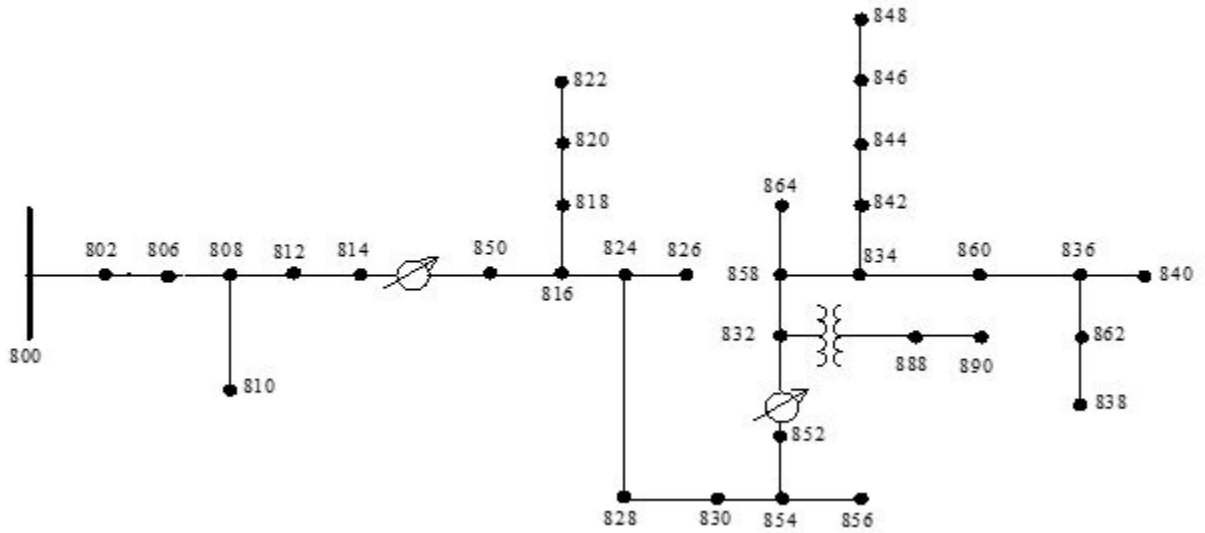


Figure 2.1 IEEE-34 node test feeder

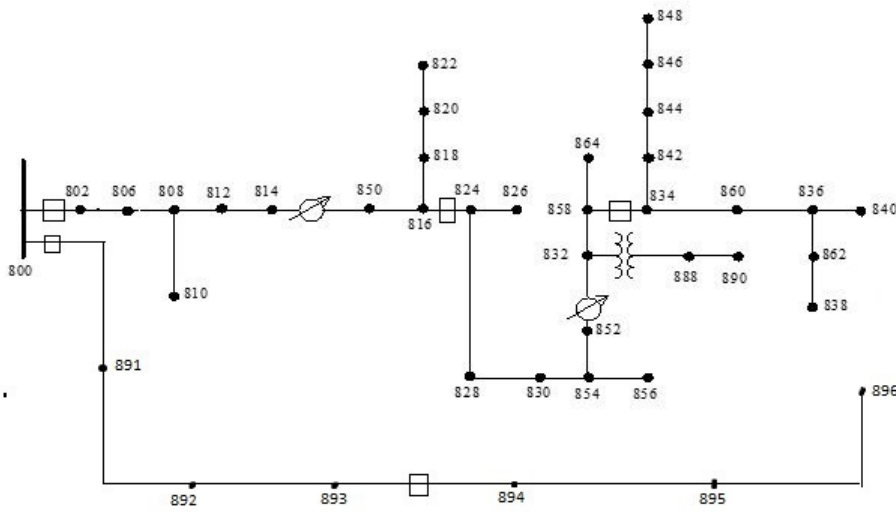
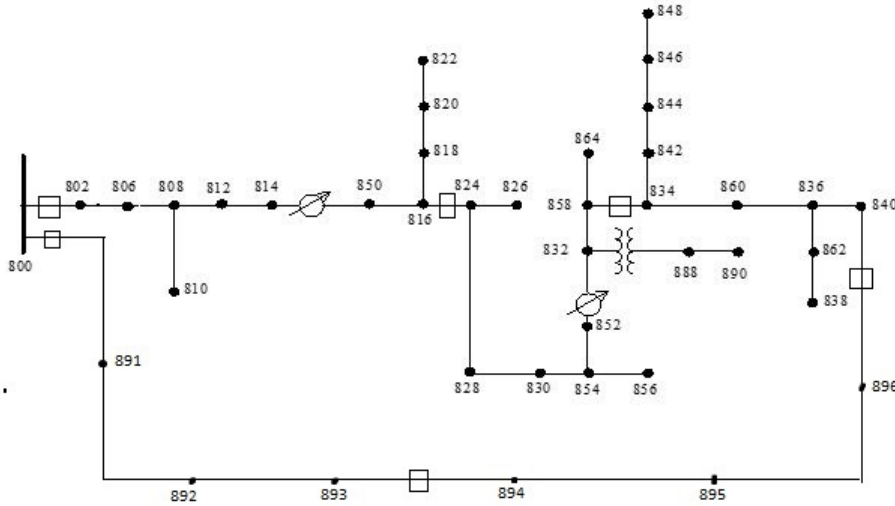


Figure 2.2 Base System



**Figure 2.3** FREEDM System

### 2.1.1 Assumptions

There were few practical assumptions made to perform the analysis. These assumptions are as follows:

- The fault rate was considered to be 0.025 faults/year/unit length for each branch.
- Average kVA per customer was assumed to be 9.
- Based on data from Duke Energy, diversity factor was considered to be 0.6 and 0.5 for loads less than 25kW and greater than 25kW respectively.

An excel worksheet was developed to calculate SAIDI and SAIFI for the IEEE-34 node system which gave the following results:

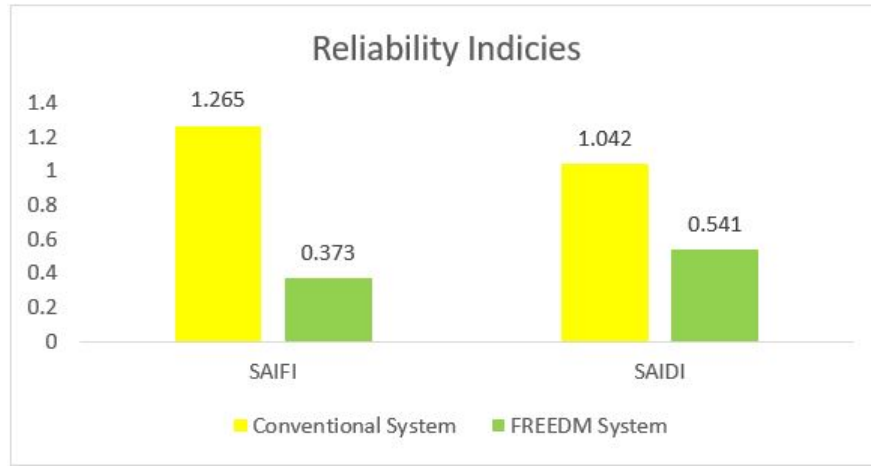
#### **Base System:**

SAIFI = 1.265 outages/year

SAIDI = 1.0416 hours/year

#### **FREEDM Systems:**

SAIFI = 0.3732 outages/year



**Figure 2.4** SAIFI and SAIDI comparison for the two cases

SAIDI = 0.54 hours/year

It is observed that SAIFI and SAIDI were improved by 70.49% and 48.06% respectively; in the case with FREEDM System.

## 2.2 Volt/VAR Study

The primary objectives of Volt/VAR Control (VVC) include maintaining voltage on a distribution system within acceptable range, and reducing power and energy loss. Voltage Regulators and shunt capacitors are the widely used conventional devices for the purpose.

### 2.2.1 Volt/VAR Control on Conventional Systems

Voltage control is a fundamental operating requirement for an electric distribution system, as it is the responsibility of the utility to keep the customer voltage within specified tolerances.

In a conventional distribution system, the substation is the sole source of the feeder, and the voltage along a feeder will drop gradually from the substation towards the end of the feeder as shown in figure 2.5. Under heavy load conditions, the nodes far away from the substation may have under-voltage violation, as shown in figure 2.6. One simple way to fix this problem is to manually raise the source voltage, as shown in figure 2.7. But this would cause the problem of over-voltage violation under light load conditions. Hence, Volt/Var control schemes are needed to guarantee a desired system voltage profile under all possible operating conditions.

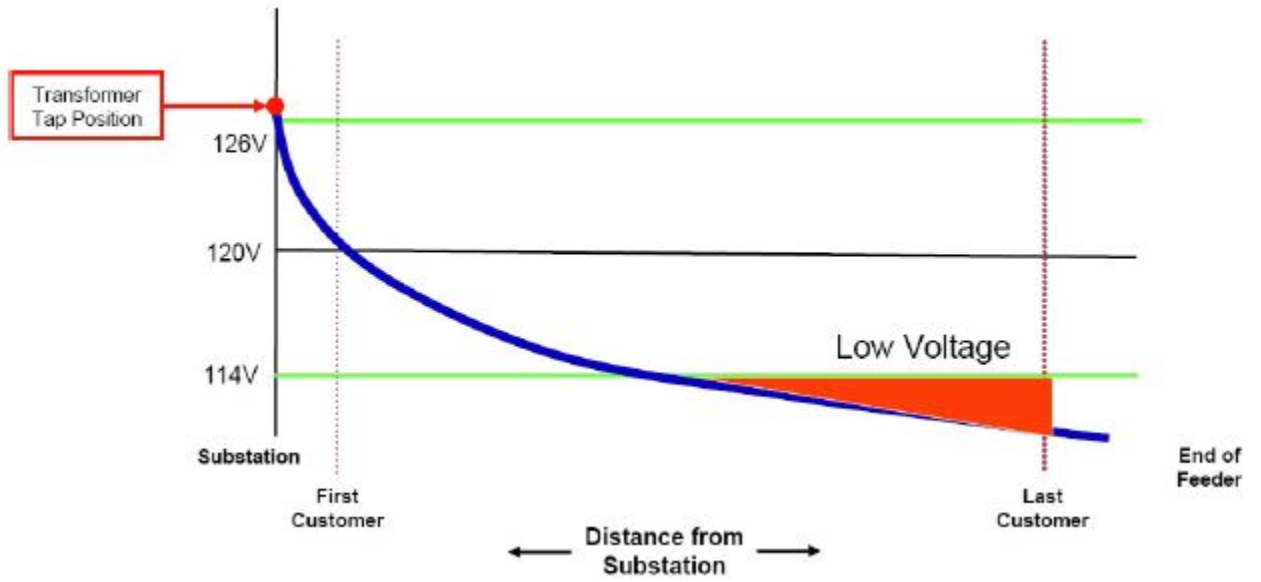


Figure 2.5 Without Volt/VAR Control under heavy load conditions

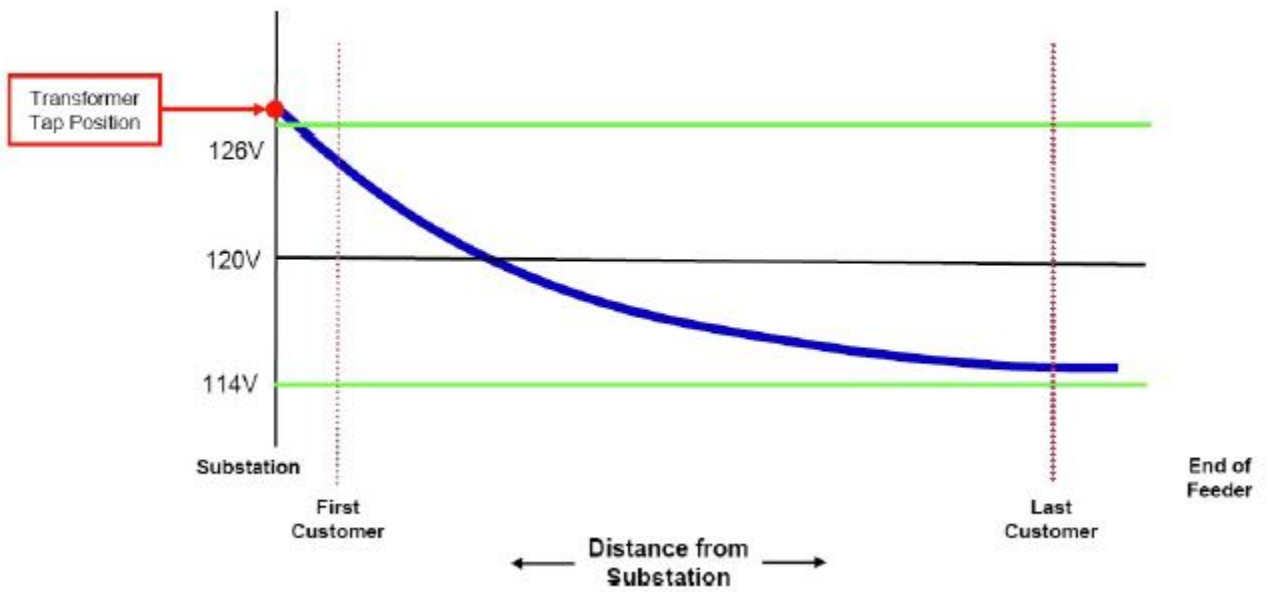
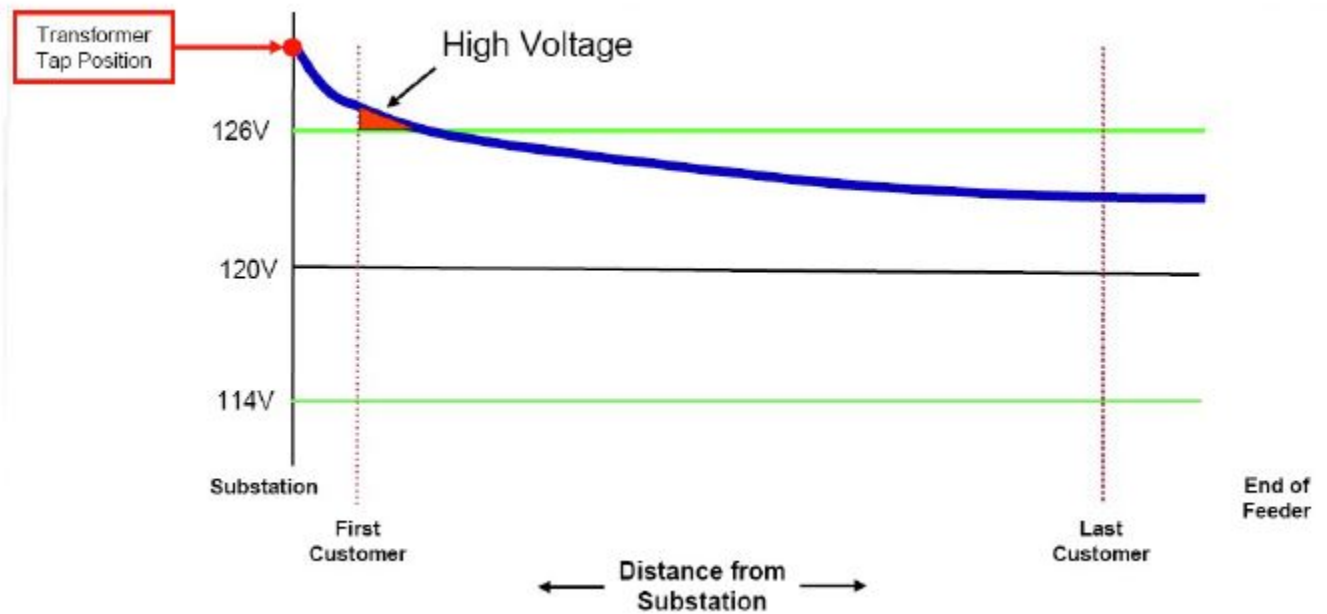


Figure 2.6 After raising the source voltage under heavy load conditions



**Figure 2.7** Without VVC under light load conditions after raising the source voltage

The most commonly used VVC devices on a conventional distribution system are voltage regulators (VRs) and capacitor banks (CAPs). Conventional control schemes of VRs and CAPs are simply standalone control schemes, in which a standalone controller receives measurements of current and voltage from local sensors and sends command signals to the corresponding VR or CAP.

### 2.2.2 Volt/VAR Control on FREEDM System

FREEDM system has Solid State Transformers (SST's) replacing the conventional iron transformers. The SST's can actually work under unity power factor or its reactive power from the feeder can be controlled. Therefore, SST's acts as a VAR compensation device in the FREEDM system, completely eliminating the use of capacitors. If needed the conventional voltage regulators can be used with the FREEDM system to achieve a better Volt/VAR schemes.

### 2.2.3 Proposed Approach

The objective of the study is to investigate impacts of PV penetration and to estimate the benefits of the FREEDM system over the conventional system.

The study was performed in the following steps:

- Determine PV Penetration cases.
- Determine and quantify the metrics needed for assessment of impacts of PV penetration.
- Perform time series simulations.

### 2.2.4 Metrics

To assess the impacts we need to quantify them. Thus, here metrics have been defined, which correspond to different recognized impacts [20]. These metrics will be calculated in different cases, providing us with a picture about the system performances under different levels of PV penetration.

The metrics are basically categorized under two major categories:

- Voltage Profile

#### 1. Voltage Violation

Kirchhoff's Law defines the voltage variation along the feeder in a distribution system. But, the equipment of the customers have a desired working voltage range. The ANSI C84.1 standards specify the steady-state voltage tolerances for an electrical power system. The standard divides voltages into two ranges. Range A is the optimal voltage range. Range B is acceptable, but not optimal. As figure 2.8 illustrates, the recommended service voltage range A by ANSI C84.1 standard to be  $\pm 5\%$  of the nominal voltage. A good Volt/Var control scheme should successfully make the primary-side voltage profile meet this standard. To quantify this Voltage Violation metric (VViol) was defined. It took into account both, the frequency and the duration of voltage violation.

$$VViolation = (\text{frequency of violation} \times \text{duration of violation})_{i,y} \quad (2.3)$$

$$VViol = \sum_i \sum_y \text{frequency of violation} \times \text{duration of violation} \quad (2.4)$$

where, i represents nodes and y represents phases A,B,C.

For the worst case condition Voltage Violation Index was defined:

$$VViol_{INDEX} = \text{Max}(VViolation_{i,y}) \quad (2.5)$$

#### 2. Voltage Drop

Voltage drops in a radial circuit according to the Kirchhoff's Law. The drop in voltage at a particular node with respect to the a reference point is defined as the voltage drop. In

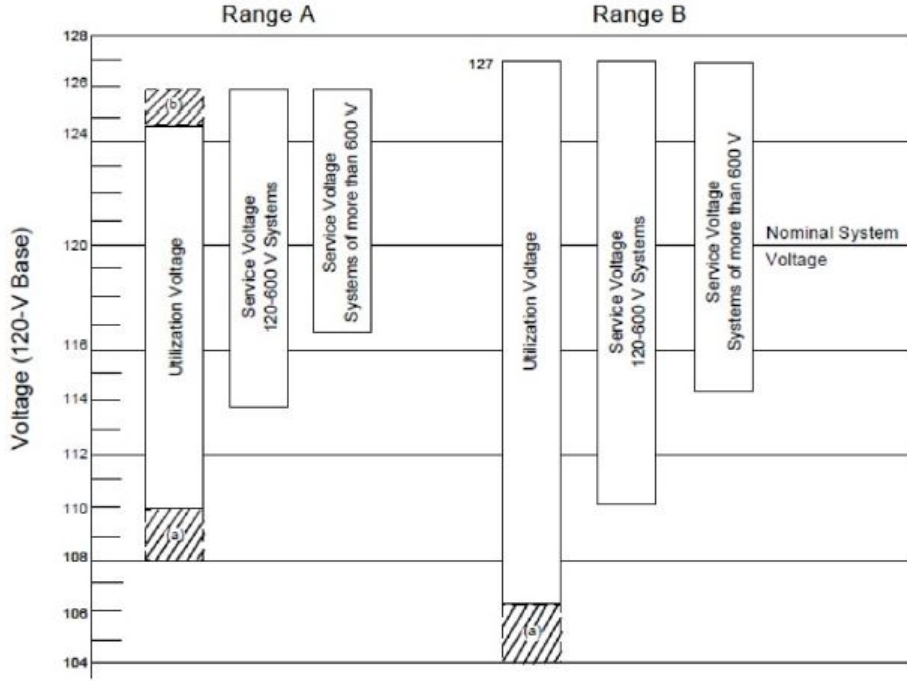


Figure 2.8 ANSI C84.1 Voltage Range for 120 Voltage Level

this case the reference is chosen to be 1.05 i.e the upper limit of the ANSI Standard. Thus, the voltage drop (VD) at a node is measured by the following equation:

$$VD = 1.05 - V_{iy} \tag{2.6}$$

where  $V_{iy}$  is the voltage on the  $i^{th}$  node and  $y^{th}$  phase

Again for the worst case condition Voltage Drop Index (VDI) was defined as follows:

$$VDI = Max(VD_{iy}) \tag{2.7}$$

### 3. Voltage Unbalance

In an unbalanced distribution system, at each node, the voltages among three phases can be different. For certain three-phase loads, such as a motor, unbalanced voltage may cause damage. Voltage Unbalance (VU) is the maximum voltage difference among three

phases at a particular node. This value is calculated using the following equation:

$$VU_i = \text{Max}(V_{i,y}) - \text{Min}(V_{i,y}) \quad (2.8)$$

where i represents the node and y represents the phases A,B,C.

Here again, Voltage Unbalance Index (VUI) is defined for the worst case condition and is given by the following equation:

$$VUI = \text{Max}(VU_i) \quad (2.9)$$

#### 4. Voltage Variation

Voltage variation (VV) measures the maximum voltage change observed at a node under different operating conditions during the whole simulation period and is given by the following formula:

$$VV_{i,y} = \text{Max}(V_{i,y}) - \text{Min}(V_{i,y}) \quad (2.10)$$

where, i is the node number and y represents the phases A,B,C.

For worst case scenario Voltage Variation Index (VVI) was defined:

$$VVI = \text{Max}(VV_{i,y}) \quad (2.11)$$

High voltage variation is not desirable as VVI also measures the effectiveness of Volt/VAr scheme of a system. In terms of impact, the rate of change of voltage is important as high rate causes so called "flicker". To quantify voltage flicker we use the following equation:

$$VF_i = \frac{V_{i,y,t} - V_{i,y,(t-1)}}{T} \quad (2.12)$$

where, i is the node number and y represents the phase A,B or C, t is the time and T represents sample duration.

For the worst case scenario Voltage Flicker Index (VFI) was defined:

$$VFI = \text{Max}(VF_{i,y}) \quad (2.13)$$

where, i represents the node and y represents phase A,B,C.

#### 5. Voltage Regulators Operations

A voltage regulator with lesser number of tap changes will have longer life than the one incurring more number of tap changes. This serves as a direct economic saving. The

number of operations for a voltage regulator can be counted and compared which will give an idea about the increment in the life of the Voltage Regulator and thus deferment of cost.

- Power & Energy

1. *Power & Energy Loss*

The amount of power loss that occurs in a distribution circuit is an important performance metric used by utilities. Hence, power and energy loss is considered as one of the metrics in this study.

2. *Peak Demand Reduction*

Peak demand reduction is also an operational goal in system operation as it helps us to evaluate how much generation can be deferred. This helps to bring down the ramp rate requirements, hence, peak demand reduction is also considered as a performance metric.

3. *Power Flow at Substation*

Total demand as measured at substation changes considerably when DERs are deployed as the effect of their intermittency. Thus, the power flow at the substation needs to be monitored as it directly affects the generation ramp rate. It would be interesting to see how the profile of real power flow through the substation ( $P_{SUB}$ ) changes in different scenarios. Hence, total demand is also included as one of the impact metrics.

### 2.2.5 PV Penetration Scenarios

In this study the test system was penetrated at different levels with PV to see the impacts in different scenarios. This created several different cases discussed herewith.

- 80% PV Penetration - Hourly Data

The resolution of the data was hourly for this case and it was considered that each load carrying node has PV with  $PV_{max} = 0.8 \times Load_{max}$ . For FREEDM case, full deployment scenario was considered and SST's were considered to be operating at unity p.f.

- 80% PV Penetration - 15 min Data

To monitor the impacts of PV in a better manner, a higher resolution data was chosen. This is because PV is cannot be expected to be constant or linear for the period as long as one hour. Here again all the load carrying nodes were considered to have PV with 80% penetration as in

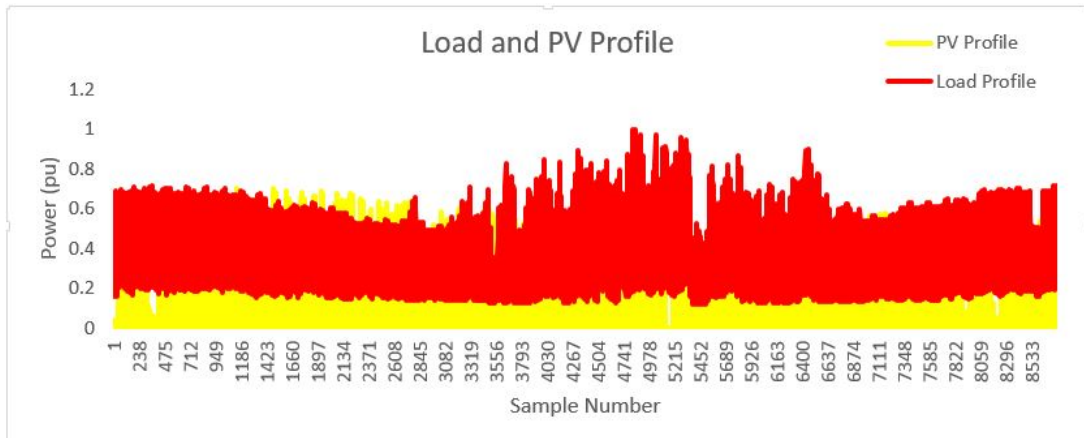
hourly case. For FREEDM case, still full deployment was considered and SST's were considered to be operating at unity p.f.

- 45.34% PV Penetration - 15 min Data  
To develop this case, initially all nodes were listed in the decreasing order of the amount of peak load being served by them. The top half of the nodes in this list were considered to have PV with  $PV_{max} = 0.5 \times Load_{max}$ . Thus, this was partial PV deployment scenario. Furthermore, with respect to FREEDM it was still a full deployment scenario and all SST's were set to operate at unity p.f.
- 90.68% PV Penetration - 15 min Data  
This case was developed in line with the 45.34% PV penetration case. The only difference is that in here  $PV_{max} = Load_{max}$ .
- 90.68% PV Penetration - 15 min Data (with Partial FREEDM Deployment)  
This is exactly the same case as 90.68% PV Penetration case in terms of PV penetration. The difference is in terms of FREEDM Deployment. In this case SST's were considered to be only present on the nodes having PV and rest other nodes were still having conventional transformers. SST's were still set to operate at unity p.f.
- 90.68% PV Penetration - 15 min Data (Minimum FREEDM Deployment needed)  
This case is an extrapolation of the previous case. In here a parametric study was done to find out the minimum number of SST's needed to take care of all the impacts on the feeder. SST's were present only on node 844 in FREEDM case and were set to operate at unity p.f. at all time.
- 80% PV Penetration - 15 min Data (Commercial Scale PV Penetration)  
To develop this case, initially the peak load on the feeder was calculated. The maximum PV was considered to be 80% of this peak load was put at the end of the feeder (at node 840). In this case, for FREEDM, SST's were not operating at unity p.f. but were set to operate at 0.9 lagging p.f.

### 2.2.5.1 PV Penetration

PV penetration is the degree to which PV supplies the loads in a distribution system. Thus, percentage PV penetration is defined as the ratio of maximum PV to the maximum load. This can also be represented by the following equation:

$$Percentage\ PV\ Penetration = \frac{PV\ Peak}{Load\ Peak} \quad (2.14)$$



**Figure 2.9** Annual Load and PV Profiles

### 2.2.5.2 Scenario I: 80% PV Penetration - Hourly Data

In this case, the ratio of PV peak to load peak was considered to be 0.8. For simplicity we made some assumptions and approximations which are defined as follows:

- The load given in the IEEE published results was considered as the peak load of the system.
- Each load serving node in the system has PV.
- Each node has same load and PV profile.
- For each phase (per node),  $P_{V_{PEAK}}$  is 80% of the  $P_{LOAD-PEAK}$ .
- Volt/VAR control for FREEDM was set to default, where all SST's have unity pf.

#### Load and PV Profile

The annual load and PV profiles are displayed by figure 2.9. The load data was downloaded from the PG & E website and the PV data was collected from the FREEDM rooftop PV installations. This profile is on hourly resolution, thus, it has 8760 data points.

#### Assessment of Impacts on Conventional System

Time series simulation have been done to determine the system performance metrics for assessment of impacts.

- Voltage Profile

##### 1. Voltage Violation:

Simulations show that PV penetration causes voltage violations on the test feeder. It

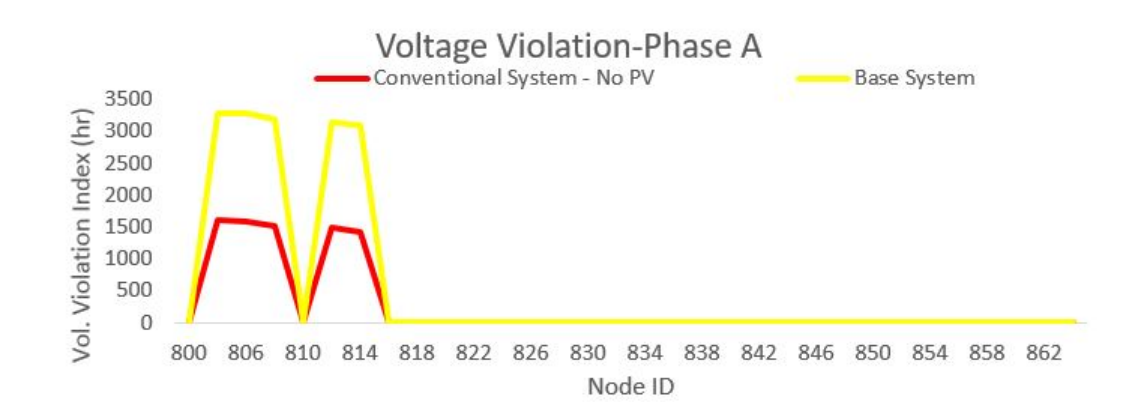


Figure 2.10  $VViol_{INDEX}$  on Phase A

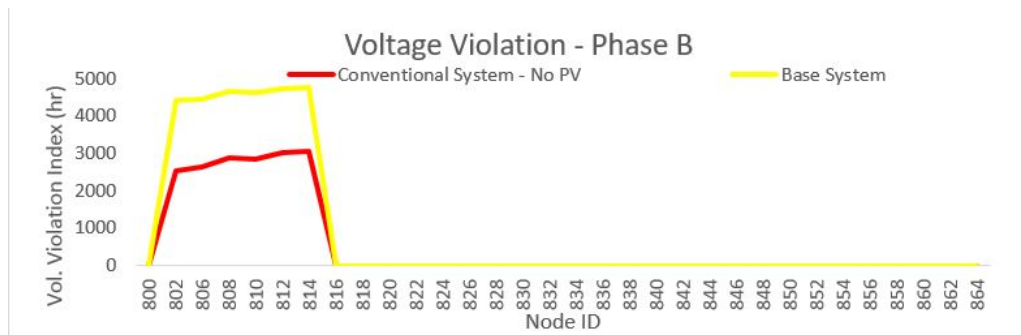


Figure 2.11  $VViol_{INDEX}$  on Phase B

is observed in the figures 2.10-2.12 that the voltage violation index is too high for base case than the conventional case for all phases. This is expected as PV would improve the voltage profile, thus, the nodes closer to the upper limit might go over 1.05 pu.  $VViol_{INDEX}$  for conventional case and base case is 3045 hrs and 4755 hrs respectively. This implies that PV penetration worsens  $VViol_{INDEX}$  by 56.15%.

2. Voltage Drop:

The IEEE 34 nodes feeder has eight feeder ends, Node 838, 810, 822, 826, 856, 864, 848 and 840. The voltage drop at these eight ends are shown in table 2.2. The voltage drop index of the system is the maximum value of the drop among all feeder ends. The worst case VDI for base case is 0.0566 pu, which is more than 0.0556 pu in the conventional system.

Generally, it is expected that voltage drop profile will be improved due to PV penetration. In here (from table 2.2), it is visible that there are some nodes wherein the voltage drop

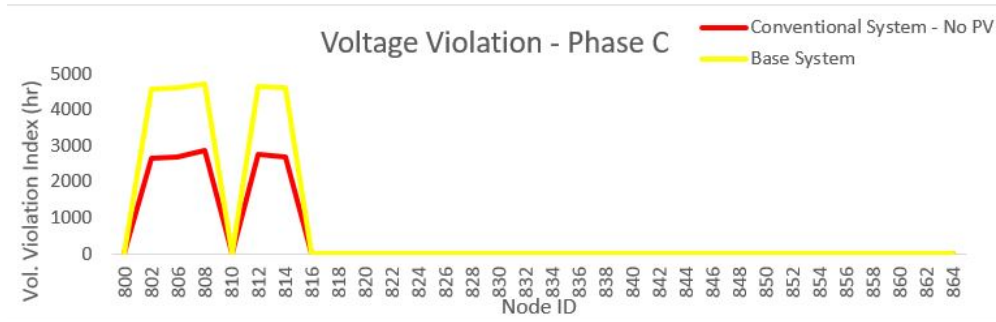
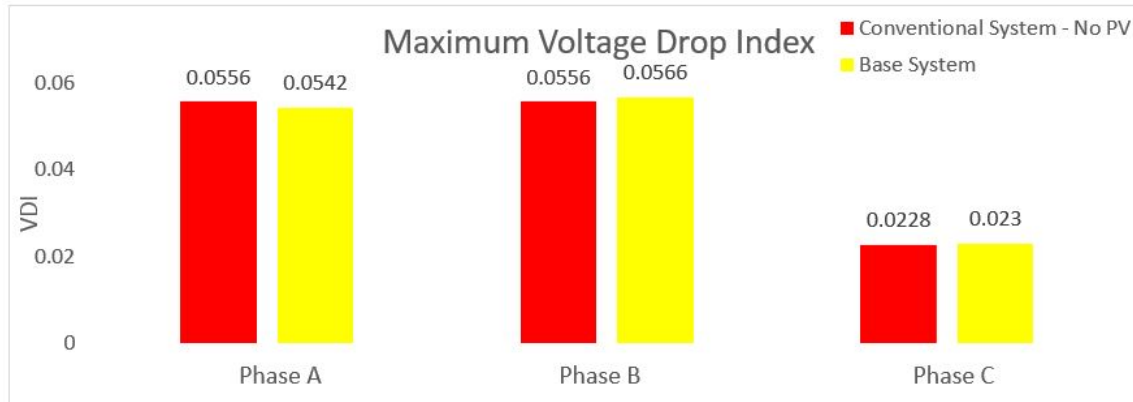


Figure 2.12  $V Viol_{INDEX}$  on Phase C

Table 2.2 Voltage Drop Index

VDI	Conventional System(No PV)			Base System		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		0.0229			0.0233	
810		0.0206			0.018713	
822	0.0556			0.0542		
826		0.0403			0.0403	
856		0.0556			0.0566	
864	0.0235			0.0253		
848	0.0224	0.0222	0.022	0.02588	0.0225	0.0224
840	0.0232	0.0229	0.0228	0.0234	0.0234	0.0232



**Figure 2.13** Maximum Voltage Drop Index

profile has improved due to PV penetration while there are some nodes of the opposite nature. If we closely observe, the terminals violating the expected results are the one lying after voltage regulator 2. This indicates that the capacitors on the nodes 848 and 840 are over-compensating the system in the second half.

Figure 2.13 shows the comparison of VDI's on all three phases for both systems i.e. conventional - No PV and base system.

### 3. Voltage Unbalance:

IEEE 34 node test feeder is a highly unbalanced system. Hence, we need to investigate the impact of PV penetration over voltage unbalance (VU). VU as defined earlier is the maximum difference between the voltages per node. Figure 2.14 shows the VU variation along the feeder.

Here, it is observed that PV penetration improves voltage unbalance. Although, if PV penetration is unbalanced, then it may adversely affect VU. The worst case VUI in conventional case is 0.0479 pu and in base case is 0.0428 pu. Hence, PV penetration improves VUI by 10.65%.

### 4. Voltage Variation:

With PV penetration the voltage variation (VV) always remains higher than that in case without PV as observed from figures 2.15-2.17. Without PV the VVI is 0.1121 pu whereas it climbs to 0.1432 pu with PV. This is expected as the PV is intermittent in nature. Table 2.3 gives the VVI's for the three phases over the feeder. Another common method to evaluate the voltage variation is to draw the histogram of all the voltages under all operating conditions on the feeder as shown in figure 2.18-2.19. The highest bar in the

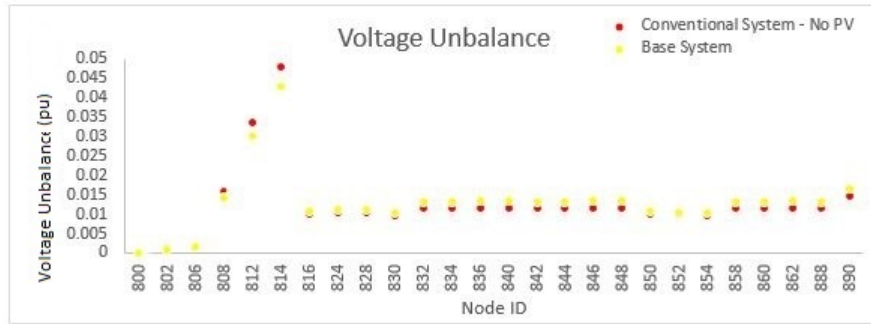


Figure 2.14 Voltage Unbalance Index along the feeder

Table 2.3 Voltage Variation Index

System	$VVI_a$	$VVI_b$	$VVI_c$	Max(VVI)
Conventional - No PV	0.1121	0.0688	0.0736	0.1121
Base System	0.1432	0.0865	0.0931	0.1432

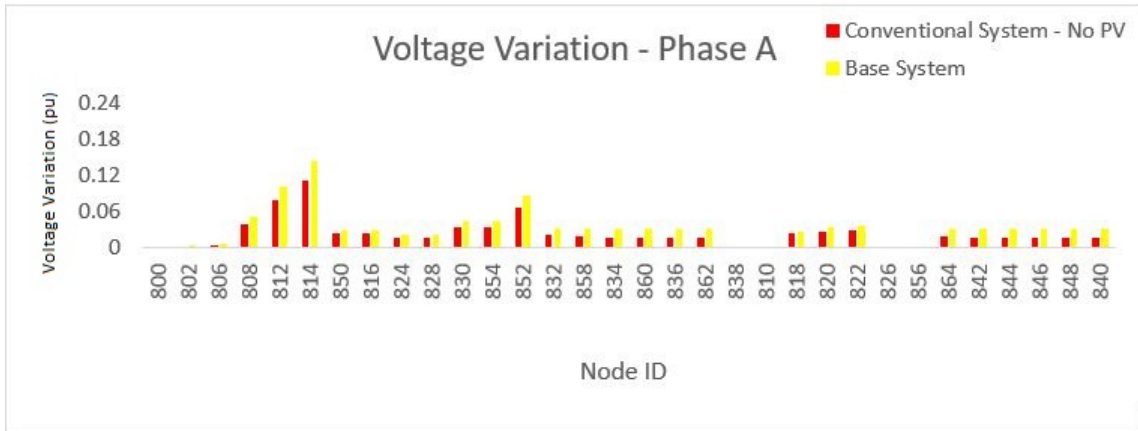


Figure 2.15 Voltage Variation on Phase A

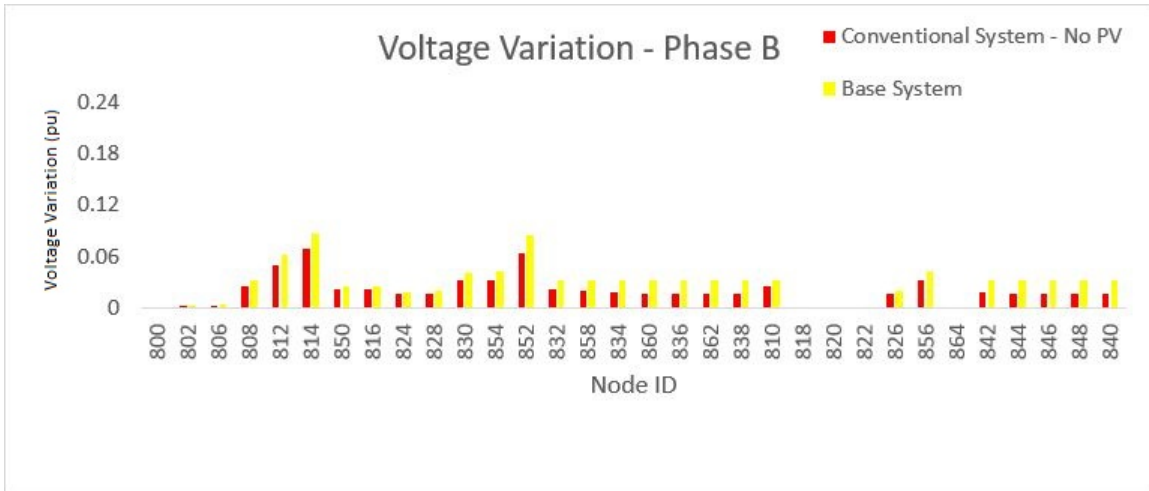


Figure 2.16 VoltageVariation on Phase B

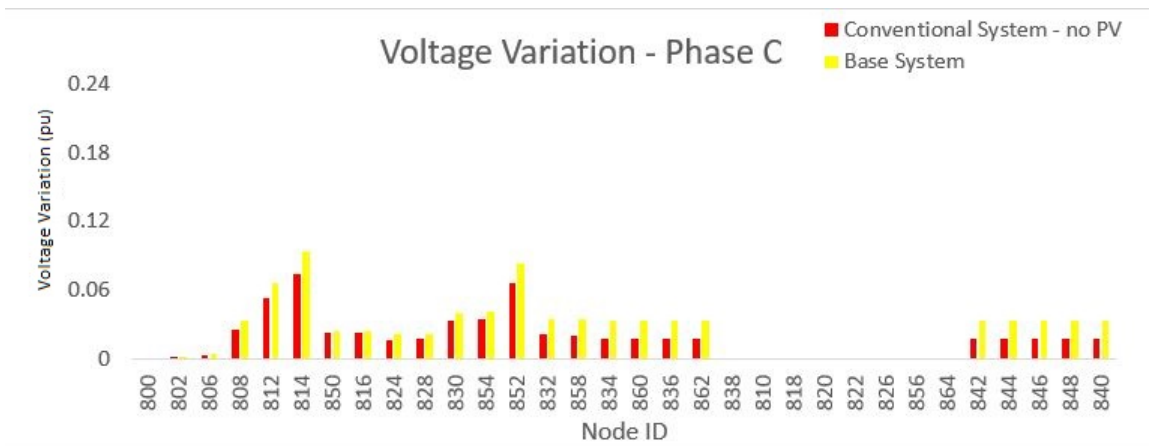
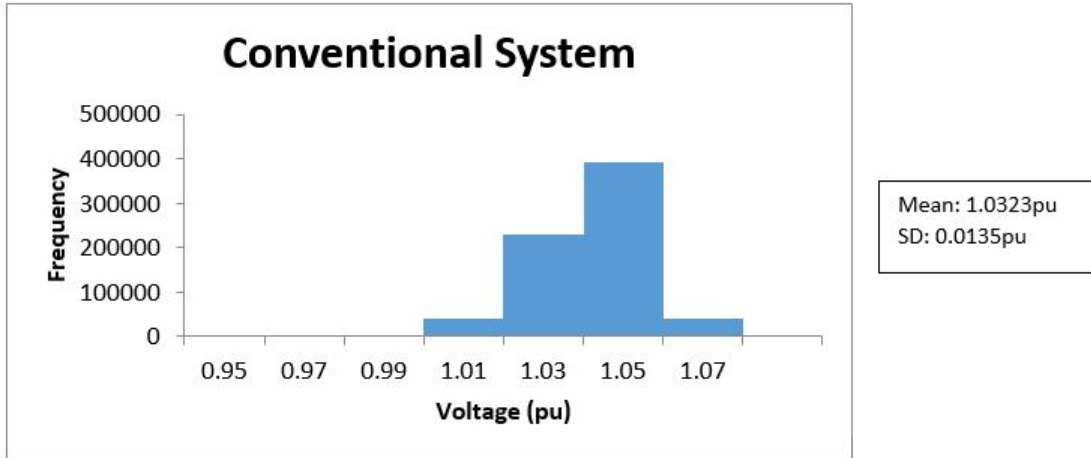


Figure 2.17 VoltageVariation on Phase C



**Figure 2.18** Histogram of voltages on primary side of feeder in conventional system without PV penetration

histogram indicates that voltage within that bin has the most possibility. However, when we have more nodes close to the substation, the mean inclines to the substation voltage, which means that, compared with taking the maximum and minimum values, taking average value is not a good choice to weigh the voltage violation.

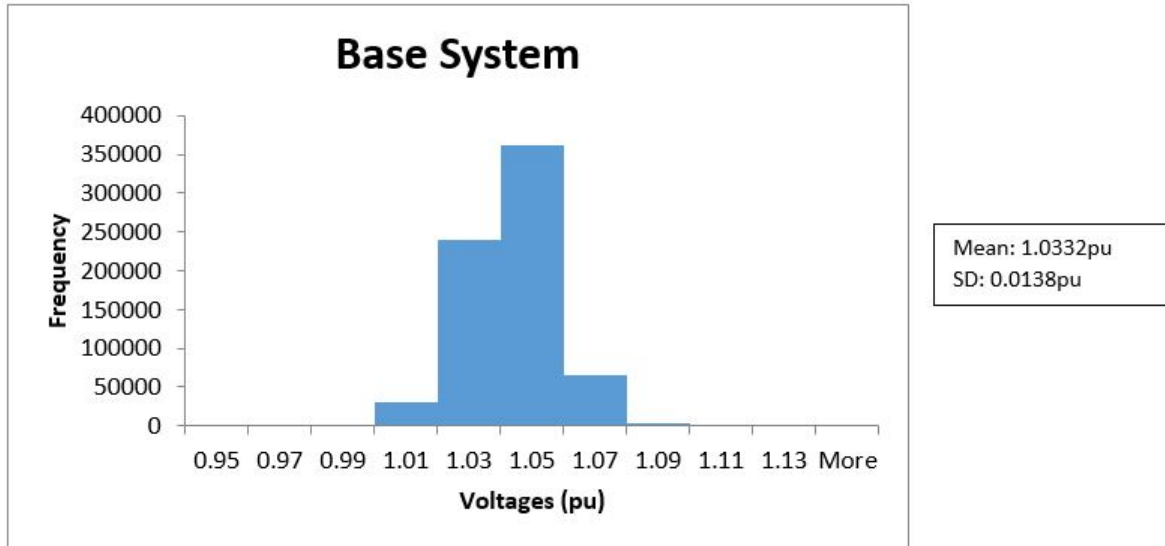
5. Voltage Regulator Operations:

Intermittent output of PV's affect the voltage regulator operations. From simulations VR tap movements have been obtained for both cases which is displayed in table 2.4:

**Table 2.4** No. of Voltage Regulator Operations

System Type	No. of Tap Changes /year		
	Phase A	Phase B	Phase C
<b>Conventional System</b>	VR1 - 4256	VR1 - 3114	VR1 - 3224
	VR2 - 4103	VR2 - 3817	VR2 - 3830
<b>Base System</b>	VR1 - 5199	VR1 - 4027	VR1 - 4174
	VR2 - 4985	VR2 - 4696	VR2 - 4720

Assessing table 2.4, it can be concluded that, there are always lesser number of operations



**Figure 2.19** Histogram of voltages on primary side of feeder in base system

with no PV installations, as expected. As we highly penetrate the system, the number of operations for voltage regulators increase in response to the intermittent nature of PV.

- Power & Energy

1. Power Loss:

Power loss accounts to direct economic loss to the utility. Hence, it becomes an important metric to analyze. The plots for line power loss in both cases displayed in figures 2.20-2.21.

The analysis of the plots show that there is indeed a drop in the power losses after PV penetration. We calculated average loss (kW) per load (kVA)[average of (loss/load) at each hour] to concrete our observations and it comes out to be 7.33% for conventional case and 6.10% for base case. Thus, the system has high losses without PV penetration.

2. Peak Demand Reduction:

The 15 min peak demand in the two cases are as follows:

Conventional System(No PV) =2043.56 kW

Base System = 1884.62 kW

This accounts for a peak shaving of 158.94 kW. Furthermore, an energy demand reduction of 28.32% was observed.

3. Power Flow at Substation:

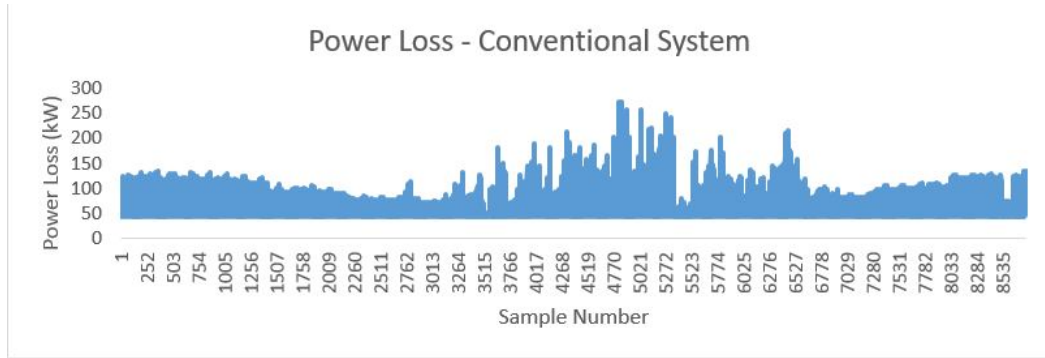


Figure 2.20 Power Loss in Conventional System (No PV)

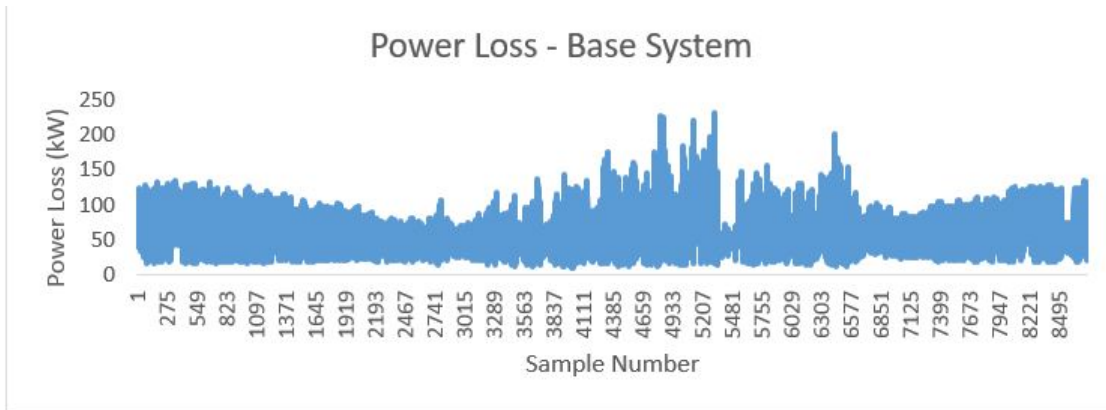


Figure 2.21 Power Loss in Base System

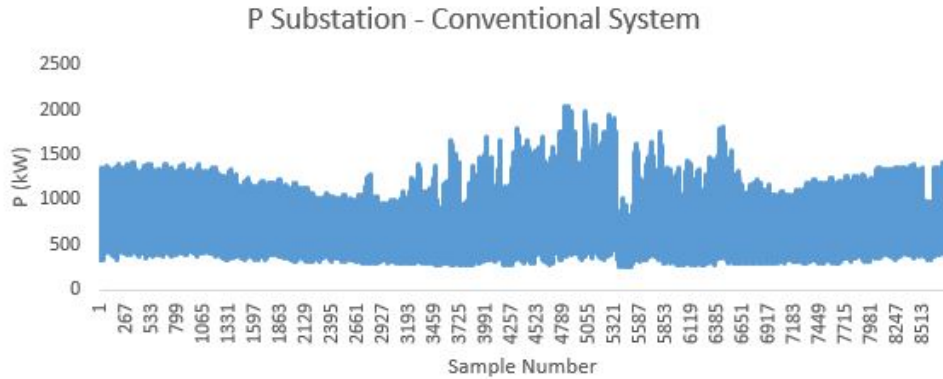


Figure 2.22  $P_{SUB}$  variation for Conventional System (No PV)

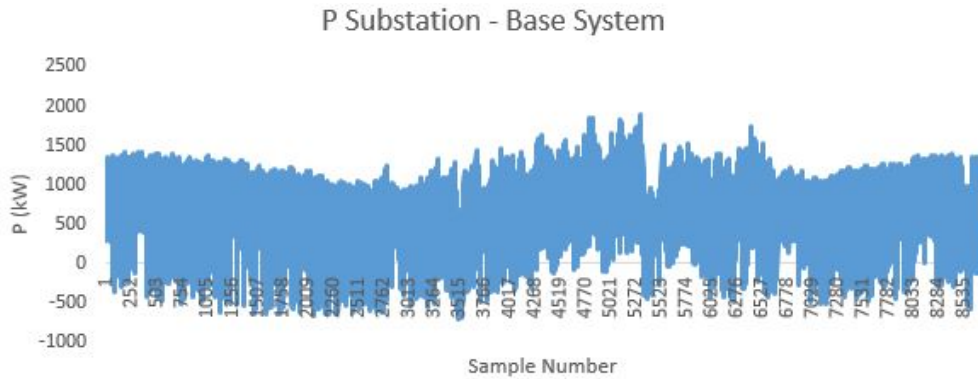


Figure 2.23  $P_{SUB}$  variation for Base System

The power flow at substation ( $P_{SUB}$ ) affects the generation ramp rates. Hence, It becomes an important metric to be considered.  $P_{SUB}$  variation over the year period, in both cases is displayed in figures 2.22-2.23.

From figures 2.22 and 2.23, we deduce that PV penetration helps in scaling down the  $P_{SUB}$  profile but there is reverse power flow which demands some attention. Storage is an option to mitigate this issue but it is yet to be researched whether it will be a cost effective option or not.

**FREEDM System Impacts**

The impact of PV on conventional system was discussed in the previous section. Now, the analysis will be repeated for the FREEDM test system.

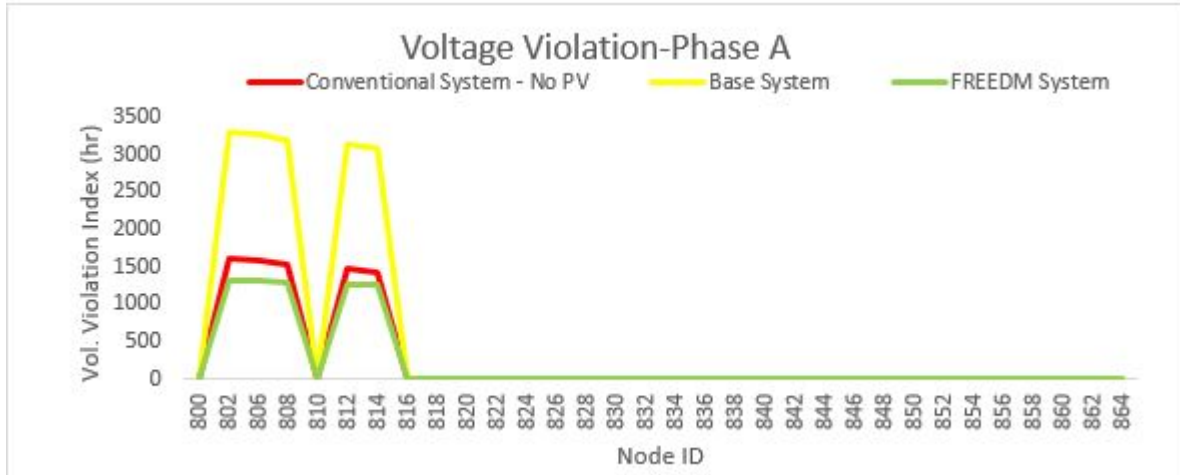


Figure 2.24  $VViol_{INDEX}$  on Phase A

### Assessment of Impacts on FREEDM System

The list of metrics will be again calculated for in this section but for the FREEDM System and will be compared with the base case to note the difference in performance of both systems.

- Voltage Profile

1. Voltage Violation:

The  $VViol_{Index}$  for FREEDM System is 1364 hrs which is much less than that of conventional system (3045 hrs) and base system (4755 hrs). Also, from figures 2.24-2.26 it can be seen that FREEDM system has lesser voltage violations than the conventional system.

2. Voltage Drop:

The system is still the same and hence has the same eight terminal nodes. The voltage drop index with respect to those eight nodes are displayed in the table 2.5:

Here, it can be observed that FREEDM system offers better voltage drop than the base system, for terminals which lie before the node 852. Beyond node 852, base system performs better as there is no voltage regulator on node 852 for the FREEDM topology but as the secondary is always regulated in FREEDM its not a point of concern. Figure 2.27 shows the maximum voltage drop index comparison for systems.

3. Voltage Unbalance:

As earlier discussed that the test system is a highly unbalanced system and voltage unbal-

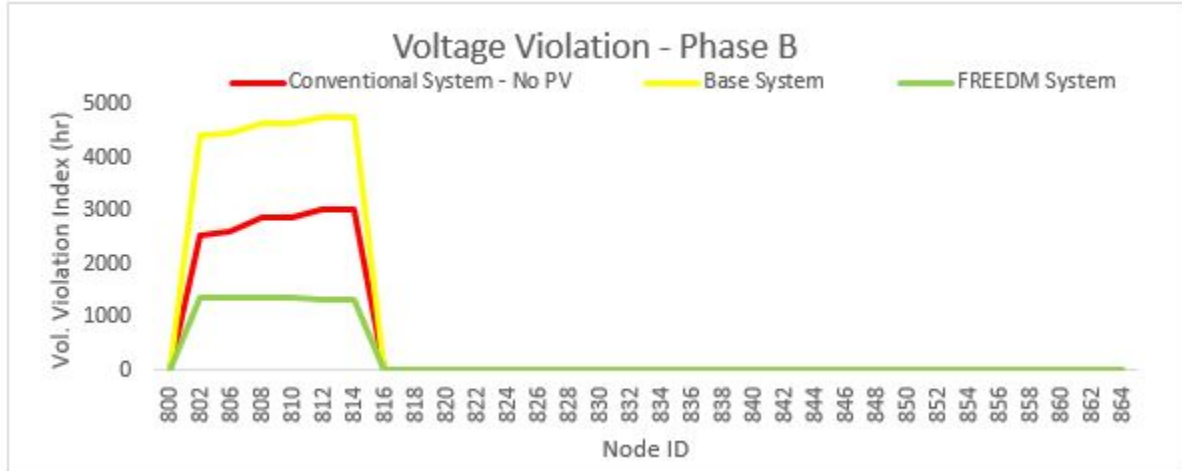


Figure 2.25  $V Viol_{INDEX}$  on Phase B

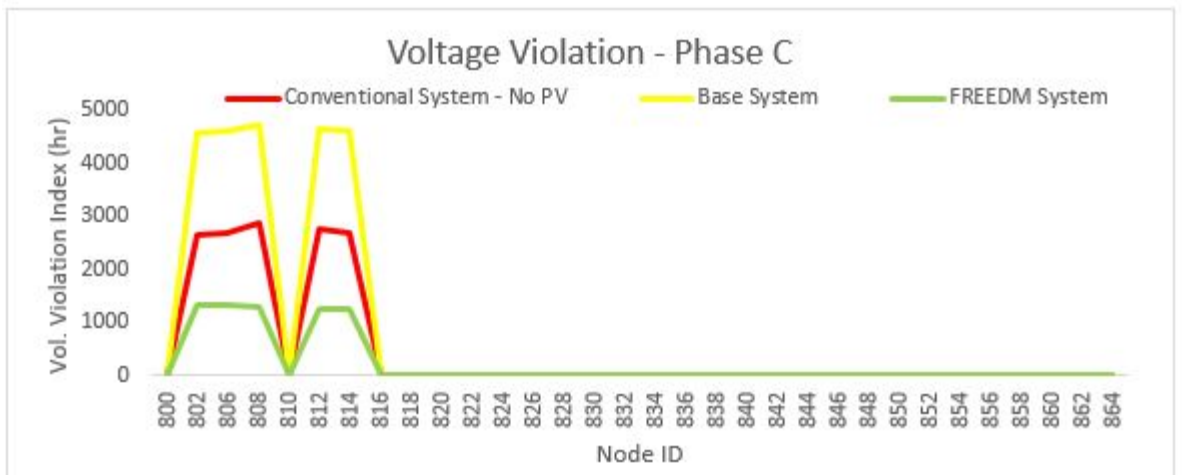
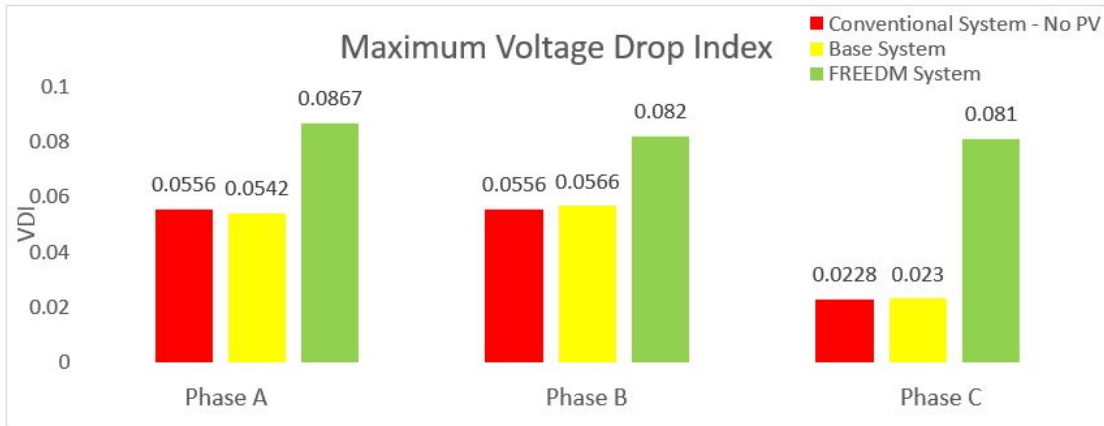


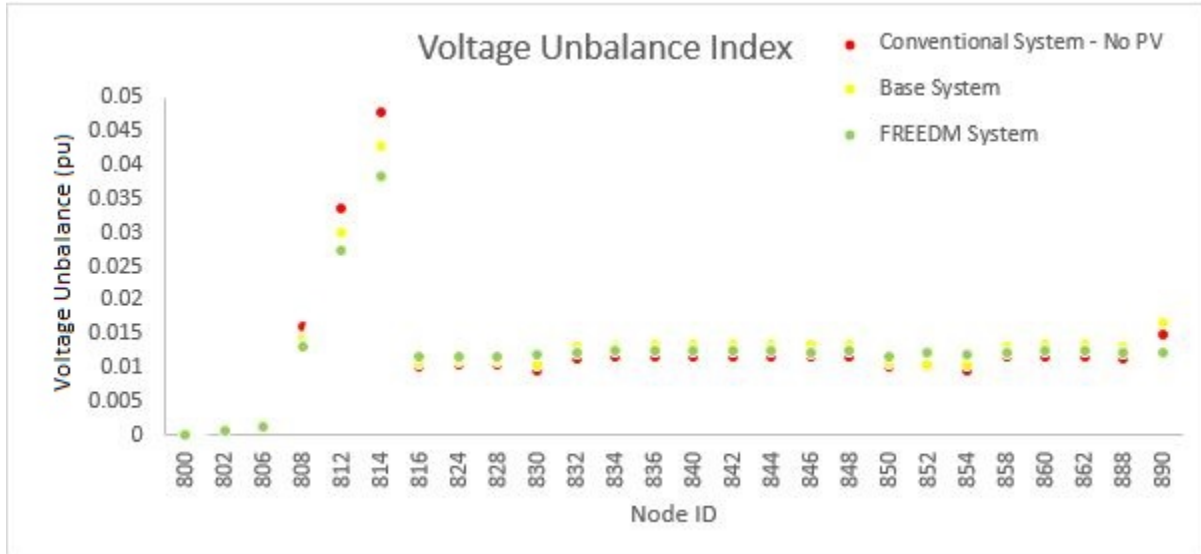
Figure 2.26  $V Viol_{INDEX}$  on Phase C

**Table 2.5** Voltage Drop Index

VDI	Base System			FREEDM System		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		0.0233			0.0819	
810		0.018713			0.0152	
822	0.0542			0.0498		
826		0.0403			0.04	
856		0.0566			0.0536	
864	0.0253			0.0833		
848	0.02588	0.0225	0.0224	0.0867	0.0821	0.081
840	0.0234	0.0234	0.0232	0.0867	0.0818	0.081



**Figure 2.27** Maximum Voltage Drop Index



**Figure 2.28** Voltage Unbalance Index along the feeder

ance may lead to motor failure and other issues, thus, VU becomes an important metric to be analyzed. The plot in the figure 2.28 shows that FREEDM System addresses the issue of voltage unbalance well and shows an improvement in the Voltage Unbalance Index (VUI). Worst case VUI for base system is 0.0428 pu whereas it is 0.0384 pu for the FREEDM system, fetching out an improvement of 10.28%. As the secondary in FREEDM is regulated, we can thereby also again claim VU to be zero with FREEDM case.

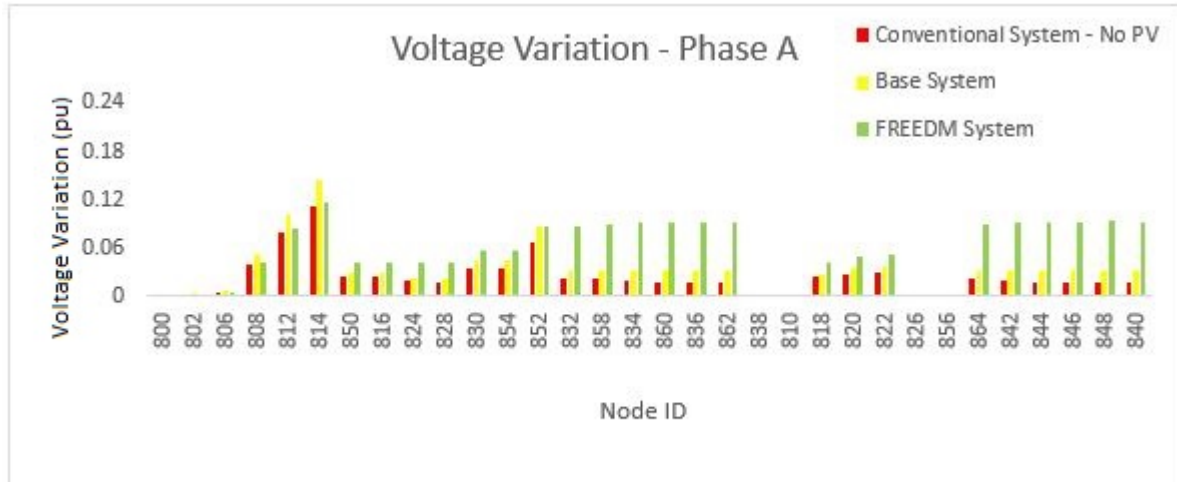
#### 4. Voltage Variation:

The voltage variation in case of FREEDM system was found to be lesser than base case but a bit more than the conventional case. This proves that FREEDM system improves voltage variation but it cannot fully curb the impact of intermittent nature of PV. FREEDM system provides an improvement of 18.3% in voltage variation index as compared to the base system. Furthermore VFI was defined to take into account the worst case rate of change of voltage. The value of VFI is 0.0958 V/s for conventional case, 0.2119 V/s for base case and 0.1922 V/s in FREEDM System. Thus, it can be observed that FREEDM improves maximum rate of change of voltage in the system.

Table 2.6 gives information about the voltage variation index in different systems:

**Table 2.6** Voltage Variation Index

System	$VVI_a$	$VVI_b$	$VVI_c$	VVI
Conventional - No PV	0.1121	0.0688	0.0736	0.1121
Base System	0.1432	0.0865	0.0931	0.1432
FREEDM System	0.117	0.077615	0.075556	0.117



**Figure 2.29** Voltage Variation on Phase A

The plots in figures 2.29-2.31 shows that after node 852 the base system performs better than the FREEDM system in terms of voltage variation. This is expected as node 852 contains a voltage regulator in the base system which is absent in the FREEDM case. But still the peak voltage variation is shaved off by FREEDM System as it occurs before node 852. Here again, voltage variation can be claimed to be zero, taking into account that the secondary in FREEDM is always regulated. Furthermore, we also have the histogram in figure 2.32 to have a better idea of voltage variation in the FREEDM System.

5. Voltage Regulator Operations:

FREEDM system was also investigated for the number of operations for voltage regulators. Assessing table 2.7, it can be observed that, there are always lesser number of operations with no PV installations, as expected. As we highly penetrate the conventional system, the number of operations for voltage regulators increase. In case with the FREEDM System, we observe a drop in number of operations as compared to the base system.

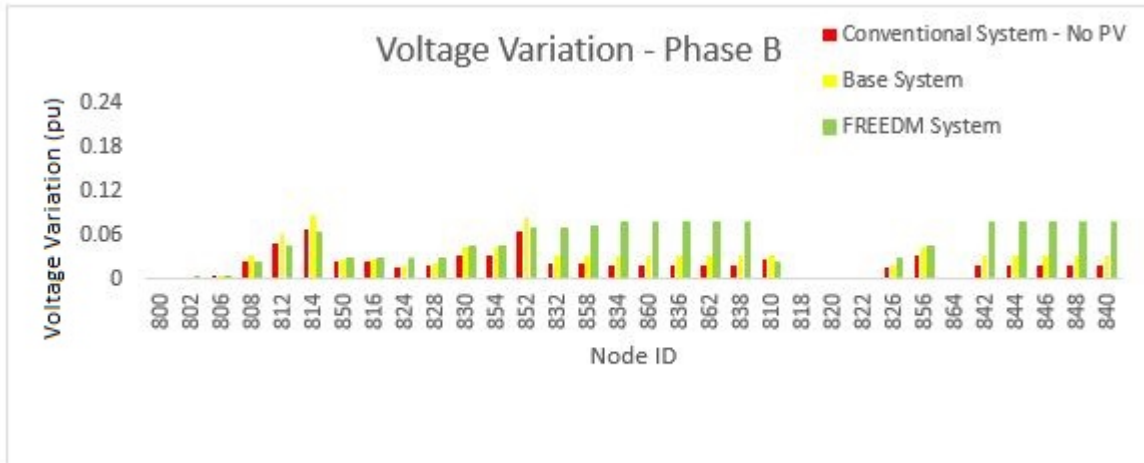


Figure 2.30 Voltage Variation on Phase B

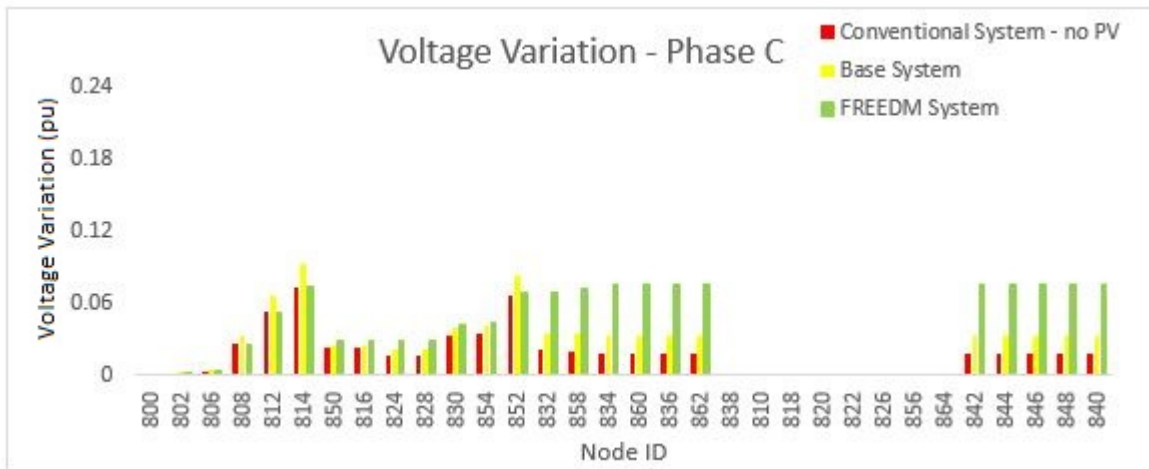


Figure 2.31 Voltage Variation on Phase C

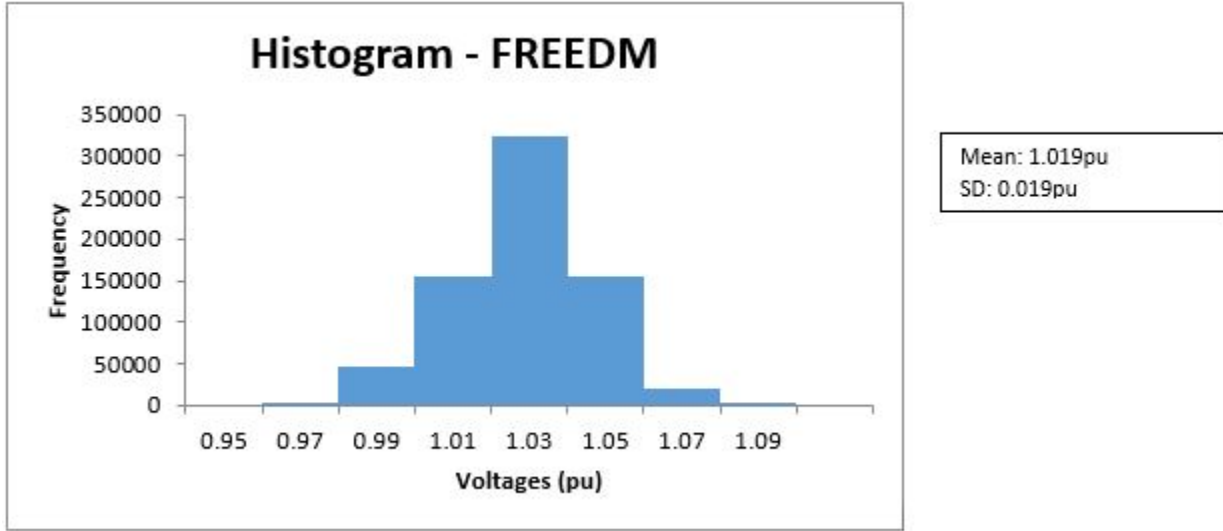


Figure 2.32 Histogram of voltages on primary side of feeder in FREEDM system

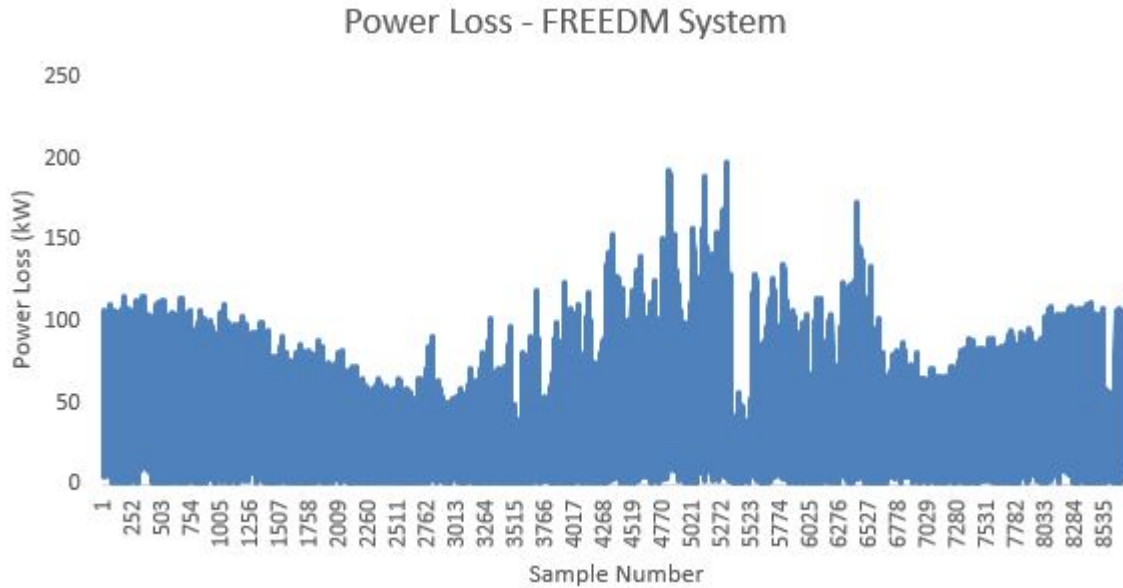
Table 2.7 Number of Operations for Voltage Regulators

System Type	No. of tap Changes/year		
	Phase A	Phase B	Phase C
<b>Conventional System (No PV)</b>	VR1 - 4148	VR1 - 3431	VR1 - 3790
	VR2 - 3905	VR2 - 3750	VR2 - 4045
<b>Base System</b>	VR1 - 5199	VR1 - 4027	VR1 - 4174
	VR2 - 4985	VR2 - 4696	VR2 - 4720
<b>FREEDM System</b>	VR1 - 4662	VR1 - 2798	VR1 - 3307
	VR2 - N/A	VR2 - N/A	VR2 - N/A

- Power & Energy

1. Power and Energy Loss:

The line power loss in the FREEDM system is plotted in figure 2.33. It is evident that the FREEDM system has lesser loss than the base system. The average loss per load goes



**Figure 2.33** Power Loss in FREEDM System

down to 2.95% with the FREEDM system which is 6.10% in the base system. Total Energy loss figures in the three cases are presented below in the format of 'line loss + transformer loss = total loss':

- Conventional System (No PV) - 561847.87 kWh + 44624.52 kWh = 606.47 MWh
- Base System - 464808.83 kWh + 43996.58 kWh = 508.80 MWh
- FREEDM System - 249314.58 kWh + 273253.6 kWh = 522.57 MWh

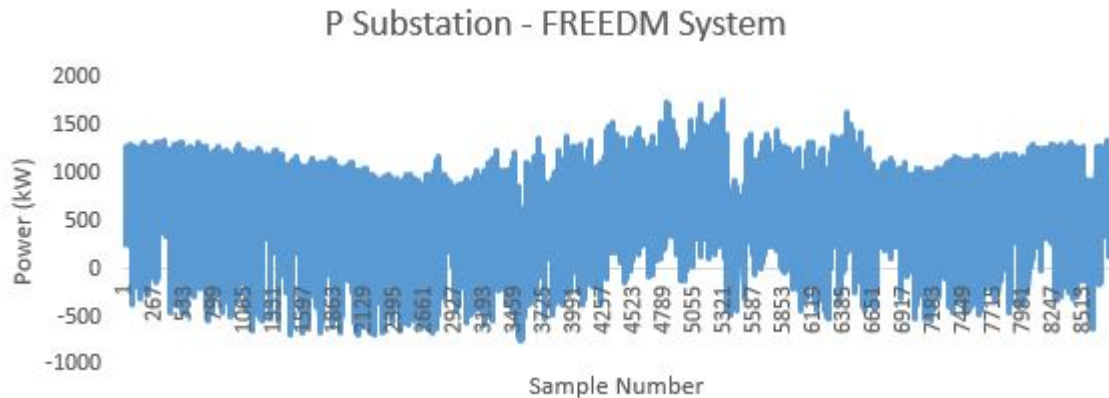
Thus, if total losses are considered then FREEDM incurs more loss than the base system.

## 2. Peak Demand Reduction:

As the peak demand reduction is solely caused by the PV penetration, both FREEDM and base case offer same peak demand reduction of 158.94 kW i.e. around 7.77%. Furthermore, the energy demand reduction caused due to PV penetration is 1857.90 MWh which is around 28.32%.

## 3. Power Flow at Substation:

The power flow at the substation remains almost the same as in base case. This is expected as PV is the sole source of real power in both cases which is the same. Figure 2.34 shows the real power flow variation for the FREEDM case.



**Figure 2.34**  $P_{SUB}$  Variation in FREEDM System

### 2.2.5.3 Summary

Including PV into the conventional system has several advantages and disadvantages. As the results of the study suggests the following are the benefits of PV.

- Better Voltage Profile at nodes.
- Lesser system Energy Loss (energy loss improved by 51.63%).
- Lesser Voltage Drop (VD improved by 9.2% on node 810).
- Improved Voltage Unbalance (VUI improved by 10.65%).

Although there are positive impacts, there are some negative impacts accompanying the same. The negative impacts are listed as follows:

- More Voltage Violations ( $VViol_{INDEX}$  increased by 56.15%).
- There is reverse power flow.
- Higher voltage variation (VVI worsened by 27.74%).
- Higher No. of Operations of Voltage Regulators.

The motivation behind the FREEDM system was to accommodate the negative impacts of PV. As our results show, FREEDM system takes care of all the negative impacts of PV pretty well and that too only with one voltage regulator.

- FREEDM system improves the voltage profile and at the same time it reduces the voltage violations by 71.3%. In this case, the conventional system itself has some voltage violations and it can be seen that the FREEDM system offers even lesser voltage violations than the conventional case.
- FREEDM system improves  $P_{SUB}$  profile and improves average loss per load by 48.36%.
- It improves voltage drop index by 18.72% over node 810 and ameliorates voltage unbalance index by 10.28%.
- It also performs better than the base system in terms of voltage variation. The VVI doesn't reflect that, as it considers the worst case, and FREEDM has only one VR. If we consider the nodes before node 852 (where conventionally VR-2 was placed) VV is lesser for in the case with FREEDM system.
- There is only one VR used in FREEDM system. Thus it saves the cost of a VR as well as it offers lesser number of operations for the VR present with respect to the base system with PV.

The results above, prove that FREEDM system can accommodate PV's better than the conventional system.

#### 2.2.5.4 Scenario Ia: 80% PV Penetration - 15-min Data

Previous study was performed on hourly basis over the whole year. For load variations an hour is a good enough resolution but to study the impacts of PV, one hour is a too long period to visualize the effects of its intermittency. Thus a higher resolution simulations i.e. 15 minute interval simulations were performed. If the 15-minute study would have been carried out over the whole year, there would have been lots of data points and the computational time would have been high. To take care of that part four weeks were chosen; each from the four distinguished seasons of the year. It was considered that the weeks are representative of their respective season. Thus, to extrapolate the results for an year, each week of a particular season was considered to be same as the representative week of that season.

The weeks were chosen such that it includes the peak load condition in the simulations. Furthermore, the hourly load data was processed to get the data in 15-min resolution. To be a bit fancy, we added a noise of 10% at each interpolation. The PV data was also processed to get it in 15-min

resolution format.

The weeks chosen are as follows:

- Winter week - 1/7/2013 - 1/13/2013
- Spring Week - 3/11/2013 - 3/17/2013
- Summer Week - 7/21/2013 - 7/27/2013
- Fall Week - 9/9/2013 - 9/15/2013

The other issue which was noticed is that the conventional system has voltage violations. This is because we do not know the actual Volt/VAR settings and how it is changed throughout the year in real practice. Thus, the LTC settings for the four different weeks were changed in order to achieve no voltage violations in the conventional case.

The LTC taps were set as:

- Winter - 1.03pu
- Spring - 1.02pu
- Summer - 1.04pu
- Fall - 1.02pu

The required changes in the VVC settings were made and the four week - 15 min simulations were performed. As after the changes, the conventional system does not carry any voltage violations; only the cases of interest (base case and FREEDM case) were considered for comparison from here onwards.

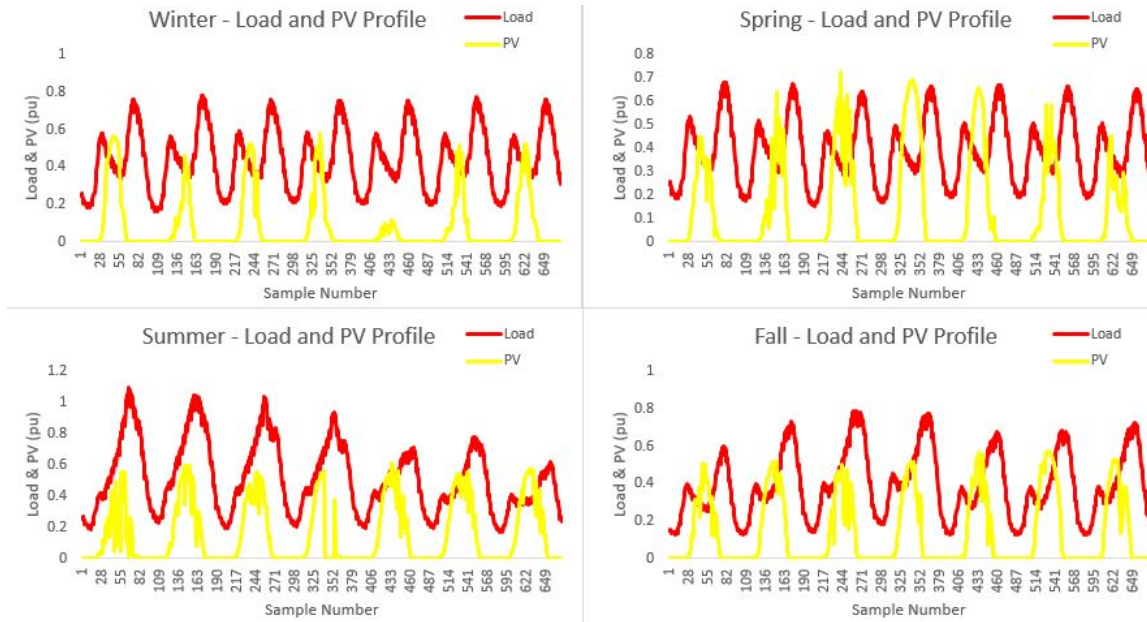
### **Load and PV Profile**

The four week load and PV profiles are displayed in figure 2.35. This profile is on 15-min resolution, thus, it has 2688 data points for four weeks.

### **Assessment of Impacts**

Here again the defined metrics were calculated and the performance of the two systems were compared.

- Voltage Profile



**Figure 2.35** Load and PV Profiles (for 4 weeks)

1. Voltage Violation:

It can be seen from figures 2.36-2.38 that there is no voltage violation on any phase except on phase A. Now we see the base case has more  $VVIOL_{INDEX}$  than FREEDM case. But in both cases, the voltage violation is present on nodes 814 and 852, which does not serve any load. Thus, there is no real issue if the voltage limits are violated on those nodes.

2. Voltage Drop:

The voltage drop at the eight ends are shown in table 2.8. The VDI in base case is 0.065 and it is 0.091 pu for FREEDM case. Furthermore, Figure 2.39 gives a comparison of worst case VDI on both systems. It seems that FREEDM performs inferior than the base case in terms of voltage drop but it actually offers better VD for the nodes lying before VR-2. In the later half of the system it goes high because VR-2 is absent in FREEDM case. Although it's not a matter of concern as the secondary is always regulated in FREEDM.

3. Voltage Unbalance:

The worst case VUI in base case is 0.03393 pu and for FREEDM case is 0.03 pu. This shows that FREEDM improves voltage unbalance. Furthermore, it's again applicable that there will be no voltage unbalance in FREEDM as the secondary is regulated and values presented before are with respect to primary. Figure 2.40 shows the voltage unbalance

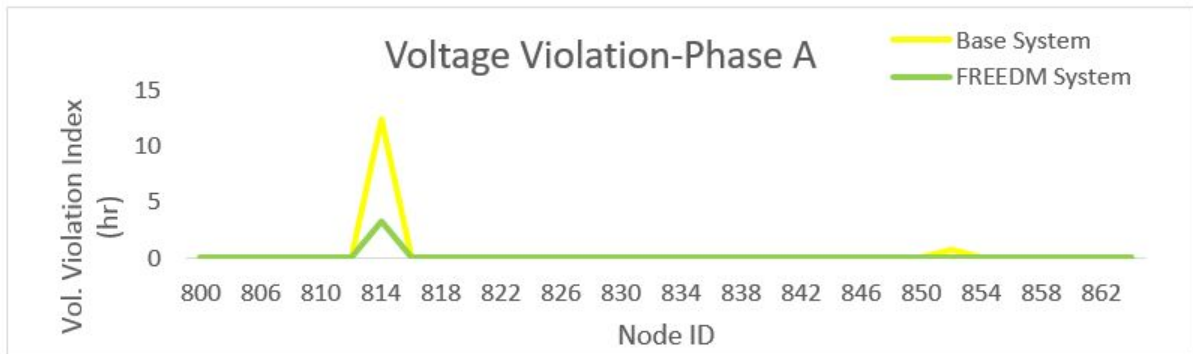


Figure 2.36  $V Viol_{INDEX}$  on Phase C

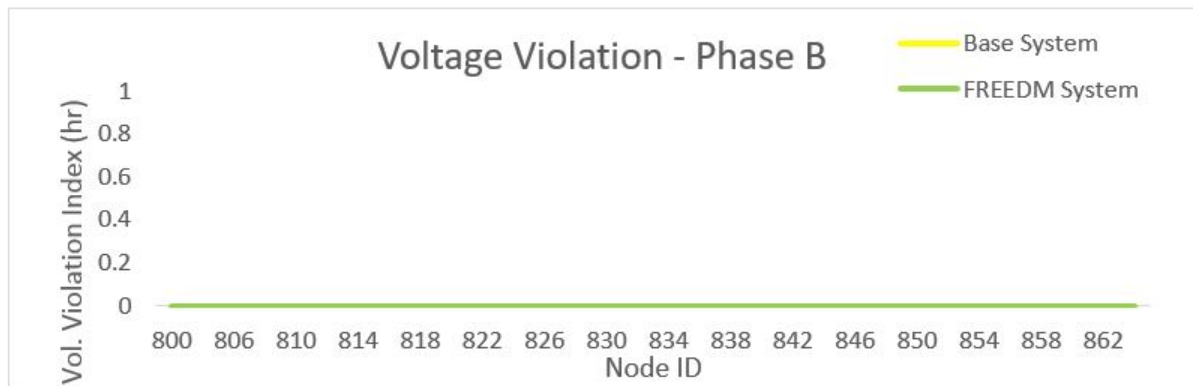


Figure 2.37  $V Viol_{INDEX}$  on Phase B

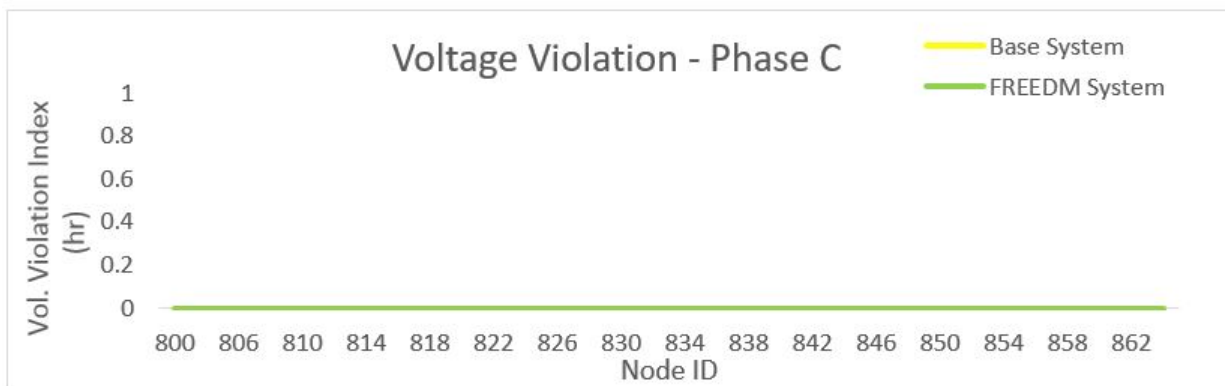
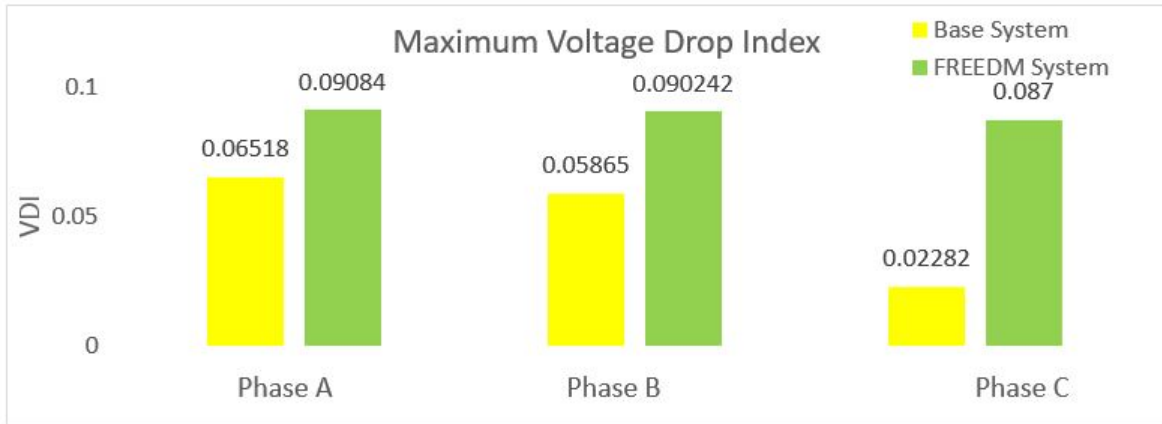


Figure 2.38  $V Viol_{INDEX}$  on Phase C

**Table 2.8** Voltage Drop Index

VDI	Base System			FREEDM System		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		0.02274			0.09011	
810		0.04165			0.04117	
822	0.0651			0.04964		
826		0.04017			0.03998	
856		0.05864			0.05501	
864	0.0233			0.08705		
848	0.0223	0.02197	0.02203	0.09084	0.09024	0.087
840	0.0231	0.02274	0.02281	0.09083	0.08998	0.08685



**Figure 2.39** Maximum Voltage Drop Index

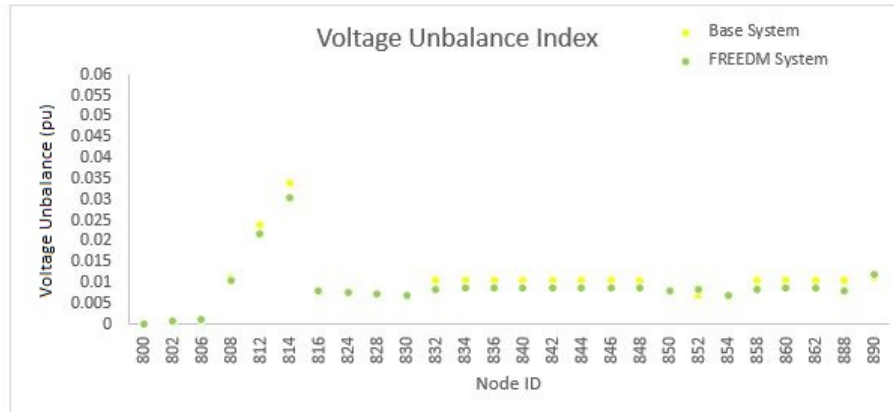


Figure 2.40 Voltage Unbalance Index along the Feeder

index variation along the feeder. Again from the figure 2.40 it is clear that for all nodes VUI is better with FREEDM system.

4. Voltage Variation:

VVI in base case is 0.1347 pu. It is clear that FREEDM accommodates this better as VVI is 0.1054 pu with FREEDM. Table 2.9 gives information about VVI in the two systems. Furthermore, figures 2.41-2.43 show the voltage variation on the three phases over the feeder which clearly shows that FREEDM performs better than the base system. Although after node 852, base system appears to be performing better than FREEDM but this is solely because of absence of second voltage regulator in FREEDM. Also, as the secondary is expected to be regulated, it is not a matter of concern.

Furthermore, the value of VFI is 0.947V/s for base case and 0.7736 V/s in FREEDM System. Thus, here again it can be observed that FREEDM improves worst case rate of change of voltage in the system.

Table 2.9 Voltage Variation Index

System	$VVI_a$	$VVI_b$	$VVI_c$	VVI
Base System	0.134745	0.086756	0.083173	0.1347
FREEDM System	0.105426	0.081859	0.072753	0.1054

Histograms also give us a very good idea of voltage variation. Thus, figures 2.44-2.45

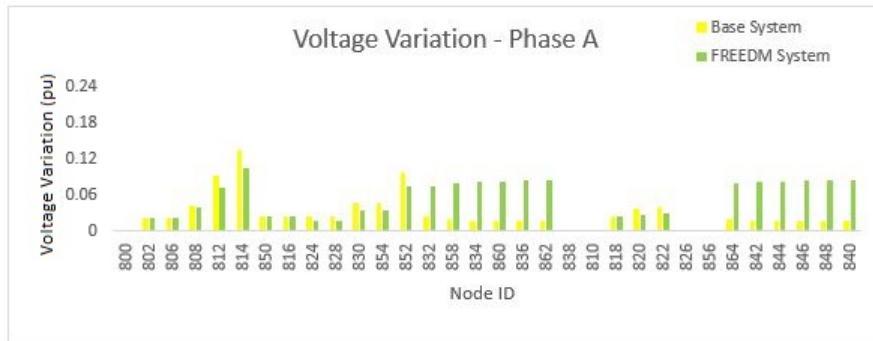


Figure 2.41 Voltage Variation on Phase A

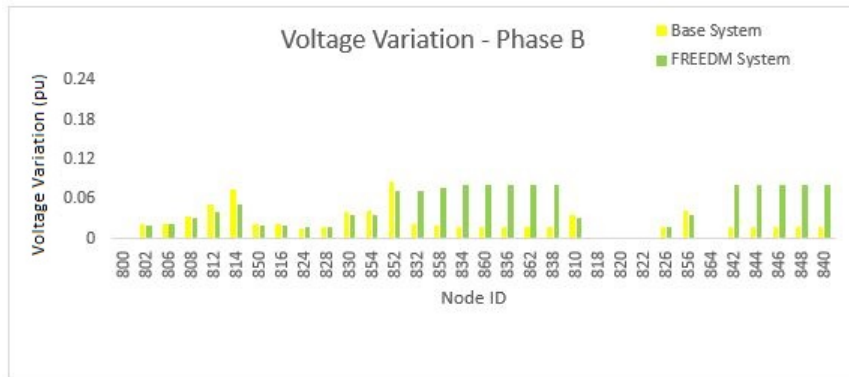


Figure 2.42 Voltage Variation on Phase B

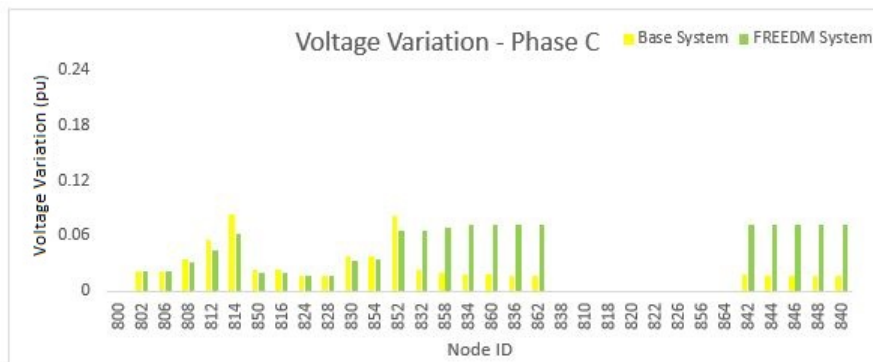
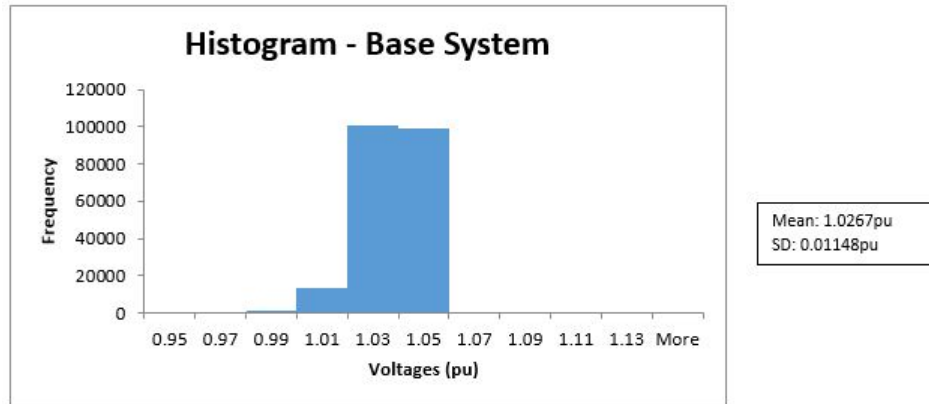


Figure 2.43 Voltage Variation on Phase C



**Figure 2.44** Histogram of voltages on primary side of feeder in Base System

present with the histograms for the voltages in the two systems showing more voltage variation for FREEDM. This can be again accounted on the absence of VR-2.

5. Voltage Regulator Operations:

Table 2.10 and 2.11 gives the number of Voltage Regulator operations for four weeks and the annual projection respectively. It is observed that the FREEDM offers lesser number of operations, adding life to the equipment as well as directly saves the cost of one voltage regulator.

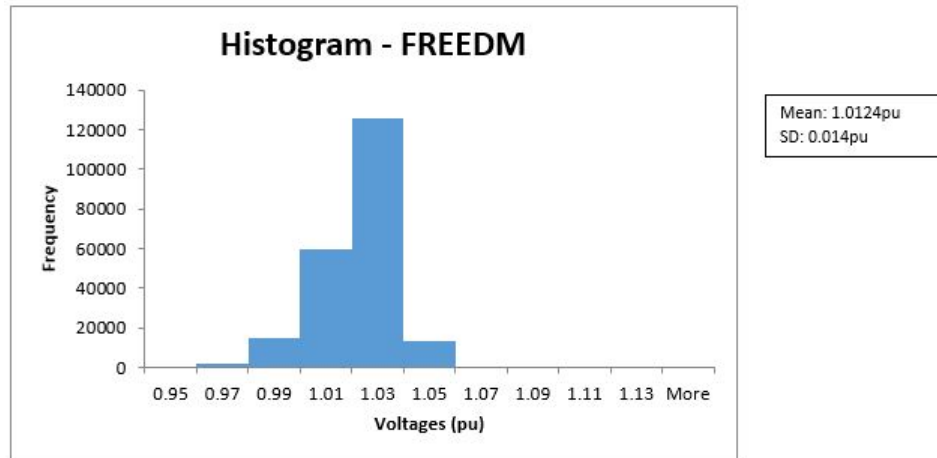
**Table 2.10** Number of Operations for Voltage Regulators (4-weeks)

System	No. of tap Changes - 4 weeks		
	Phase A	Phase B	Phase C
<b>Base System</b>	VR1 - 239	VR1 - 154	VR1 - 166
	VR2 - 206	VR2 - 178	VR2 - 192
<b>FREEDM System</b>	VR1 - 198	VR1 - 105	VR1 - 122
	VR2 - N/A	VR2 - N/A	VR2 - N/A

- Power & Energy

1. Power & Energy Loss:

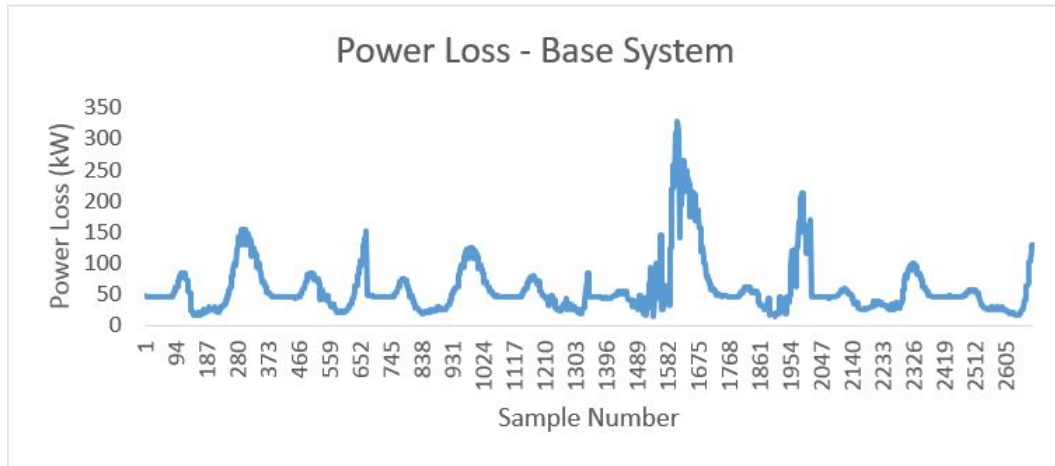
The line power loss profile for the two systems is presented in figures 2.46-2.47. The



**Figure 2.45** Histogram of voltages on primary side of feeder in FREEDM System

**Table 2.11** Number of Operations for Voltage Regulators (Annual Projection)

System	No. of tap Changes/year		
	Phase A	Phase B	Phase C
<b>Base System</b>	VR1 - 3107	VR1 - 2002	VR1 - 2158
	VR2 - 2678	VR2 - 2314	VR2 - 2496
<b>FREEDM System</b>	VR1 - 2574	VR1 - 1365	VR1 - 1586
	VR2 - N/A	VR2 - N/A	VR2 - N/A



**Figure 2.46** Line Power Loss - Base System

average loss (kW) per load (kVA) comes out to be 6.06% for base case and 3.34% for FREEDM system. Thus, FREEDM system has lesser system (or feeder) losses.

Total energy losses in each case is presented below in the format of 'system energy loss + transformer loss = total loss':

– Base System - 39187.49 kWh + 13540.49 kWh = 52.78 MWh

– FREEDM System - 23284.62 kWh + 23815.93 kWh = 47.1 MWh

A loss reduction of 5.68 MWh can be observed in the FREEDM case. Translating this loss reduction over an year gives us a loss reduction of 73.84 MWh.

### 2. Peak Demand Reduction:

It was observed that the 15-min peak demand had been reduced by 41.02 kW i.e. 1.8%. The energy demand reduction was observed to be 30.37% which is around 176.57 MWh in four weeks (2295.41 MWh annually). The reduction is only accounted to the level of PV penetration and thus both the systems offer similar reductions.

### 3. Power Flow at Substation:

Figures 2.48-2.49 show the  $P_{SUB}$  variation in the two cases.

$P_{SUB}$  variation has to do mostly with the level of PV penetration and less with the type of system. Thus, both plots look similar as expected. The slight difference is accounted to the amount of loss incurred in the two systems.

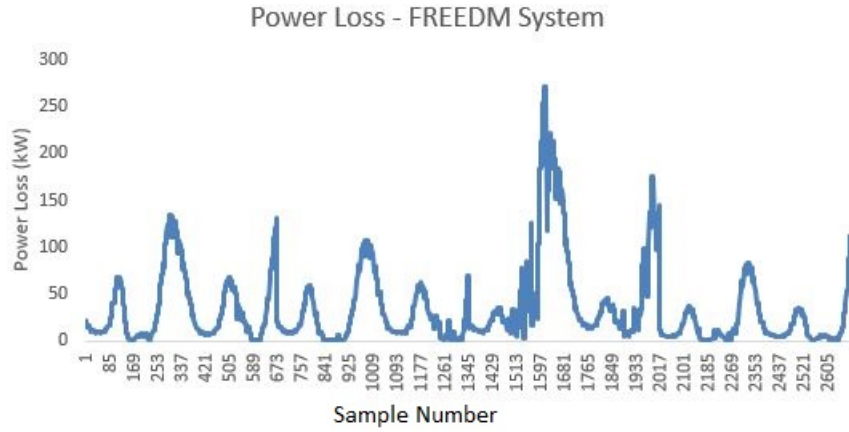


Figure 2.47 Line Power Loss - FREEDM System

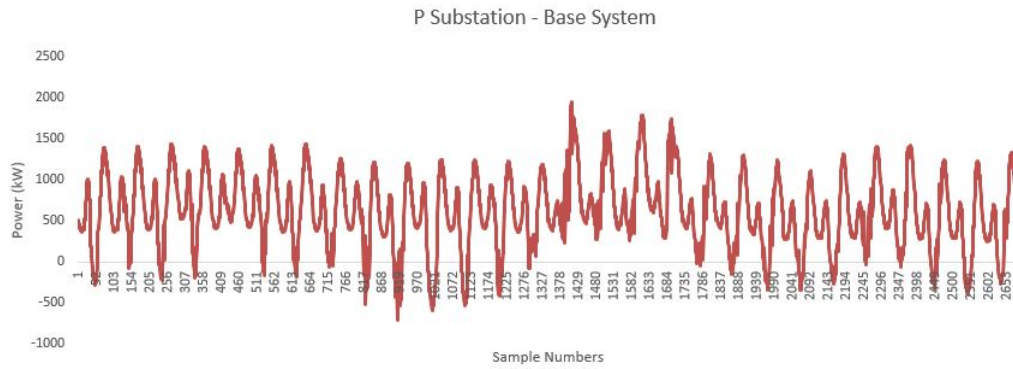


Figure 2.48  $P_{SUB}$  variation in Base System

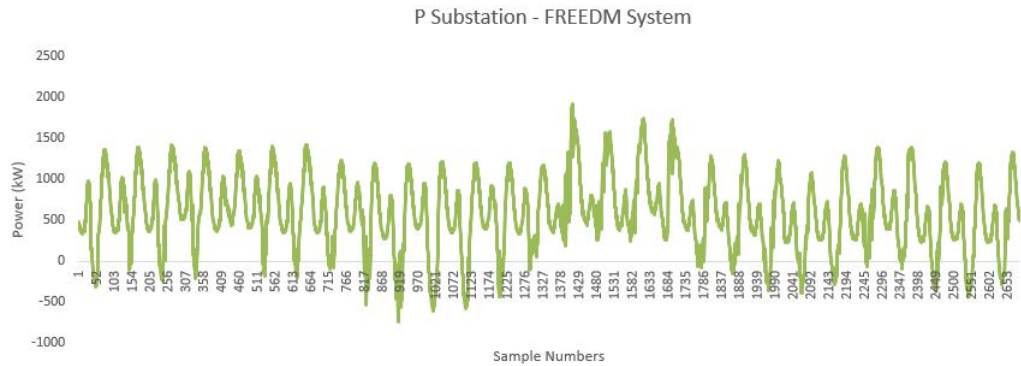


Figure 2.49  $P_{SUB}$  variation in FREEDM System

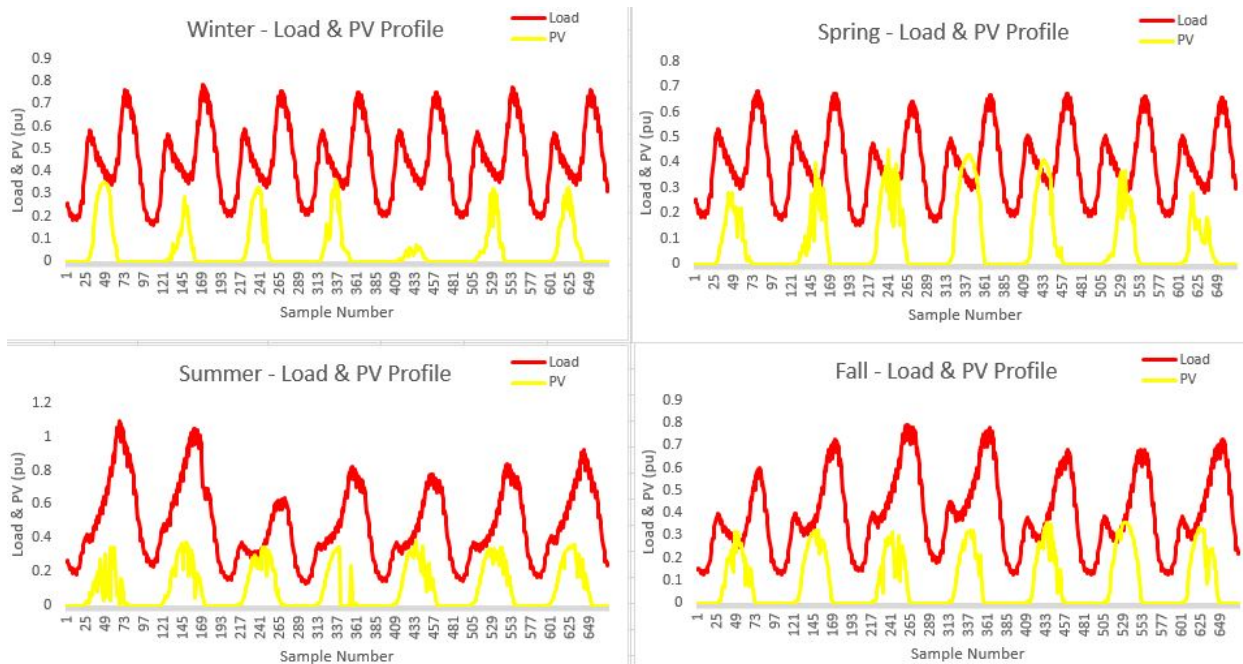


Figure 2.50 Load and PV Profiles (for 4 weeks)

### 2.2.5.5 Scenario II: 45.34% PV Penetration - 15 min Data

In this case, the  $PV_{max}$  was chosen to be 50% of the  $Load_{max}$ . Also PV is only present on the 50% of the load carrying nodes. The nodes to have PV were chosen to be the ones having maximum loads. This accounts for an effective PV penetration of 45.34%. The nodes carrying PV are 860, 840, 844, 848, 830, 890, 806, 810, 822, 836, 846. It must be noted that in this process distributed load were considered as to be situated on the successive node among the two nodes between which they are situated. Again, it was done just to figure out where to place PV's and while simulations distributed loads were simulated as per their actual position. Here again each node has same load and PV (applicable for PV if present on that node) profiles.

#### Load and PV Profiles

The load profile remains the same but the PV profile gets a bit scaled down in this case as  $PV_{max}$  is chosen to be 0.5 times of the  $Load_{max}$ . Figure 2.50 shows the load and PV profiles.

#### Assessment of Impacts

The impacts on the two systems will be assessed and compared for the 45.34% penetration case using the defined metrics.

- Voltage Profile

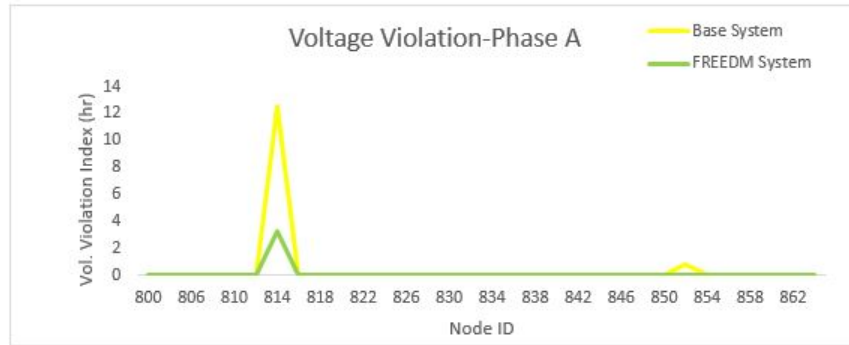


Figure 2.51  $V Viol_{INDEX}$  on Phase A

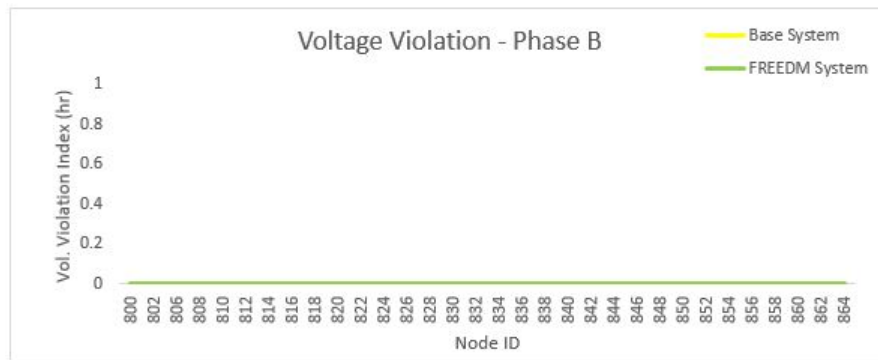


Figure 2.52  $V Viol_{INDEX}$  on Phase B

1. Voltage Violation:

FREEDM offers better results but actually there are no considerable voltage violations in any case. The node experiencing the violation serves no load and thus any violation there is of no concern. This is expected as there was no voltage violation even with 80% PV penetration. Figures 2.51-2.52 shows the voltage violation index along the feeder on different phases.

2. Voltage Drop:

The voltage drop at the eight ends are shown in table 2.12. The worst case VDI in base case is 0.0658pu. This goes as high as 0.0919pu for FREEDM case. Furthermore figure 2.54 shows the maximum voltage drop index in the two cases over the three phases. it appears that FREEDM performs inferior to the base system if we consider the worst case but on close observation it can be seen the worst case appears on the terminals lying in the second half of the system. This is due to absence of VR-2 in FREEDM system and is

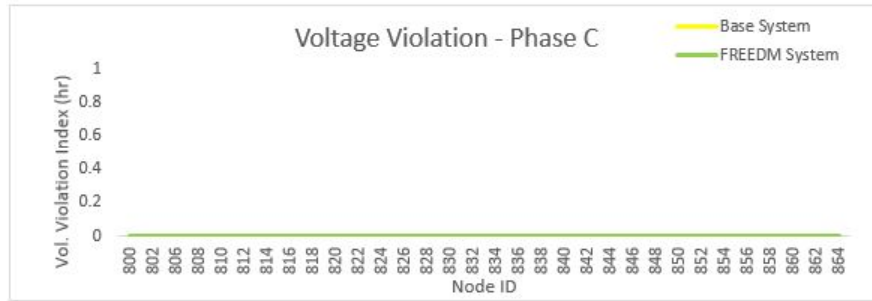


Figure 2.53  $V Viol_{INDEX}$  on Phase C

actually of no concern as the secondary is always regulated in FREEDM system.

Table 2.12 Voltage Drop Index

VDI	Base Case			FREEDM System		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		0.0231			0.09093	
810		0.04172			0.0413	
822	0.0658			0.04991		
826		0.0402			0.04005	
856		0.05727			0.05682	
864	0.0233			0.0881		
848	0.0223	0.02224	0.02204	0.09199	0.09118	0.08894
840	0.0231	0.02305	0.02281	0.09196	0.09085	0.0888

3. Voltage Unbalance:

The worst case VUI in base case is 0.03393 pu and for FREEDM case is 0.0304pu. Also, figure 2.55 shows the VUI variation along the feeder. This shows that in terms of voltage unbalance, FREEDM again accommodates PV's better than the base system.

4. Voltage Variation:

In base case VVI is 0.1192 pu. It is evident that FREEDM outperforms the base system as VVI is 0.082 pu with FREEDM. Table 2.13 shows the voltage variation index in the two cases. Furthermore, figures 2.56-2.58 show the voltage variation along the feeder which again tells that FREEDM has lesser voltage variation (before node 852).

Moreover, the value of VFI is 1.0581 V/s for base case and 0.8031 V/s in FREEDM System.

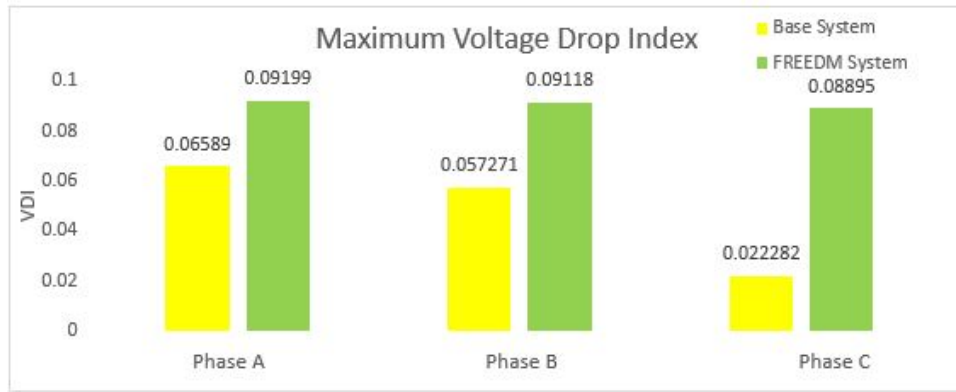


Figure 2.54 Maximum Voltage Drop Index

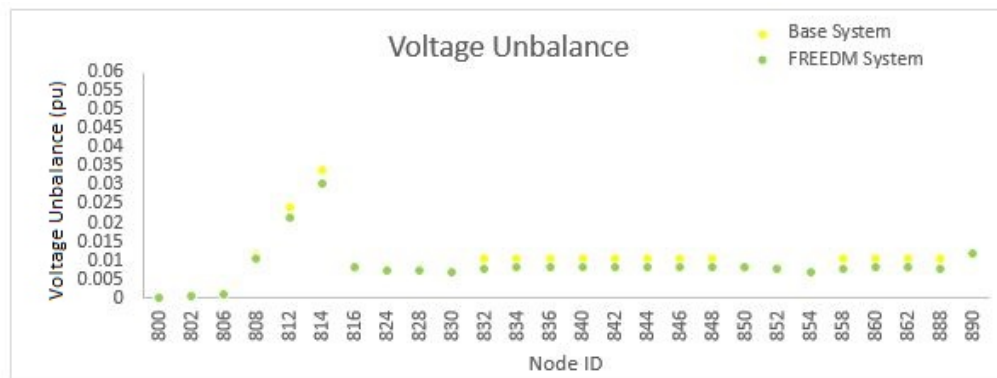


Figure 2.55 Voltage Unbalance Index along the feeder

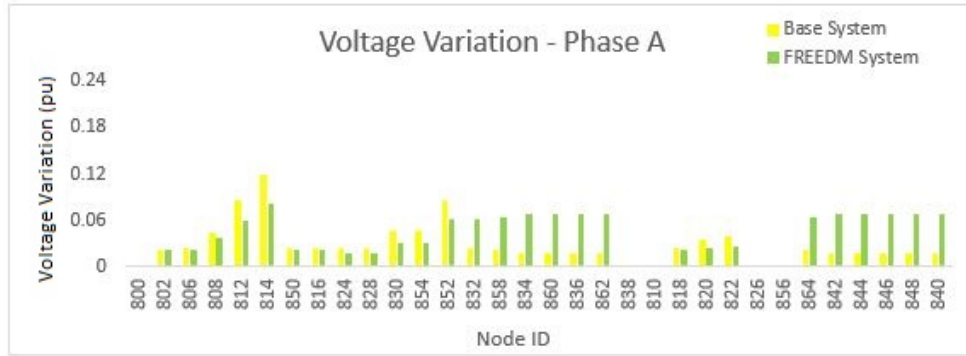


Figure 2.56 Voltage Variation on Phase A

Thus, it can be deduced that FREEDM improves the rate of change of voltage in the system.

The histograms give a very good idea of Voltage Variation, and are presented in figures

Table 2.13 Voltage Variation Index

System	$VVI_a$	$VVI_b$	$VVI_c$	VVI
Base System	0.119219	0.072447	0.077629	0.1192
FREEDM System	0.082012	0.06579	0.069115	0.082

2.59-2.60. This gives an overall view and FREEDM appears to have higher voltage variation but again its not a matter of concern as the secondary is regulated. The reason behind this remains the same i.e. absence of VR-2 in FREEDM.

5. Voltage Regulator Operations:

Table 2.14 gives the number of tap changes for Voltage Regulators in the two cases, for four weeks and and table 2.15 gives annual translation of the 4 week simulation. It can be observed that FREEDM offers much less voltage regulator operations than the base system adding life to the equipment and deferring costs.

- Power & Energy

1. Power & Energy Loss:

The average loss (kW) per load (kVA) comes out to be 6.57% for base case and 3.75% for

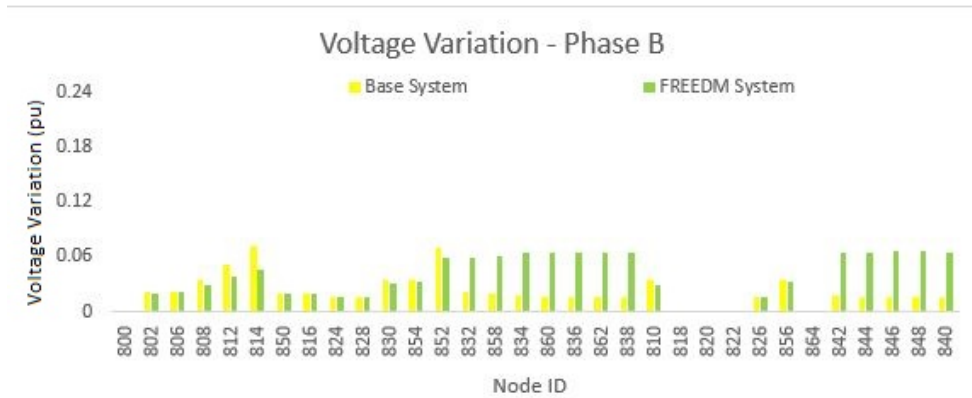


Figure 2.57 Voltage Variation on Phase B

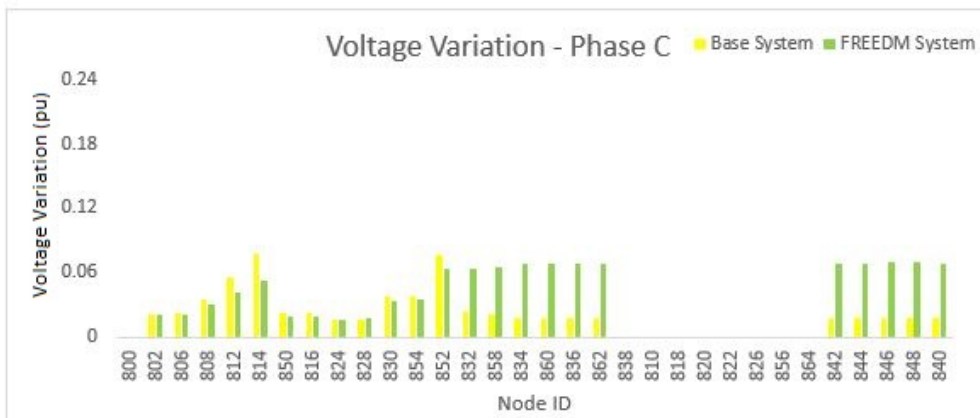


Figure 2.58 Voltage Variation on Phase C

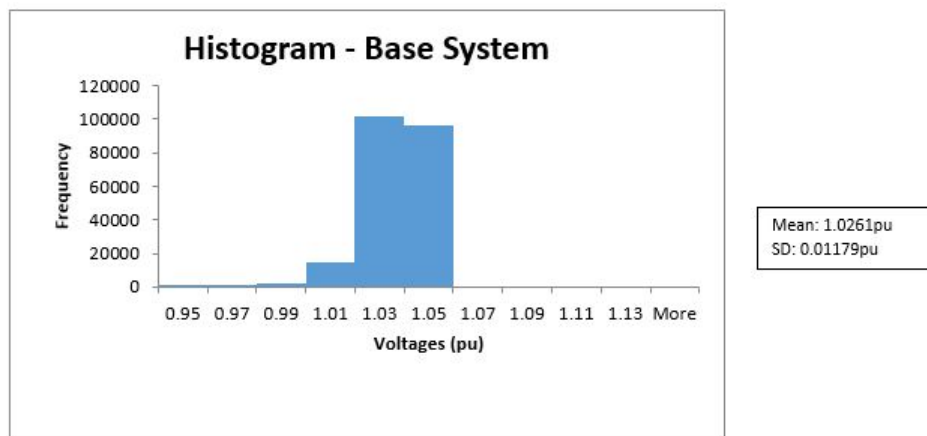


Figure 2.59 Histogram of voltages on primary side of feeder in Base System

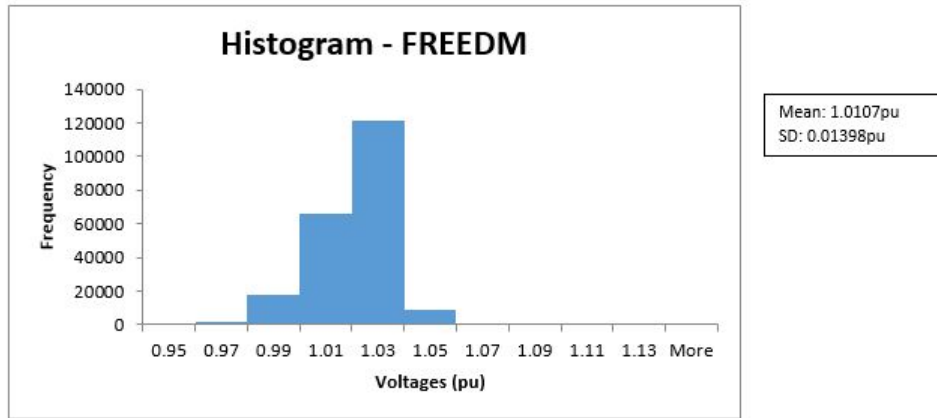


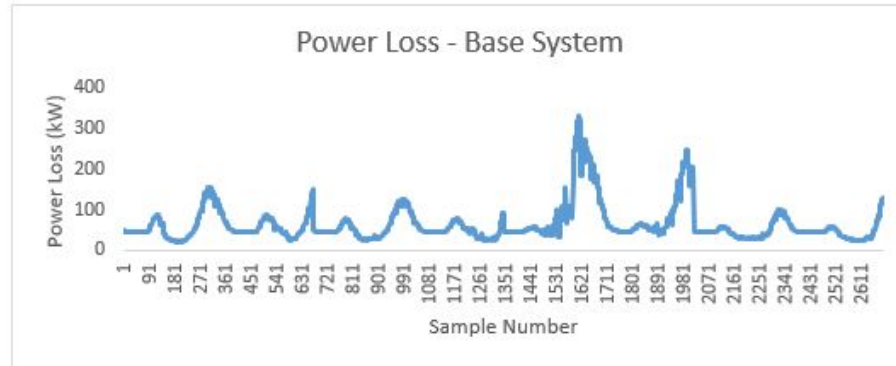
Figure 2.60 Histogram of voltages on primary side of feeder in FREEDM System

Table 2.14 Number of Operations for Voltage Regulators (Four Weeks)

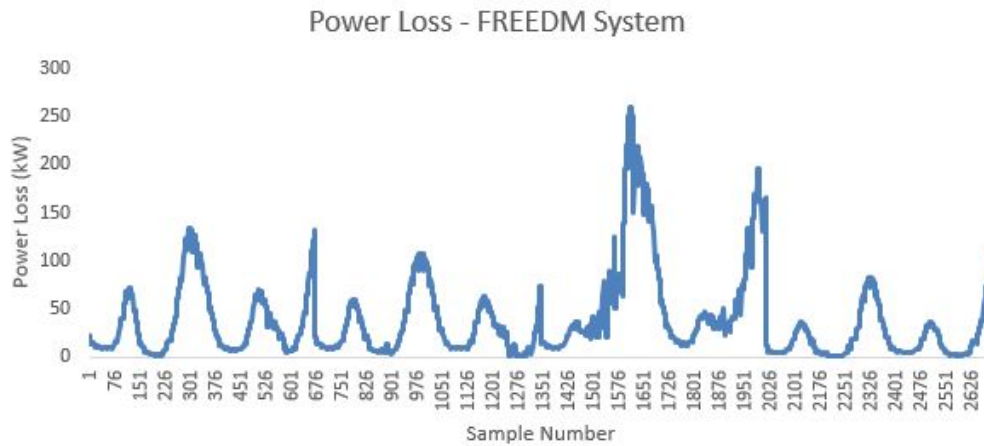
System	No. of tap Changes - 4 weeks		
	Phase A	Phase B	Phase C
Base System	VR1 - 201	VR1 - 127	VR1 - 144
	VR2 - 180	VR2 - 158	VR2 - 163
FREEDM System	VR1 - 164	VR1 - 64	VR1 - 94
	VR2 - N/A	VR2 - N/A	VR2 - N/A

Table 2.15 Number of Operations for Voltage Regulators (Annual Projection)

System	No. of tap Changes/year		
	Phase A	Phase B	Phase C
Base System	VR1 - 2613	VR1 - 1651	VR1 - 1872
	VR2 - 2340	VR2 - 2054	VR2 - 2119
FREEDM System	VR1 - 2132	VR1 - 832	VR1 - 1222
	VR2 - N/A	VR2 - N/A	VR2 - N/A



**Figure 2.61** Line Power Loss - Base System



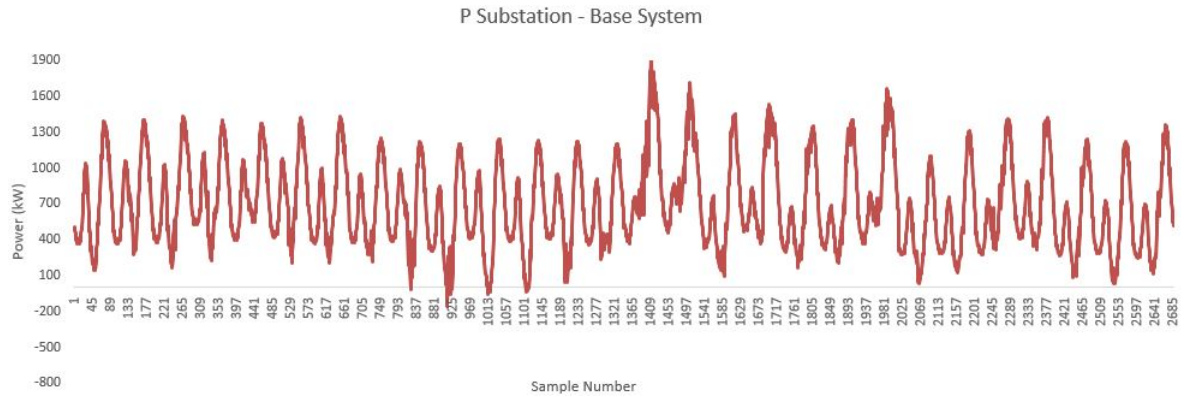
**Figure 2.62** Line Power Loss - FREEDM System

FREEDM system. This proves that FREEDM indeed incurs lesser line losses than the base system. Figures 2.61-2.62 shows the line power loss curves in the two systems, which again tells that FREEDM incurs system lesser losses than its counterpart.

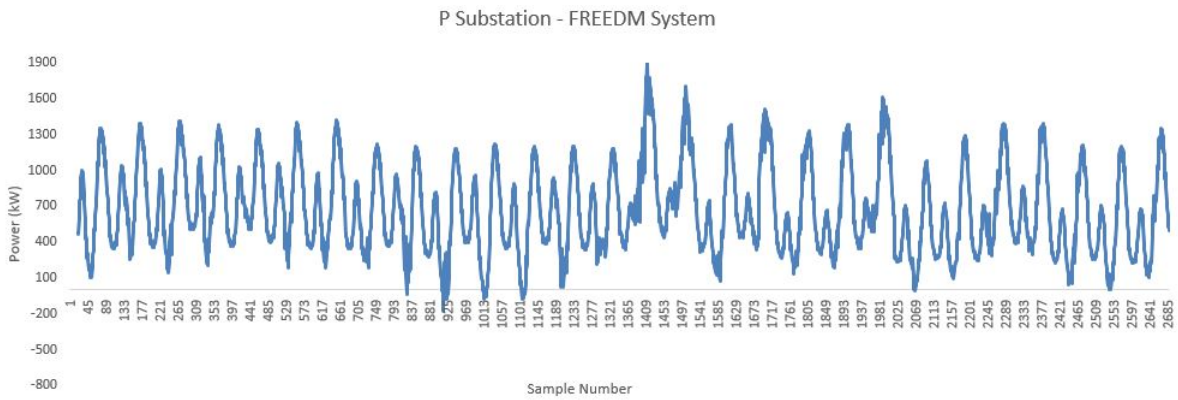
Total Energy loss in four weeks in the two cases is displayed below in the format of 'line loss + transformer loss = total loss':

- Base System - 43241.18 kWh + 13643.63 kWh = 56.88 MWh
- FREEDM System - 26254.25 kWh + 24578.22 kWh = 50.83 MWh

There is a saving of 6.05 MWh with FREEDM in terms of energy loss, over four weeks. This translates to an annual saving of 78.65 MWh.



**Figure 2.63**  $P_{SUB}$  variation in Base System



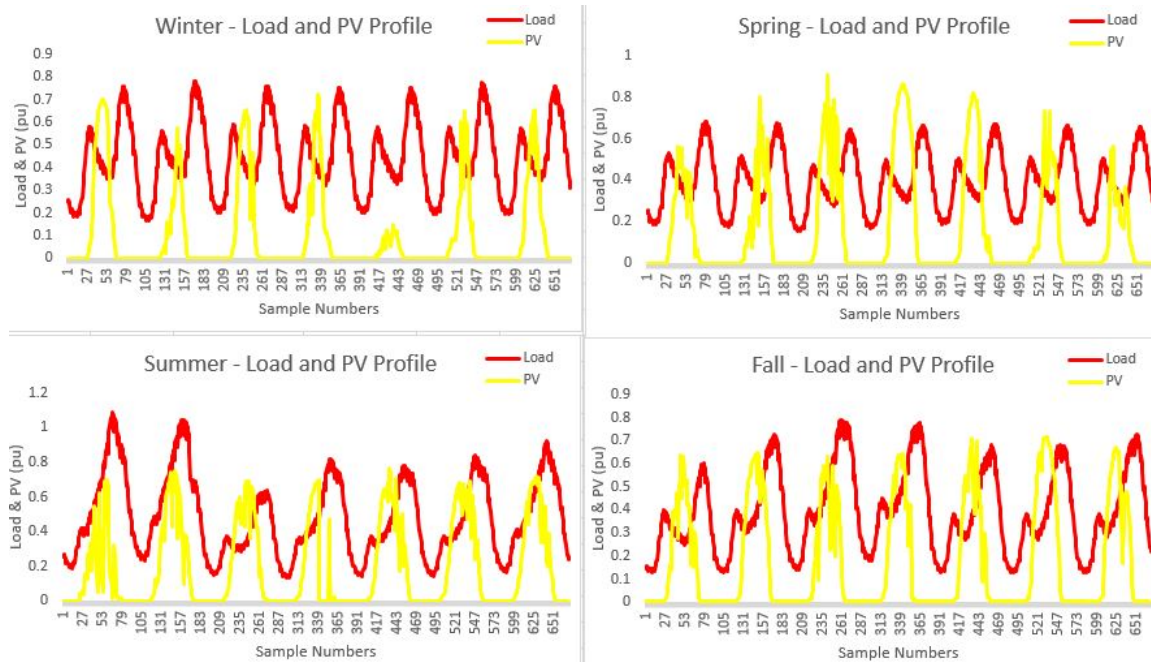
**Figure 2.64**  $P_{SUB}$  variation in FREEDM System

2. Peak Demand Reduction:

It was observed that the 15-min peak demand had been reduced by 31.18 kW i.e. 1.37%. The energy demand reduction was observed to be 17.39% which is around 101.14 MWh in four weeks (1314.81 MWh annually). The reduction is only accounted to the level of PV penetration and thus both the systems offer similar reductions.

3. Power Flow at Substation:

As we know  $P_{SUB}$  is mostly accounted over level of PV penetration, thus, the figures 2.63-2.64, which shows the  $P_{SUB}$  variation in the two cases look very similar.



**Figure 2.65** Load and PV Profiles

### 2.2.5.6 Scenario III: 90.68% PV Penetration - 15 min Data

Two different levels of PV penetration were considered and it was found that they were not able to create good enough impact on the IEEE-34 node test feeder. Thus, very high penetration level of 90.68% was chosen.

In here, PV was only present on the 50% of the load carrying nodes but  $P_{V_{max}}$  was equal to the 100% of the load maxima. Again, the nodes to have PV were chosen to be the ones having maximum load. The nodes carrying PV are 860, 840, 844, 848, 830, 890, 806, 810, 822, 836, 846.

#### Load and PV Profiles

Figure 2.65 shows the load and PV profiles considered in this case, for the four week period.

#### Assessment of Impacts

The impacts on the two systems will be assessed and compared for the 90.68% penetration case using the defined metrics.

- Voltage Profile

1. Voltage Violation:

Here, we observe that there are issues in all phases in the base case. For FREEDM there is

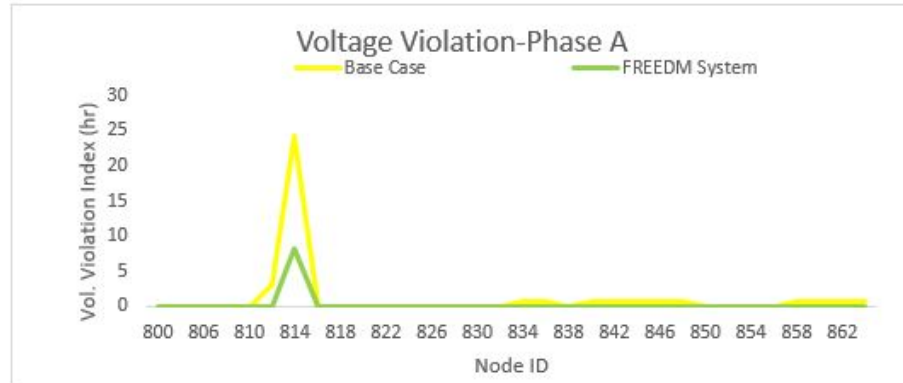


Figure 2.66  $V Viol_{INDEX}$  on Phase A

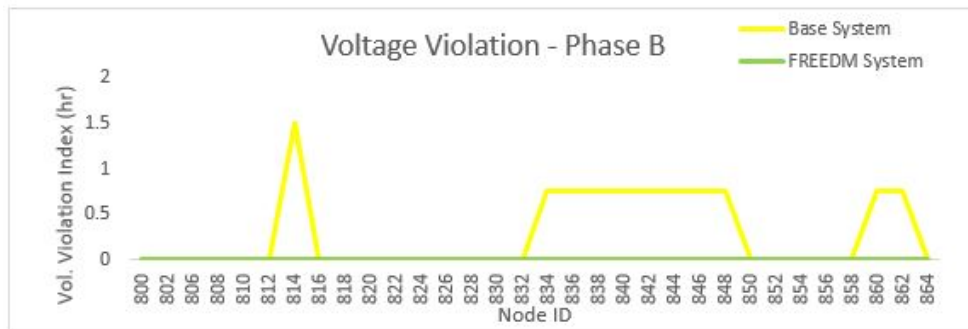


Figure 2.67  $V Viol_{INDEX}$  on Phase B

issue only on phase A and that too the node having issue is 814 which serves no load. Furthermore, these violations are with respect to primary and not secondary which is regulated in FREEDM. Thus, giving out zero voltage violations in FREEDM case.  $V Viol_{INDEX}$  is 24.75hrs and 8.25hrs in base case and FREEDM case respectively.  $V Viol$  is 76.75 hrs and 8.25 hrs for base case and the FREEDM case respectively (in four weeks). This means that the base case will have 3991 incidences of voltage violations of 15-minute durations as compared to 429, 15-minute violations in the FREEDM case, annually. If we neglect the voltage violations for nodes not serving any load,  $V Viol$  becomes 14.75 hrs for the base case and zero for FREEDM. This means that the base case will have 767 annual incidences of voltage violations of 15-minute durations. Figures 2.66-2.68 shows voltage violation index over the feeder.

It seems that only phase B has serious voltage violations but this is not the case. All the three phases have similar voltage violations but in phase A and phase C it doesn't appear,

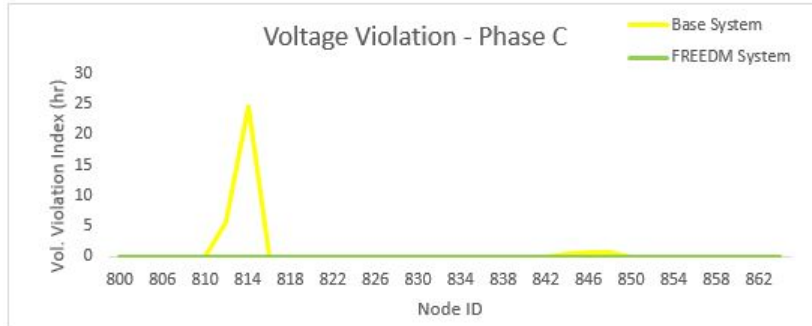


Figure 2.68  $VVI_{INDEX}$  on Phase C

as it is suppressed. It must be noted that the y-axis of the three plots are not same. Voltage violation on phases A and C at node 814 is too high suppressing the visibility of voltage violations on other nodes in the plot.

2. Voltage Drop:

The voltage drop at the eight ends are shown in table 2.16. The worst case VDI in base case is 0.0652pu. This goes as high as 0.0993pu for FREEDM case. Furthermore figure

Table 2.16 Voltage Drop Index

VDI	Base System			FREEDM System		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		0.02331			0.09026	
810		0.04166			0.04118	
822	0.0652			0.04873		
826		0.04033			0.03997	
856		0.05873			0.05636	
864	0.024			0.08707		
848	0.0223	0.02238	0.02196	0.09093	0.09052	0.08528
840	0.0231	0.02325	0.02279	0.0909	0.09018	0.08515

2.69 shows the maximum voltage drop index in the two cases over the three phases. FREEDM offers better results before node 852 because the second voltage regulator is absent in the FREEDM case. Thus, if we just observe the figure 2.69, it doesn't give the right intuition.

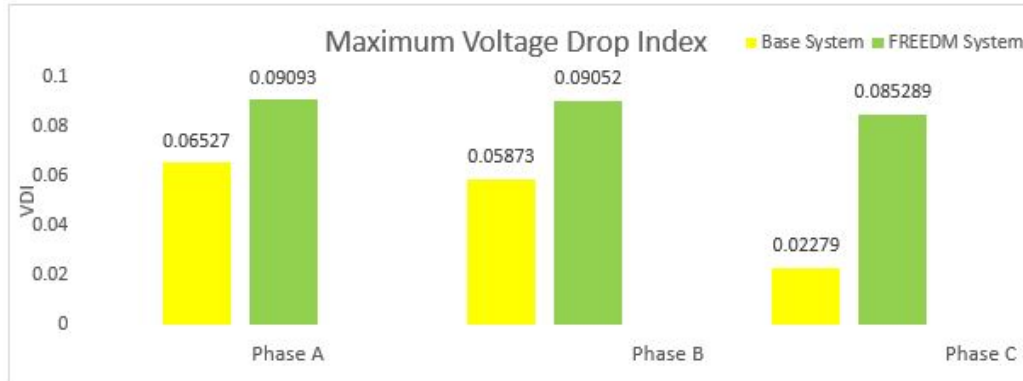


Figure 2.69 Maximum Voltage Drop Index

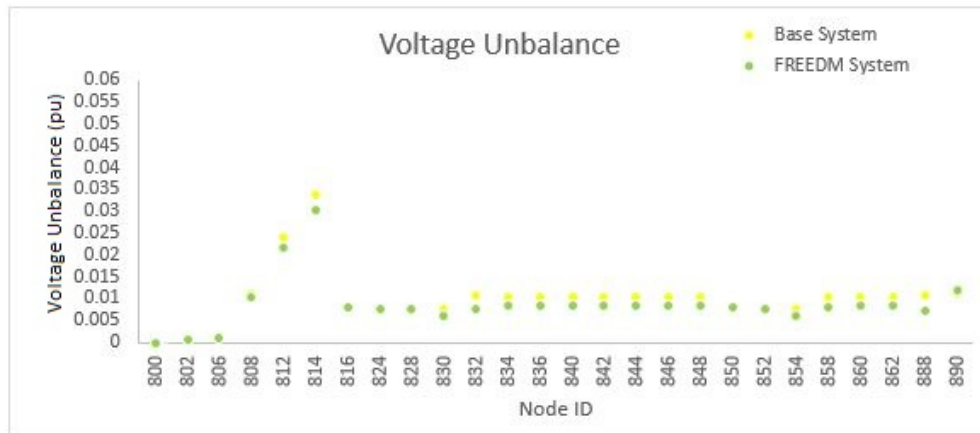


Figure 2.70 Voltage Unbalance Index along the feeder

3. Voltage Unbalance:

Figure 2.70 shows the VUI variation along the feeder which clearly shows that FREEDM improves voltage unbalance. The worst case VUI in base case is 0.03393 pu and for FREEDM case is 0.0304 pu. This shows that FREEDM reduces worst case voltage unbalance index by 11.58%.

4. Voltage Variation:

In base case VVI is 0.1397 pu. It is evident that FREEDM outperforms the base system as VVI is 0.1063 pu with FREEDM. Table 2.21 gives the voltage variation index in the two cases. Furthermore, figures 2.71-2.73 shows the voltage variation along the feeder from which it may be concluded that FREEDM offers lesser voltage variation over the feeder

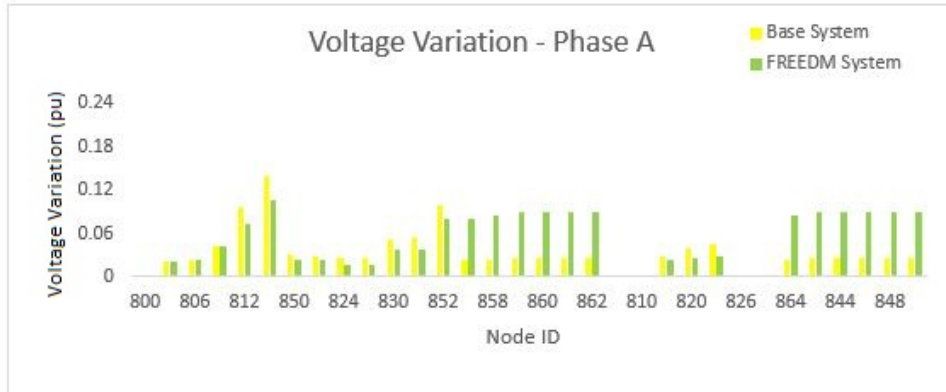


Figure 2.71 Voltage Variation on Phase A

(before node 852 as VR-2 is absent for FREEDM).

Moreover, the value of VFI is 0.9364 V/s for base case and 0.7753 V/s in FREEDM System. Thus, it can be seen that FREEDM improves rate of change of voltage in the system. The

Table 2.17 Voltage Variation Index

System	$VVI_a$	$VVI_b$	$VVI_c$	VVI
Base System	0.13967	0.089357	0.091082	0.13967
FREEDM System	0.1064	0.08647	0.08	0.1064

histograms give a very good idea of Voltage Variation, thus, figures 2.74-2.75 display the histograms of voltages over the two systems.

5. Voltage Regulators Operations:

Table 2.18 gives the number of tap changes for Voltage Regulators in the two cases, for four weeks and table 2.19 gives the annual translation of the 4 week simulation. It can be observed that FREEDM offers much less number of operations than the base system, adding life to the equipment and deferring costs.

- Power & Energy

1. Power & Energy Loss:

The average loss (kW) per load (kVA) comes out to be 5.99% for base case and 3.23% for

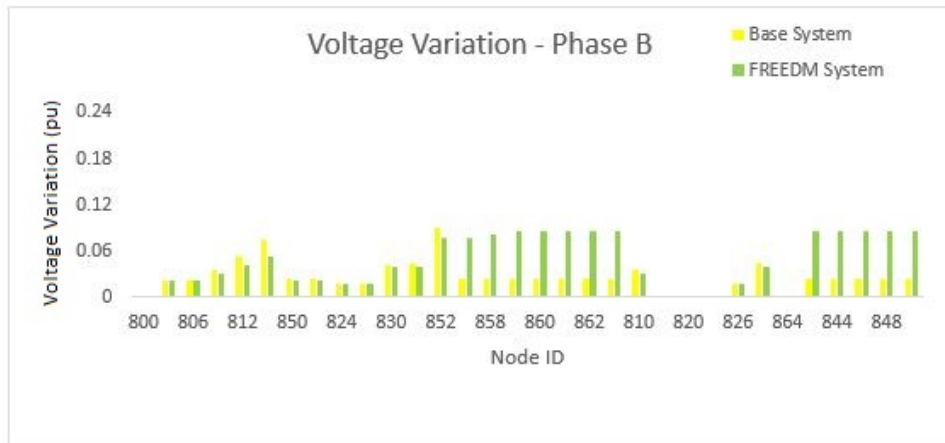


Figure 2.72 Voltage Variation on Phase B

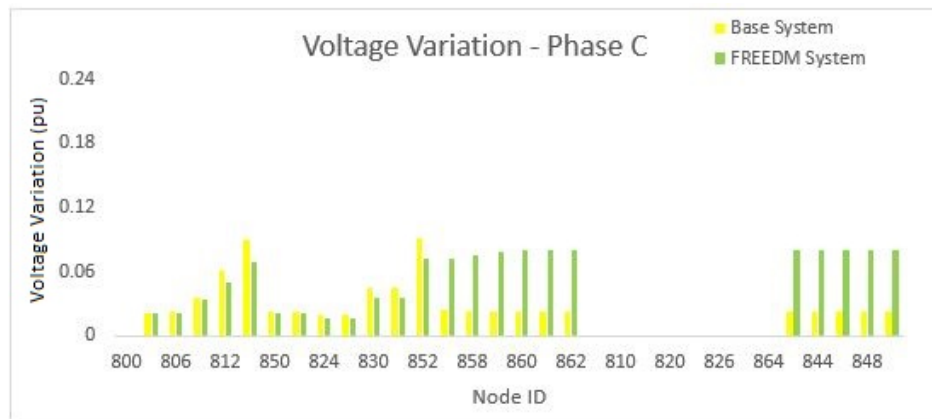


Figure 2.73 Voltage Variation on Phase C

Table 2.18 Number of Operations for Voltage Regulators (Four Weeks)

System	No. of tap Changes - 4 weeks		
	Phase A	Phase B	Phase C
Base System	VR1 - 243	VR1 - 155	VR1 - 176
	VR2 - 213	VR2 - 190	VR2 - 201
FREEDM System	VR1 - 209	VR1 - 105	VR1 - 142
	VR2 - N/A	VR2 - N/A	VR2 - N/A

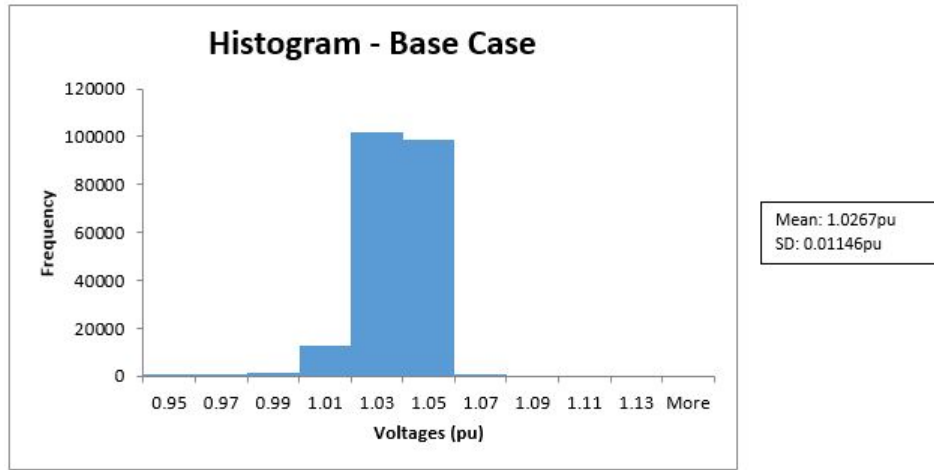


Figure 2.74 Histogram of voltages on primary side of feeder in Base System

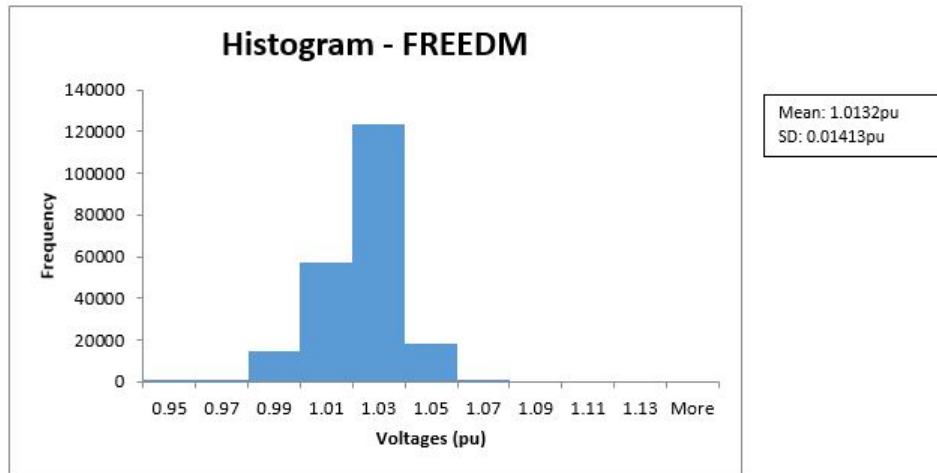
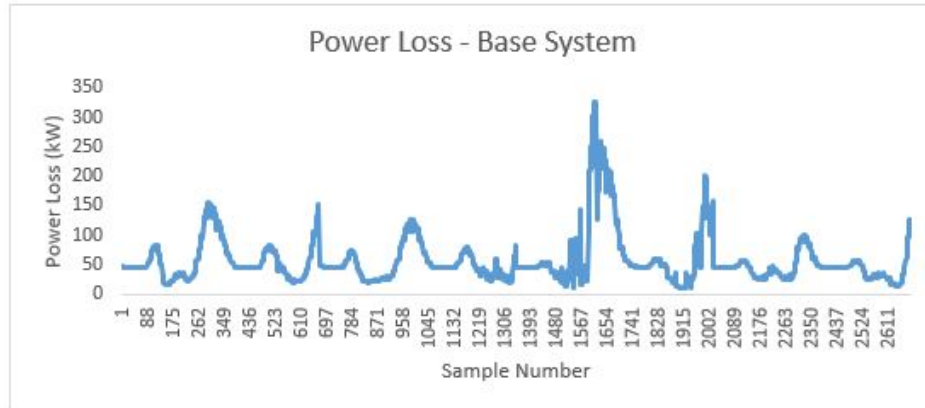


Figure 2.75 Histogram of voltages on primary side of feeder in FREEDM System

Table 2.19 Number of Operations for Voltage Regulators (Annual Projection)

System	No. of tap Changes/year		
	Phase A	Phase B	Phase C
Base System	VR1 - 3159	VR1 - 2015	VR1 - 2288
	VR2 - 2769	VR2 - 2470	VR2 - 2613
FREEDM System	VR1 - 2717	VR1 - 1365	VR1 - 1846
	VR2 - N/A	VR2 - N/A	VR2 - N/A



**Figure 2.76** Line Power Loss - Base System

FREEDM system. Figures 2.76-2.77 shows the line power loss curves in the two systems. Thus, we can conclude that FREEDM incurs lesser line power loss than the base system.

Total Energy loss in four weeks in the two cases is given below in the format of 'line loss + transformer loss = total loss':

- Base System - 38427.73 kWh + 13521.08 kWh = 51.94 MWh
- FREEDM System - 22142.81 kWh + 23458.69 kWh = 45.6 MWh

There is a saving of 6.34 MWh with FREEDM in terms of energy loss, over four weeks. This translates to an annual saving of 82.4 MWh.

## 2. Peak Demand Reduction:

It was observed that the 15-min peak demand has been reduced by 48.52 kW i.e. 2.13%. The energy demand reduction was observed to be 33.98% which is around 197.56 MWh in four weeks (2568.24 MWh annually). The reduction is only accounted to the level of PV penetration and thus both the systems offer similar reductions.

## 3. Power Flow at Substation:

As we know  $P_{SUB}$  is mostly accounted over level of PV penetration, thus, the figures 2.77-2.78, which shows the  $P_{SUB}$  variation in the two cases look very similar.

### 2.2.5.7 Scenario IV: 90.68% PV Penetration - 15 min Data (Partial FREEDM Deployment)

Till this far, the cases were developed with the thought that if new FREEDM system is put instead of putting a conventional system at any new location. But there was a thought, how can we upgrade

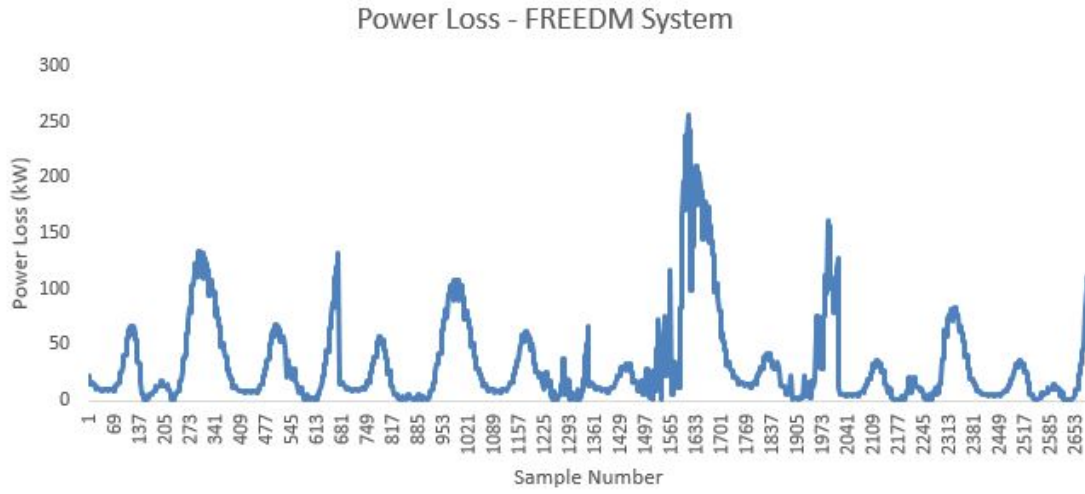


Figure 2.77 Line Power Loss - FREEDM System

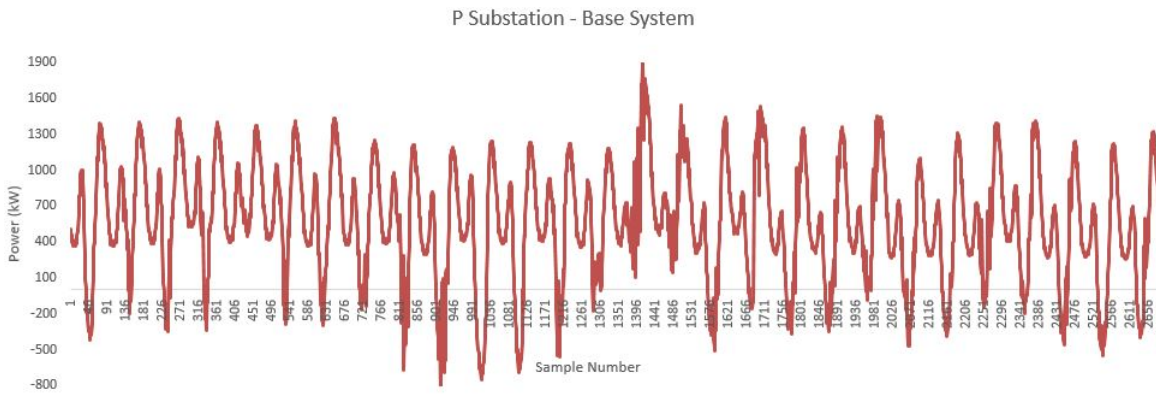


Figure 2.78  $P_{SUB}$  variation in Base System

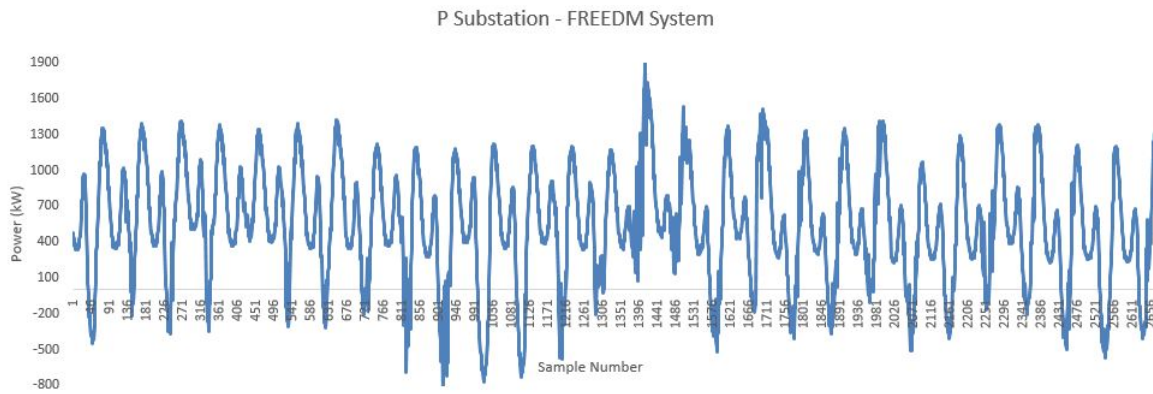


Figure 2.79  $P_{SUB}$  variation in FREEDM System

our present systems to the FREEDM system. Also, it was thoughtful to look whether it is required to put full FREEDM or even partial deployment of FREEDM can accommodate all impacts. Thus, partial FREEDM deployment cases were considered.

This scenario is same as Scenario III but differs in the FREEDM aspect. In here, partial FREEDM deployment was considered and SST's were placed only on the nodes having PV. Thus all the nodes having PV also have SST i.e. nodes 860, 840, 844, 848, 830, 806, 810, 822, 836, 846 have SST's. Also, as the penetration level remains same, the load and PV profiles remain exactly same as in Scenario III.

### **Assessment of Impacts**

Again the impacts on the two systems will be assessed and compared using the defined metrics. Obviously, the base case impacts will remain the same as in Scenario III and the impacts of FREEDM are of primary focus as now the question is whether partial deployment of FREEDM can accommodate the impacts or not.

- Voltage Profile

1. Voltage Violation:

It can be seen in figures 2.80-2.82 that partial FREEDM deployment takes care of all the voltage violation issues.  $VViol_{INDEX}$  is 24.75 hrs and 9.5 hrs in base case and FREEDM case respectively.  $VViol$  is 76.75 hrs and 9.5 hrs for base case and the FREEDM case respectively (in four weeks). This means that the base case will have 3991 annual incidences of voltage violations of 15-minute durations as compared to 494, 15-minute violations in the FREEDM case. If we neglect the voltage violations for nodes which do not serve any load,  $VViol$  becomes 14.75 hrs for the base case and zero for FREEDM. This means that the base case will have 767 annual incidences of voltage violations of 15-minute durations whereas FREEDM has none.

2. Voltage Drop:

The voltage drop at the eight ends are shown in table 2.20. The worst case VDI in base case is 0.0652pu which goes as high as 0.0932pu for FREEDM system. Furthermore figure 2.83 shows the maximum voltage drop index in the two cases over the three phases. But it can be seen that FREEDM offers better results before node 852. Base system performs better after node 852 because the second voltage regulator is absent in the FREEDM case. Thus, if we just make judgements using the figure 2.83, it doesn't give the right intuition. Furthermore, as the secondary is always regulated in FREEDM higher voltage drop in FREEDM is not a matter of concern.

3. Voltage Unbalance:

The worst case VUI in base case is 0.03393 pu and for FREEDM case is 0.0269pu. This

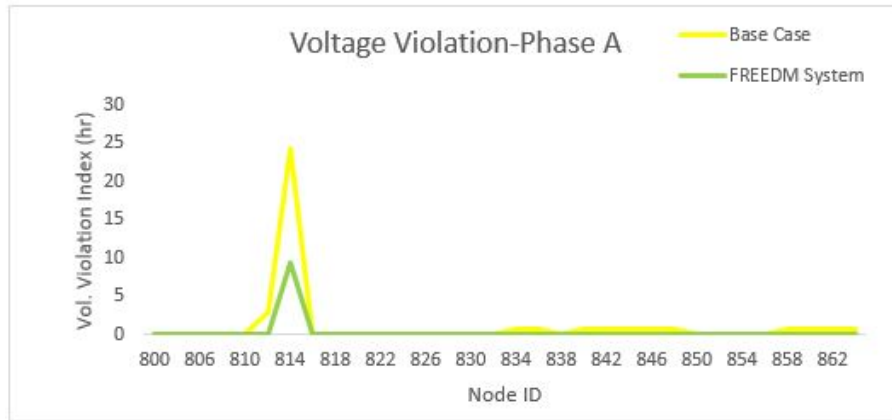


Figure 2.80  $V Viol_{INDEX}$  on Phase A

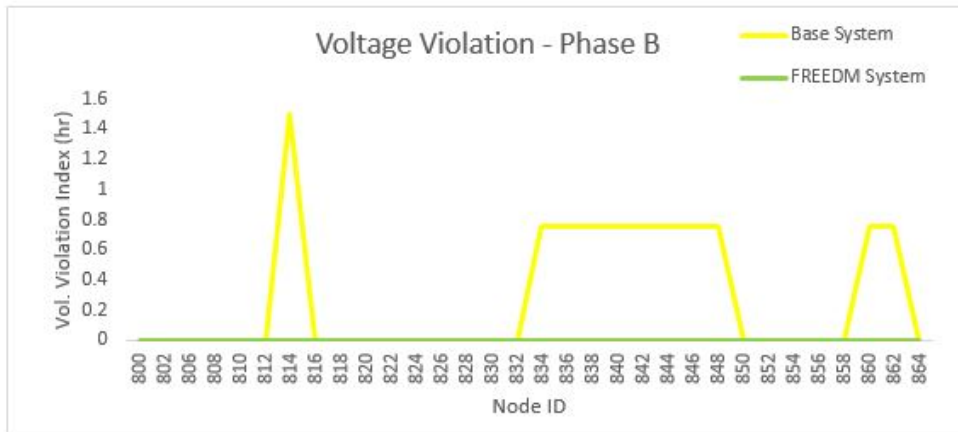


Figure 2.81  $V Viol_{INDEX}$  on Phase B

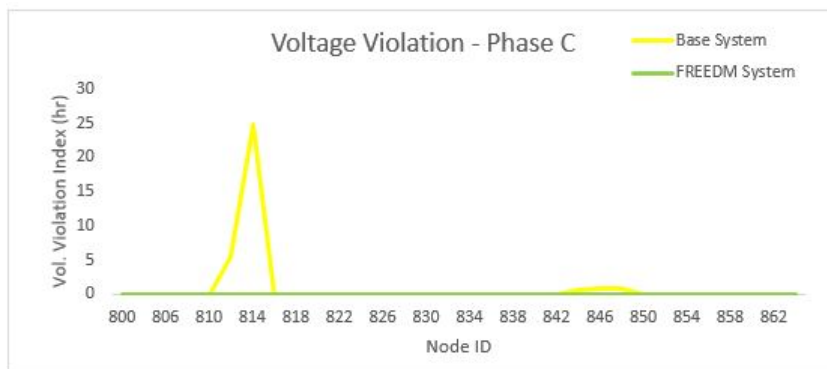
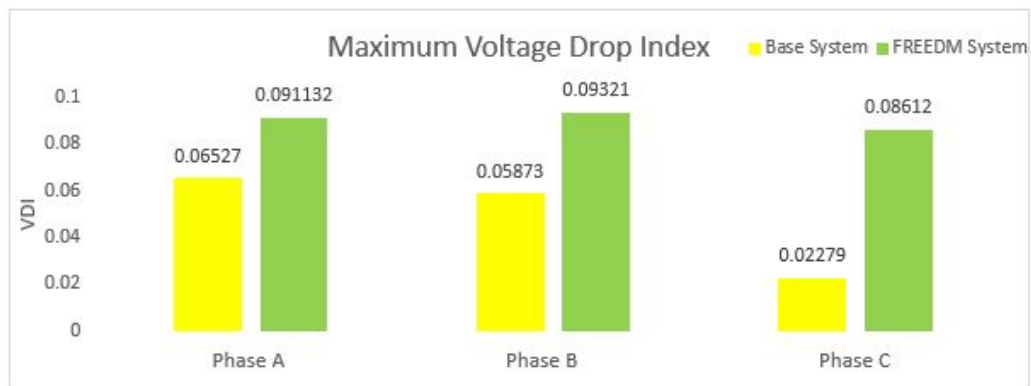


Figure 2.82  $V Viol_{INDEX}$  on Phase C

**Table 2.20** Voltage Drop Index

VDI	Base System			FREEDM System		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		0.02331			0.09321	
810		0.04166			0.04271	
822	0.0652			0.04993		
826		0.04033			0.04022	
856		0.05873			0.05673	
864	0.024			0.08727		
848	0.0223	0.02238	0.02196	0.09113	0.09319	0.08612
840	0.0231	0.02325	0.02279	0.09108	0.09303	0.08595



**Figure 2.83** Maximum Voltage Drop Index

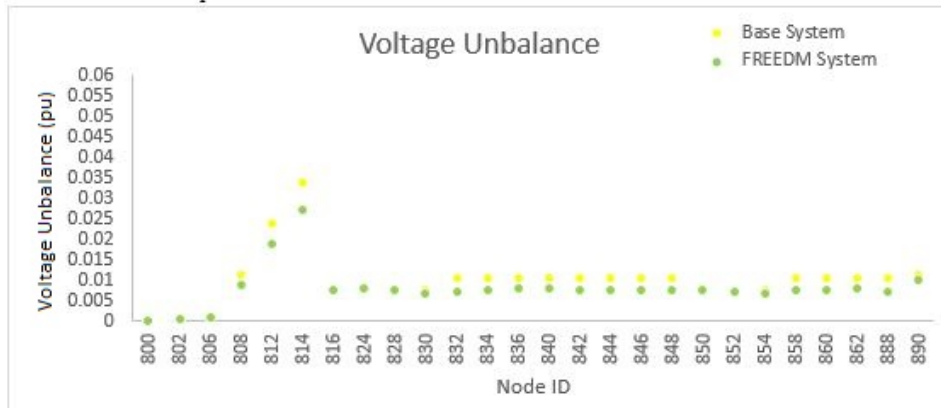


Figure 2.84 Voltage Unbalance Index along the feeder

shows that FREEDM system reduces voltage unbalance. Figure 2.84 shows the VUI variation along the feeder wherein again it is visible that FREEDM has lower voltage unbalance at each node as compared to the base system.

4. Voltage Variation:

In base case VVI is 0.1397 pu. It is evident that FREEDM outperforms the base system as VVI is 0.111 pu with FREEDM. Table 2.21 shows the voltage variation indices in the two cases. Furthermore, figures 2.85-2.87 shows the voltage variation along the feeder from where it can be concluded that FREEDM reduces voltage variation (before node 852 as VR-2 is absent in FREEDM).

Furthermore, the value of VFI still remains 0.9364 V/s for base case but its 0.7806 V/s in FREEDM System. Thus, it can be seen that still FREEDM improves the rate of change of voltage or the so called flicker in the system. Also, the histograms present a very

Table 2.21 Voltage Variation Index

System	$VVI_a$	$VVI_b$	$VVI_c$	VVI
Base System	0.13967	0.089357	0.091082	0.13967
FREEDM System	0.111	0.08649	0.0806	0.111

good idea of Voltage Variation, thus, figure 2.88 displays the histograms of voltages in the FREEDM case.

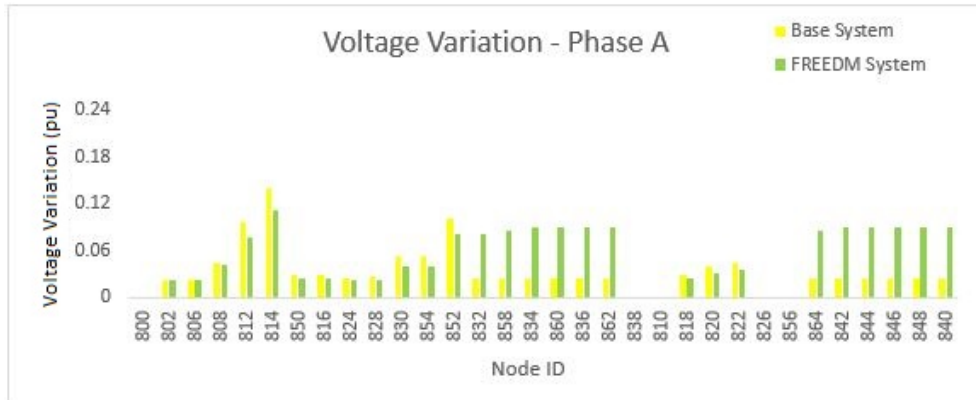


Figure 2.85 Voltage Variation on Phase A

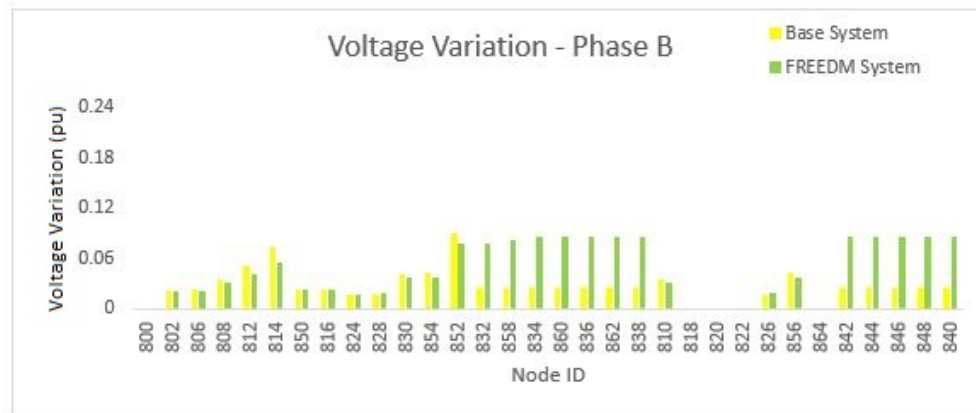


Figure 2.86 Voltage Variation on Phase B

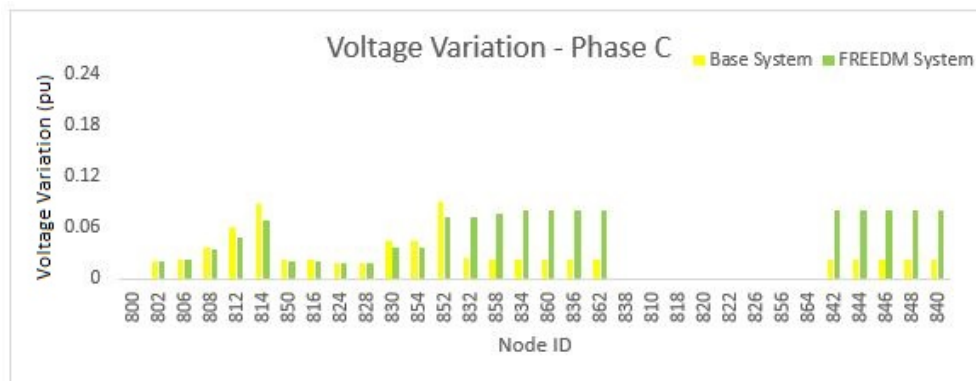
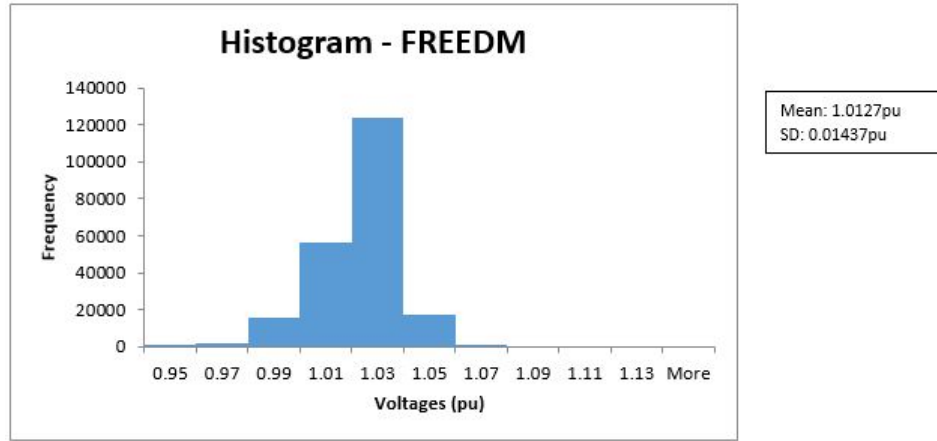


Figure 2.87 Voltage Variation on Phase C



**Figure 2.88** Histogram of voltages on primary side of feeder in FREEDM System

5. Voltage Regulator Operations:

Table 2.22 gives the number of tap changes for Voltage Regulators in the two cases, for four weeks and and table 2.23 gives annual translation of the 4 week simulation. It can be observed that FREEDM offers much less voltage regulator operations than the base system, adding life to the equipment and deferring costs.

**Table 2.22** Number of Operations for Voltage Regulators (Four Weeks)

System	No. of tap Changes - 4 weeks		
	Phase A	Phase B	Phase C
<b>Base System</b>	VR1 - 243	VR1 - 155	VR1 - 176
	VR2 - 213	VR2 - 190	VR2 - 201
<b>FREEDM System</b>	VR1 - 206	VR1 - 109	VR1 - 141
	VR2 - N/A	VR2 - N/A	VR2 - N/A

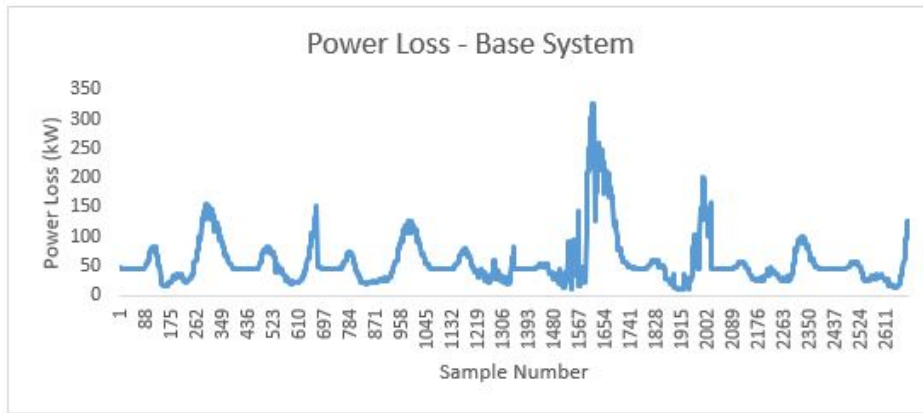
- Power & Energy

1. Power & Energy Loss:

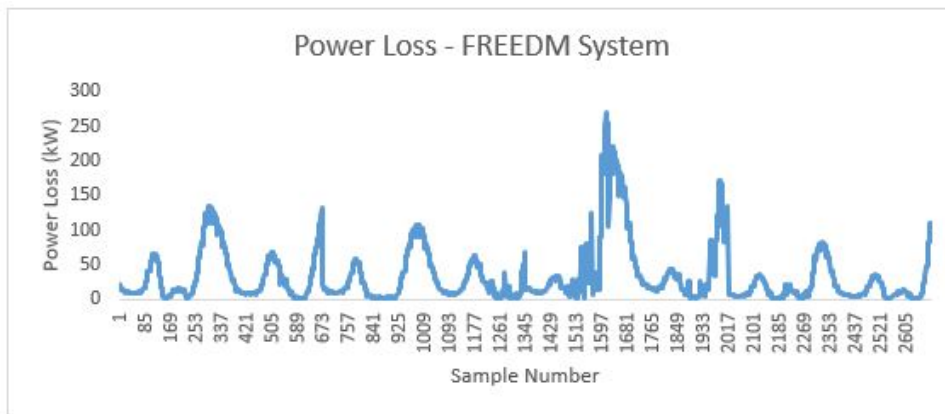
The average loss (kW) per load (kVA) comes out to be 5.99% for base case and 3.26% for FREEDM system. Figures 2.89-2.90 shows the line power loss curves in the two systems which again shows that line power losses are lesser in FREEDM case.

**Table 2.23** Number of Operations for Voltage Regulators (Annual Projection)

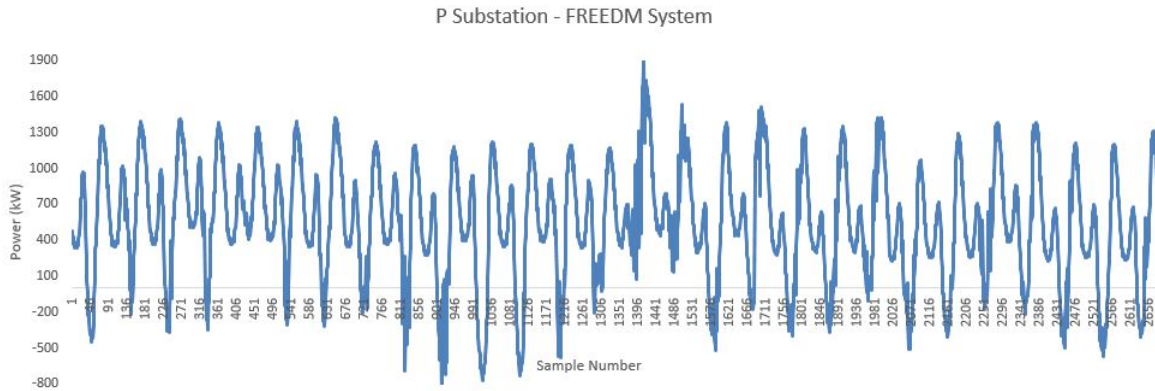
System	No. of tap Changes/year		
	Phase A	Phase B	Phase C
Base System	VR1 - 3159	VR1 - 2015	VR1 - 2288
	VR2 - 2769	VR2 - 2470	VR2 - 2613
FREEDM System	VR1 - 2678	VR1 - 1417	VR1 - 1833
	VR2 - N/A	VR2 - N/A	VR2 - N/A



**Figure 2.89** Line Power Loss - Base System



**Figure 2.90** Line Power Loss - FREEDM System



**Figure 2.91**  $P_{SUB}$  variation in FREEDM System

Total Energy loss in four weeks in the two cases is presented in the format of 'line loss + transformer loss = total loss':

- Base System - 38427.73 kWh + 13521.08 kWh = 51.94 MWh
- FREEDM System - 22496.36 kWh + 22823.23 kWh = 45.32 MWh

There is a saving of 6.62 MWh with FREEDM in terms of energy loss, over four weeks. This translates to an annual saving of 86 MWh.

## 2. Peak Demand Reduction:

The peak demand reduction will essentially remain the same as in Scenario III as the PV penetration level is same. Thus only to reiterate; the 15-min peak demand was observed to be reduced by 48.52 kW i.e. 2.13%. The energy demand reduction was observed to be 33.98% which is around 197.56 MWh in four weeks (2568.24 MWh annually).

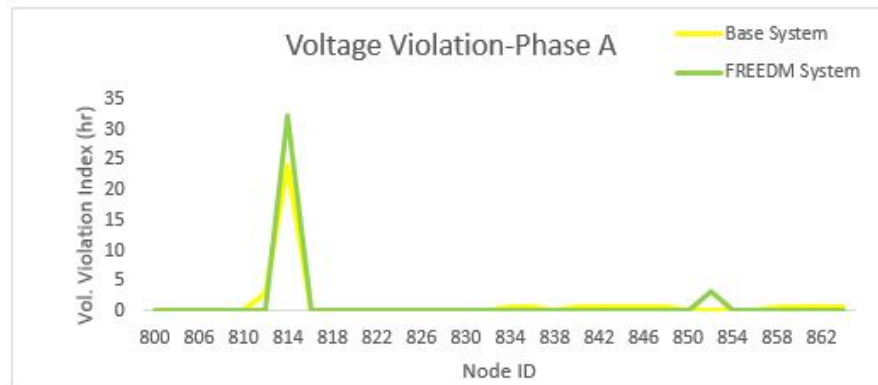
## 3. Power Flow at Substation:

Again,  $P_{SUB}$  is mostly accounted over level of PV penetration, thus, figure 2.91 showing  $P_{SUB}$  variation in the FREEDM cases looks similar as that of the base case.

The above results tell us that partial FREEDM deployment is capable of mitigating all issues.

### 2.2.5.8 Scenario V: 90.68% PV Penetration - 15 min Data (Minimum FREEDM Deployment needed)

After partial deployment case successfully handled high PV penetration impacts it was a concern that how many minimum number of nodes shall have SST's to accommodate the impacts well. Thus, a parametric analysis was done, which is presented as Scenario V. Again, the base case remains the



**Figure 2.92**  $VViol_{INDEX}$  on Phase A

same (as in Scenario III) and only the FREEDM case changes. A parametric study was performed to find the minimum number of nodes needing SST's to accommodate all impacts. In this scenario, SST's were placed only on the node (on primary) which serves the highest load i.e. node 844. Again, as the penetration level remains same, the load and PV profiles remain exactly same as in Scenario III.

### Assessment of Impacts

Obviously, the base case impacts will remain the same as in Scenario III and the impacts of FREEDM are of primary focus. Thus, impacts on the FREEDM system will be assessed using the defined metrics.

- Voltage Profile

1. Voltage Violation:

It can be seen in figures 2.92-2.94 that FREEDM has no voltage violation issues.  $VViol_{INDEX}$  is 24.75 hrs and 32.25 hrs in base case and FREEDM case respectively.  $VViol$  is 76.75 hrs and 32.25 hrs for base case and the FREEDM case respectively (in four weeks). But as can be seen in the figures FREEDM has violations only on node 814 which do not serve any load and thus, it does not count. If we neglect the voltage violations for nodes serving no load,  $VViol$  becomes 14.75 hrs for the base case and zero for FREEDM. This means that the base case will have 767 incidences of voltage violations of 15-minute durations whereas FREEDM has none.

2. Voltage Drop:

The voltage drop at the eight terminals are shown in table 2.24. The worst case VDI in base case is 0.0652pu. This goes as high as 0.1179 pu for FREEDM case. Furthermore figure 2.95 shows the maximum voltage drop index in the two cases over the three phases.

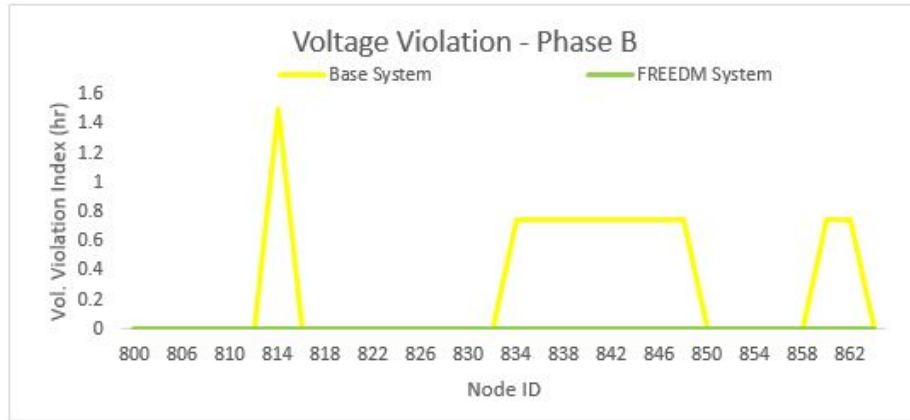


Figure 2.93  $V Viol_{INDEX}$  on Phase B

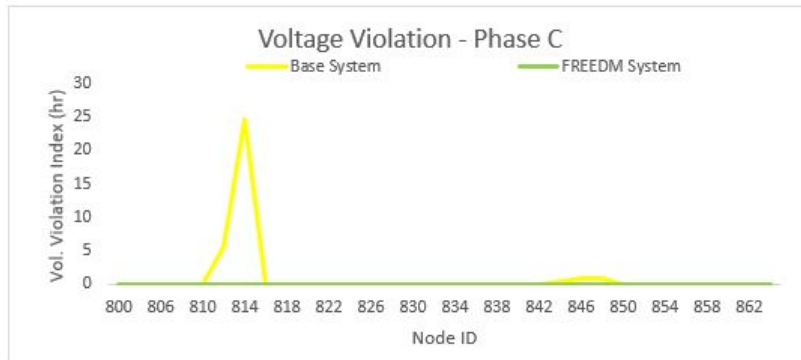
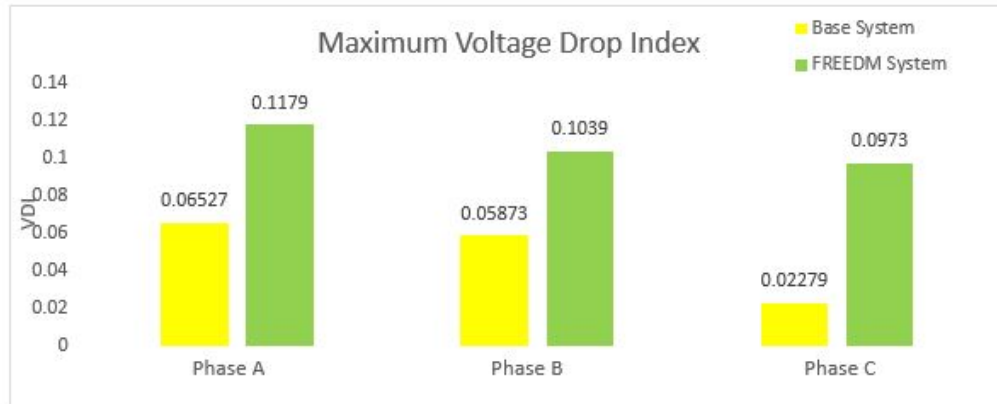


Figure 2.94  $V Viol_{INDEX}$  on Phase C

Table 2.24 Voltage Drop Index

VDI	Base System			FREEDM System		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		0.02331			0.10395	
810		0.04166			0.04565	
822	0.0652			0.07242		
826		0.04033			0.04009	
856		0.05873			0.06057	
864	0.024			0.1137		
848	0.0223	0.02238	0.02196	0.11787	0.10398	0.0973
840	0.0231	0.02325	0.02279	0.11792	0.10379	0.09724



**Figure 2.95** Maximum Voltage Drop Index

FREEDM offers better results only before node 852 as the second voltage regulator is absent in the FREEDM case, base system performs better after node 852. But as the secondary is always regulated in FREEDM, high voltage drop on terminals in the second half is not a concern.

3. Voltage Unbalance:

The worst case VUI in base case is 0.03393 pu and for FREEDM case is 0.0358pu. Thus, if just the worst case is observed, it seems that base system performs better than FREEDM in terms of voltage unbalance in this case. But, seeing figure 2.96 it is clear that minimum FREEDM has high VUI for some nodes and vice-versa. So, it can be stated that in terms of voltage unbalance, both systems perform almost equally.

4. Voltage Variation:

In base case VVI is 0.1397 pu. It is evident that FREEDM performs slightly better than the base system as VVI is 0.1301 pu with FREEDM. Table 2.25 shows the voltage variation index in the two systems. Furthermore, figures 2.97-2.99 show the voltage variation along the feeder. Thus, it can be observed that FREEDM system has lesser voltage variation than the base system (before node 852 as VR-2 is absent). Considering the secondary to be regulated, the higher voltage variations in FREEDM after node 852 is of no concern. In terms of rate of change of voltage, the value of VFI still remains 0.9364 V/s for base case but its 0.9073 V/s in FREEDM System. Thus, it can be observed as the number of SST's are reduced, rate of change of voltage worsens. Thus, more the number of SST's better is the voltage variation on the system. The histograms present a very good idea of Voltage Variation, thus, figure 2.111 displays the histograms of voltages in the FREEDM case.

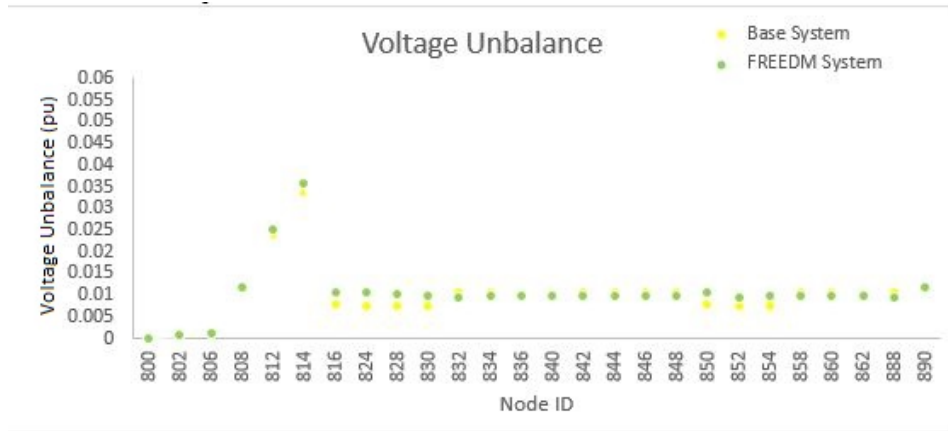


Figure 2.96 Voltage Unbalance Index along the feeder

Table 2.25 Voltage Variation Index

System	$VVI_a$	$VVI_b$	$VVI_c$	VVI
Base System	0.13967	0.089357	0.091082	0.13967
FREEDM System	0.1301	0.0961	0.0895	0.1301

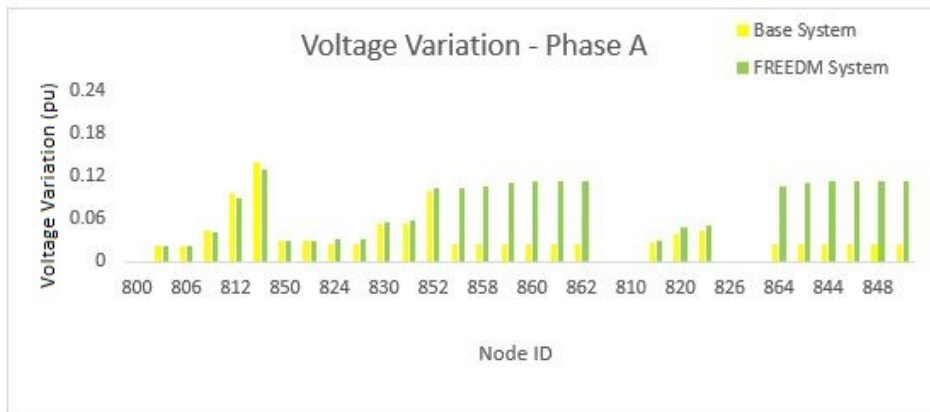


Figure 2.97 Voltage Variation on Phase A

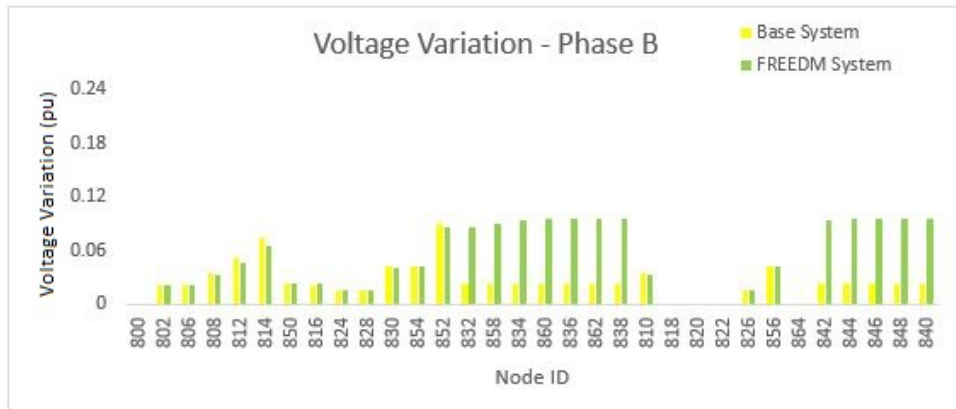


Figure 2.98 Voltage Variation on Phase B

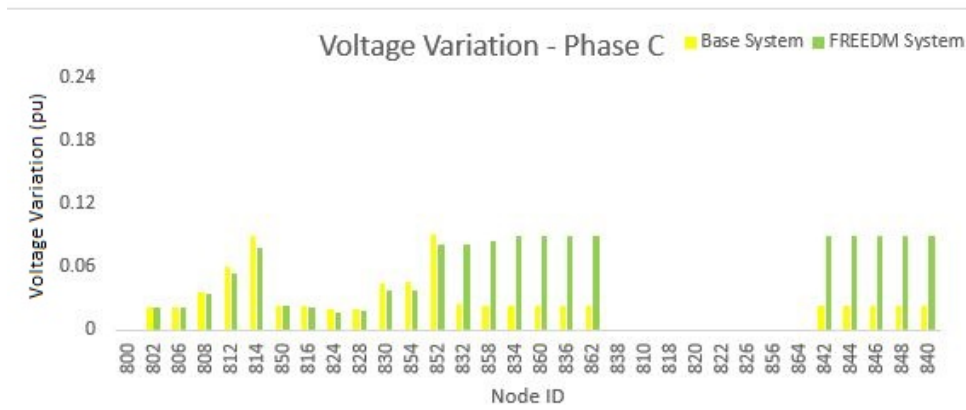


Figure 2.99 Voltage Variation on Phase C



Figure 2.100 Histogram of voltages on primary side of feeder in FREEDM System

## 5. Voltage Regulator Operations:

Table 2.26 gives the number of tap changes for Voltage Regulators for the two systems, for four weeks and table 2.27 gives annual translation of the 4 week simulation. It can be observed that FREEDM offers much less number of operations than the base system adding life to the equipment and deferring costs.

**Table 2.26** Number of Operations for Voltage Regulators (Four Weeks)

System	No. of tap Changes - 4 weeks		
	Phase A	Phase B	Phase C
<b>Base System</b>	VR1 - 243	VR1 - 155	VR1 - 176
	VR2 - 213	VR2 - 190	VR2 - 201
<b>FREEDM System</b>	VR1 - 232	VR1 - 128	VR1 - 148
	VR2 - N/A	VR2 - N/A	VR2 - N/A

**Table 2.27** Number of Operations for Voltage Regulators (Annual Projection)

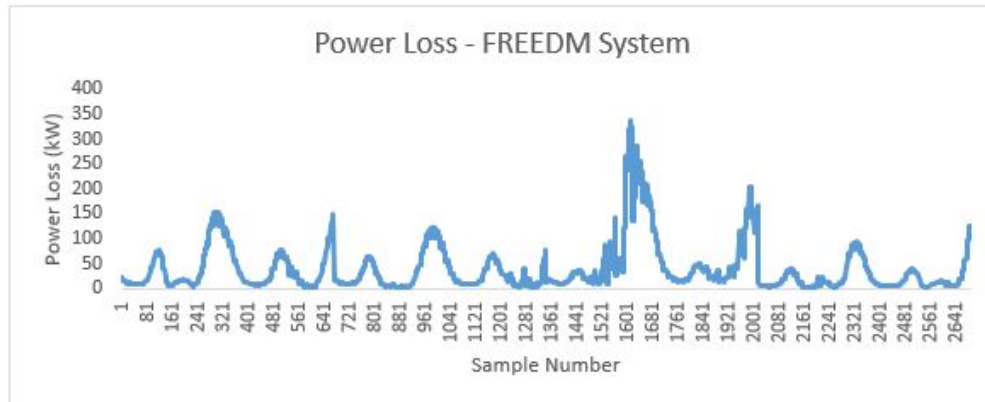
System	No. of tap Changes/year		
	Phase A	Phase B	Phase C
<b>Base System</b>	VR1 - 3159	VR1 - 2015	VR1 - 2288
	VR2 - 2769	VR2 - 2470	VR2 - 2613
<b>FREEDM System</b>	VR1 - 3016	VR1 - 1664	VR1 - 1924
	VR2 - N/A	VR2 - N/A	VR2 - N/A

- Power & Energy

## 1. Power &amp; Energy Loss:

The average loss (kW) per load (kVA) comes out to be 5.99% for base case and 3.66% for FREEDM system. Figure 2.101 shows the line power loss curve in the FREEDM case. It can be observed that FREEDM has lower line power loss than the base system.

Total Energy loss in four weeks in the two cases is presented in the format of 'line loss + transformer loss = total loss':



**Figure 2.101** Line Power Loss - FREEDM System

- Base System - 38427.73 kWh + 13521.08 kWh = 51.94 MWh
- FREEDM System - 26958.7 kWh + 16847.35 = 43.81 MWh

Thus, there is a saving of 8.13 MWh with FREEDM in terms of energy loss, over four weeks. This translates to an annual saving of 105.74 MWh.

2. Peak Demand Reduction:

The peak demand reduction will essentially remain the same as in Scenario III as the PV penetration level is same. Thus, only to reiterate; the 15-min peak demand was observed to be reduced by 48.52 kW i.e. 2.13%. The energy demand reduction was observed to be 33.98% which is around 197.56 MWh in four weeks (2568.24 MWh annually).

3. Power Flow at Substation:

Again,  $P_{SUB}$  is mostly accounted over level of PV penetration, thus, figure 2.102 showing  $P_{SUB}$  variation in the FREEDM cases looks similar as that of the base case.

This proves that even if SST's are placed only on node 844 then also all the issues are mitigated well enough.

### 2.2.5.9 Scenario VI: 80% PV Penetration - 15 min Data (Commercial Scale PV)

All the scenarios discussed this far were with respect to residential level PV's. There have been scenarios where the PV can be present on commercial level. This scenario was also considered and is discussed as Scenario VI.

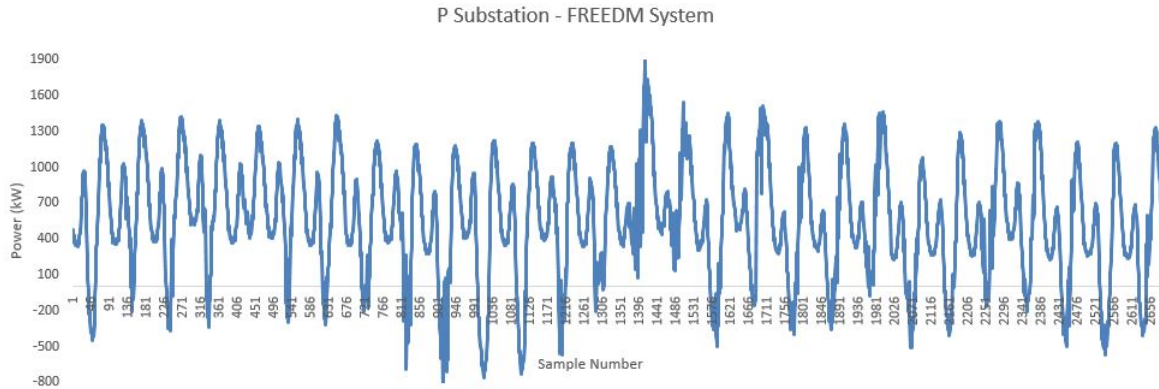


Figure 2.102  $P_{SUB}$  variation in FREEDM System

This scenario was an attempt to simulate the commercial scale PV. The PV was decided to be placed at the end of the feeder i.e. node 840. The PV of 1818.07 kW capacity was chosen.

Furthermore, FREEDM offers advanced Volt/VAR control and thus, it is expected to take care of all impacts well. It was essential to change the Volt/VAR scheme for different seasons to accommodate all the impacts, thus, In this case, Volt/VAR optimization for FREEDM was done. The Volt/VAR scheme used for FREEDM for different seasons is defined in table 2.28. Furthermore, this case involves partial FREEDM deployment and the SST’s were only placed on the nodes which were having voltage violations in the base case. The nodes containing SST’s are 860, 844, 848, 858, 864, 834, 836, 838, 846.

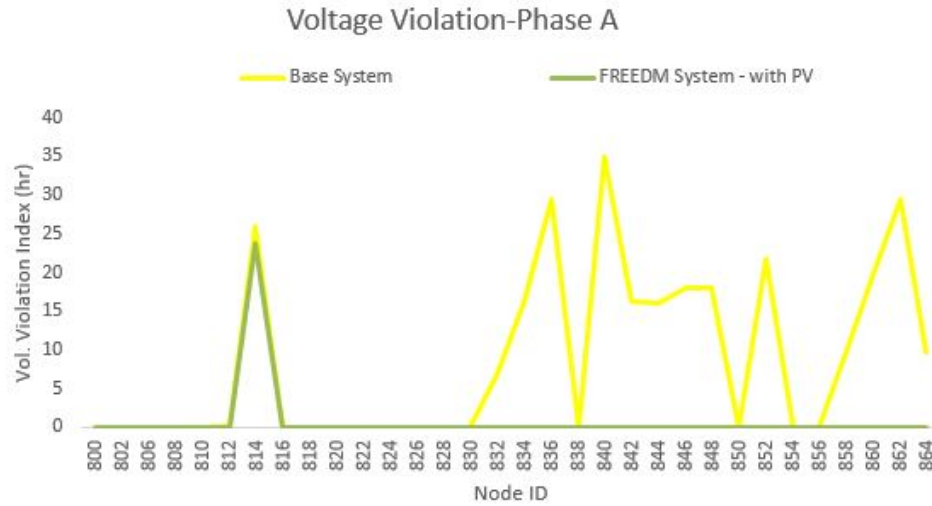
Table 2.28 Volt/VAR schemes for different seasons for FREEDM

Seasons	LTC tap	SST’s p.f.	PV inverter p.f.	VR-1	VR2
Winter	1.03	0.9 lagging	0.9 lagging	122	Off
Spring	1.02	0.9 lagging	0.85 lagging	122	Off
Summer	1.04	0.9 lagging	0.9 leading	122	118
Fall	1.02	0.9 lagging	0.88 lagging	122	Off

**Assessment of Impacts**

In here, the defined metrics will be calculated and compared for the base case and the FREEDM to have a picture of system performance with commercial PV penetration of 80%.

- Voltage Profile



**Figure 2.103**  $V Viol_{INDEX}$  on Phase A

1. Voltage Violation:

It can be seen in figures 2.103-2.105 that there are no any voltage violation issues with FREEDM but base system has high voltage violations.  $V Viol_{INDEX}$  is 70 hrs and 23.75 hrs in base case and FREEDM case respectively.  $V Viol$  is 1041 hrs and 42.75 hrs for base case and the FREEDM case respectively (in four weeks). But as can be seen in the figures FREEDM has violations only on node 814 and 812 which do not serve any load and thus, it does not count. If we neglect the voltage violations for non load serving nodes,  $V Viol$  becomes 680 hrs for the base case and zero for FREEDM. This means that the base case will have 2720 incidences (35,360 incidences annually) of voltage violations of 15-minute durations whereas FREEDM has none.

2. Voltage Drop:

The voltage drop at the eight terminals are shown in table 2.29. The worst case VDI in base case is 0.0655pu and it goes as high as 0.0846pu for FREEDM system. Furthermore figure 2.106 shows the maximum voltage drop index in the two cases over the three phases. FREEDM offers better results before node 852 but base system performs better after node 852 and that is because the second voltage regulator is absent in the FREEDM case. Thus, if we just make judgements using the figure 2.106, it will not give the right intuition. Although higher voltage drop in FREEDM is of no concern as the secondary is always regulated.

3. Voltage Unbalance:

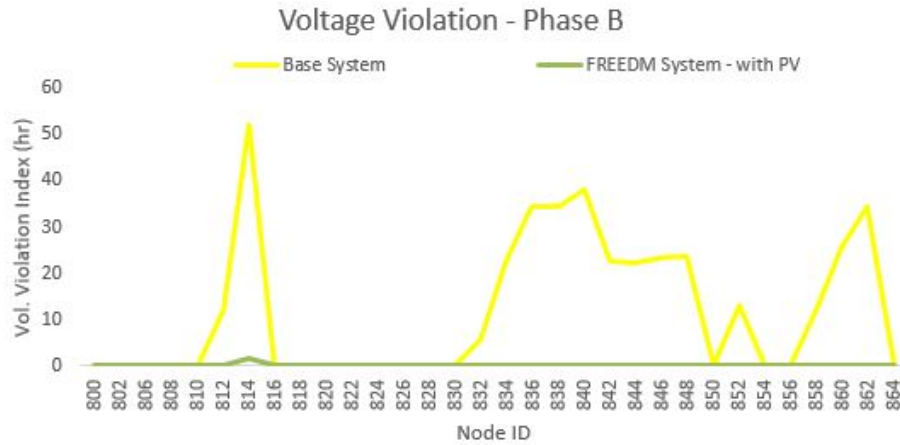


Figure 2.104  $V Viol_{INDEX}$  on Phase B

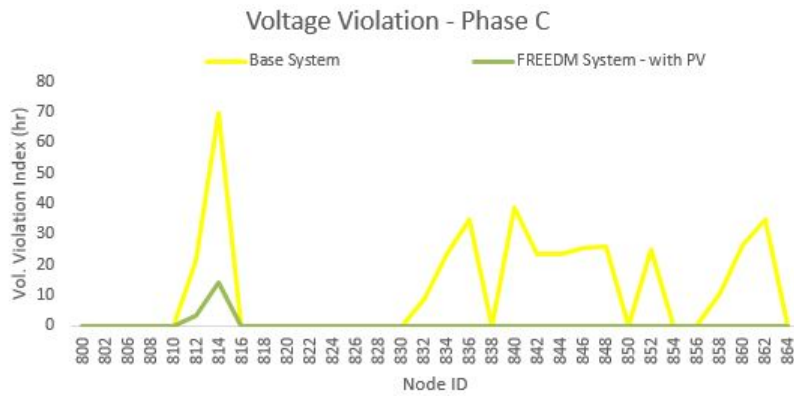
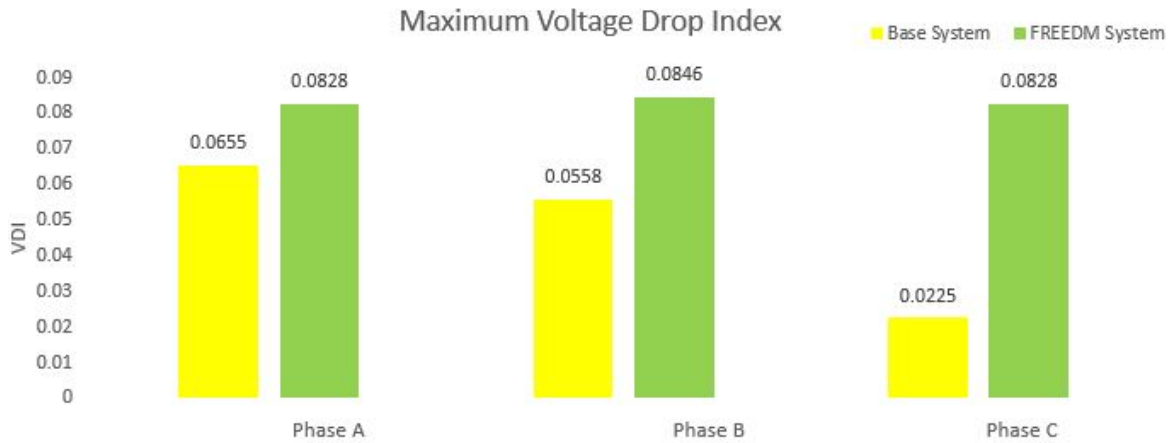


Figure 2.105  $V Viol_{INDEX}$  on Phase C

Table 2.29 Voltage Drop Index

VDI	Base System			FREEDM System		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		0.02272			0.0845	
810		0.041515			0.04696	
822	0.06555			0.06126		
826		0.04012			0.0401	
856		0.05585			0.05729	
864	0.0239			0.0796		
848	0.0223	0.02196	0.02172	0.082806	0.08462	0.0828
840	0.0231	0.02367	0.02249	0.0828	0.0844	0.0826



**Figure 2.106** Maximum Voltage Drop Index

The worst case VUI in base case is 0.034 pu and for FREEDM case is also 0.034pu. Figure 2.107 shows the VUI variation along the feeder and it is clear that FREEDM performs better than the base case as, for most of the nodes FREEDM has much less VDI as compared to its counterpart.

#### 4. Voltage Variation:

In base case VVI is 0.1371 pu. It is evident that FREEDM performs better than the base system as VVI is 0.0988 pu with FREEDM. Table 2.30 shows the voltage variation indices in the two cases. Furthermore, figures 2.108-2.110 shows the voltage variation along the feeder. It can be seen that FREEDM has lower voltage variation before node 852 and vice-versa. This is because of the absence of the VR-2. But, this is not an issue as the secondary is always regulated in FREEDM.

Moreover, the value of VFI is 0.9437 V/s for base case and it's 1.0486 V/s in FREEDM System. Thus, this is the case wherein FREEDM cannot improve the rate of change of voltage over the system. This might be because for 75% of the year FREEDM does not use the second voltage regulator and the VFI peak would have occurred during a period when VR-2 was not operating. The histograms present a very good idea of Voltage Variation, thus, figures 2.111-2.112 displays the histograms of voltages in the base case and the FREEDM case. It should be taken into account that, all the under or over-voltages appearing in the histograms are on the nodes which do not serve any load.

#### 5. Voltage Regulator Operations:

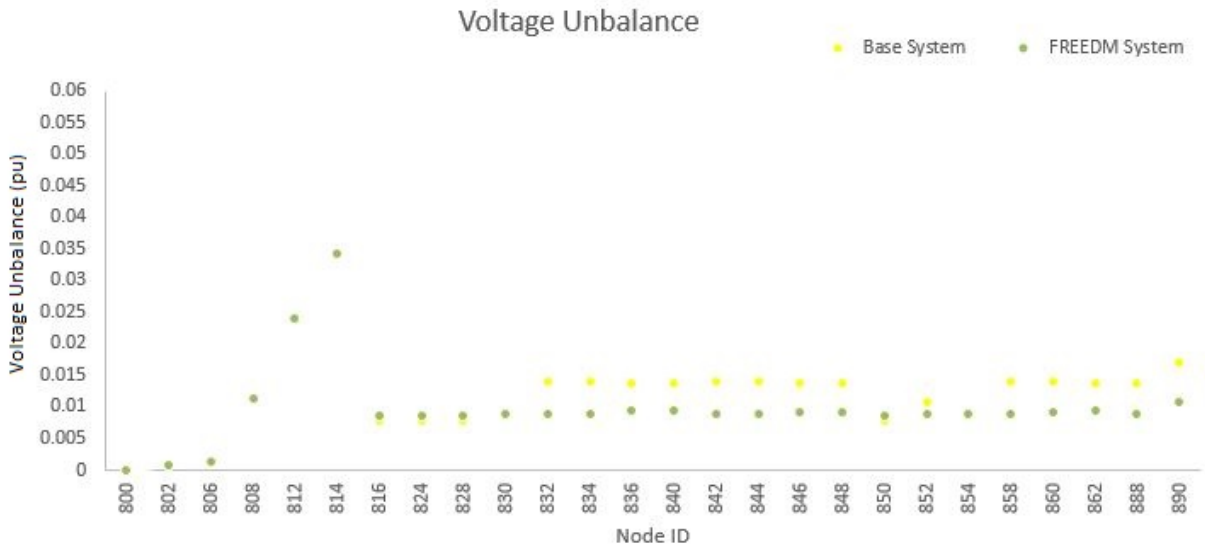


Figure 2.107 Voltage Unbalance Index along the feeder

Table 2.30 Voltage Variation Index

System	$VVI_a$	$VVI_b$	$VVI_c$	VVI
Base System	0.1372	0.09881	0.1098	0.1378
FREEDM System	0.09886	0.07975	0.08396	0.09886

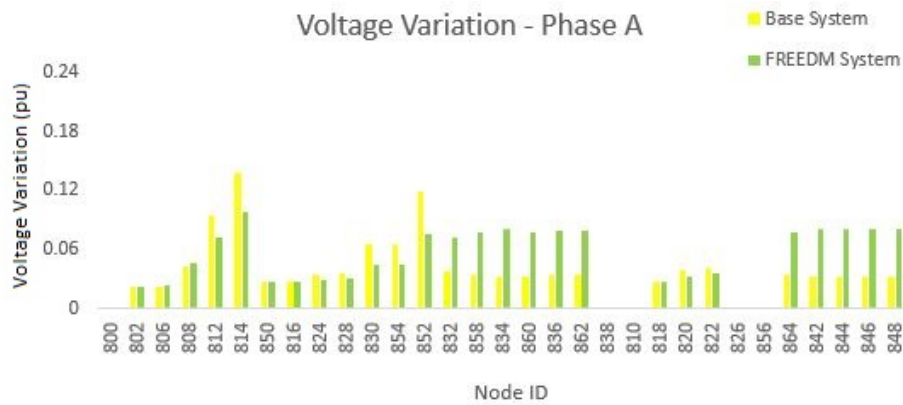


Figure 2.108 Voltage Variation on Phase A

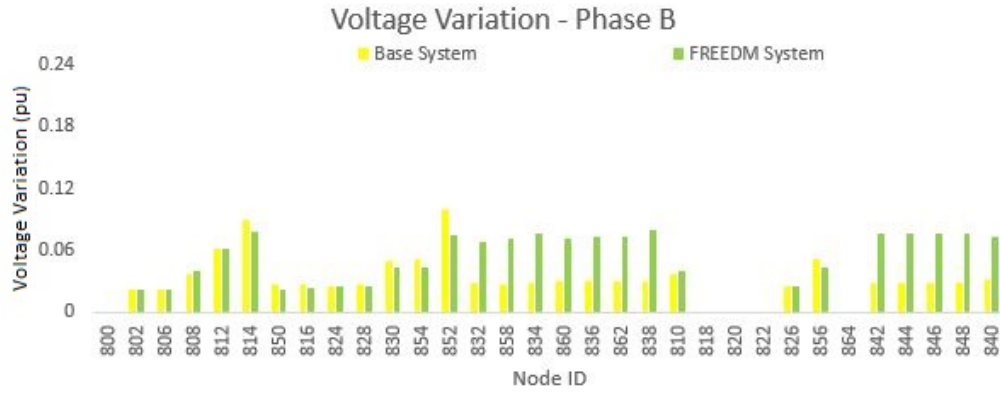


Figure 2.109 Voltage Variation on Phase B

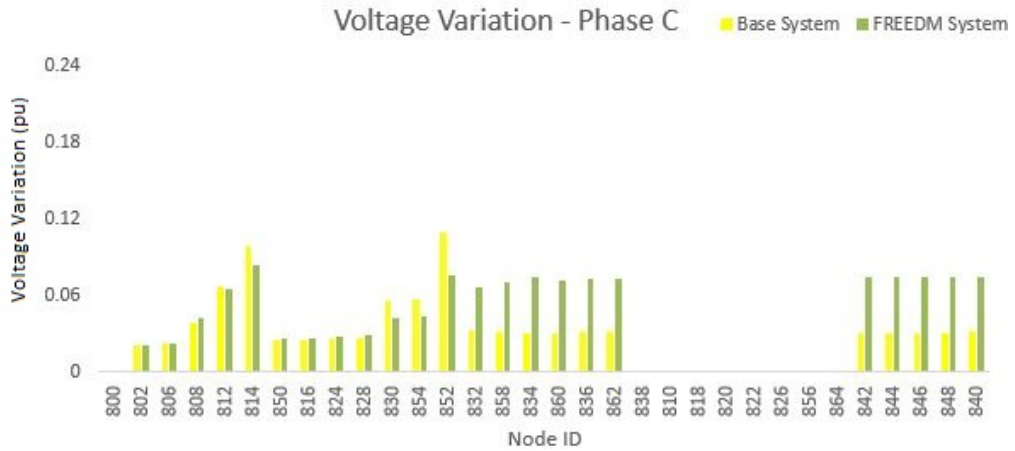


Figure 2.110 Voltage Variation on Phase C

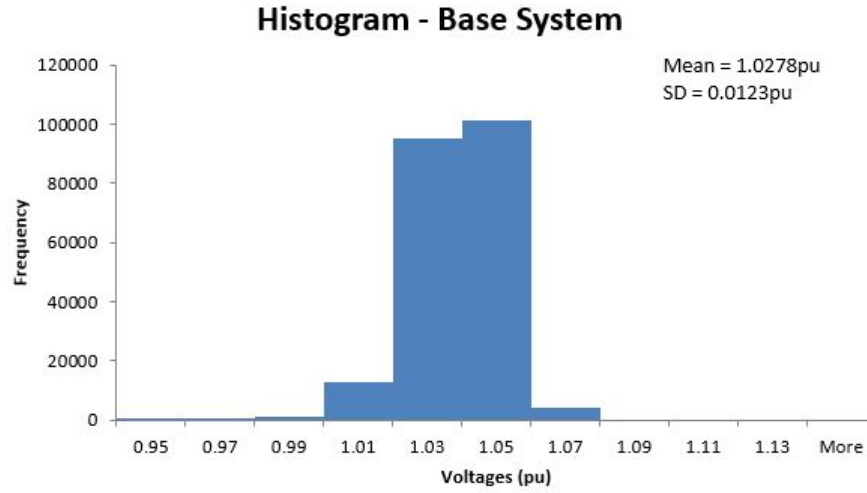


Figure 2.111 Histogram of voltages on primary side of feeder in Base System

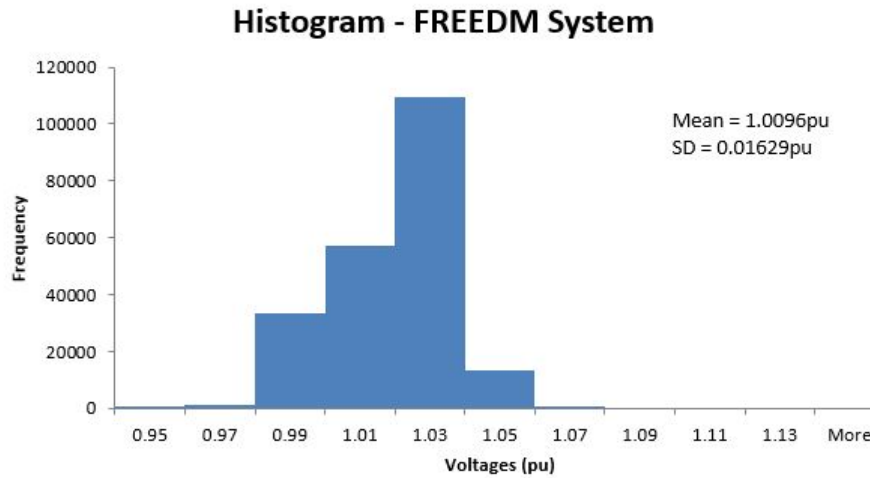


Figure 2.112 Histogram of voltages on primary side of feeder in FREEDM System

Table 2.31 gives the number of tap changes for Voltage Regulators for the two systems, for four weeks and table 2.32 gives annual translation of the 4 week simulation. It can be observed that FREEDM offers much less number of operations than the base system adding life to the equipment and deferring costs.

**Table 2.31** Number of Operations for Voltage Regulators (Four Weeks)

System	No. of tap Changes - 4 weeks		
	Phase A	Phase B	Phase C
Base System	VR1 - 227	VR1 - 169	VR1 - 182
	VR2 - 200	VR2 - 195	VR2 - 204
FREEDM System	VR1 - 195	VR1 - 130	VR1 - 141
	VR2 - 62	VR2 - 60	VR2 - 60

**Table 2.32** Number of Operations for Voltage Regulators (Annual Projection)

System	No. of tap Changes/year		
	Phase A	Phase B	Phase C
Base System	VR1 - 2951	VR1 - 2197	VR1 - 2366
	VR2 - 2600	VR2 - 2535	VR2 - 2652
FREEDM System	VR1 - 2535	VR1 - 1690	VR1 - 1833
	VR2 - 806	VR2 - 780	VR2 - 780

- Power & Energy

1. Power & Energy Loss:

The average loss (kW) per load (kVA) comes out to be 6.41% for base case and 5.24% for FREEDM system. Figures 2.113-2.114 shows the line power loss curve for the both systems. It can be seen that FREEDM has lesser power loss than the base system.

Total Energy loss in four weeks in the two cases is presented in the format of 'line loss + transformer loss = total loss':

- Base System - 40932.75 kWh + 13613.72 kWh = 54.55 MWh

- FREEDM System - 35409.52 kWh + 26290.05 kWh = 61.7 MWh

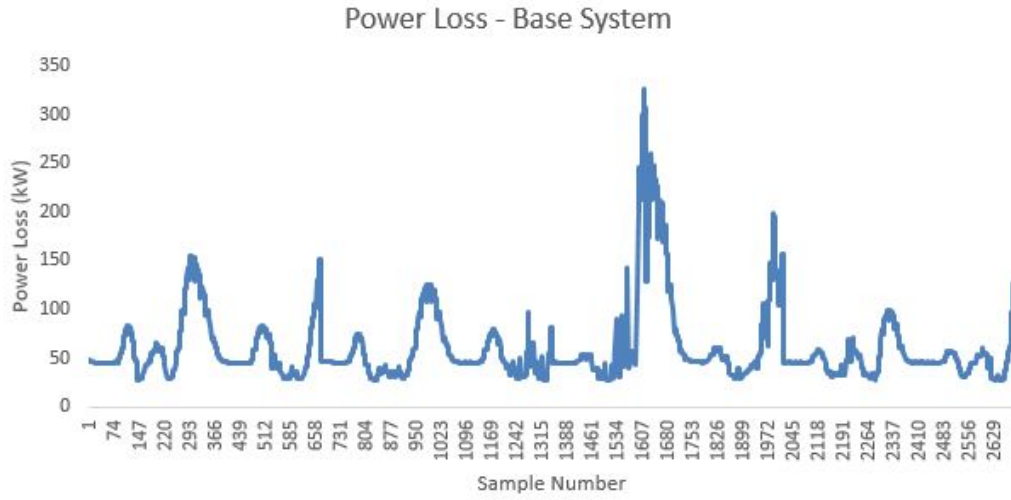


Figure 2.113 Line Power Loss - Base System

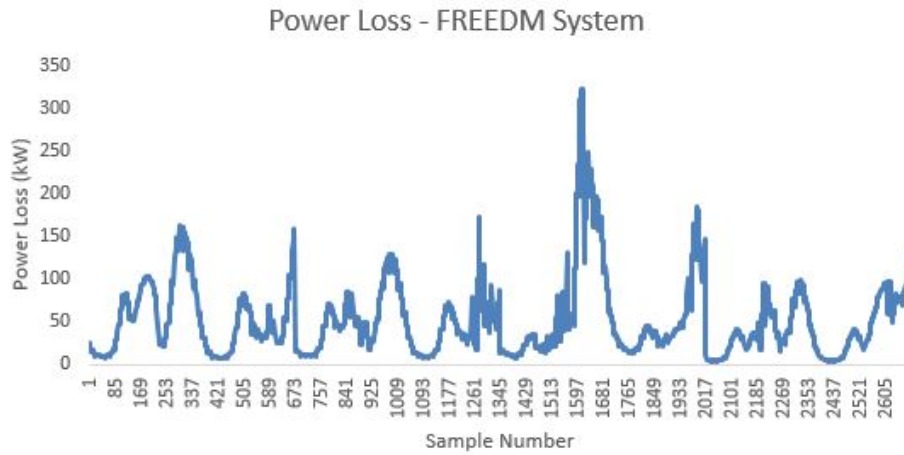
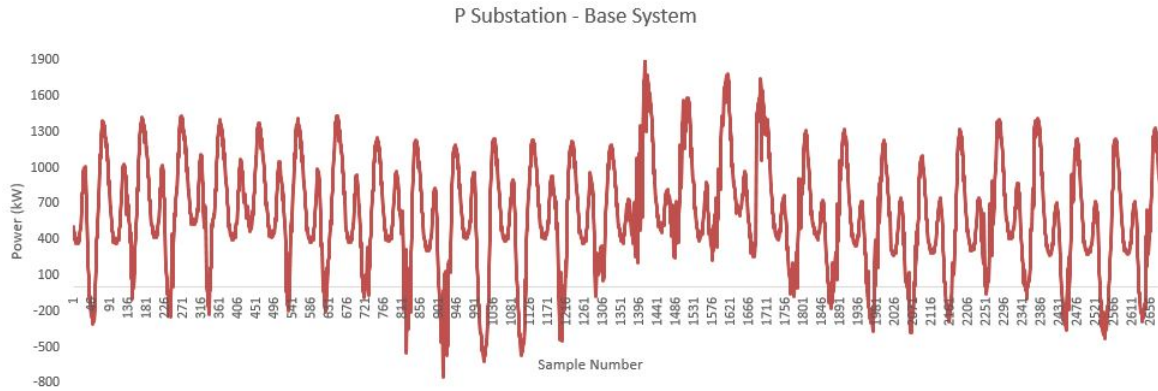


Figure 2.114 Line Power Loss - FREEDM System



**Figure 2.115**  $P_{SUB}$  variation in base System

Thus, FREEDM incurs 7.15 MWh more energy loss in the 4 weeks period. This translates to 92.95 MWh annually. Thus, for the commercial PV case, FREEDM incurs more loss in terms of total losses.

2. Peak Demand Reduction:

The peak demand reduction will essentially remain the same for both the system as it is dependent of degree of PV penetration and not on system type. It was observed that the 15-min peak demand was reduced by 56.33 kW i.e. 2.48%. The energy demand reduction was observed to be 38.44% which is around 223.49 MWh in four weeks (2905.47 MWh annually).

3. Power Flow at Substation:

Again,  $P_{SUB}$  is accounted over level of PV penetration, thus, figures 2.115-2.116 showing  $P_{SUB}$  variation in both cases expectedly looks similar.

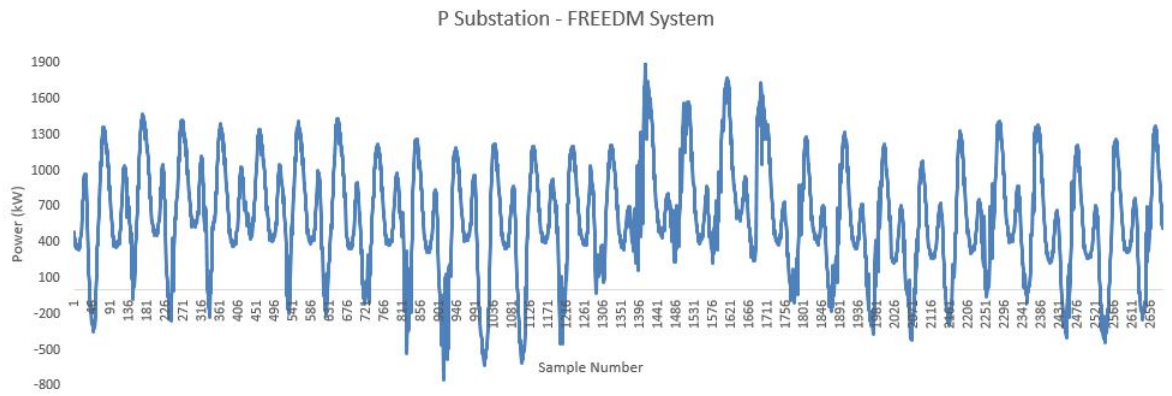


Figure 2.116  $P_{SUB}$  variation in FREEDM System

## CHAPTER

# 3

## COST BENEFIT ANALYSIS (CBA)

It was important to monetize the quantified benefits to know their real dollar value and compare them against the costs being incurred. This would give an idea about the economic viability of the project. This cost benefit study was performed in line with EPRI's report on methodological approach for estimating benefits and costs [11]. In this thesis, we will discuss the net benefit incurred in an year. Before going ahead it is important to discuss few terminologies and the methodology for CBA.

### **3.1 Methodology**

The methodology used for CBA is as follows:

- Review project technologies/element and goals.
- Identify functions for the technologies deployed.
- Assess the characteristics reflected in the project.
- Map each function onto a standardized set of benefit categories.
- Define Baseline

- Data - Identify and obtain data needed to estimate the baseline and to calculate each type of benefits.
- Quantify benefits.
- Monetize benefits.
- Estimate relevant costs.
- Compare costs to benefits.

### 3.1.1 Benefits

As per the definition given in the EPRI report [11], Benefit is:

- An impact that has value to a firm, a household or society in general.
- An outcome of a project which has value - it is not simply a project's performance or intermediate outcomes of a project.
- For example lower electricity cost, lower transmission and distribution losses, better power quality, reduced cost of power interruptions, reduced greenhouse gas emissions damages etc.

To gauge the magnitude of benefits, they should be quantified and to facilitate comparison, monetization of the same is required.

### 3.1.2 Categories of Benefits

The benefits were placed under four mutually exclusive categories:

- Economic
- Reliability and Power Quality
- Environmental
- Security and Safety

### 3.1.3 Beneficiaries

Furthermore, it was important to identify with respect to whom are the benefits accruing. Thus, the beneficiaries were identified and total benefit was equal to the sum of benefits in all categories to all beneficiaries. Table 3.1 shows the benefit matrix used for the purpose.

**Table 3.1** Benefit Matrix

Category	Beneficiary		
	Utility	Customers	Society
Economic			
Reliability & Power Quality			
Environmental			
Security & Safety			

Smart Grid Assets	Functions												
	Fault Current Limiting	Wide Area Monitoring, Visualization, and Control	Dynamic Capability Rating	Flow Control	Adaptive Protection	Automated Feeder Switching	Automated Islanding and Reconnection	Automated Voltage and VAR Control	Diagnosis & Notification of Equipment Condition	Enhanced Fault Protection	Real-Time Load Measurement & Management	Real-time Load Transfer	Customer Electricity Use Optimization
Advanced Interrupting Switch													
AMI/Smart Meters													
Controllable/regulating Inverter													
Customer EMS/Display/Portal													
Distribution Automation													
Distribution Management System													
Enhanced Fault Detection Technology													
Equipment Health Sensor													
FACTS Device													
Fault Current Limiter													
Loading Monitor													
Microgrid Controller													
Phase Angle Regulating Transformer													
Phasor Measurement Technology													
Smart Appliances and Equipment (Customer)													
Software - Advanced Analysis/Visualization													
Two-way Communications (high bandwidth)													
Vehicle to Grid 2-way power converter													
VLI (HTS) cables													

**Figure 3.1** Mapping of Assets to Functions

### 3.1.4 Mapping

Mapping is needed to identify the functions of the assets and the benefits of the functions. Figures 3.1-3.2 show the mapping matrices. Furthermore, figure 3.3 shows an example of mapping function to benefit.

### 3.1.5 Baseline

Baseline represents the conditions that would have occurred had the project not have taken place. The baseline shall follow certain criteria to be valid, such as:

Benefits		Functions											Energy Resources					
		Fault Current Limiting	Wide Area Monitoring, Visualization, and Control	Dynamic Capability Rating	Flow Control	Adaptive Protection	Automated Feeder Switching	Automated Islanding and Reconnection	Automated Voltage and VAR Control	Diagnosis & Notification of Equipment Condition	Enhanced Fault Protection	Real-Time Load Measurement & Management	Real-time Load Transfer	Customer Electricity Use Optimization	Distributed Generation	Stationary Electricity Storage	Plug-in Electric Vehicles	
Economic	Improved Asset Utilization	Optimized Generator Operation		•														
		Deferred Generation Capacity Investments																
		Reduced Ancillary Service Cost																
	T&D Capital Savings	Reduced Congestion Cost		•														
		Deferred Transmission Capacity Investments	•	•														
		Deferred Distribution Capacity Investments			•	•												
	T&D O&M Savings	Reduced Equipment Failures	•															
		Reduced Distribution Equipment Maintenance Cost																
		Reduced Distribution Operations Cost																
	Theft Reduction	Reduced Meter Reading Cost																
Reduced Electricity Theft																		
Energy Efficiency	Reduced Electricity Losses																	
	Reduced Electricity Cost																	
Reliability	Power Interruptions	Reduced Sustained Outages																
		Reduced Major Outages																
	Power Quality	Reduced Restoration Cost																
		Reduced Momentary Outages																
Environmental	Air Emissions	Reduced Sags and Swells																
		Reduced CO <sub>2</sub> Emissions																
Security	Energy Security	Reduced SO <sub>x</sub> , NO <sub>x</sub> , and PM-10 Emissions																
		Reduced Oil Usage (not monetized)																
		Reduced Widescale Blackouts																

Figure 3.2 Mapping of Functions to Benefits

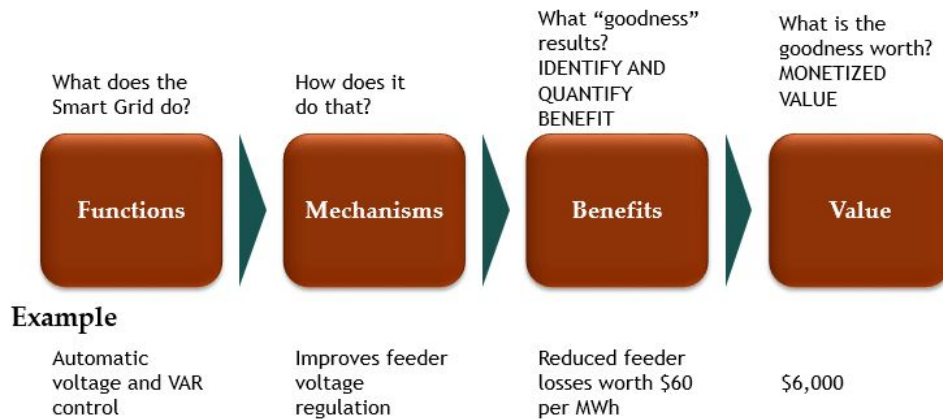


Figure 3.3 Mapping of Functions to Benefits - example

FREEDM System Features/Functions	Specific Benefits	Benefit Category			
		Economic	Reliability	Societal	Security
<b>Accommodate High PV Penetration</b>					
Value of Solar	Net benefit of PV above 20%				
Plug & Play	Simplify DER integration				
Effective Volt/Var Control	Reduction in power loss				
	Mitigate voltage issues				
Energy Storage + DGI	Mitigate variability of power				
<b>High Reliability &amp; PQ</b>					
Looped Primary	High reliability				
Fault Locating, Isolation					
Service Restoration	Minimize fault impact on components				
Fast Protection with FID	High power quality				
Regulate Service voltage					
<b>Real Time Monitoring &amp; Control (M&amp;C)</b>					
Enhanced System M&C	Reduced O&M				
	Optimal capacity use				
CVR	Load management: peak demand and energy reduction				
<b>System Resiliency</b>					
Enabling micro-grid tech	Micro-grid increases resiliency				
<b>Customer Participation</b>					
DGI- Price Signals DLMP	Customer DSM				
	Peak demand reduction				
	Economic efficiency				
<b>Motivating New Business</b>					
Enhanced DSM	Transactive Energy				

Figure 3.4 FREEDM System Benefits

- Representativeness - how appropriate is the selected baseline?
- Acceptability - must be acceptable to all (universal).
- Operational - pre and post both data must be collectable.
- Precise - Should be precise to the key performance metrics that are to be measured.
- Consistency - should be consistent with other projects too.

The identified FREEDM system benefits and functions were mapped and are represented in figure 3.4 - [16].

### 3.2 Costs

After all the studies have been performed and the cost-benefit process is completed, quantification and monetization of benefits is needed. The monetized benefits will be compared against the costs incurred. Thus, we need to first calculate the costs incurred in the system. Table 3.2 [16] gives the the relevant costs figures which is used in this cost-benefit study.

**Table 3.2** Cost Estimates of Relevant Components

Component	Cost
25 kVA SST	\$3,103
25 kVA iron transformer	\$1,192
50 kVA SST	\$4,653
50 kVA iron transformer	\$2,385
3-phase FID	\$16,225
3-phase Vacuum circuit breaker	\$20,000

### 3.3 Approach

The approach used to do the cost-benefit analysis for this study was to annualize the cost and benefits. After the annualization, net benefit or net loss was calculated by using the following formula.

$$Net\ Benefit / Net\ Loss = Annualized\ Benefit - Annualized\ Cost \quad (3.1)$$

Furthermore, to annualize the costs, lifetime of FREEDM components were considered to be 25 years and the interest rate of 10% was considered. The costs were annualized using the following formula.

$$Annual\ Cost = Total\ Lifetime\ Cost \times \frac{i(i+1)^n}{(1+i)^n - 1} \quad (3.2)$$

where  $i$  is the interest rate and  $n$  is the lifetime.

### 3.4 Cost Benefit Analysis

Few benefits like value of solar, reduced O&M cost and demand side management were looked into by other groups at FREEDM System Center and thus, won't be discussed here. Peak demand reduction and Energy Demand Reduction can be monetized but peak demand reduction is dependent on the level of PV penetration and not on the system type. Thus, both base and FREEDM system will give the same peak and energy demand reduction. Hence, it's not considered for cost-benefit analysis.

Furthermore, benefits like lesser voltage violations, better voltage variation and voltage unbalance were very difficult to monetize because of the lack of data. Hence, further research is required towards monetizing voltage related benefits.

This thesis only deals with the monetization of benefits related to reliability and energy loss

reduction. Basically in this section, relevant costs will be calculated & annualized and the benefits will be monetized under different scenarios discussed in Chapter-2.

### 3.4.1 Reliability and Power Quality Benefit

#### Costs

FREEDM System has a solid state fault isolation device (FID) which has the capability to interrupt full load current faster than mechanical circuit breakers and enables technology that makes use of high frequency, high voltage switching power converters that are compact and efficient [17]. Also, FID's are fast enough to quickly reconfigure the circuit which allows looped primary in FREEDM case. In the two systems studied for reliability study, base system uses two, 3-phase vacuum circuit breakers whereas FREEDM uses six, 3-phase FID's. Thus, the initial cost involved in the two systems (in terms of protection devices) is:

- Base System = \$40,000
- FREEDM System = \$97350

Thus, FREEDM system is \$57,350 costlier than the base system over the lifetime of the components assuming the maintenance cost to be the same for both over their lifetime. This amounts to an annualized cost of \$6318. (with 25 years of lifetime and at an interest rate of 10%).

#### Benefits

Furthermore, according to [18], there is a cost associated with SAIFI and SAIDI. This associated cost is displayed in table-3.3. From table 3.3 it can be seen that utility incurs the same cost of restoration, thus, the utilities are benefitted on the ground of reduction in SAIFI only whereas for customers the interruption cost is dependent on both SAIFI and SAIDI. As discussed in [11], the cost associated

**Table 3.3** Cost per Customer

Entity	Cost/customer	
	4 hour Interruption	1 hour Interruption
Utility (cost of restoration)	\$14	\$14
Customer	\$12.73	\$8.32

with reliability can be calculated using the following formulae:

For Customers -

$$\text{Avg. Estimated Cost} (\$/\text{year}) = \text{SAIDI} * \text{SAIFI} * \text{Interruption Cost} * \text{no. of Customers} \quad (3.3)$$

For Utility -

$$\text{Avg. Estimated Cost} = \text{SAIFI} * \text{cost of restoration} * \text{no. of customers} \quad (3.4)$$

The costs associated with customers and utility was calculated for the two systems and is presented in table 3.4. Thus, the total annual benefit of FREEDM System comes out to be \$4,284. It must be

**Table 3.4** Monetized Reliability Costs for Residential Customers & Utility in the two systems

System	SAIDI	SAIFI	1 hr	4 hrs	Tot Est. Cost - Customer	Tot. Est. Cost - Utility
Base System	1.036	1.265	\$8.32	\$12.73	\$2086.306	\$3364.90
FREEDM System	0.543	0.3742	\$8.32	\$12.73	\$174.5998	\$992.18

noted that this benefit applies only to the full deployment scenarios.

#### Net Loss

Annual Net Loss (in terms of reliability) = \$2034

Thus, in terms of reliability, FREEDM system has to incur around \$2034 more than the base system, annually.

#### 3.4.2 Power & Energy Savings

In this section, energy loss reduction over the feeder will be monetized in different scenarios as discussed in Chapter-2 and relevant costs will also be calculated and annualized. Monetization of energy loss is done using the equation 3.5.

$$\text{Monetized Energy Loss} (\$) = \text{Energy Loss} * \text{Average Energy Cost} (\$0.1176) \quad (3.5)$$

Average energy cost was considered for the state of Arizona as the test system is situated in Arizona. The average cost of energy came out to be \$0.1176 and was used to monetize the energy loss benefit.

### 3.4.2.1 Scenario Ia: 80% PV Penetration

#### Costs

The base system uses 36, 25-kVA transformers and 24, 50-kVA transformers. This case being the full FREEDM deployment scenario, FREEDM also uses same number of SST's for the FREEDM system as the number of conventional transformers in base system. Furthermore, base system uses 2, 3-phase voltage regulators costing approximately \$13000 each [16] while FREEDM uses only one 3-phase voltage regulator. Thus, the costs involved in the two systems are:

- Base System = \$126152
- FREEDM System = \$236380

Thus, the FREEDM system is costing around \$110228 more than the base system i.e. \$12,144 per year (with 10% interest rate and 25 years of life).

#### Benefits

Table 3.5 gives the monetized value of losses over 4-week period and its annual translation. Thus,

**Table 3.5** Loss Monetization for Scenario Ia

Parameter	Base System	FREEDM System
Losses (kWh)	52,727.98	47,100.55
4 week Cost of Energy Lost	\$6,200.81	\$5,539.02
4 week Energy Cost Saving	-	\$661.78
Annual Energy Cost Saving	-	\$8,603.21

FREEDM offers a net loss of \$3,540 per year in terms of energy loss reduction, for full deployment case with 80% PV penetration.

### 3.4.2.2 Scenario II: 45.34% PV Penetration

#### Costs

The system is same, only the penetration level is different. Also, as this too is a full FREEDM deployment case, there is no change in the costs involved. Thus, in this case too FREEDM costs \$110228 more than the base system which comes out to be \$12,144 at 10% interest rate, considering 25 year lifetime.

#### Benefits

Table 3.6 gives the monetized value of losses over 4-week period and its annual translation. Thus, it

**Table 3.6** Loss Monetization for Scenario II

<b>Parameter</b>	<b>Base System</b>	<b>FREEDM System</b>
Losses (kWh)	56,884.81	50,832.47
4 week Cost of Energy Lost	\$6,689.65	\$5,977.89
4 week Energy Cost Saving	-	\$711.75
Annual Energy Cost Saving	-	\$9,252.76

is observed that FREEDM incurs a net loss of \$2,891 per year in terms of energy loss reduction, for full FREEDM deployment with 45.34% PV penetration.

#### 3.4.2.3 Scenario III: 90.68% PV Penetration

##### Costs

Again being the full FREEDM deployment case the cost involved will be the same as in the above two cases and FREEDM will cost \$110228 more than the base system which comes out to be around \$12,144 at 10% interest rate, considering 25 year lifetime.

##### Benefits

Table 3.7 gives the monetized value of losses over 4-week period and its annual translation. Thus, it

**Table 3.7** Loss Monetization for Scenario III

<b>Parameter</b>	<b>Base System</b>	<b>FREEDM System</b>
Losses (kWh)	51,948.81	45,601.5
4 week Cost of Energy Lost	\$6,109.18	\$5,362.73
4 week Energy Cost Saving	-	\$746.44
Annual Energy Cost Saving	-	\$9,703.76

can be observed that FREEDM offers a net loss of \$2,440 per year in terms of energy loss, over the base system for full FREEDM deployment with 90.68% PV penetration.

#### 3.4.2.4 Scenario IV: 90.68% PV Penetration with Partial FREEDM Deployment

##### Costs

In this case SST's are not present on each node, rather they are present only on the nodes having PV. Still the base system uses 36, 25kVA transformers and 24, 50kVA transformers plus 2, 3-phase voltage regulators but now the FREEDM system uses 30, 25-kVA SST's, 6 conventional 25-kVA transformers and 21, 50-kVA SST's & 3, 50-kVA conventional transformer and 1, 3-phase voltage regulator. Thus, the costs associated with the two systems are:

- Base System - \$126152
- FREEDM System - \$218110

Thus, it is observed that FREEDM system is \$91958 costlier than the base system which translates to \$10,131 per year (again at 10% interest rate and for 25 years of life).

##### Benefits

Table 3.8 gives the monetized value of losses over 4-week period and its annual translation. Thus, it

**Table 3.8** Loss Monetization for Scenario IV

Parameter	Base System	FREEDM System
Losses (kWh)	51,948.81	45,319.59
4 week Cost of Energy Lost	\$6,109.18	\$5,329.58
4 week Energy Cost Saving	-	\$779.59
Annual Energy Cost Saving	-	\$10,134.75

is observed that FREEDM offers net benefit of \$4 per year over the base system for partial FREEDM deployment with 90.68% PV penetration.

#### 3.4.2.5 Scenario V: Minimum FREEDM Deployment needed for 90.68% PV Penetration

##### Costs

In this case again, SST's are not present on each node, rather it is present only on node 844. Still the base system uses 36, 25kVA transformers and 24, 50kVA transformers and 2, 3-phase voltage regulators, but now the FREEDM system uses 9, 25-kVA SST's, 27 conventional 25-kVA transformers and 10, 50-kVA SST's & 14, 50-kVA conventional transformer with 1, 3-phase voltage regulator. Thus, the costs associated with the two systems are:

- Base System - \$126152
- FREEDM System - \$153031

Thus, FREEDM system is \$26879 costlier than the base system which translates to \$2961 per year (again at 10% interest rate and for 25 years of life).

#### **Benefits**

Table 3.9 gives the monetized value of losses over 4-week period and its annual translation. Thus,

**Table 3.9** Loss Monetization for Scenario V

<b>Parameter</b>	<b>Base System</b>	<b>FREEDM System</b>
Losses (kWh)	51,948.81	43,806.05
4 week Cost of Energy Lost	\$6,109.18	\$5,151.59
4 week Energy Cost Saving	-	\$957.59
Annual Energy Cost Saving	-	\$12,448.65

FREEDM system offers a net benefit of \$9,487 per year over the base system for minimum FREEDM deployment with 90.68% PV penetration.

#### **3.4.2.6 Scenario VI: Commercial Scale PV (80% PV Penetration)**

##### **Costs**

In this case, SST's are again placed on selective nodes - 860,844,848,858,864,834,836,838,846. FREEDM system in here uses 2, 3-phase voltage regulators with 24, 25-kVA SST's, twelve 25-kVA conventional transformers and 17, 50-kVA SST's alongwith 7,50-kVA conventional transformers. Thus, the costs associated with the two systems are:

- Base System - \$126152
- FREEDM System - \$210572

Thus, FREEDM system is \$84,420 costlier than the base system which translates to \$9,300 per year (again at 10% interest rate and for 25 years of life).

##### **Benefits**

Table 3.10 gives the monetized value of losses over 4-week period and its annual translation. Thus, in this case FREEDM system does not appear to be cost effective and offers a negative net benefit of \$20,236 per year.

**Table 3.10** Loss Monetization for Scenario VI

<b>Parameter</b>	<b>Base System</b>	<b>FREEDM System</b>
Losses (kWh)	54,546.47	61,699.57
4 week Cost of Energy Lost	\$6,414.66	\$7,255.86
4 week Energy Cost Saving	-	-\$841.209
Annual Energy Cost Saving	-	-\$10,935.72

There are scenarios which come out to be cost ineffective in terms of energy loss reduction. But, it must be noted, this seems to be cost ineffective because only energy loss reduction is considered for monetization out of all benefits realized through Volt/VAR study. A more detailed study is needed wherein all other Volt/VAR benefits shall be monetized and added to the present benefits. The total benefits after complete monetization (considering all benefits) is expected to be more than the extra costs incurred in FREEDM.

## CHAPTER

# 4

# CONCLUSIONS & FUTURE WORK

## 4.1 Conclusion

The main contributions of this thesis includes:

- FREEDM system allows looping of primary which improves the reliability indices significantly. Simulations suggest that there is an improvement of 47.57% and 70.51% in SAIDI and SAIFI indices respectively.
- Six scenarios were considered to check for the system performances under different situations giving a broader spectrum about the behaviour of the systems under different penetration levels and level of FREEDM deployment.
- Eight metrics are adopted to assess the system performance under Vol/VAR Study. The simulation results indicate that FREEDM system has the capability to accommodate higher levels of PV and has an advantage of reducing the primary-side power and energy loss, reducing voltage unbalance, reducing voltage variations and provide with zero voltage violations. Moreover, FREEDM also avoids the use of capacitors and uses less number of voltage regulators. Besides, it also offers lesser number of operations for voltage regulators adding to the equipment's life and deferring the costs.

- A simple cost benefit analysis is done wherein yearly costs involved and benefits (only reliability and energy losses were considered) are calculated to check whether the net-benefit is positive. Results suggest that FREEDM system is not economically viable in few scenarios. But as other benefits have not been monetized, it would be an early say to declare FREEDM to be less cost effective as compared to the base system.

## 4.2 Future Work

In this thesis, few of the benefits are not quantified such as system resiliency, plug and play etc. Thus, quantification of other benefits is also, required. Furthermore, in Chapter-3 only energy losses and reliability indices were monetized. Further research is required to monetize voltage related benefits such as voltage violation, voltage unbalance, voltage variation, voltage regulator operations etc.

Secondly, with respect to reliability it was discussed about the benefits accruing to both utility and customers. This is not the case with energy loss benefits. Further work is needed to see the FREEDM benefits accruing to both utility and customer as a whole to get a better picture.

Also, in this work it was assumed that each node has same load and PV profiles. To be more realistic, different load profiles shall be considered for different nodes. Different PV profiles shall also be considered if feeder being analyzed is too long to assume similar weather conditions along its length.

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## APPENDIX

## APPENDIX

### A

## APPENDIX-I

### **A.1 Transformer Loss Calculation**

This section describes the process of transformer loss calculation used in this thesis. Table A.1 gives the number of transformers on each node of a particular type:

#### **A.1.1 Conventional Transformer Loss Calculation**

According to U.S DOE, for forced oil cooled units, approximate active power loss is 1% at 75% loading.

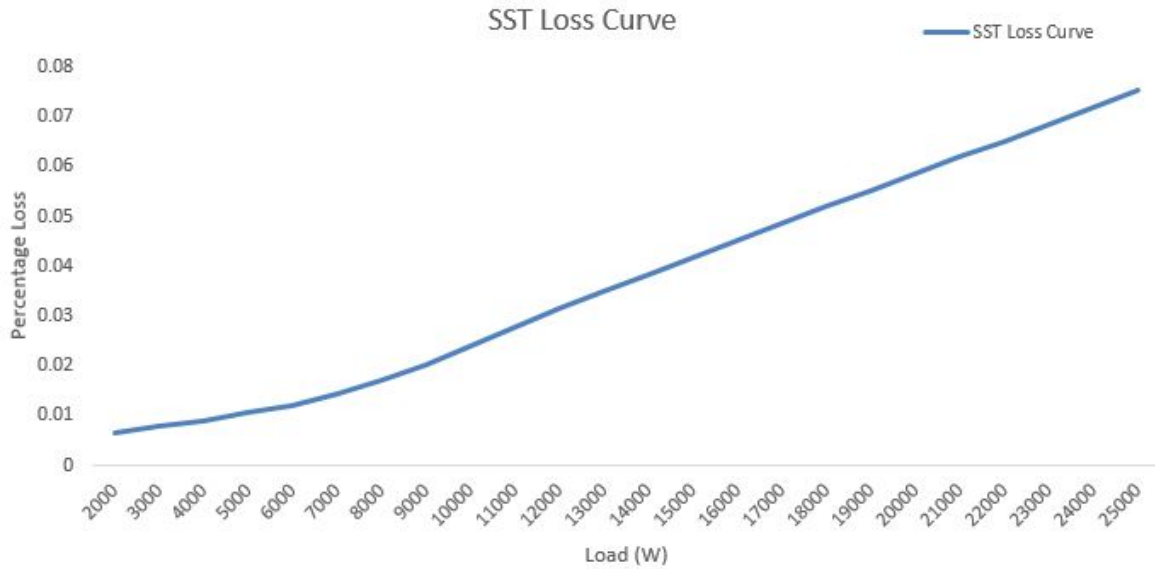
Thus,  $0.01 = 0.75 \times 0.75 \times R$

this gives us resistance,  $R = 0.0178 \text{ pu}$

The currents on each node was available through the power flow simulations in each case and was divided on each node among the transformers present, depending in the ratio of their capacity. This helped to get the current in each transformer and copper loss calculation was done by multiplying the value of resistance R with the square of currents. Furthermore, iron loss is independent of the loading and was taken to be 255W and 380W for 25kVA and 50kVA transformers respectively [19].

**Table A.1** Transformer Data

<b>Nodes</b>	<b># of 25-kVA Transformers</b>	<b># of 50-kVA Transformers</b>
802	0	0
806	2	0
808	0	0
810	1	0
812	0	0
814	0	0
850	0	0
818	0	0
824	1	0
820	0	1
822	2	3
826	0	1
828	1	0
830	1	1
854	0	0
858	1	0
888	0	0
860	4	4
842	0	0
840	2	1
862	0	0
844	9	10
846	2	0
848	4	1
816	0	0
832	0	0
856	1	0
852	0	0
864	1	0
834	0	1
836	3	1
838	1	0



**Figure A.1** SST Loss Curve

### A.1.2 SST Loss Calculation

SST has mainly three different stages i.e. rectifier, dc-dc converter and inverter. SST's were tested by Dr. Huang and his group at FREEDM Systems Center to obtain efficiency curves for the three stages. The individual efficiency curves for the three stages obtained cannot be presented as part of this work in order to maintain its confidentiality. But a net efficiency curve for SST is displayed as figure A.2; developed on the basis of the laboratory curves obtained.

We know that,

$$P_{Loss} = (1 - efficiency)P_{in} \quad (A.1)$$

Using the best efficiency plots for all three stages and the equation A.1 a combined SST percentage loss curve was plotted as shown in figure A.1. Figure A.2 gives the corresponding efficiency curve for a 25kVA SST.

Needed extrapolations were made on the efficiency curves of dc-dc and inverter stage, taking into consideration the degree of their flattening. It must be noted that the percentage loss plot for SST is with the base of 25kW. As SST's tested were 20kVA, extrapolation was done to come up with a 25kVA SST efficiency curve. The average of the difference between losses under last four loading conditions was taken and this average was added successively to reach till 25kW loading.

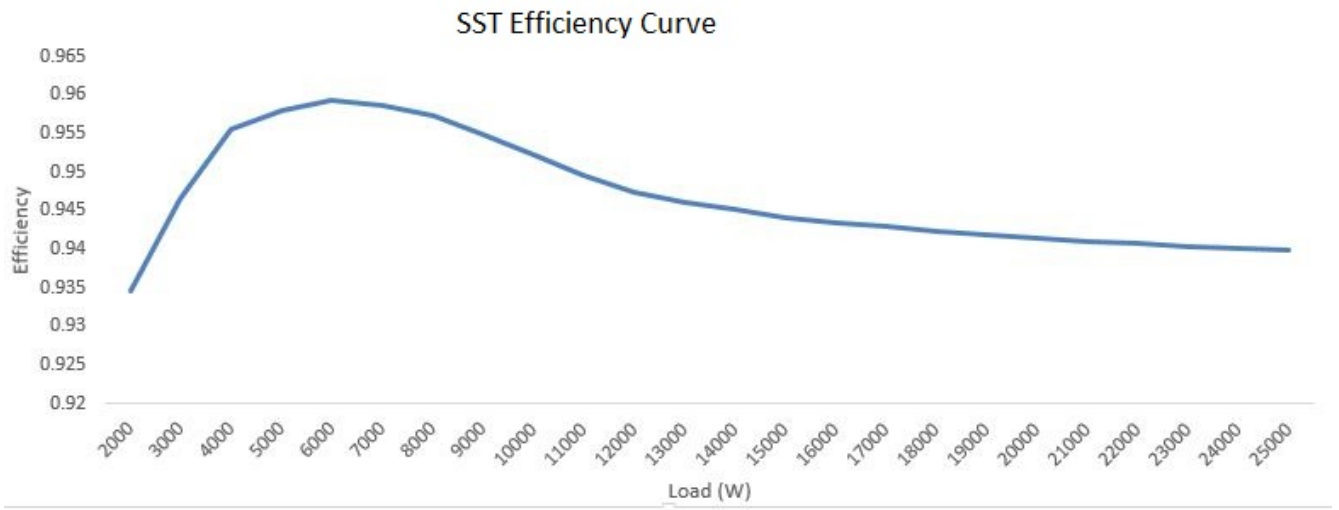


Figure A.2 SST Efficiency Curve