ABSTRACT

SHI, YUE. An Investigation of Volt/Var Control on FREEDM Systems. (Under the direction of Dr. Mesut E. Baran).

Main objectives of Volt/Var control (VVC) include maintaining voltage on a distribution system within the acceptable range, and reducing power and energy loss. Devices such as voltage regulators and shunt capacitors are widely used in conventional distribution systems. Recent interest in integrating more Distributed Renewable Engery Resources (DRER) with the distribution systems necessitated the upgrading of current systems. In the FREEDM Systems, Solid State Transformers (SST) replace the traditional distribution transformers to facilitate high penetration of DRERs.

In this thesis, the Volt/Var control schemes on FREEDM systems are investigated. A power flow based simulation method has been adopted for this purpose. The investigation involved performing case studies on two prototype feeders, the Notional Feeder and IEEE 34 Nodes Test Feeder. In the first part of this thesis, the focus is on assessment of the effectiveness of a given FREEDM VVC scheme. Various performance metrics have been considered and used for this purpose. In the secondary part of this thesis, alternative FREEDM VVC schemes are considered and assessed. Two options of design of alternative FREEDM VVC are proposed and compared.

The simulation results show that for both systems the FREEDM VVC can successfully maintain voltages within the acceptable range, even with high PV penetration. Furthermore, the FREEDM VVC has the advantage of less primary-side power and energy loss, lower voltage unbalance, and lower voltage variation as compared with the conventional VVC.

An Investigation of Volt/Var Control on FREEDM Systems

by
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DEDICATION

To My Parents

Baode Shi and Zhimin Sun

BIOGRAPHY

Yue Shi was born in Dandong, Liaoning, China, in 1989. She received her B.Eng. in Electrical Engineering from Tianjin University, in 2012. In 2012 she joined North Carolina State University to pursue Master of Science in Electrical Engineering. In 2013 she joined the FREEDM System Center as a research assistant under the guidance of Dr. Mesut E. Baran.

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To all my friends, for the time we've been through together. I feel so lucky to have you all.

And last and foremost, to my parents, Baode Shi and Zhimin Sun, for their love and support throughout my entire life.

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Chapter 1 Introduction

Distribution Volt/Var Control (VVC) aims at keeping the voltages in a distribution system within a required range under different operating conditions, such as the load variation. With the introduction of Distributed Renewable Energy Resources (DRER) to distribution systems, operating conditions also include the variation of the DRER output in addition to the load variation. Voltage Regulators and Capacitor Banks are conventional VVC devices that have been widely used in power distribution systems. With the development of technology, new devices such as Solid State Transformers (SSTs) and Dynamic Var Compensators (DVCs) are employed for VVC [1].

1.1 Volt/Var Control on Conventional Systems

Voltage control is a fundamental operating requirement for an electric distribution system, as it is the utility's responsibility 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. Under heavy load conditions, the nodes far away from the substation may have under-voltage violation, as shown in Fig. 1.1. One simple way to fix this problem is to manually raise the source voltage, as shown in Fig. 1.2. 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.

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.

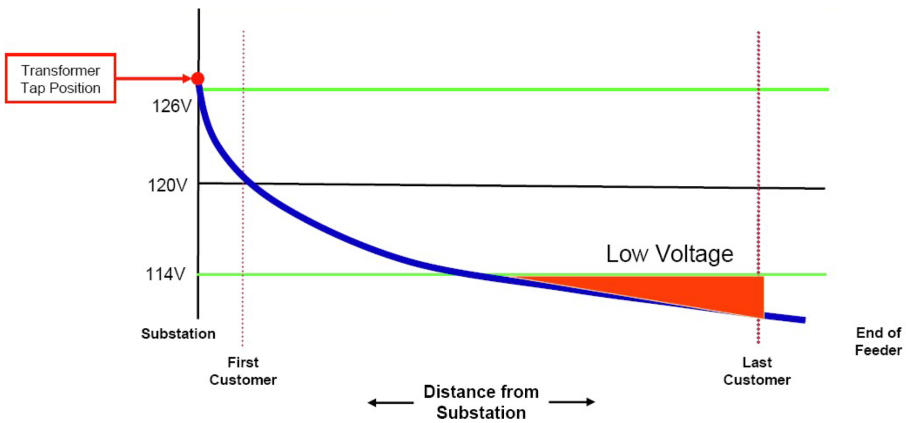

Fig. 1.1 Without Vol/Var Control under heavy load conditions

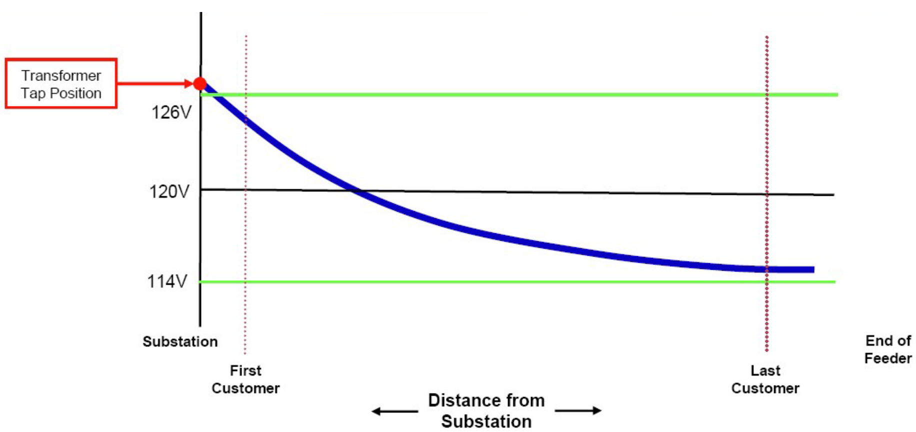

Fig. 1.2 After raising the source voltage under heavy load conditions

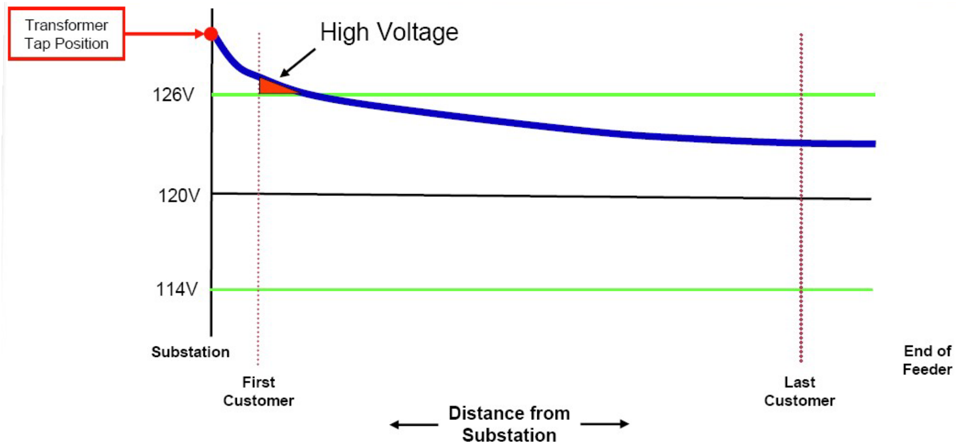

Fig. 1.3 Without VVC under light load conditions after raising the source voltage

1) Voltage Regulators

Feeder VRs [2] are used extensively to regulate the voltage at each feeder separately to maintain a reasonable constant voltage at the point of utilization. They are either induction type or step type. Step type VRs can be either station type or distribution type. Station type VR can be single or three-phase, and can be used in substations for bus voltage regulation or individual feeder voltage regulation. A distribution type VR can only be single-phase and used pole-mounted out on overhead primary feeders. A step type VR is an autotransformer with many taps in the series winding. Most voltage regulators are designed to correct the line voltage from 10% boost to 10% buck in 32 steps, with a 0.625% voltage change per step.
In addition to its autotransformer component, a step-type regulator also has two other major components, the tap-changing mechanism and the control mechanism. Each VR ordinarily is equipped with the necessary controls and accessories so that the taps are changed automatically under load by a tap changer which responds to a voltage-sensing control to

maintain a predetermined output voltage. By receiving its inputs from potential and current transformers, the control mechanism provides control of voltage level and bandwidth (BW). VRs located in the substation or on a feeder are used to keep the voltage constant at a fictitious regulation or regulating point (RP) without regard to the magnitude or power factor of the load. The RP is usually selected to be somewhere between the VR and the end of the feeder. VR uses local measurements (current and voltage) to adjust the voltage at its terminals by varying its taps. VR is controlled by a Voltage-regulating relay (VRR) and has two control options. The first one is to regulate the voltage at its terminals. The second option is to regulate a remote point down the feeder. This is achieved through a “line drop compensation” scheme, as illustrated in Fig. 1.4, which involves estimating voltage at the remote target point by using the current measurement. As illustrated in Fig. 1.5, this relay has the following three basic settings that control tap changes:

- Set voltage (SV): It is the desired output of the regulator. It is also called the set point or band-center.
- Bandwidth (BW): VR controls monitor the difference between the measured and the set voltages. Only when the difference exceeds one-half of the BW will a tap change start.
- Time-delay (TD): It is the waiting time between the time when the voltage goes out of the band and when the controller initiates the tap change. Longer TDs reduce the number of tap changes. Typical TDs are 10-120sec.

VRR compares the voltage V_{VRR} with SV, if the difference between V_{VRR} and SV exceeds half of the BW, timers start counting. When timer reaches TD, VRR sends a signal to move tap one step up or down.

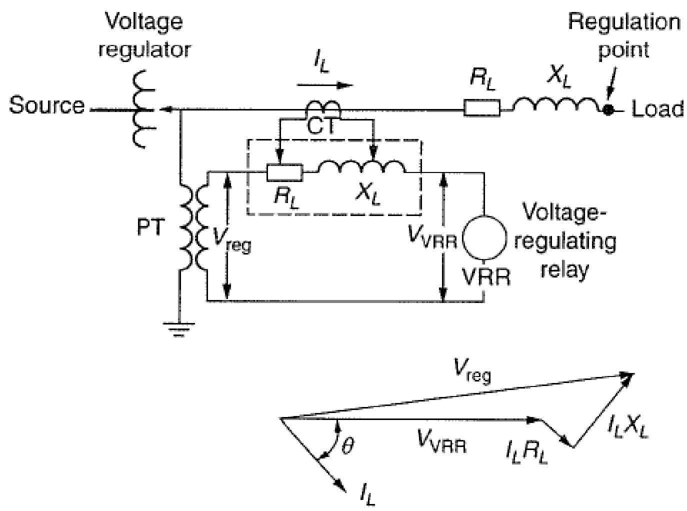

Fig. 1.4 Simple schematic diagram and phasor diagram of the control circuit and line-drop compensator circuit of a step or induction voltage regulator.

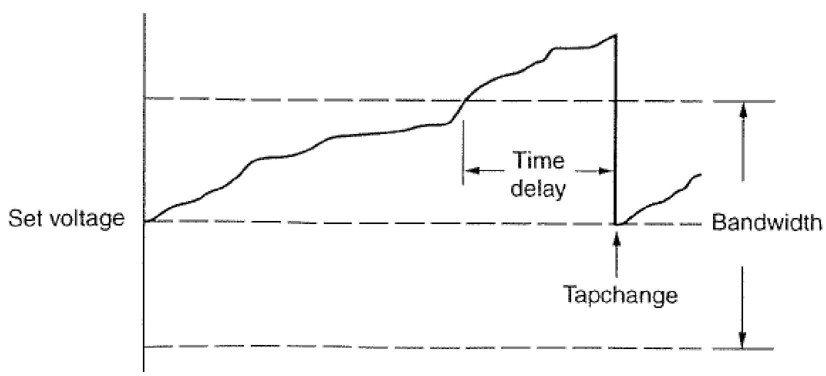

Fig. 1.5 Regulator tap controls based on the set voltage, bandwidth and time-delay

2) Capacitor Banks

In a conventional distribution system, the reactive power of the load could be supplied by the substation or capacitors. Capacitor Banks (CAP) on a distribution feeder are placed in order to correct the power factor of the load [2]. Installed capacitors can either be fixed or switched. Fig. 1.6 illustrates the effects of a fixed capacitor on the voltage profiles of a feeder with uniformly distributed load under heavy and light load conditions. If only fixed capacitors are installed, as shown in Fig 1.6 (c) the utility will experience an excessive leading power factor and a voltage rise on that feeder. Therefore, fixed capacitors are placed to provide minimum voltage boost needed during normal loading and they are sized to meet the minimum reactive load. Thus, some capacitors are installed as switched capacitors so that they can be switched off during light load conditions. The switching process of capacitors can be performed by manual control at substation or by automatic control, including time-switched, voltage-controlled, voltage-time-controlled, voltage-current-controlled and temperature-controlled schemes [2].

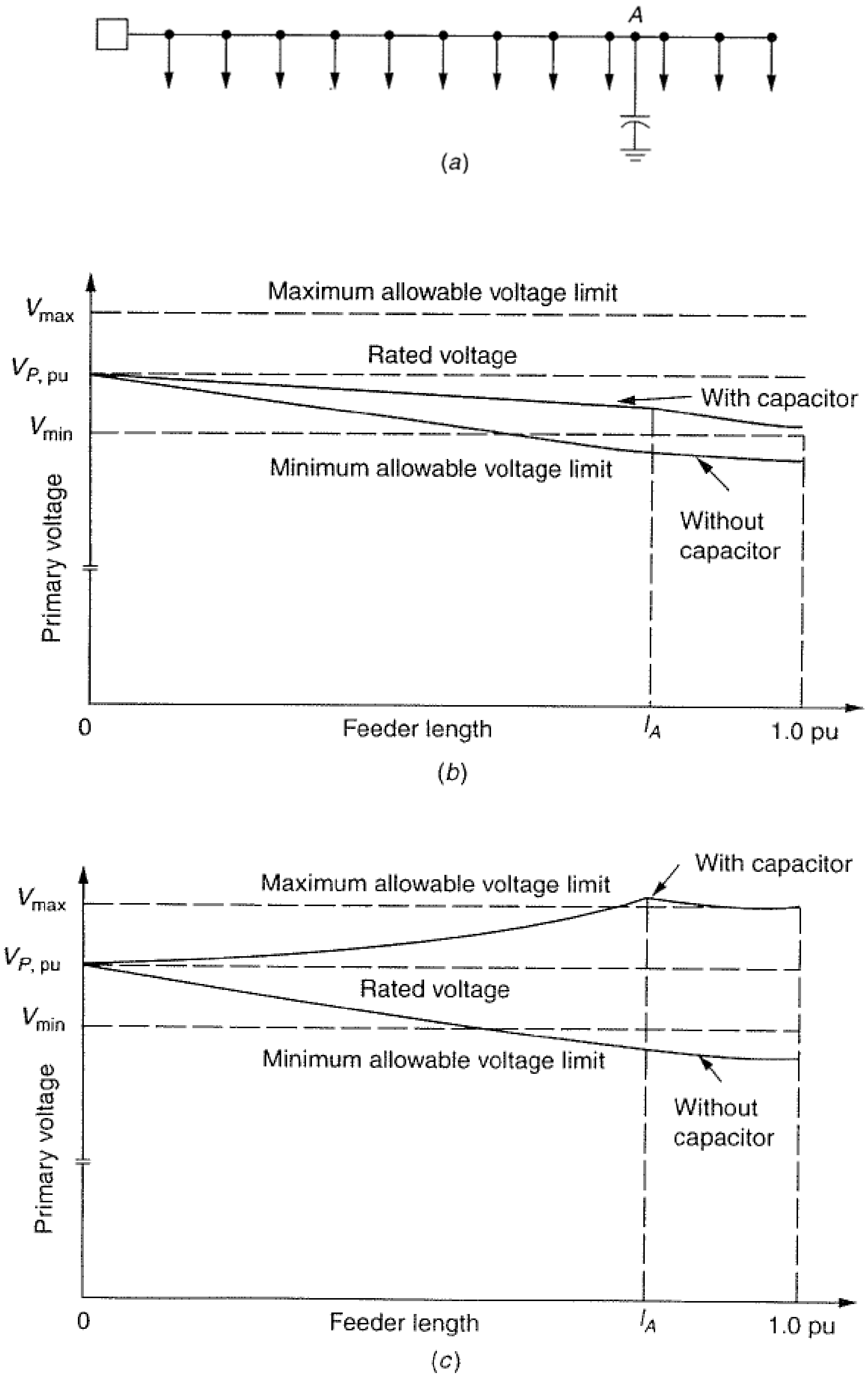

Fig. 1.6 The effects of a fixed capacitor on the voltage profile of: (a) feeder with uniformly distributed load, (b) at heavy load, (c) at light load.

1.2 Volt/Var Control on the FREEDM Systems

The FREEDM system is a new distribution system which uses new power electronics based devices in order to facilitate the challenges associated with integration of DRERs at high penetration levels [3] [4] [5] [6]. Integrating large number of DRERs into a conventional distribution system may cause unexpected operating conditions [7], especially if these DRER has Photovoltaics (PV) with intermittent output during a day. In this study, high penetration of PVs have been considered as the prototype case. From the control point of view, PV can impact the system voltages, power quality, operations control devices and power loss significantly [7]. Hence, new Volt/Var control schemes are needed. One special feature of the FREEDM system is that 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 [8]. Therefore, SST, as a Var compensation device, plays an important role in the Volt/Var control on the FREEDM systems.

1) Solid State Transformer (SST)

The SST is an inverter-based transformer that does more than just a step-down transformer. An SST steps down AC voltage similar to a conventional step-down transformer. However, the traditional 60 Hz transformer is replaced by a high frequency transformer to provide isolation and the step function based on power electronic converters. As illustrated in Fig. 1.7, the SST consists of three stages, an AC/DC rectifier, a dual active bridge converter with a high frequency transformer and a DC/AC inverter. The AC/DC rectifier converts the AC voltage to DC output while maintaining unity power factor at the input side [8]. Therefore, the SST can provide reactive power to compensate load and correct the power factor just as a shunt capacitor. But as compared with a shunt capacitor, it can also provide reactive power with continuous change to guarantee a unity power factor. In the power loss analysis in this thesis, we assume a loss percentage of 3% for an SST and 1% for a traditional distribution transformer.

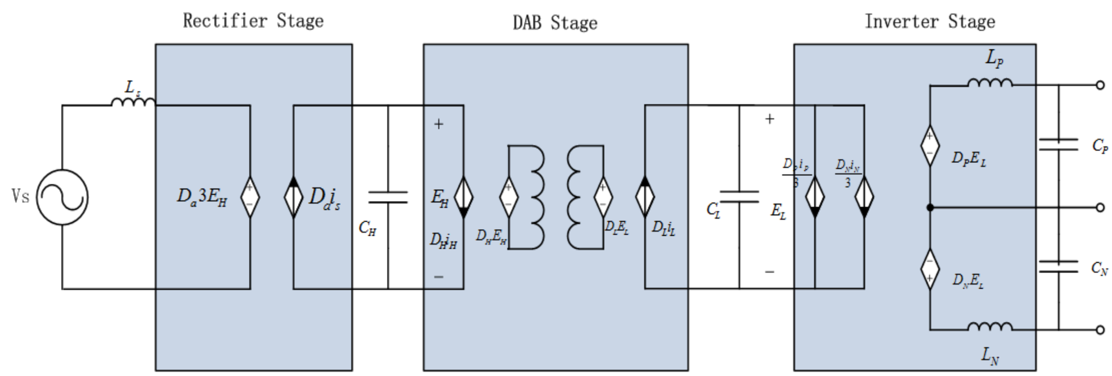

Fig. 1.7 SST Average Model Structure

2) Other VVC devices used in FREEDM systems

Although the FREEDM Volt/Var control features a SST based scheme, to improve the system performance, sometimes conventional Volt/Var control devices are also employed. On the FREEDM Notional Feeder SSTs are used together with the Load Tap Changer (LTC) [2] at substation. On the FREEDM 34 Nodes Test Feeder, SSTs are used together with Voltage Regulators.

1.3 Proposed Approach

The objective of this thesis is to assess the effectiveness of the Volt/Var control schemes applied to the FREEDM systems, the FREEDM Notional Feeder and FREEDM 34 Nodes Test Feeder, and to investigate how to design an effective Volt/Var control scheme for the FREEDM Systems.

The study consists of the following steps:

1. Determine the metrics used to assess the effectiveness of a VVC scheme.
2. Simulate the two prototype feeders with VVC.
3. Assess the VVC schemes applied to these two feeders.
4. Propose alternative VVC schemes for FREEDM Systems.

Chapter 2 Assessment of Volt/Var Control on FREEDM Systems

2.1 Assessment of Volt/Var Control Scheme

The focus in this chapter is on the development of a methodology that can be used to assess the performance of a given Volt/Var control scheme on a given distribution feeder. To achieve this goal, the main performance metrics for assessment have been determined first. Then, a simulation platform has been adopted to determine the effectiveness of a given Volt/Var scheme on a given system. Finally, two prototype systems with different characteristics are used to illustrate the generality of the proposed approach.

2.1.1 Objectives of Volt/Var Control

Power distribution systems may experience both over-voltage and under-voltage violations during daily operations. In a conventional distribution system, the substation is usually the sole source connected to feeders with a radial structure. Therefore current flow through transformer and line impedance causes voltage drop which reduces voltage magnitude from a maximum value nearest to the substation to a minimum value at the end of the circuit. Also, for any fixed location, voltage may experience over-voltage under light load condition and under-voltage under heavy load conditions. Thus, the primary goal of Volt/Var control is to maintain the voltages on a distribution feeder within an appropriate range. For all electric distribution systems, voltage regulation is a fundamental operating requirement.

Voltage regulation brings benefits including reducing power loss and energy loss. And it is always desired to reduce power and energy loss in power distribution. Thus, reducing loss can be used as the secondary goal of Volt/Var control schemes.

2.1.2 Metrics for Assessment of Volt/Var Control

The following metrics are commonly used to evaluate the Volt/Var management [9].

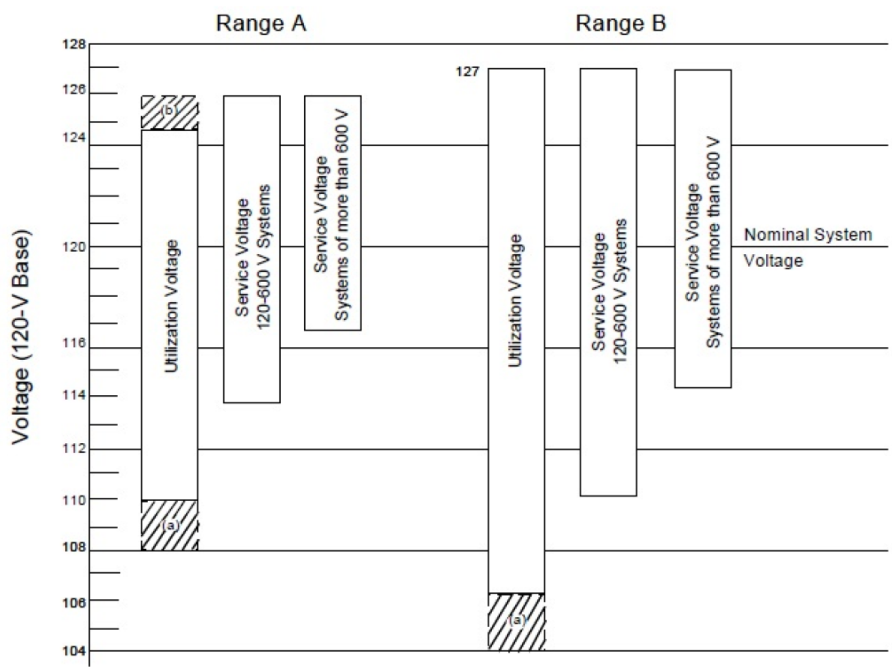

Fig. 2.1 ANSI C84.1 Voltage range for 120V voltage level

1. Voltage Profile

In a distribution system, voltages along the feeder vary due to Kirchhoff's Laws. But for customers, all the equipment used has a desired working voltage range. The ANSI C84.1 standards [10] 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 Fig. 2.1 illustrates, the recommended service voltage range A by ANSI C84.1 standard is $\pm 5\%$ of the nominal value. A good Volt/Var control scheme should successfully make the primary-side voltage profile meet this standard.

2. Power Loss and Energy Loss

As a current goes through a conductor, power loss happens. Since power loss is proportional to the square of the current, for a distribution system which usually has lower voltage level than a transmission system, the issue of power and energy loss is more severe. As mentioned before, reducing power loss and energy loss is a secondary goal of Volt/Var control. Thus, power and energy loss are used as a metric for assessing Vol/Var management as well. In this thesis, the energy loss on both primary and secondary sides is considered.

3. Voltage Regulation

Voltage regulation is a percentage voltage drop of a line with respect to the receiving-end voltage [9] and it is calculated by the following equation:

$$\% Regulaiton = \frac{|V_s| - |V_r|}{|V_r|} \times 100\% .$$

Small %Regulation usually means less voltage drop or rise along the feeders. Thus, a low %Regulation is a necessity for a well-regulated distribution system. For each phase, the voltage regulation of the system is the maximum value of the %Regulation at all feeder ends. We name the maximum %Regulation among three phases as the Voltage Regulation Index (VRI). The formula for VRI is as follows:

$$VRI = Max\left(\% Regulation_{iy} \right)$$

where i is the node number of the end nodes, and y represents phase A, B, C.

4. Voltage Unbalance (VU)

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 [9]. This value is calculated using the following equation:

$$VU_i = Max\left(V_{iy}\right) - Min(V_{iy})$$

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

We use the maximum of VU among all nodes to represent the worst voltage unbalance of the system. The Voltage Unbalance Index (VUI) is such a metric which is calculated by:

$$VUI = Max\left(VU_i\right)$$

ANCI standards also define a percentage VU [10], shown as in the formula below, to assess the voltage unbalance condition.

$$\%VU = \frac{Maximum\ deviation\ from\ average}{Average\ from\ three\ phase\ voltage} \times 100\%$$

The true definition of voltage unbalance is defined as the ratio of the negative sequence voltage component to the positive sequence voltage component [11]. The percentage voltage unbalance actor (% VUF), or the true definition, is given by

$$\%VUF = \frac{Negative\ sequence\ component}{Positive\ sequence\ component} \times 100\%$$

5. Voltage Variation (VV)

Since Volt/Var control should be able to regulate voltage under different operating conditions, the voltage variation under all possible conditions during a day can be used as a metric to assess the effectiveness. As load conditions and device operation conditions (eg. Voltage Regulator tap change) change during a day, voltage at one node would also vary as shown in Fig. 2.2.

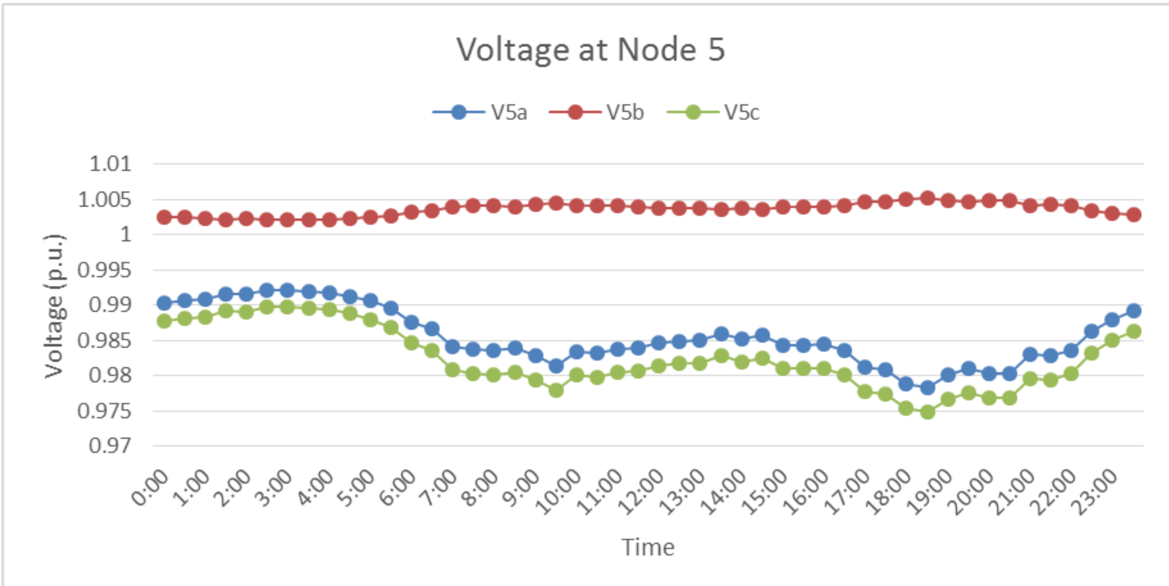

Fig. 2.2 Voltage profile of Node 5 during a day

Voltage Variation (VV) [9] is the maximum voltage change under different operating conditions during a day. It is calculated by the equation:

$$VV_i = Max(V_{ix}) - Min(V_{ix})$$

where i is the node number and V_{ix} is the node voltage under operating condition x.

The worst voltage variation in the system can be represented by the maximum VV for all nodes and all phases. Voltage Variation Index (VVI) is calculated by:

$$VVI = Max(VVI_y)$$

where $VVI_y = Max(VV_i)$ and y represents phase A, B, C. In this thesis, voltage variations on both primary-side and secondary side are considered.

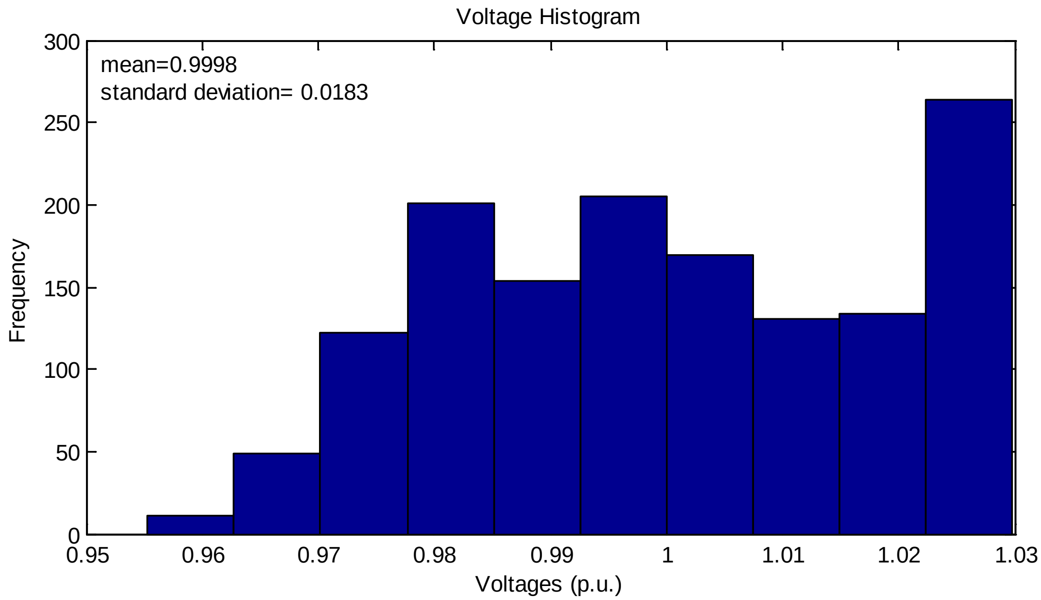

Fig. 2.3 Histogram of voltages on the primary-side of the Notional feeder under conventional VVC (zero PV)

Another common method to evaluate the voltage variation is to draw the histogram of all the voltages under all operating conditions on the feeder, shown as in Fig. 2.3. The highest bar in the 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.

6. Voltage Regulator Tap Change (VRTC) and Number of Operations (#Operations)

Any device has its lifespan. A voltage regulator with less tap changes during its operations would have longer lifetime, making the Volt/Var control scheme more economical. Such control cost can be represented by Voltage Regulator Tap Change (VRTC). VRTC is the maximum change of tap positon in one phase of a voltage regulator, which is calculated by:

$$VRTC_y = Max\left(Tap_{iy}\right) - Min\left(Tap_{iy}\right)$$

where Tap is the tap position of a voltage regulator, i represents the operation condition, and y represents phase A, B and C. For one voltage regulator, the maximum tap change is represented by the maximum VRTC among three phases. The Voltage Regulator Tap Change Index (VRTCI) is such a metric, which is calculated by:

$$VRTCI = Max\left(VRTC_y\right)$$

where y represents phase A, B and C.

Another way to assess the usage of a VR is to count the total number of operations, which is also the count of move-up and move-down of the tap. An example is seen in Tab. 2.1. The Number of Operations Index (#Op Index) is such a metric, which is calculated by:

$$\#Op\ Index = Max\left(\#Operations_y\right)$$

where y represents phase A, B and C.

Tab. 2.1 An example of the number of operations

Time	00:00	00:30	01:00	01:30	02:00	02:30	…
Tap Position	2	2	3	5	3	3	
#Operations	1	1	2	3	4	4	

2.2 Simulation Platform

Since all the metrics mentioned above can be calculated based on the steady-state currents and voltages at each node, both time-domain simulation and phasor-domain simulation can provide the currents and voltages needed to assess the effectiveness of Volt/Var control scheme applied.

1. Time-domain simulation

In time-domain simulation, a power system is represented by differential and algebraic equations, and both transient and static currents and voltages can be obtained.

PSCAD can be used as the time-domain simulation platform to assess the Volt/Var control scheme on the two prototype feeders, FREEDM notional feeder and FREEDM IEEE 34 nodes system. Circuits of these two feeders can be modeled in detail. Lines can be represented by equivalent circuits with mutual inductance terms. Loads can be represent on a phase basis as constant impedances, since the fixed load model in PSCAD has certain dynamic behavior. Volt/Var control scheme can also be simulated by connecting the models of Volt/Var control devices (eg. SSTs, voltage regulator, capacitor, etc.) to the feeder model.

2. Phasor-domain simulation

In phasor-domain simulation, steady-state currents and voltages are presented by phasors with both amplitude and phase. The phasor-domain simulation can reduce the mathematical model of the power system to only algebraic equations, which greatly reduces the cost of calculation compared with time-domain simulation if we only care about the steady-states of the system.

In MATLAB, a distribution power flow (DPF) based program is used to simulate the system response, the response of the feeder and the devices on it to a given event (e.g. a load change, a voltage regulator movement, etc.). The DPF program here is a three-phase power flow analysis and based on a backward and forward sweep approach [12]. In DPF, the circuits can be modeled the same way as in PSCAD simulation. Different from the constant impedance load model in PSCAD, all loads in this phasor-domain simulation are modeled as constant-power model. The flow chart of a phasor domain simulation is shown in Fig. 2.4. As Volt/Var controllers respond to different loading and PV generation condition, the system goes to a new operating condition, both loading condition and states of devices, e.g. the tap positions of voltage regulators. By updating the operating condition first and then running DPF, the response of the feeder (steady-state currents and voltages) under the new operating condition is obtained. Then the metrics to assess Volt/Var control can be calculated based on the simulation results.

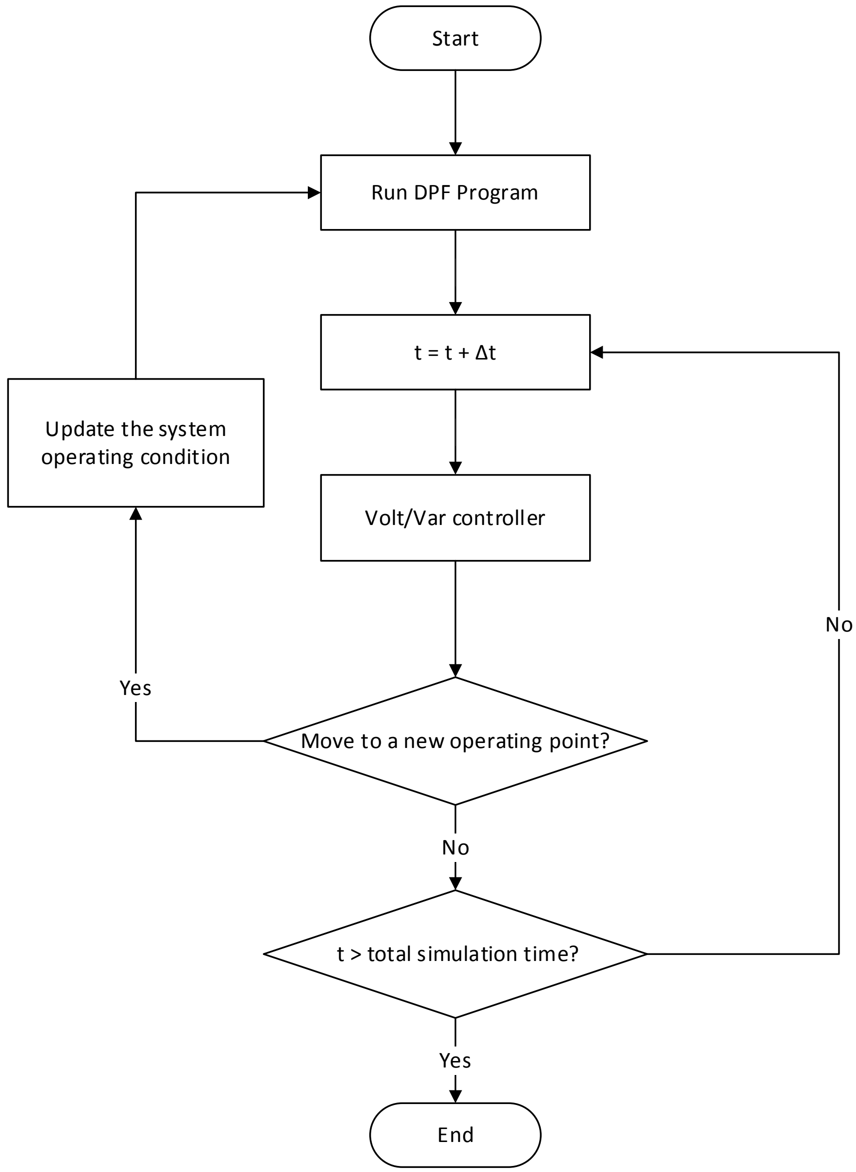

Fig. 2.4 Power Flow simulation with Volt/Var control logic

2.2.1 Prototype Feeders

1. FREEDM Notional Feeder

The FREEDM Residential Notional System is also developed based on an actual residential distribution circuit in the Progress Energy's service area. The original system has two 15 kV class feeders that operate at 12.47 kV nominal voltage. Each feeder has about 200 line segments. To facilitate the development of a notional system that can be simulated easily without the loss of detail, a compromise has been made by lumping the loads connected to sections of the feeders. As shown in Fig. 2.5, there is no voltage regulator or shunt capacitor on the system. In order to investigate the effectiveness of FREEDM VVC scheme, simulation is also conducted for PV cases. In those cases, each customer has a roof-top photovoltaic system. It is assumed that each PV system can generate up to maximum load of the residential unit. The FREEDM Residential Notional System utilizes SSTs to accommodate PV systems.

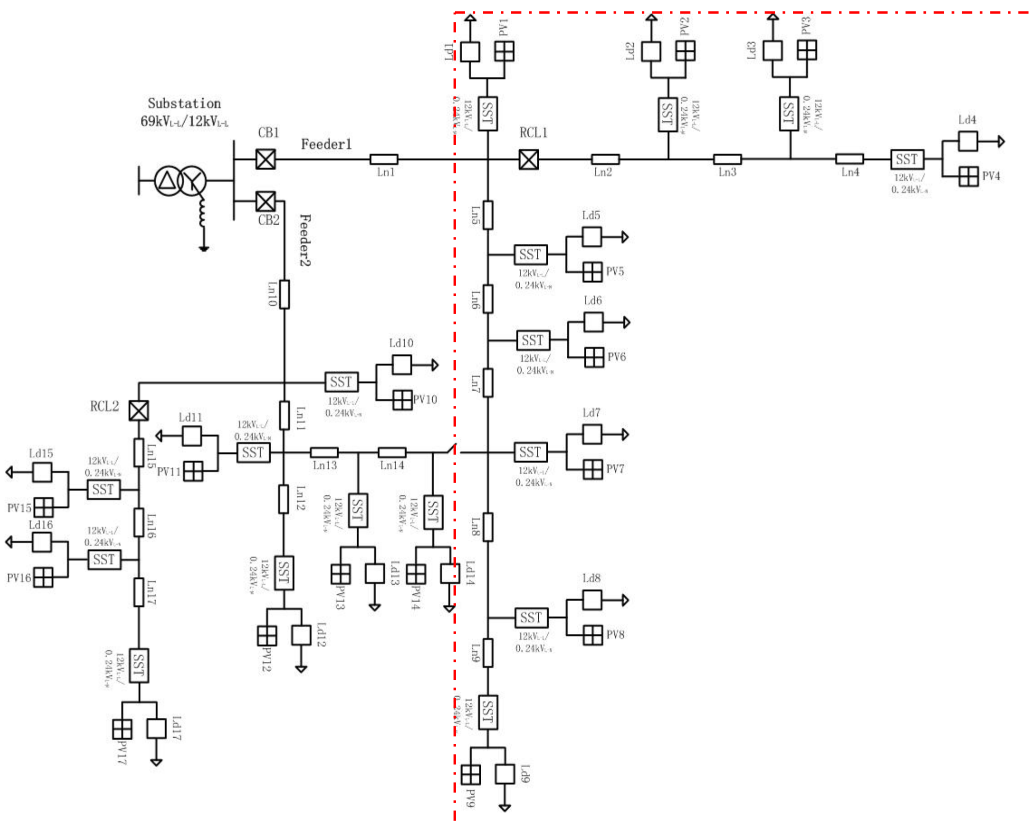

Fig. 2.5 Simple diagram of Notional Feeder

2. FREEDM IEEE 34 Nodes Test Feeder

IEEE 34 node test feeder is an actual feeder located in Arizona with nominal voltage of 24.9 kV. It is characterized by its long line length and heavy peak load. An in-line distribution transformer, between node 832 and 888, steps down the voltage to 4.16 kV for a short section of the feeder. Besides, there are two VRs connected between node 814-850 and node 852-832, and two capacitor banks connected at node 844 and 848 separately. These Var compensation and voltage regulation devices are needed to maintain a good voltage profile. IEEE 34 system is an unbalanced system with both "spot" and "distributed" loads. However, since single phase conventional transformers or SSTs are going to be used to connect loads and PVs to the primary feeder, all the loads are modified to be Y connection, shown as in Fig. 2.6. Different with the IEEE 34 system, the FREEDM IEEE 34 system uses SSTs to accommodate loads and PVs. It also removes the shunt capacitors, but voltage regulators are still kept in the system. There are five PVs connected to Node 822, 836, 844, 890 and 860, shown as in Fig. 2.7

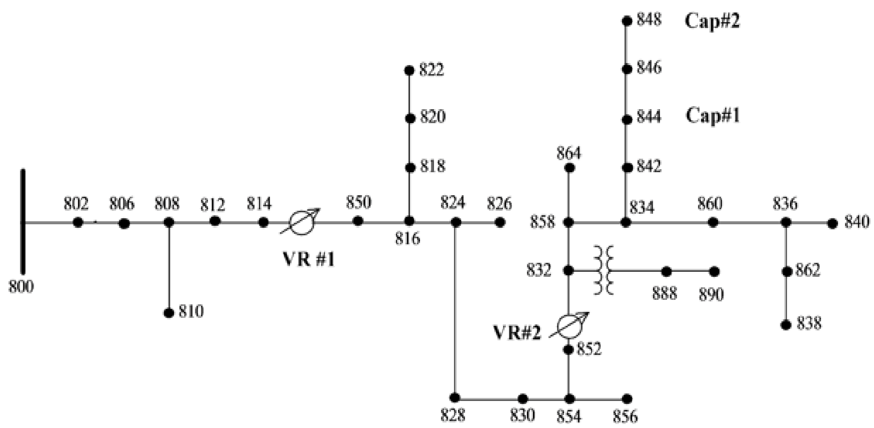

Fig. 2.6 Simple diagram of the IEEE 34 Nodes Test Feeder

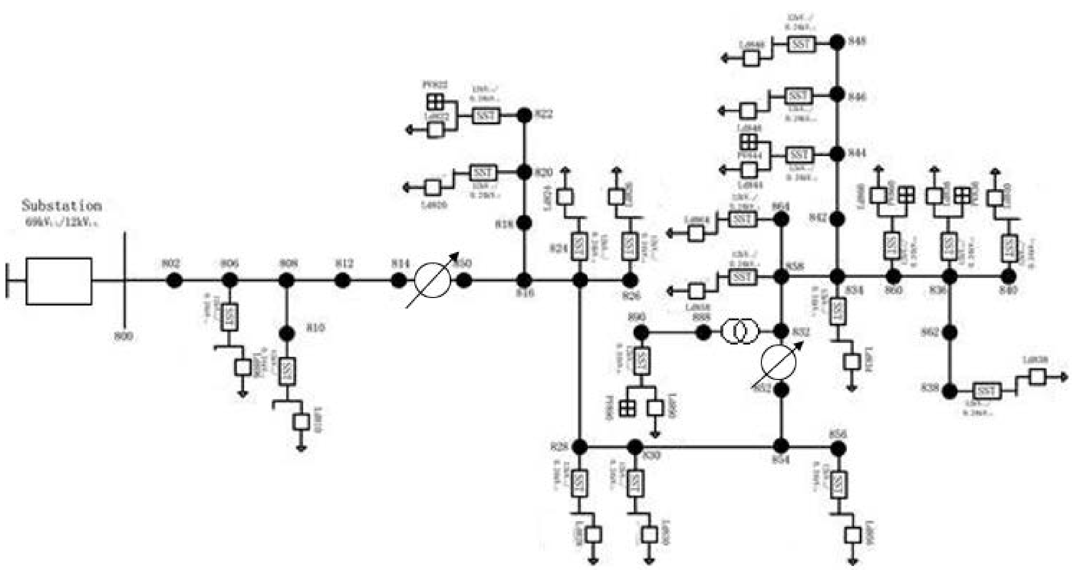

Fig. 2.7 Simple diagram of the FREEDM IEEE 34 Nodes Test Feeder

2.2.2 Component Models

1. Feeder line

Each line section is represented by a 3×3 impedance matrix, in which the non-zero off-diagonal elements indicate that the coupling effect between phases is taken into consideration.

For the FREEDM Notional feeder, since the original data of the line sections are all sequence based value as shown in the table before, all lines are using the sequence model [13].

For the FREEDM IEEE 34 feeder, since the original data of the line sections are complete model based, to guarantee the accuracy of the simulation complete models are used.

2. Load Tap Changer (LTC)

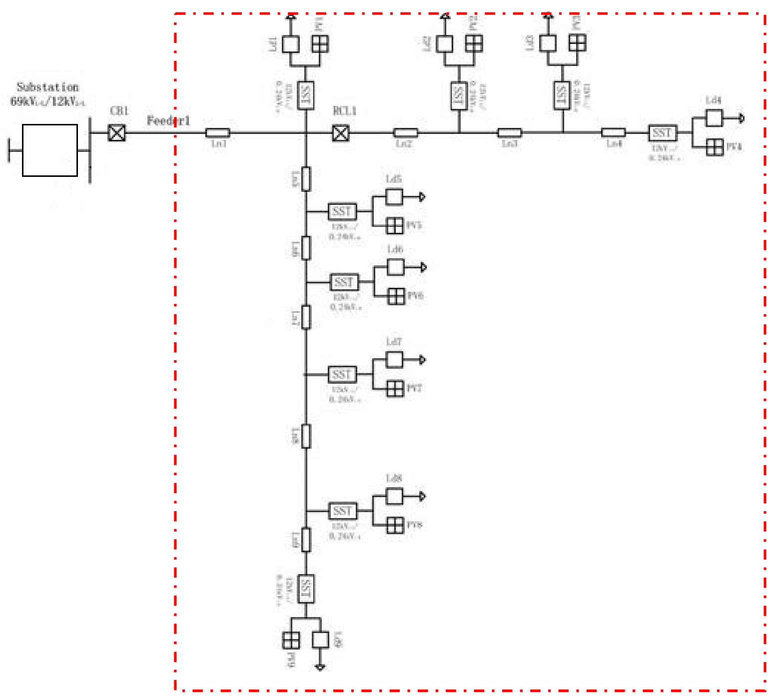

Fig. 2.8 Simple diagram of the simplified Notional Feeder

Since we assume the LTC at substation can successfully regulate the substation voltage to an ideal value, the impedance of the substation transformer is not considered in the simulation. Instead, we treat the node downstream next to substation as a slack bus with a constant voltage to model the regulation effect of LTC at the substation. For FREEDM Notional feeder system, as indicated in the Fig 1.13, there are two main feeders connected to the substation. Since the substation node is assumed to be a slack bus, the power flow calculation results of these two feeders are independent. Therefore, we can perform simulation on these two feeders separately, i.e. we can treat them as two independent systems. Here, only simulation of feeder 1 is done. A brief diagram of feeder 1 is shown in Fig. 2.8. For FREEDM IEEE 34 nodes system, since there is only one main feeder, all nodes are kept.

3. Voltage Regulator

The voltage regulator is modeled as a tap-changing transformer with line-drop compensator (LDC) integrated. The LDC is illustrated in Fig. 1.4.

The voltage parameters are set according to the original documents, seen in Tab. 2.2.

Tab. 2.2 VRs setting in FREEDM 34 Nodes system

	Location	PT Ratio	CT Ratio	Bandwidth	Voltage Level	R-setting	X-setting
VR1	814-850	120	100	2	122	2.7	1.6
VR2	852-832	120	100	2	124	2.5	1.5

A DPF program with VR controller logic can be seen in Fig. 2.9 (a). The detailed input and output of DPF and VR controller can be seen in Fig. 2.9 (b).

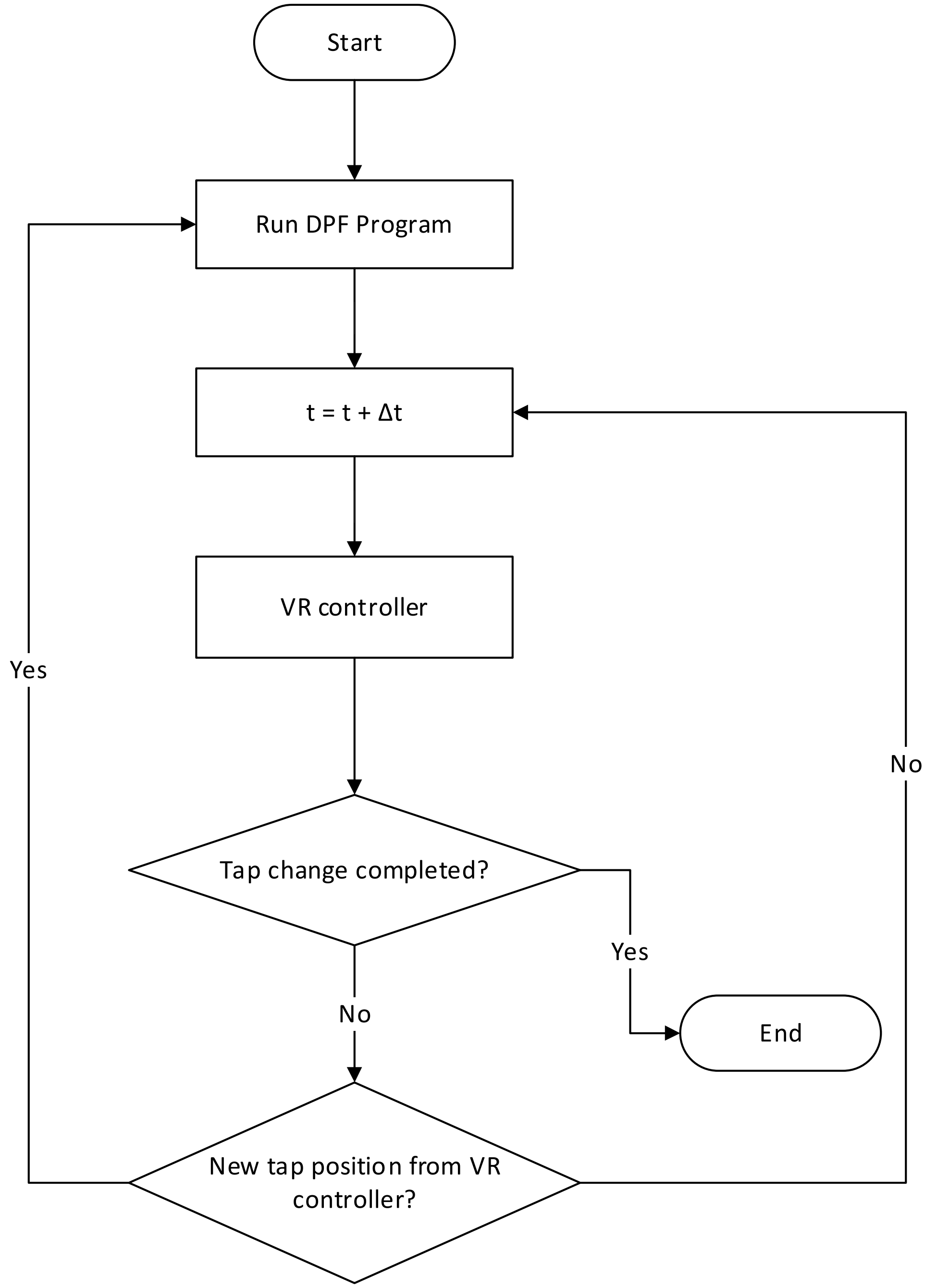

Fig. 2.9 (a) A DPF program with VR controller logic

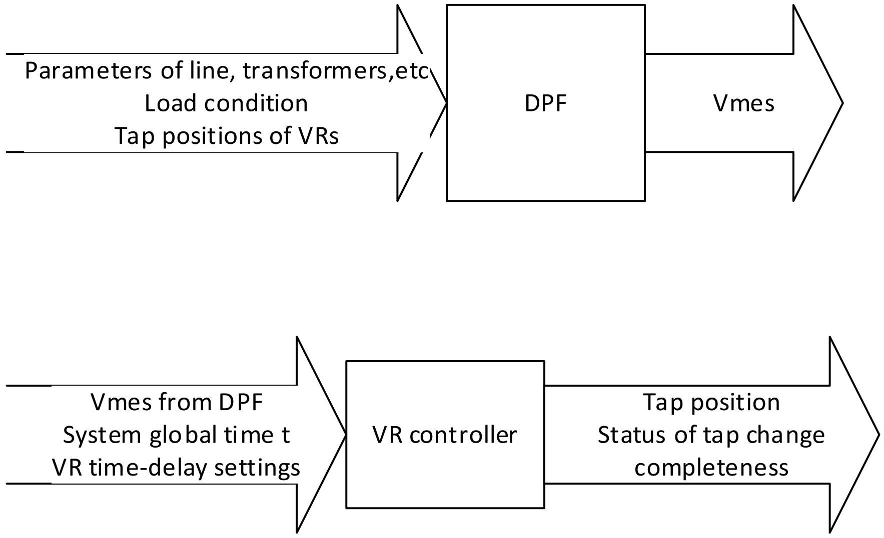

Fig. 2.9 (b) Input and output of DPF and VR controller

4. Loads

All the loads are modeled as constant PQ nodes, without considering the distribution transformers. Therefore all the voltage profiles are primary voltages.

In the 24-hour simulation of FREEDM Notional Feeder, the load at each node is a conforming load, i.e. load at each node is a fixed percentage of the total system load. The total load characteristics is seen as follows. The system load variation during a day is shown in Fig. 2.10. However, the load profile of the FREEDM IEEE 34 nodes system is non-conforming.

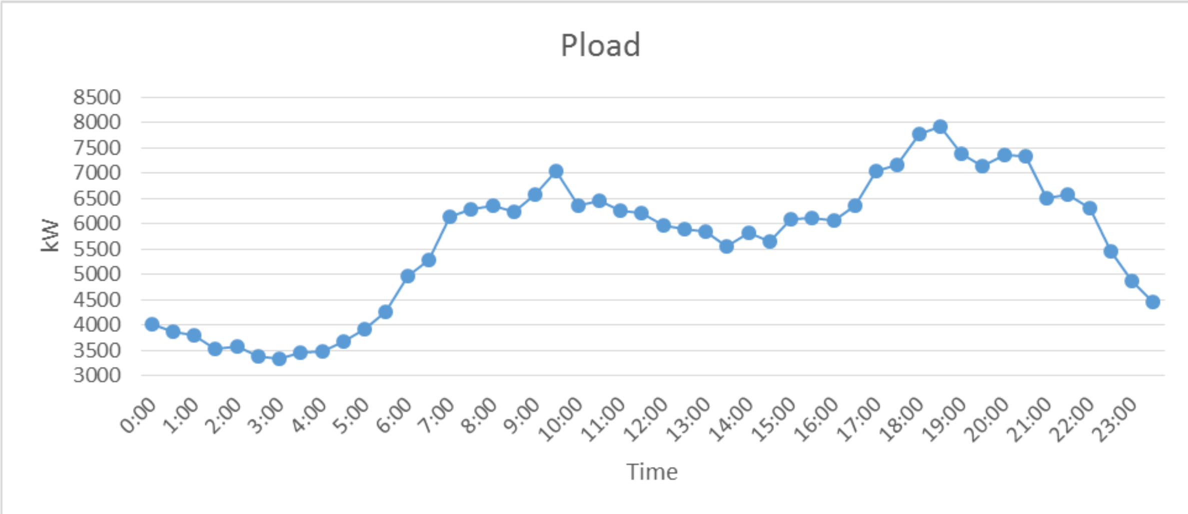

Fig. 2.10 Load Variation of the FREEDM Notional Feeder

5. PV

For PVs, only the real and reactive power output is considered, so PVs are also modeled as constant PQ nodes without considering the inverters, etc. Thus, the effect of PV can by modeled by subtracting PV output from the load.

On the FREEDM notional feeder, each residential customer has a rooftop PV system installed, and each PV system can generate up to a maximum load of the residential unit. Therefore, the total PV output at each node has a maximum generation which is the same as its peak load value. In the 24-hour simulation, all PVs in this thesis are all modeled as constant PQ nodes with a conforming character consistent with solar irradiation during a day. The PV and load profile during a day is shown in Fig. 2.11.

On the FREEDM IEEE 34 nodes feeder, there are five PV systems connected, the daily profile of PVs are generated in the same way.

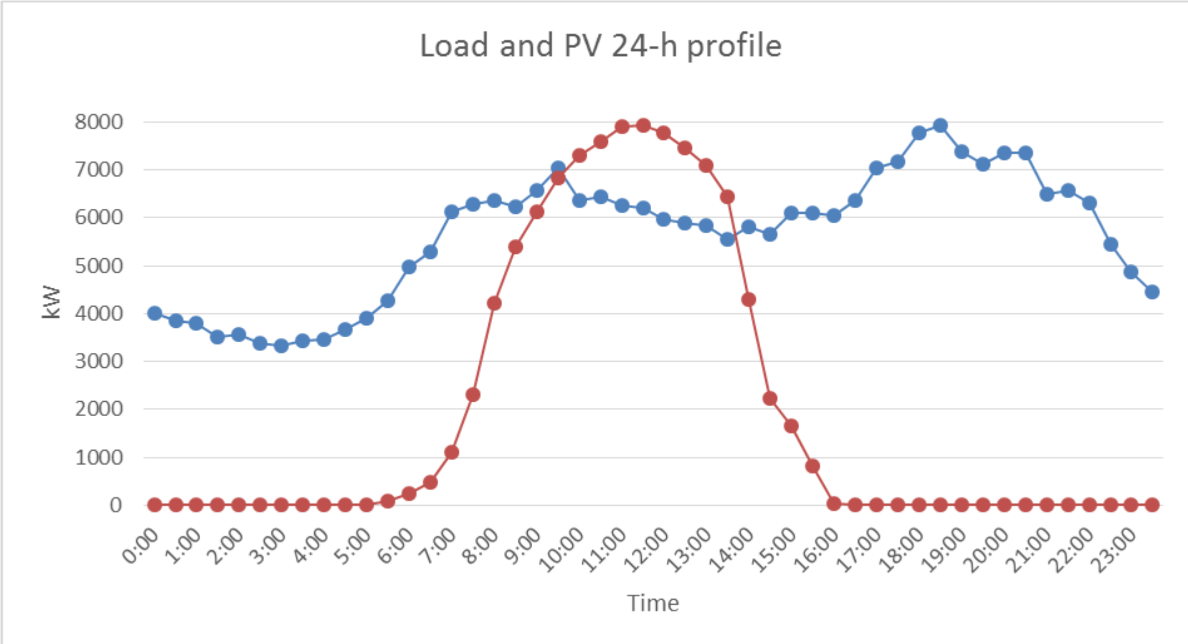

Fig. 2.11 PV and load variation of the FREEDM Notional Feeder

6. SST

Different from a conventional distribution transformer, a solid state transformer (SST) is a converter based transformer, which has the features of load voltage regulation, voltage sag compensation, fault isolation, harmonic isolation and DC output, etc [8]. Besides these, another main feature of the SST is that it can automatically work under unity power factor without receiving any control commands. In the FREEDM notional feeder all distribution transformers are SSTs. Since all the reactive load required on the secondary side will be provided by its corresponding SST, the equivalent reactive load at each node is zero, ie $Q_{inj} = 0$. Thus, with the change of load and PV output condition, the reactive power generated by SSTs can always guarantee a unity power factor at each node. This is the FREEDM default Volt/Var control scheme. In this thesis, the SST model is simplified as an ideal transformer with adjustable reactive power source. Therefore, the load, PV and SST at one node can be lumped together as a PQ node with zero reactive power.

7. Shunt Capacitor

All shunt capacitors are fixed capacitors with a constant reactance based on the rating.

2.3 Assessment of Volt/Var Control on FREEDM Notional Feeder

The simulation platform and two test cases have been used to demonstrate the assessment process. Also, a base case in which conventional VVC scheme is used to compare with FREEDM Notional Feeder. The challenge in the assessment is covering all the possible operating conditions. In this study a set of cases have been identified to address this challenge and facilitate the calculation of performance metrics.

2.3.1 Case Studies

No PV penetration

Case 1:

In this case, the conventional control scheme is adopted. There are two shunt capacitors in the system with details shown as in Tab. 2.3, also a LTC at substation to keep voltage at Node #0 at 1.025 p.u. when the total load exceeds 5MW, otherwise at 1.0 p.u.. No feeder voltage regulator or SST is applied in this conventional scheme. Only peak load condition with no PV penetration is simulated in this case. Detailed peak load data can be seen in the appendices.

Tab. 2.3 Capacitor Ratings in IEEE 34 Nodes system

Location	Capacity per phase (kVar)
Node #5	400
Node #8	200

Case 2:

In this case, the FREEDM default control scheme is adopted. The reactive power injection at each SST, Q_{inj}, is set as zero. Both capacitors are removed from the system. Voltage at the substation is regulated at 1.0 p.u.. The load and PV condition is the same as in Case 1.

Simulation results and comparison between Case 1 and Case 2.

1. Voltage Profile

For the conventional control case the maximum voltage magnitude is 1.03 p.u. and the minimum is 0.96p.u.. Therefore, the conventional VVC scheme is able to obtain the primary goal of keeping voltages within the range of 0.95-1.05 p.u.. The total power loss of the system is less than 2%, which is not a high value. In the default control case, the maximum voltage is 1.01 p.u. and the minimum voltage is 0.96 p.u., which indicates that the FREEDM Notional Feeder successfully solves the issue of voltage violation as well. Fig. 2.12 shows the three-phase voltages along the feeders under the peak load condition.

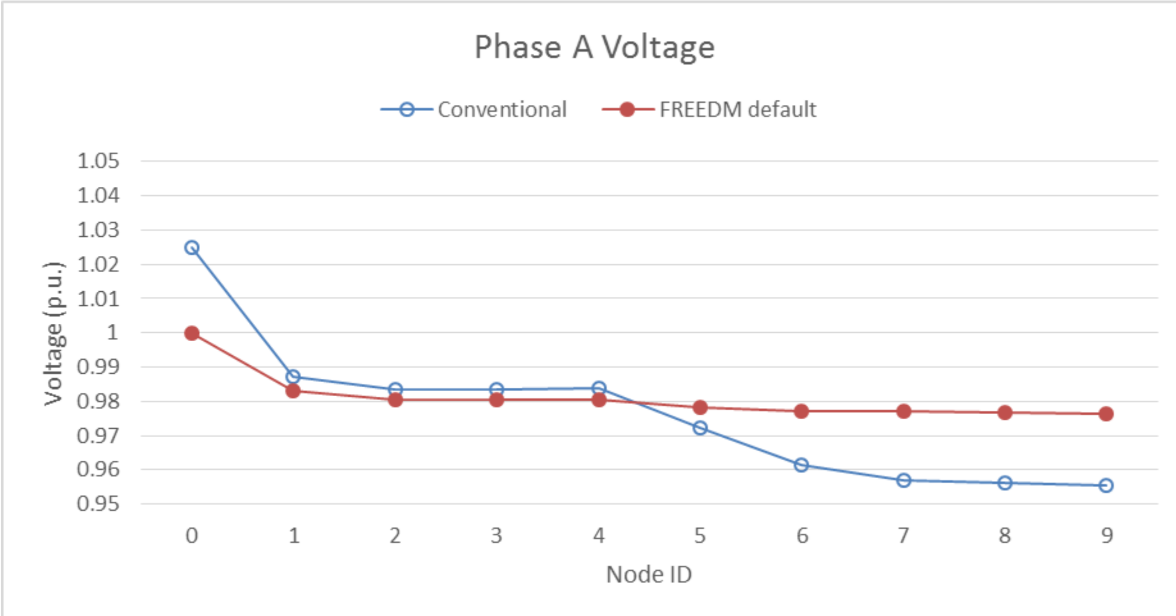

Fig. 2.12 (a)

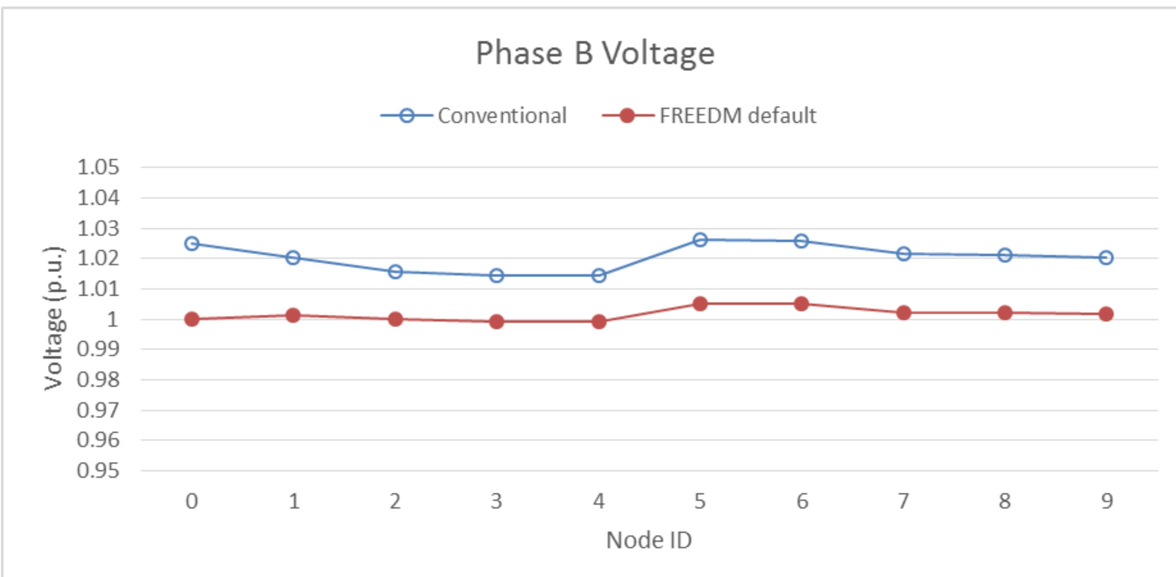

Fig. 2.12 (b)

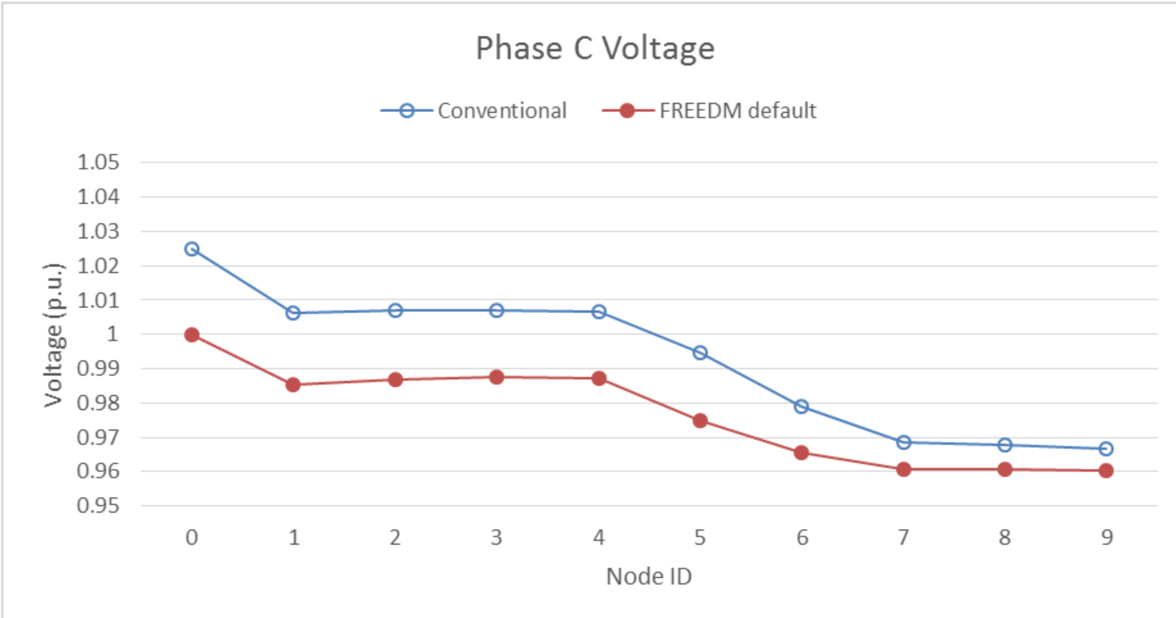

Fig. 2.12 (c)

Fig. 2.12 Voltage profile under the peak load condition

2. Power Loss

The simulation results with respect to power are shown in the table below.

Tab. 2.4 Simulation results with respect to power under peak load condition with no PV penetration

	Conventional Control Scheme	FREEDM Default Control Scheme
Psub (kW)	8065.524	8049.575
Qsub (kW)	2992.7440	523.6503
Pload (kW)	7922.87	7922.87
Qload (kW)	4095.11	4095.11
Ploss (kW)	142.6544	126.7054
Loss percentage	1.80%	1.60%

From the simulation results above, the power loss percentage in FREEDM default control (the proportion of power loss in total load) is 1.5992%, less than 1.8005% in conventional case. The FREEDM VVC on Notional Feeder can reduce more power loss.

3. Voltage Regulation

The FREEDM Notional feeder has two feeder ends, Node 4 and Node 9. The voltage regulation at these two ends are shown in the figures below. The voltage regulation of the system is the maximum value of the % regulation at all feeder ends. The three phase system voltage regulation is seen in Fig. 2.13. These figures indicate that the FREEDM default control scheme has less %Regulation than the conventional control scheme. The VRI under FREEDM control is 4.14% in Phase C, while under conventional control the value is 7.29% in Phase A. The FREEDM default control scheme reduce VRI by 43.27%.

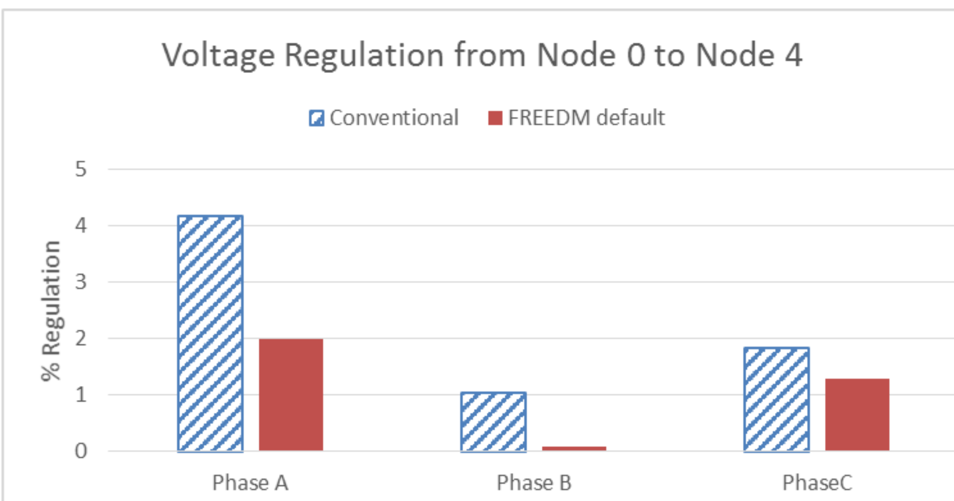

Fig 2.13 (a)

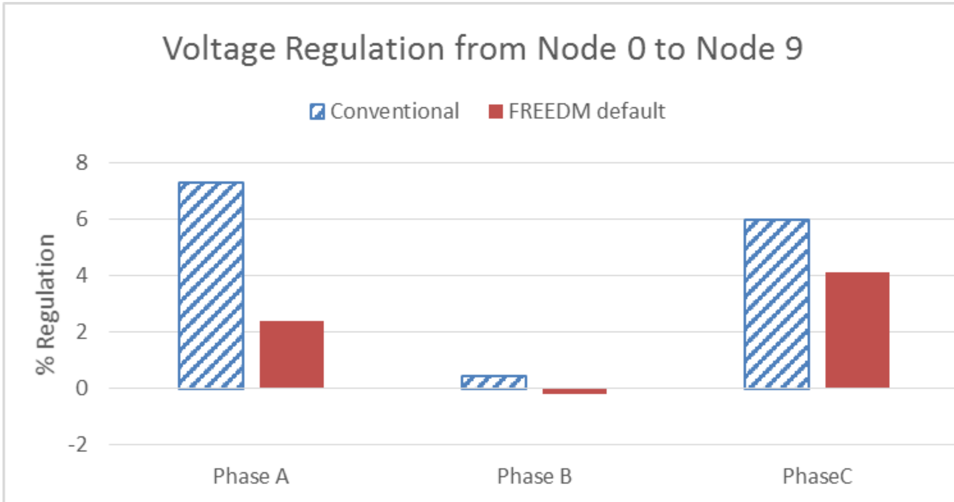

Fig. 2.13 (b)

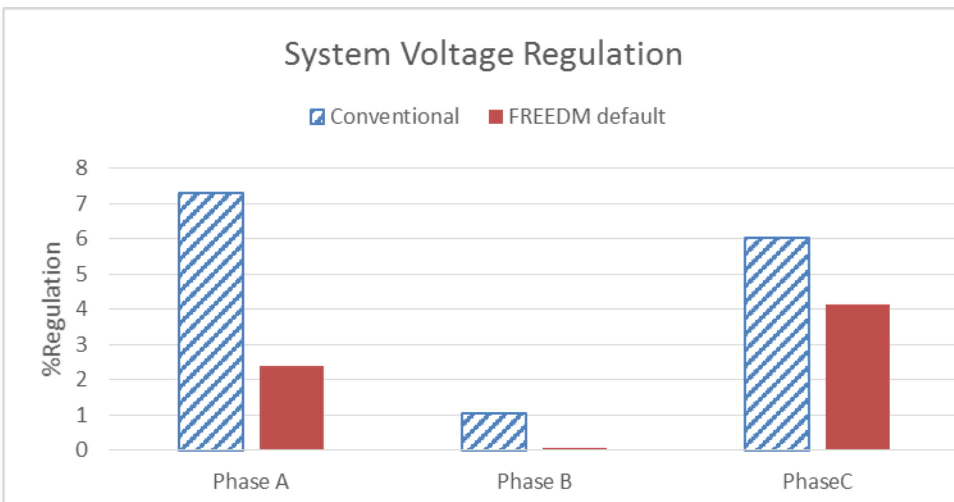

Fig. 2.13 (c)

Fig. 2.13 Voltage regulation under peak load condition

4. Voltage Unbalance

Since the load on the Notional Feeder is highly unbalanced, we need to investigate how the FREEDM VVC influences the voltage unbalance at each node.

From the simulation result shown in Fig 2.14, we can see that for each node VU in the system using the FREEDM default VVC is always less than that using conventional VVC. The VUI under conventional control is 0.065, while under FREEDM default control is 0.042. The FREEDM default control reduces the system voltage unbalance by 36.19%. Therefore, FREEDM VVC mitigates the issue of voltage unbalance.

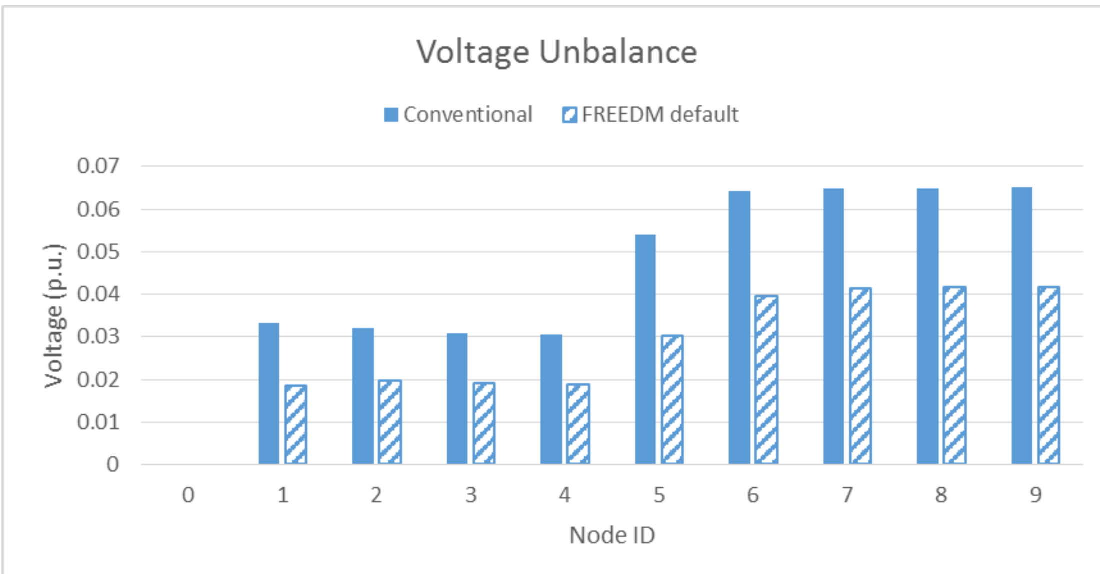

Fig. 2.14 Voltage Unbalance under peak load condition with no PV penetration

***Case 3*：**

In this case, a 24-hour simulation is conducted to explore if the FREEDM VVC is still effective when load varies during a day. Both the FREEDM VVC and the conventional VVC are simulated to compare the effectiveness of the two control schemes.

The 24-hour simulation results are as follows:

1. Voltage Profile

Under FREEDM default control, the minimum voltage is 0.9602 pu at Node 9 in phase C at 18:30. The maximum voltage is 1.0053 p.u. at Node 5 in phase B at 18:30 as well. The FREEDM VVC scheme successfully keep the voltages within the range 0.95-1.05 p.u. in spite of the load variation during a day. 24-hour voltage profiles at Node 9 and 5 are shown in Fig. 2.15.

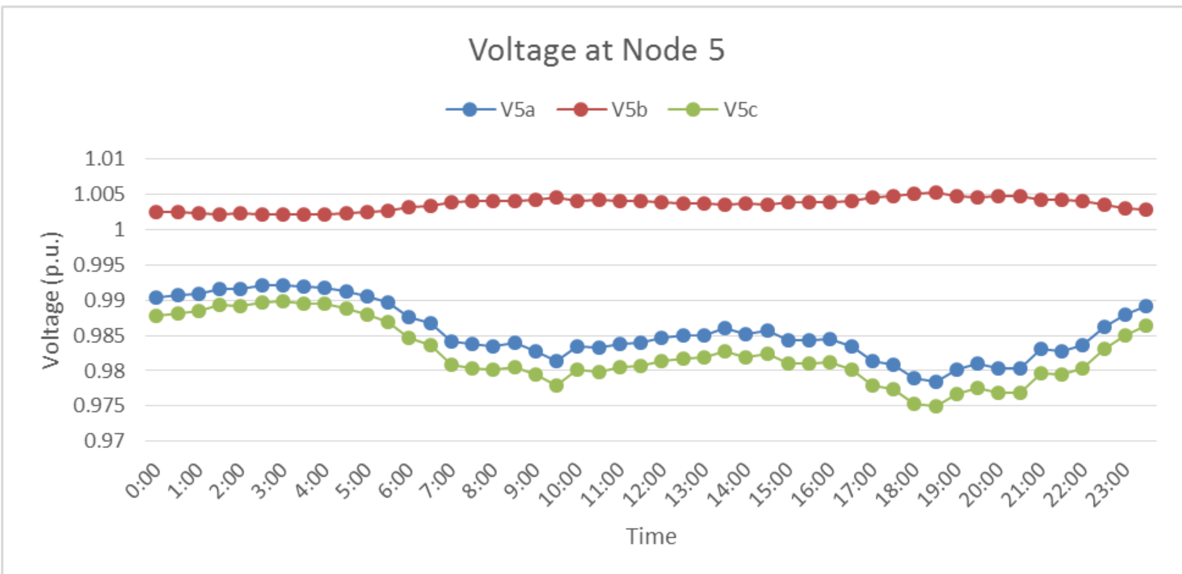

Fig. 2.15 (a)

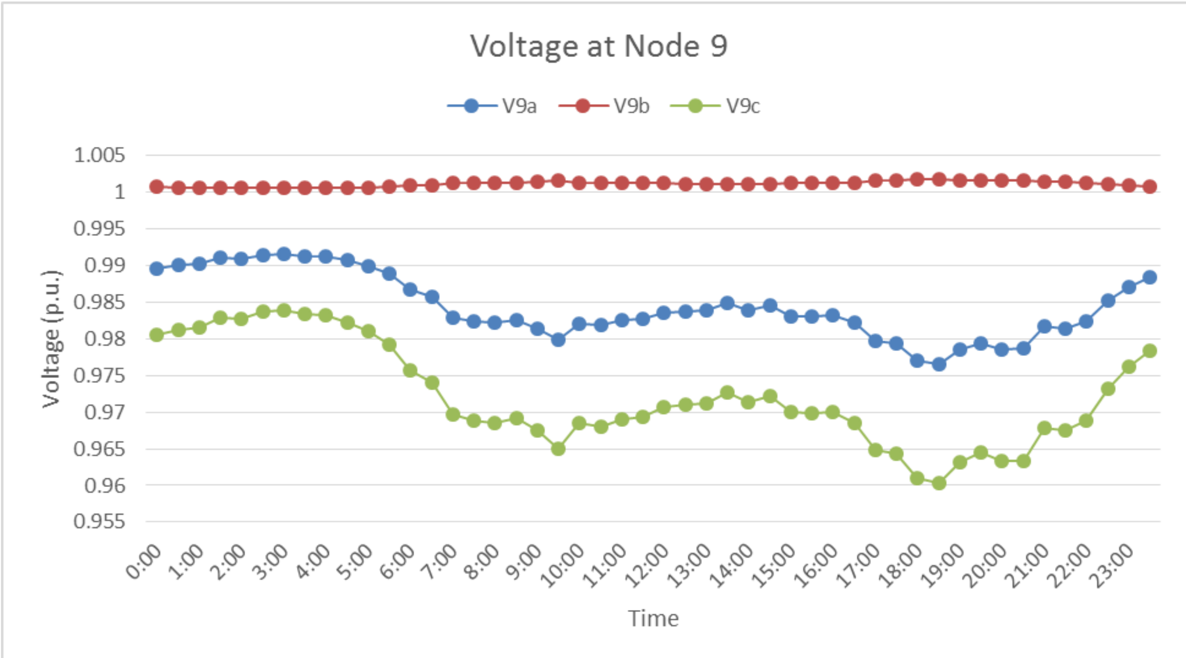

Fig. 2.15 (b)

Fig. 2.15 24-hour voltage profile at Node 5 and Node 9

2. Power Loss and Energy Loss

Under FREEDM default control, the 24-hour primary-side power loss ranges from 21.91kW at 3:00 to 126.71kW at 18:30, with a loss percentage range of 0.66%-1.60% respectively. Under FREEDM default control the line currents in each phase are lower than those in the conventional case, thus less power loss. Under conventional control the primary-side power loss is always higher during a day, which indicates the FREEDM VVC mitigates the issue of power loss better. From Fig. 2.16, the power loss shows the same pattern as the load condition of the system, which verify that as load goes up power loss increases.

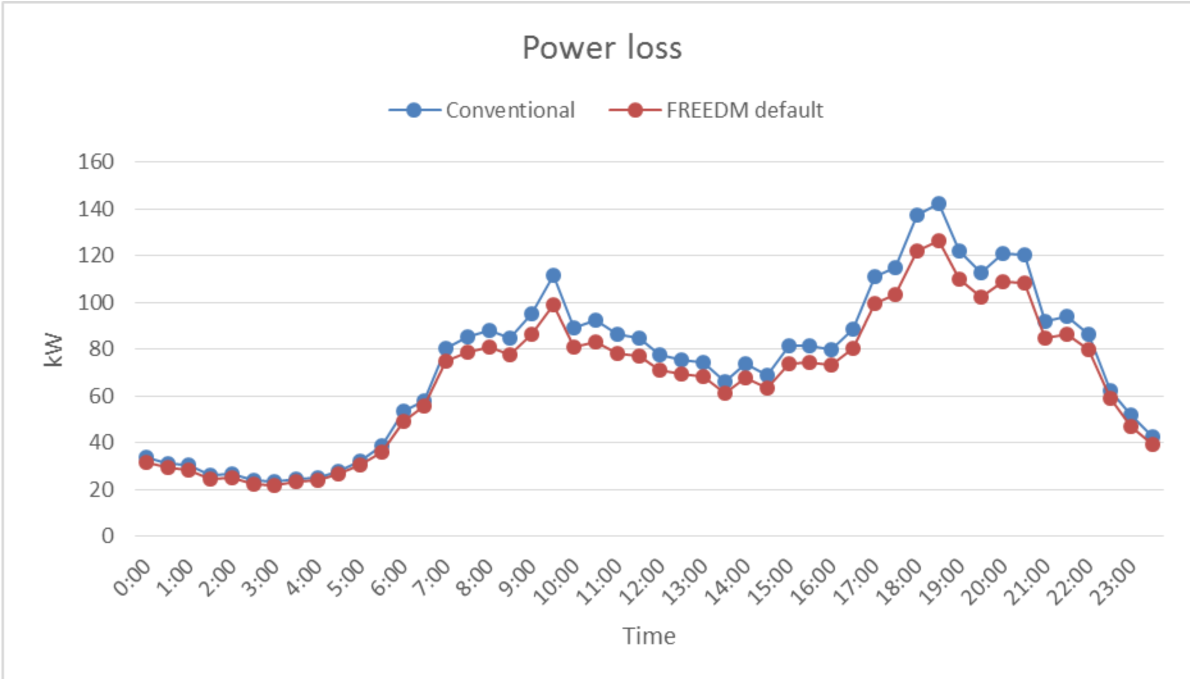

Fig. 2.16 Power loss during a day without PV penetration

Power loss characteristics with respect to load condition with a range from 40% to 110% can be seen in Fig. 2.17. We can find a positive correlation between relationship between load condition and loss percentage and this relationship is almost linear.

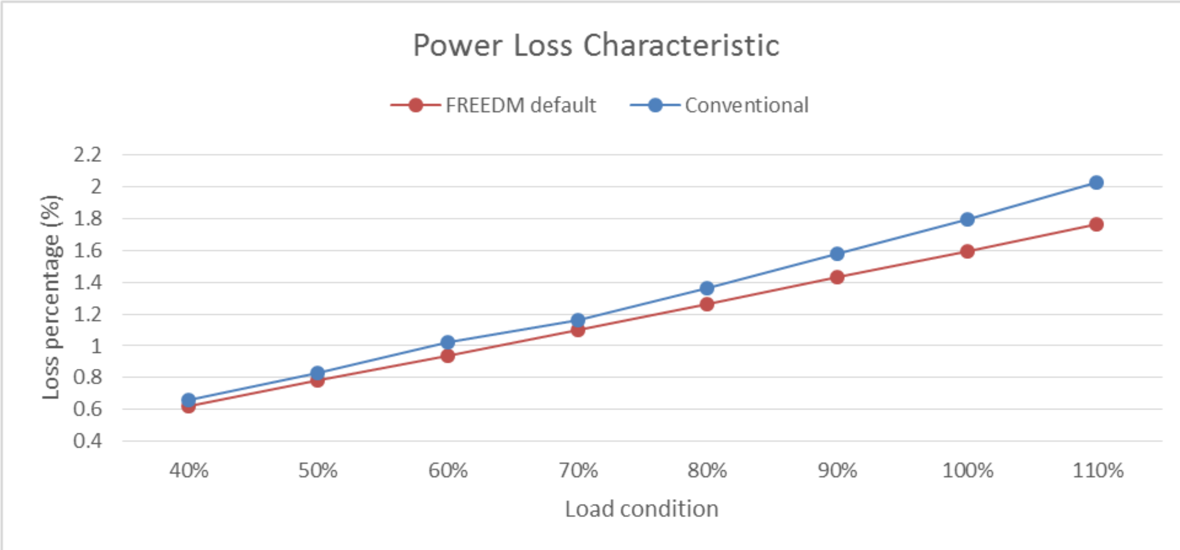

Fig. 2.17 Power loss characteristic with respect to load condition

Under FREEDM default control, as shown in Tab. 2.5, the primary-side energy loss is 1612.869 kWh for a day, which is less than 1767.756 kWh under conventional control. Thus, the FREEDM default control can reduce primary-side energy loss as well. Energy loss percentage in the table is defined as the proportion of energy loss in total load consumption. The sum of both primary-side and secondary-side energy loss is 3123.093 kWh under conventional VVC, and 5678.881 kWh under FREEDM default control. Thus, the FREEDM default control can reduce primary-side energy loss, but it increases the total loss on both primary and secondary sides.

Tab. 2.5 Daily primary-side energy loss without PV penetration

	Conventional	FREEDM default
Energy loss for one day (kWh)	1767.756	1612.869
Energy loss percentage (%)	1.304292	1.190013

3. Voltage Regulation

During the 24 hours, the maximum voltage regulations in both conventional control and FREEDM default control cases occur under peak load condition. Thus the reduction of VRI during a day is the same with the VRI reduction in the peak load condition simulation. As shown in Fig. 2.18, for most of the time during a day %Regulation of the feeder under FREEDM control is less than that under conventional control. Even though, around 3:00 the %Regulation under FREEDM control is higher than that under conventional control, the difference is very small.

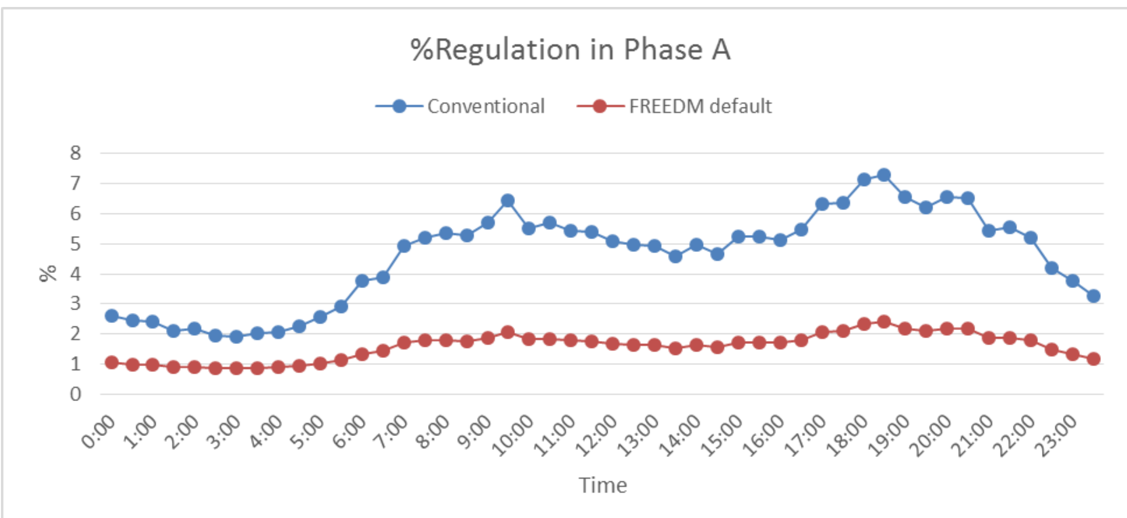

Fig. 2.18 (a)

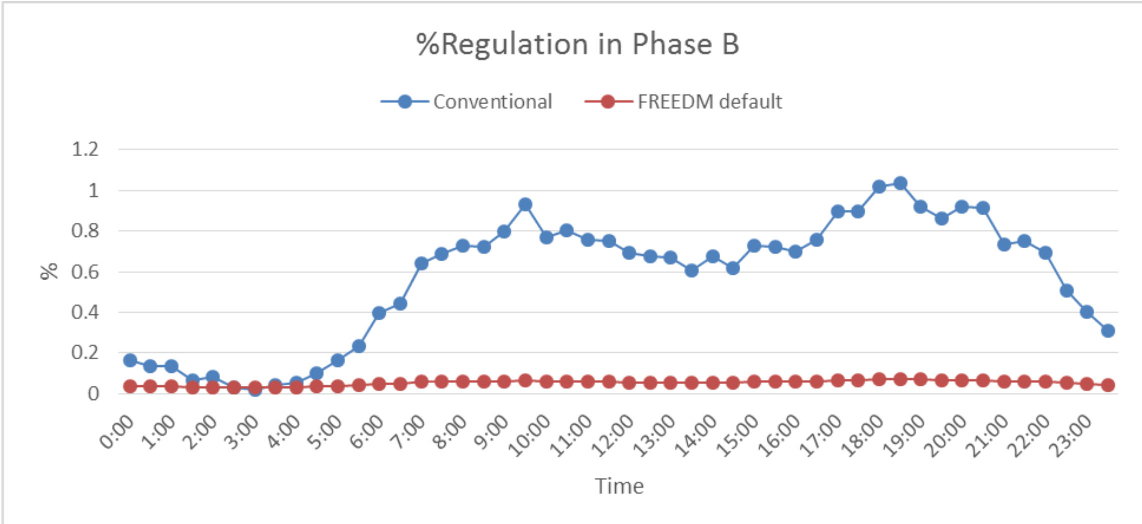

Fig 2.18 (b)

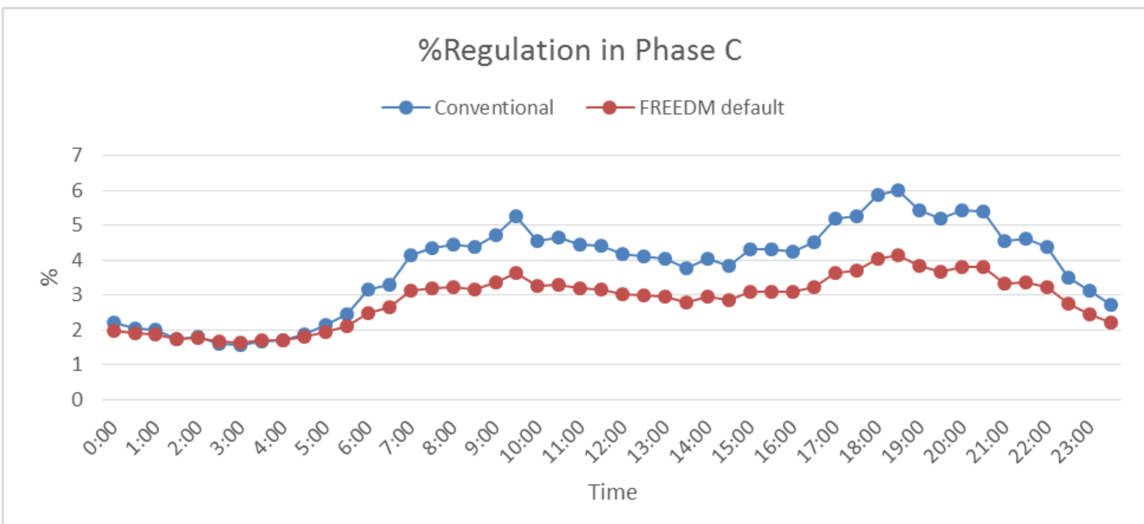

Fig. 2.18 (c)

Fig. 2.18 The system voltage regulation profile during a day without PV penetration

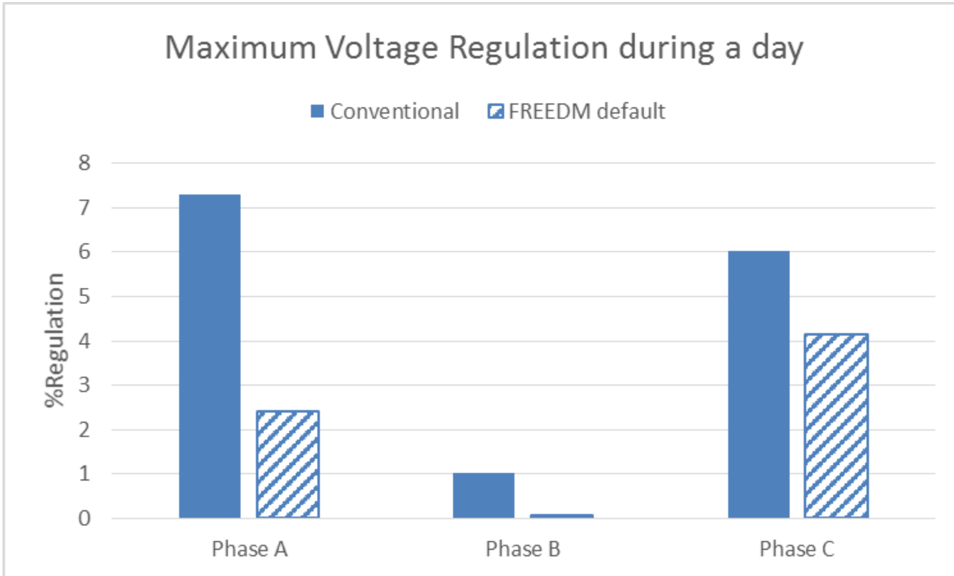

Fig. 2.19 System voltage regulation per phase during a day without PV penetration

4. Voltage Unbalance

From the 24-hour simulation results, for all the nodes, the voltage unbalance under FREEDM default control is lower than the voltage unbalance under conventional control. And among all the nodes, Node 9 always has the biggest voltage unbalance during 24 hours. From Fig. 2.20, we can find that at Node 9 voltage unbalance under FREEDM default control is always lower than that under conventional control. Therefore, the FREEDM default control better reduces the voltage unbalance of the system. The simulation results also shows that for each node the maximum voltage unbalance occurs at peak load condition. In this 24-h simulation the VUI is 0.0652 in conventional case and 0.0416 in FREEDN default control case. The FREEDM default control reduce the VUI by 36.2%. Other voltage unbalance indices are also calculated, as shown in Tab. 2.6.

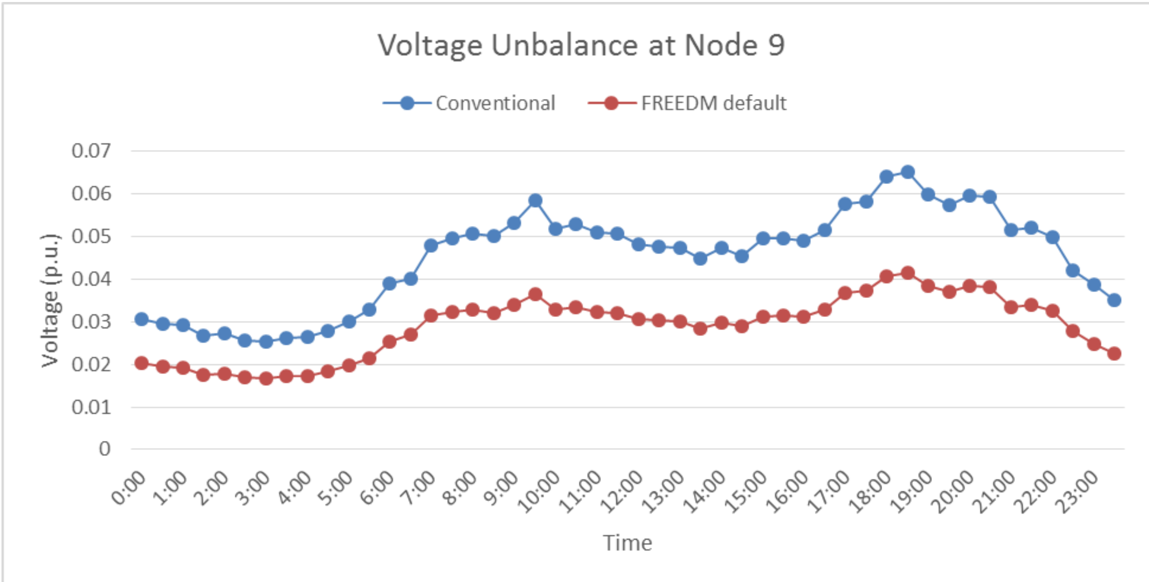

Fig. 2.20 24-hour voltage unbalance at Node 9 without PV penetration

Tab. 2.6 Voltage Unbalance Index of Notional Feeder for zero PV case

	VVC	VUI (p.u.)	%PVUR Index	%VUF Index
Zero PV	Conventional	0.06520	4.04060	1.08194
	FREEDM default	0.04160	2.29597	0.81636

5. Voltage Variation

Since for each node, we care about the voltage under different operating condition, the Voltage Variation (VV) on primary side at all the nodes are calculated and shown in Fig. 2.21. Since in conventional control scheme, the LTC at substation regulates voltage at Node 0 at 1.0 and 1.025 p.u., for the nodes whose voltage does not depend much on load conditions, the voltage variation is close to 0.025 shown as the figure for phase B. But under FREEDM control the substation voltage is always 1.0 p.u., which makes the voltage variation get rid of the tap changing effect of LTC at substation. Thus, for phase B the

FREEDM control reduces the voltage variation greatly. For each node, the VV's under FREEDM control is smaller than that under conventional control. The maximum VVI under FREEDM control is 0.0236 p.u., under conventional control is 0.0313 p.u., shown as in Tab. 2.7. The FREEDM default control reduces the maximum VVI by 24.39%. As to the voltage variations on the secondary-side, at each node with SST the VV is zero, since the SST can regulate the secondary-side voltage constant [8]. In conventional distribution systems, in which traditional distribution transformers are used, the voltage variations on the secondary-side is the same as those on the primary-side. This is due to the assumption of an almost constant voltage drop through the distributed transformer under different operation conditions.

The histogram of primary-side voltages under conventional VVC are shown in Fig. 2.3. The histogram of primary-side voltages under FREEDM default VVC are shown in Fig. 2.22.

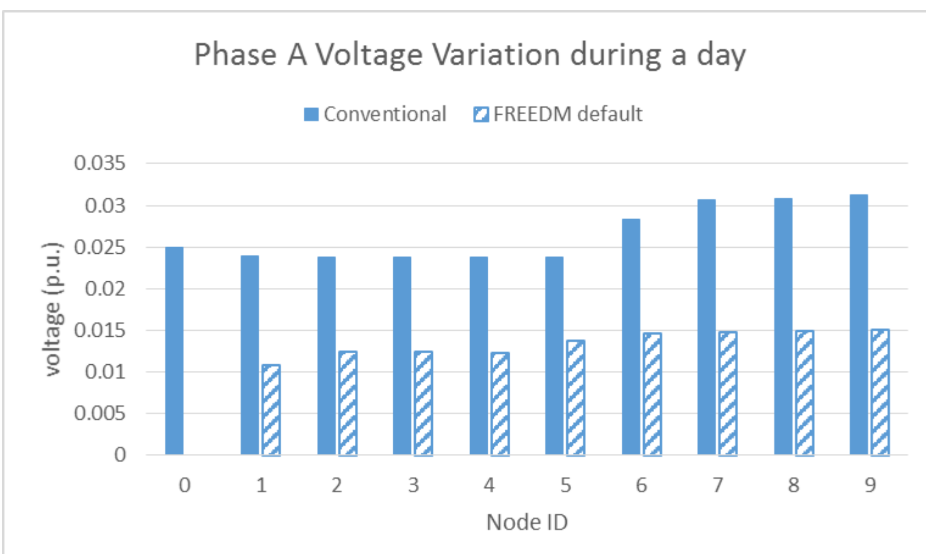

Fig 2.21 (a)

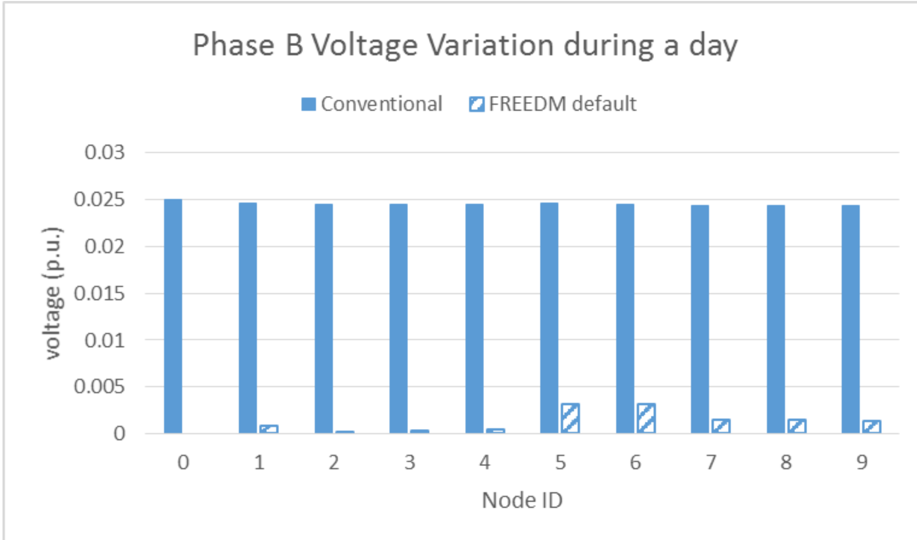

Fig 2.21 (b)

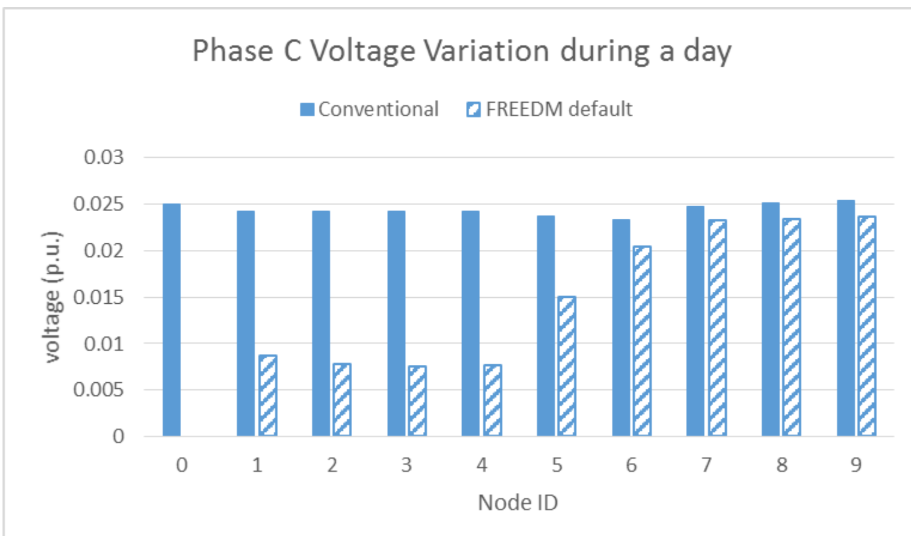

Fig. 2.20 (c)

Fig. 2.21 Voltage Variation without PV penetration

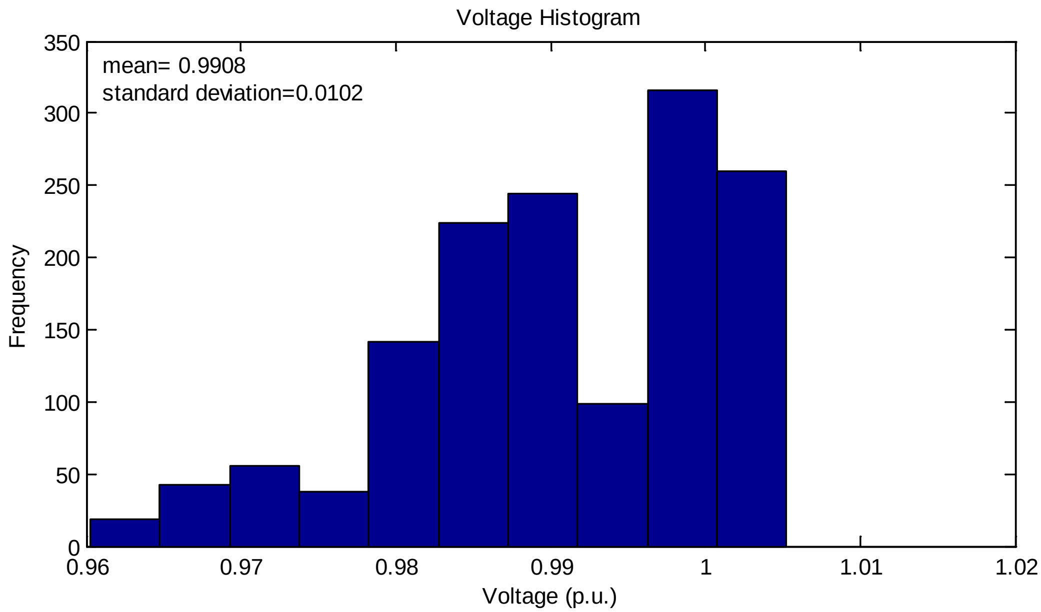

Fig. 2.22 Histogram of voltages on the primary-side of the Notional feeder under FREEDM default VVC (zero PV)

Tab. 2.7 VVI comparison with no PV penetration

Control	VVI_a	VVI_b	VVI_c	Max(VVI)
Conventional	0.0151	0.0032	0.0236	0.0236
FREEDM default	0.0313	0.0250	0.0254	0.0313

High PV penetration

Since there is no PV output during the peak load time 18:30, all the simulations under the peak load condition have the same results with Case 1 and Case 2. Therefore, with PV penetration, the FREEDM VCC is still effective under peak load condition.

Case 4:

In this case, a 24-hour simulation is conducted to explore if the FREEDM VVC is still effective when there is high PV penetration in the system.

1. Voltage Profile

Under FREEDM default control, the minimum voltage is 0.9602 p.u. at Node 9 in phase C at 18:30. The maximum voltage is 1.0084 p.u. at Node 9 in phase C at 12:00 when the PV output exceeds the load which leads to a reverse power flow. Phase C voltage at Node 9 is shown in Fig. 2.23.

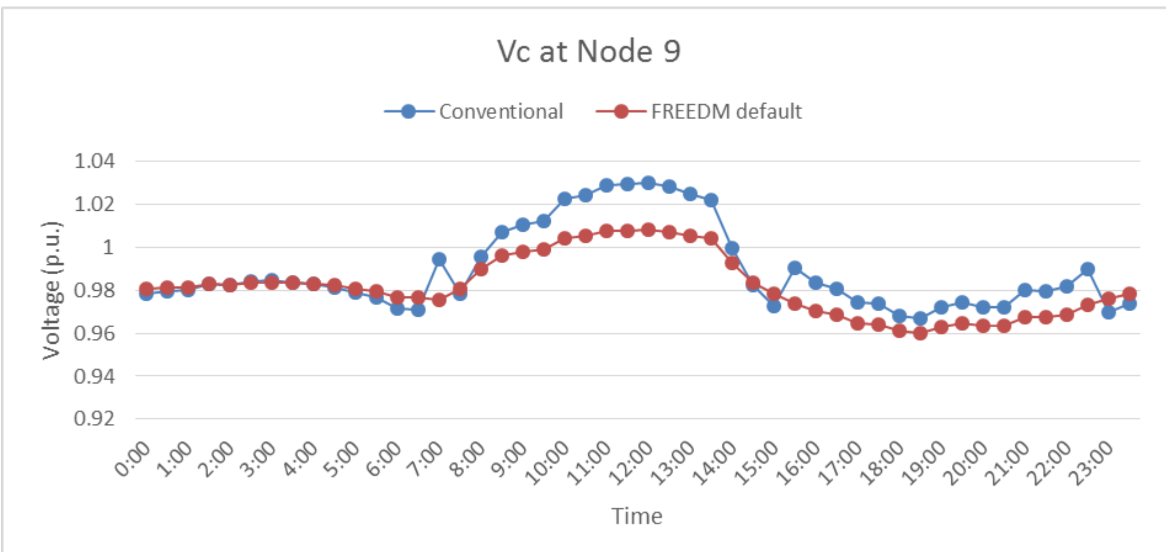

Fig. 2.23 Phase C voltage at Node 9 during a day with high PV penetration

Both the maximum and minimum voltages during a day is within the required range, indicating the FREEDM VVC successfully regulating the voltages if PVs are connected to the system. The simulation results of voltage profiles under conventional control is also within the required range. Phase C voltage at Node 9 under conventional control is included in the figure below as well. The abnormal voltage change in the conventional control case around 7:00 and 15:00 o'clock is due to the tap change of LTC at substation.

2. Power Loss and Energy loss

Under FREEDM default control, the 24-hour primary-side power loss ranges from 0.0877kW at 9:30 to 126.71kW at 18:30. From Fig. 2.24, we can see that under conventional control the primary-side power loss is always higher during a day, which indicates the FREEDM VVC mitigates the issue of power loss better. Under FREEDM default control the line currents in each phase are lower than that in the conventional case, thus less power loss. Although the system load in both case are high during the daytime, PVs help to reduce the power loss.

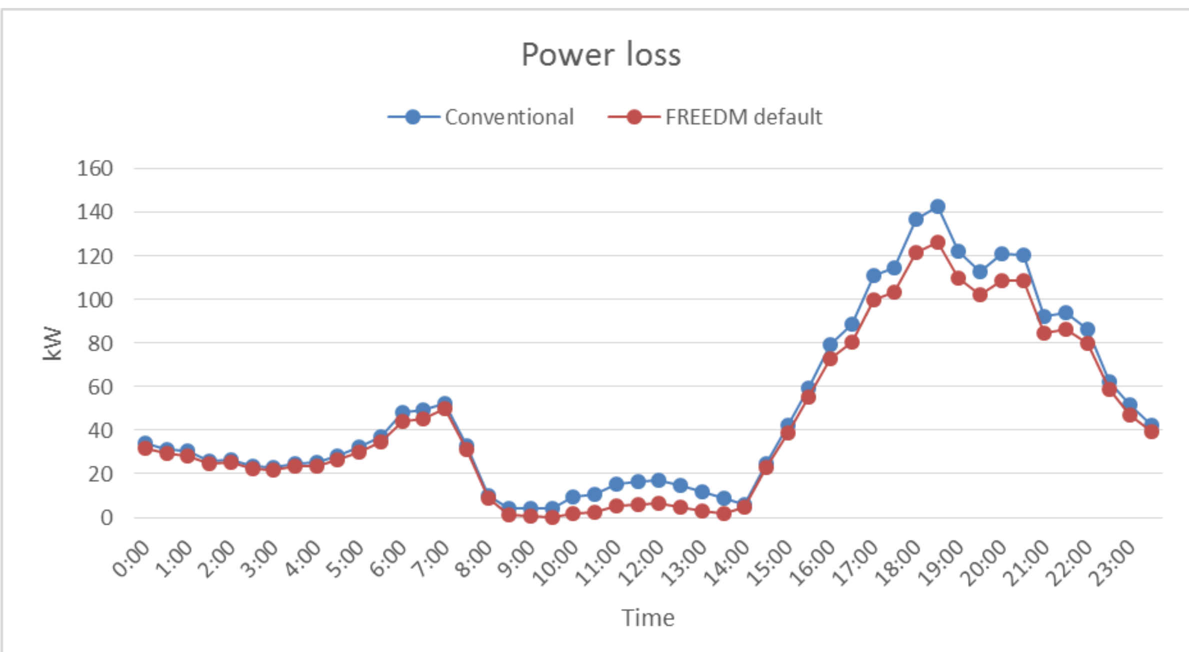

Fig. 2.24 Power loss during a day with high PV penetration

As shown in Tab. 2.8, under FREEDM default control, the energy loss is 1043.161 kWh for a day, which is less than 1183.144 kWh under conventional control. Thus, the FREEDM default control can reduce energy loss if the system has PVs connected as well. Energy loss percentage in the table is defined as the proportion of energy loss in total load consumption. The sum of both primary-side and secondary-side energy loss is 4124.320 kWh under conventional VVC, and 3680.209 kWh under FREEDM default control. Thus, the FREEDM default control can reduce both primary-side and secondary-side energy loss.

Tab. 2.8 Daily energy loss with high PV penetration

	Conventional	FREEDM default
Energy loss for one day (kWh)	1183.144	1043.161
Energy loss percentage (%)	0.872952	0.769669

3. Voltage Regulation

In the results of 24-hour simulation, some of the % Regulations of the feeder are negative, because voltage rises along the feeder. The voltage rise along the feeder can result from either reverse power flow, or highly unbalance of the system or both. For Phase A and Phase C, the maximum voltage regulations in both control cases occur under peak load condition, at 18:30. For Phase B the maximum absolute value of %Regulation under conventional control is under peak PV output condition, at 12:00, while in FREEDM default control case the maximum %Regulation still occurs at 18:30. For most of the time during a day the absolute value of %Regulation of the feeder under FREEDM control is less than that under conventional control.

A comparison of maximum absolute value %Regulation during 24 hours is shown in the Fig. 2.25. The VRI under conventional control is 7.29%, under FREEDM control is 4.14%. The FREEDM reduce the VRI by 43.27%.

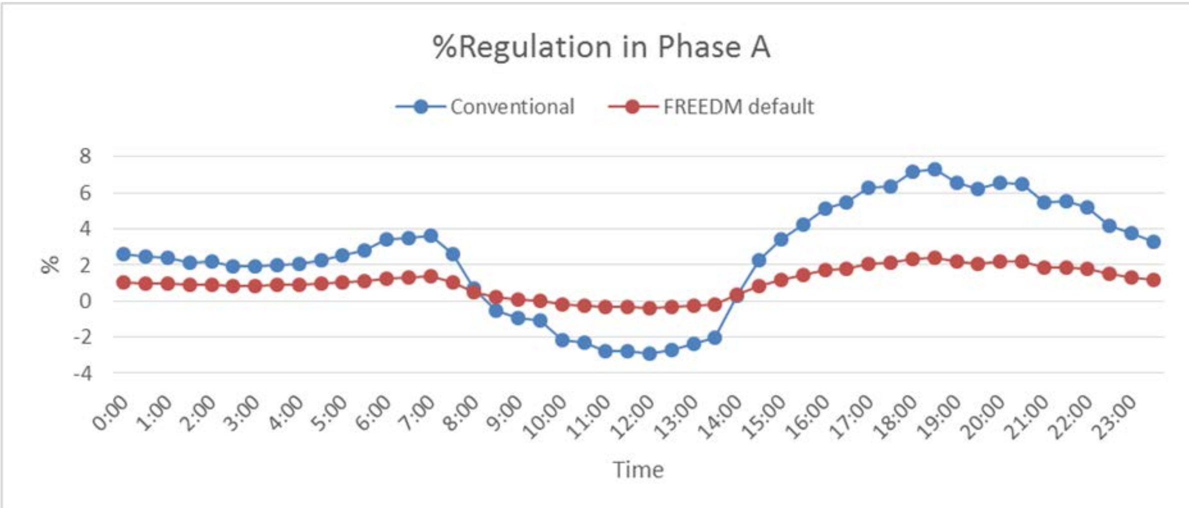

Fig. 2.25 (a)

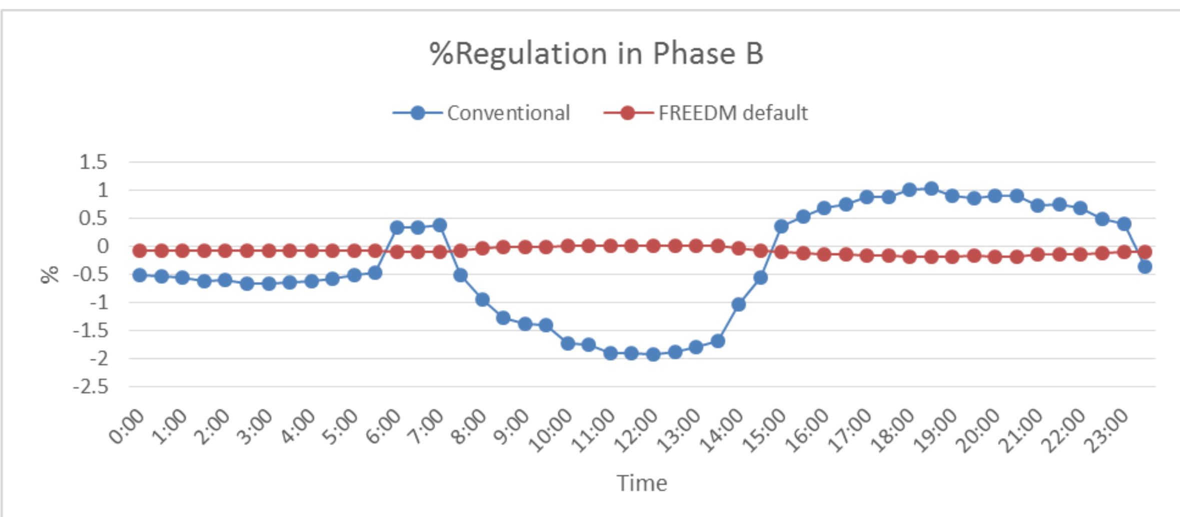

Fig. 2.25 (b)

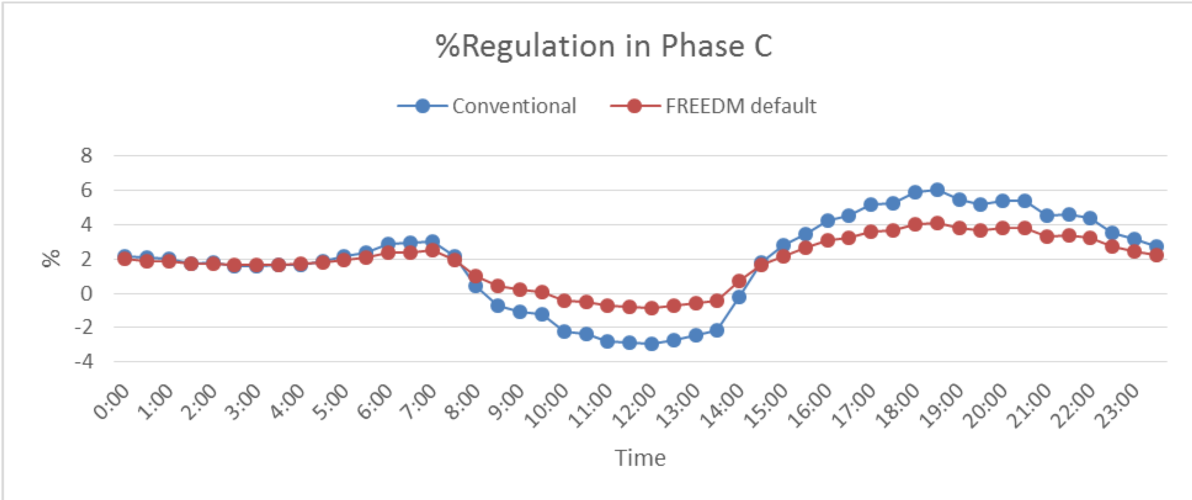

Fig. 2.25 (c)

Fig. 2.25 System voltage regulation per phase during a day with high PV penetration

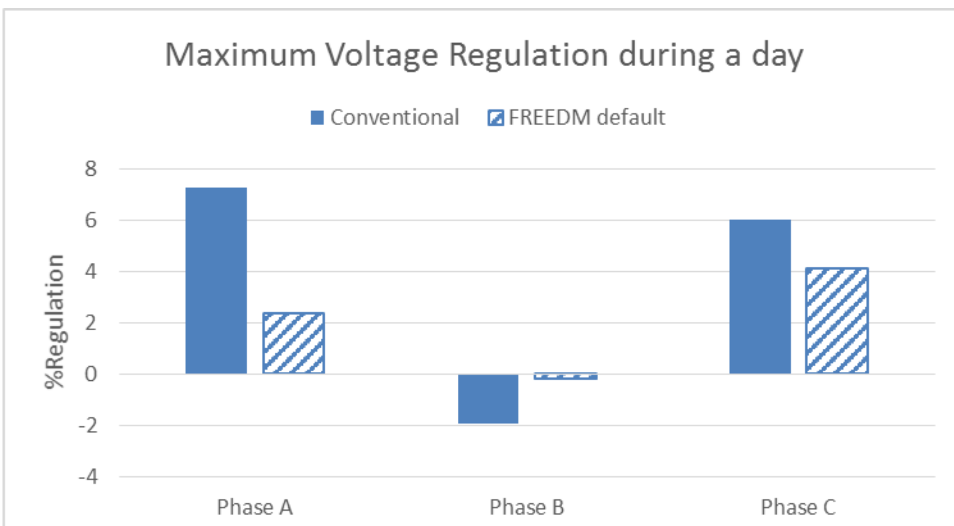

Fig. 2.26 Maximum voltage regulation during a day with high PV penetration

4. Voltage Unbalance

As to voltage unbalance, the simulation results for system with PV shows that Node 9 always has the biggest voltage unbalance during 24 hours. From the Fig. 2.27, we can find that at Node 9, voltage unbalance under FREEDM default control is always lower than that under conventional control. The maximum voltage unbalance during a day also occurs under peak load condition, thus the reduction of VVI is also 36.2%. Therefore, the FREEDM default control better reduces the voltage unbalance of the system. Other voltage unbalance indices are also the same in zeros PV case, shown in Tab. 2.6

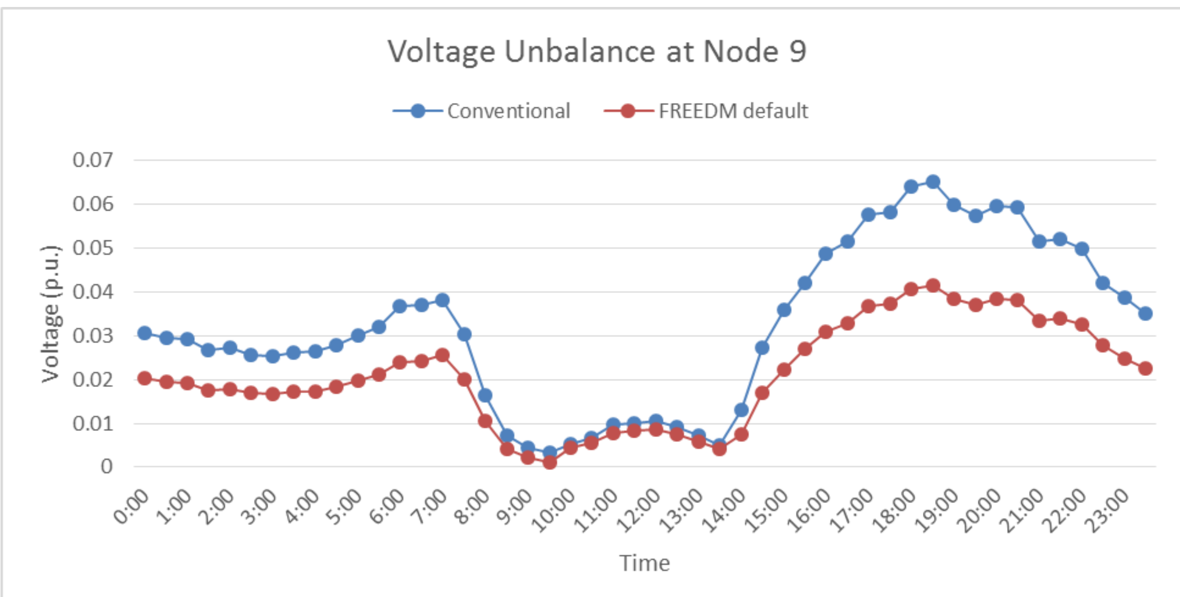

Fig. 2.27 Voltage unbalance at Node 9 during a day with high PV penetration

5. Voltage Variation

The voltage variation for each node and each phase is shown in Fig. 2.28. Since in conventional control scheme, the LTC at substation regulates voltage at Node 0 at 1.0 and

1.025 p.u., the voltage variation at some nodes is much larger than 0.025 p.u.. That is because at noon the PV output exceeds the system load, and the consequent reverse power flow makes the maximum voltage larger than 1.025 p.u., even though the LTC at substation still regulates voltage at Node 0 to 1.0 p.u.. At the same time the minimal voltage remains the same as in zero-PV case. Thus, the variation is larger than that in zero-PV case. But in FREEDM control case the maximal voltage due to the reverse power flow is close to 1.0 p.u., while the minimal voltage is close to that in conventional control case, thus the voltage variation is lower.

The maximum VVI under FREEDM control is 2.36%, under conventional control is 3.13%. The FREEDM control reduce the VVI by 24.39%. The results is the same as those in non-PV cases, shown as in Tab. 2.9. As to the voltage variations on the secondary-side, at each node with SST the VV is zero, since the SST can regulate the secondary-side voltage constant [8]. In conventional distribution systems, in which traditional distribution transformers are used, the voltage variations on the secondary-side is the same as those on the primary-side.

The histogram of primary-side voltages under conventional VVC are shown in Fig. 2.29. The histogram of primary-side voltages under FREEDM default VVC are shown in Fig. 2.30.

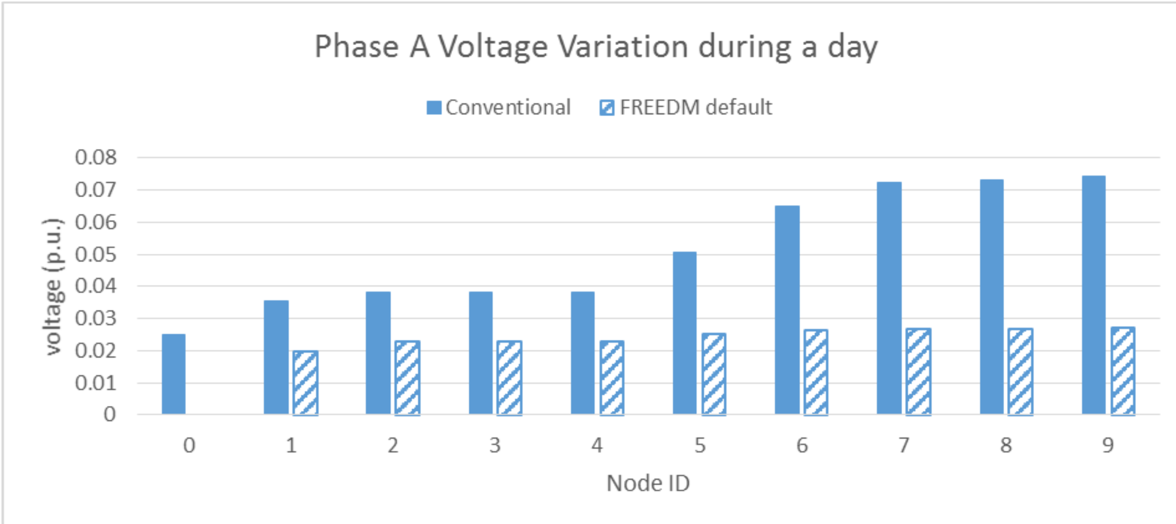

Fig. 2.28 (a)

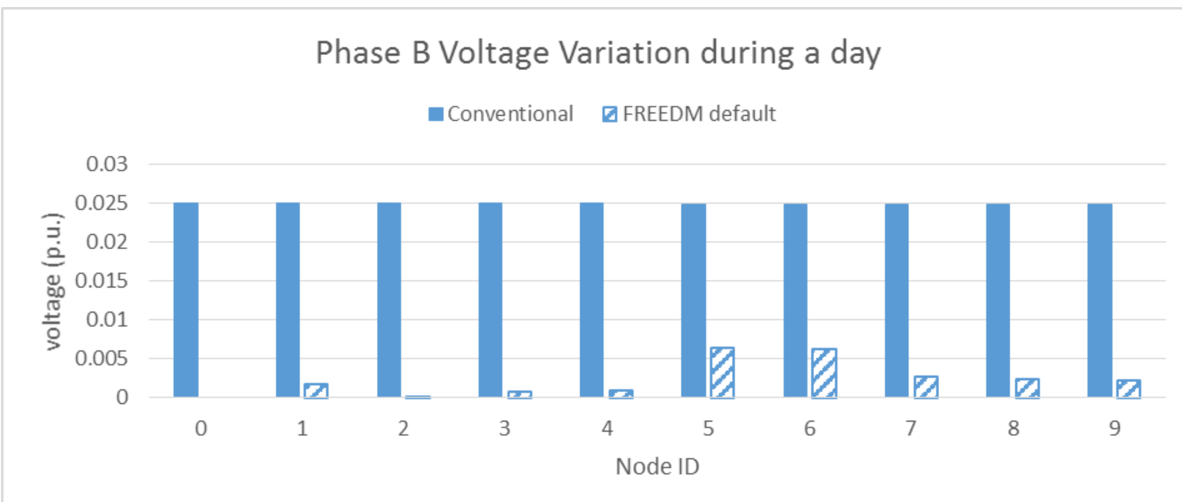

Fig. 2.28 (b)

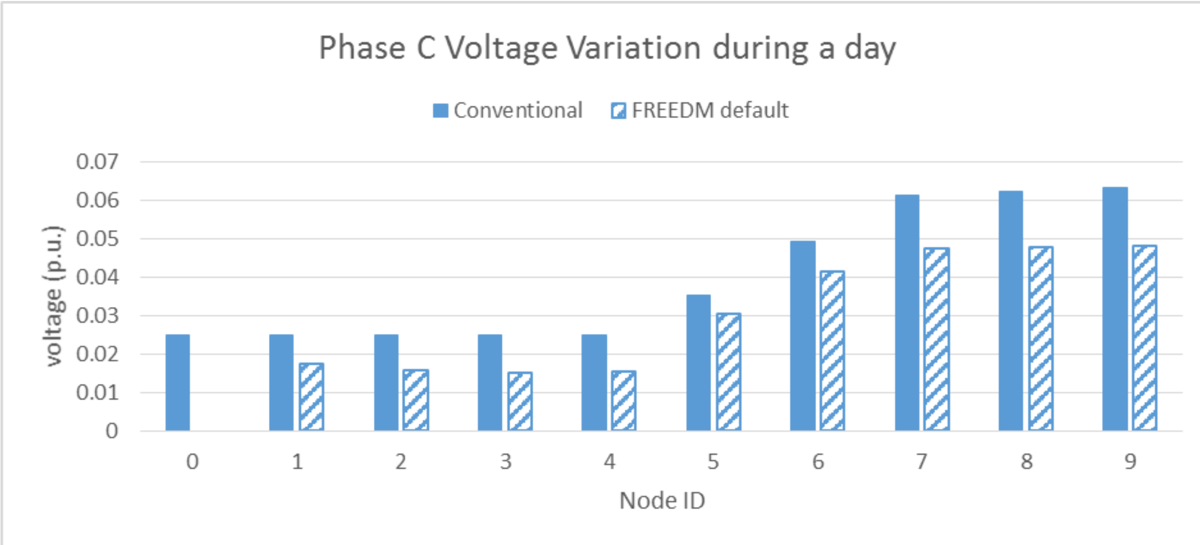

Fig. 2.28 (c)

Fig. 2.28 Three-phase voltage variation during a day with high PV penetration

Tab. 2.9 VVI comparison with high PV penetration

Control	VVI_a	VVI_b	VVI_c	Max(VVI)
FREEDM	0.0272	0.0064	0.0481	0.0481
Conventional	0.0743	0.0250	0.0634	0.0743

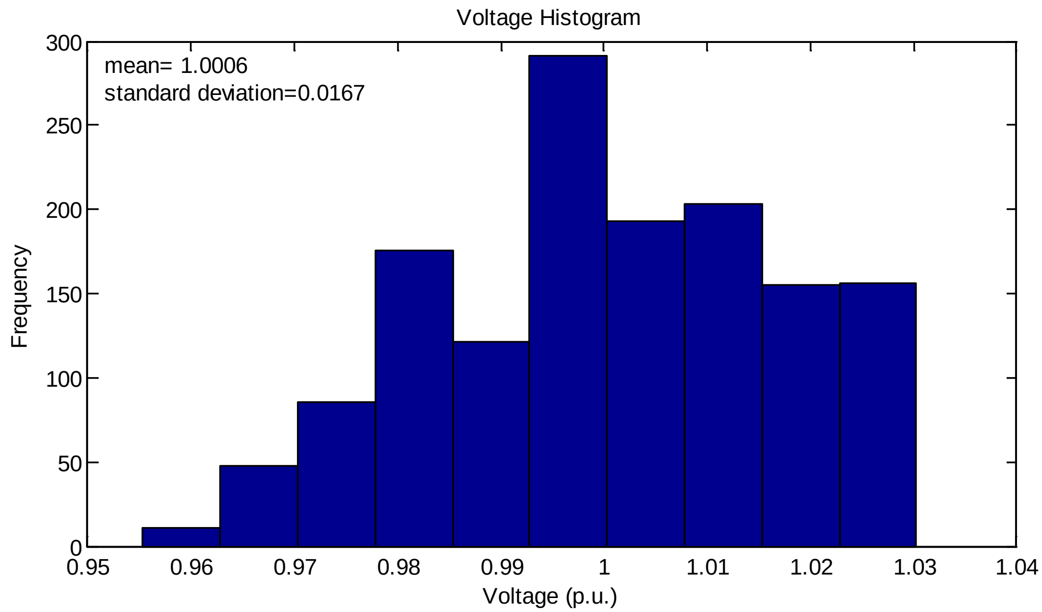

Fig. 2.29 Histogram of voltages on the primary-side of the Notional feeder under conventional VVC (high PV)

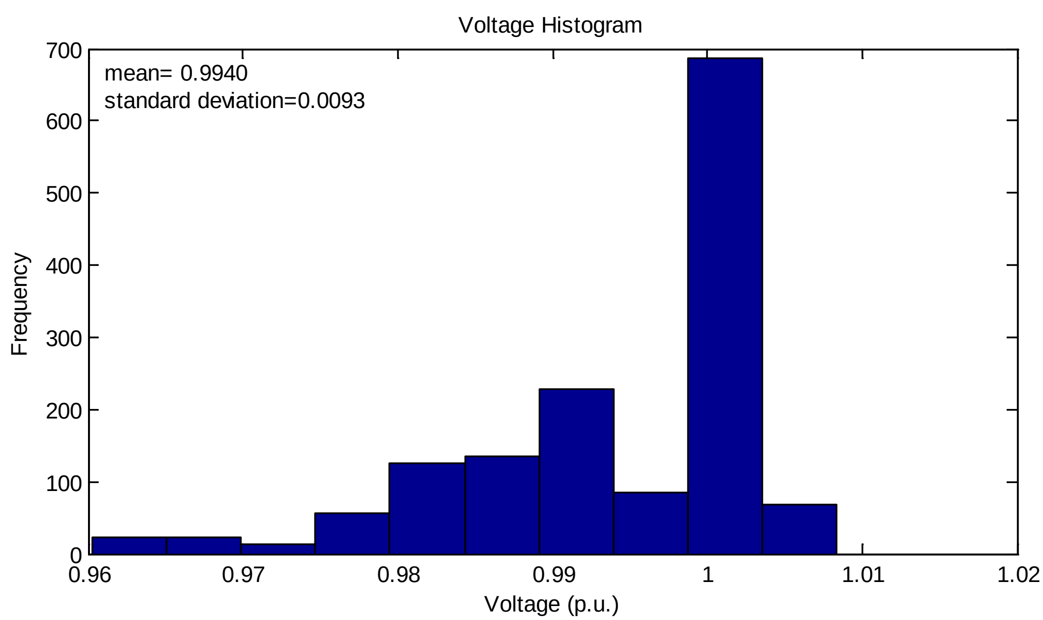

Fig. 2.30 Histogram of voltages on the primary-side of the Notional feeder under conventional VVC (high PV)

2.3.2 Summary

1. The primary-side voltages in the system can be regulated within the recommended service voltage range of 0.95-1.05 p.u. (range A by ANSI C84.1) under both the conventional and FREEDM default control schemes. Even when there is high PV penetration in the sytem, the voltages are still within the required range under both Volt/Var control schemes.

2. Under peak load condition, the primary-side power loss under the conventional control is 142.65kW; with the FREEDM default control the primary-side power loss is 126.71kW. A reduction of 11.17% is achieved. For a typical day, with minimum (zero) PV output, the primary-side energy loss under conventional control is 1767.8kWh, under FREEDM default control is 1612.9kWh. The FREEDM default control reduces primary-side energy loss by 8.76%. With full PV penetration (peak PV generation at each node equals peak load), the primary-side energy loss under the conventional control is 1183.1kWh, under FREEDM default control is 1043.2kWh. A reduction of 11.83% is achieved. When considering the secondary-side loss, the FREEDM VVC has more total energy loss than the conventional control in a zero-PV day, but less total energy loss in a high-PV day.

3. The FREEDM default control greatly reduces the voltage regulation of the feeder. The VRI under conventional control is 7.29%, under FREEDM control is 4.14%. A reduction of 43.27% is achieved by the FREEDM default control scheme.

4. The FREEDM default control greatly reduces the voltage unbalance of the system. The VUI is 0.0652 p.u. under the FREEDM default control, and 0.0416 p.u. under conventional control. A reduction of 36.2% is achieved by the FREEDM default control scheme.

5. The FREEDM default control also reduces the voltage variation on the primary-side under different operating conditions during a day. In a zero-PV day, the maximum VVI among three phases is 0.0236 p.u. under FREEDM default control, and 0.0313 p.u. under conventional control. The FREEDM default control scheme achieves a voltage variation reduction of 24.39%. In a high-PV day, the maximum VVI among three phases is 0.0481 p.u. under FREEDM default control, and 0.0743 p.u. under conventional control. The FREEDM default control scheme achieves a voltage variation reduction of 35.29%. Besides, the FREEDM control guarantees a zero voltage variation on the secondary-side.

2.4 Assessment of Volt/Var Control on FREEDM IEEE 34 Nodes Feeder

Similar to the FREEDM Notional Feeder, the FREEDM IEEE 34 Nodes Feeder also use SSTs to accommodate all loads and PVs. There are two VRs in the system, connected between node 814 and 850, 852 and 832.

2.4.1 Case Studies

No PV penetration

Case 0:

In this case, no Volt/Var control scheme is applied. Both voltage regulators and capacitors are removed from the conventional IEEE 34 Nodes feeder. This case is simulated to prove the necessity to apply VVC on this feeder.

Since under peak load condition, the system will have the largest voltage drop and power loss, to further investigate the effectiveness of FREEDM Volt/Var control scheme under the worst case, Case 1 and Case 2 are developed.

Case 1:

In this case, the conventional control scheme is applied. Besides the two voltage regulators as mentioned before, there are two fixed capacitor banks in IEEE 34 system, with the detailed data shown in Tab. 2.10.

Tab. 2.10 Capacitor data for IEEE 34 System

Cap #	Connected to	IQL A(kVAR)	IQL B (kVAR)	IQL C (kVAR)
1	844	100	100	100
2	848	150	150	150

Case 2:

In this case, the FREEDM default control scheme is applied. The reactive power injection at each SSTs, Q_{inj} is set as zero. Capacitors are removed, but VRs are kept.

The simulation results of these three cases under peak load condition are seen as follows.

1. Voltage Profile

Since ANSI C 84.1 range A voltage is limited to service voltage, only voltages on primary side are compared with range A, 0.95-1.05 p.u.. In FREEDM IEEE 34 nodes system, Node 888 and 890 are on the secondary side of the distribution transformer located between Node 832 and 888, thus their voltage profiles are not considered.

As illustrated in Fig. 2.31, in Case 0, voltages at many nodes are lower than 0.95, thus it is necessary to apply Volt/Var Control scheme to regulate the voltages in the system. In case 1, under conventional control scheme, the maximum voltage is 1.05 p.u. and the minimum is 0.961p.u.. The conventional VVC scheme is able to obtain the primary goal of keeping voltages within the range of 0.95-1.05 p.u.. In case 2, under FREEDM default VVC, the maximum voltage is 1.05 p.u. and the minimum is 0.971 p.u.. which indicates that the FREEDM VVC successfully solves the issue of voltage violation as well.

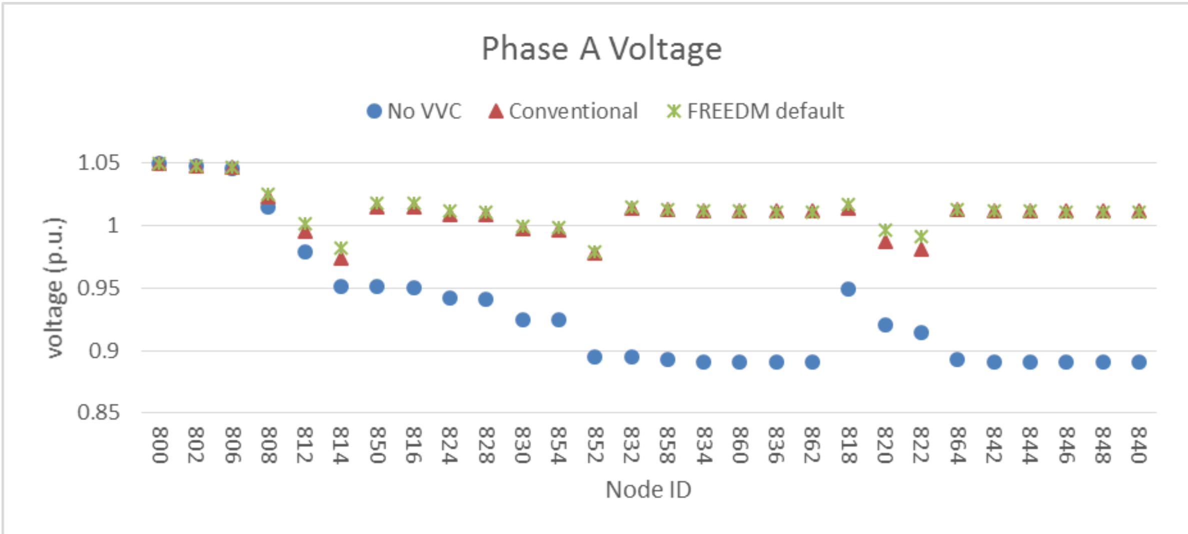

Fig 2.31 (a)

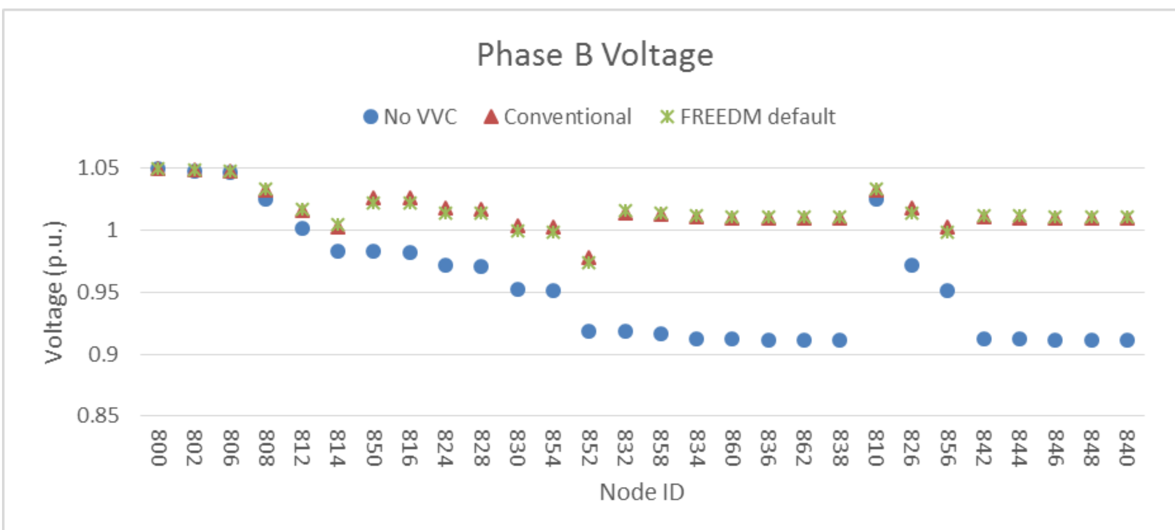

Fig. 2.31 (b)

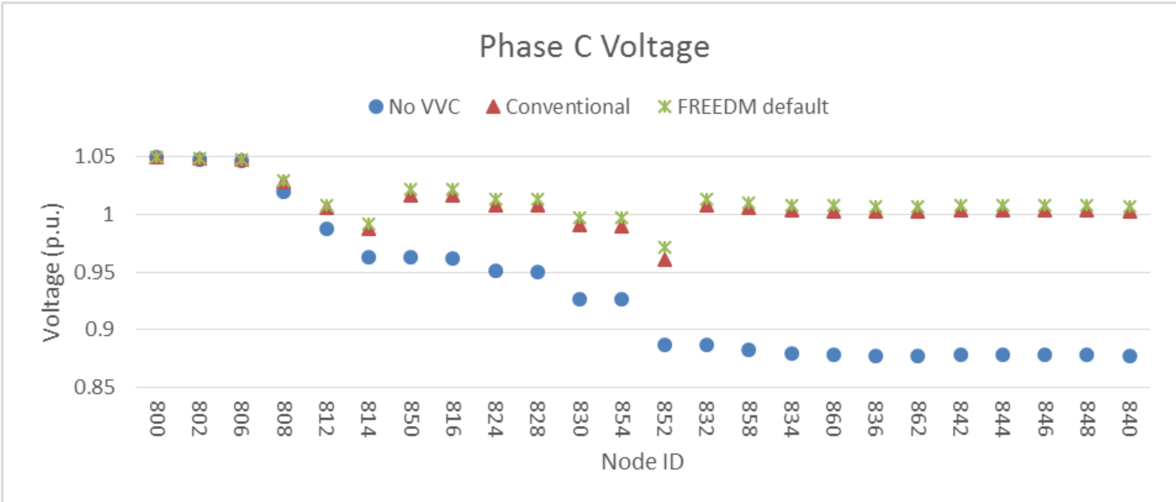

Fig. 2.31 (c)

Fig. 2.31 Feeder Voltage profile under peak load condition

2. Power Loss

The simulation results with respect to power are shown in Tab. 2.11.

Tab. 2.11 Simulation results with respect to power under peak load condition

	No VVC	Conventional Control	FREEDM Default
Psub	1800.731	1701.581	1680.42
Qsub	1077.209	326.575	141.6328
Pload	1496.651	1496.651	1496.651
Qload	857.7689	857.769	857.769
Ploss	304.0802	204.9306	183.769
Loss percentage	20.32%	13.69%	12.28%

Both Conventional and FREEDM VVC can reduce the power loss, and the power loss percentage under FREEDM VVC is 12.28%, which is smaller than that in case 1, under conventional VVC. Thus, under peak load condition, the FREEDM VVC can reduce more power loss than conventional VVC in IEEE 34 nodes systems.

3. Voltage Regulation

The IEEE 34 nodes feeder has eight feeder ends, Node 838, 810, 822, 826, 856, 864, 848 and 840. The voltage regulation at these eight ends are shown in Tab. 2.12 below. The voltage regulation of the system is the maximum value of the % regulation at all feeder ends. As shown in Fig. 2.32, the VRI under FREEDM control is 7.04%, which is less than 5.91% under conventional control. The FREEDM VVC reduce the voltage regulation by 15.97%, compared to the conventional VVC.

Tab. 2.12 Voltage regulation under peak load condition

%Regulation	Conventional VVC			FREEDM default VVC		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
838		4.023293			3.86973	
810		1.741885			1.644932	
822	7.037624			5.913467		
826		3.180478			3.558937	
856		4.725862			5.123481	
864	3.643014			3.618383		
848	3.715755	3.929307	4.593714	3.81824	3.849974	4.189102
840	3.81358	3.993094	4.719465	3.834366	3.847718	4.228905

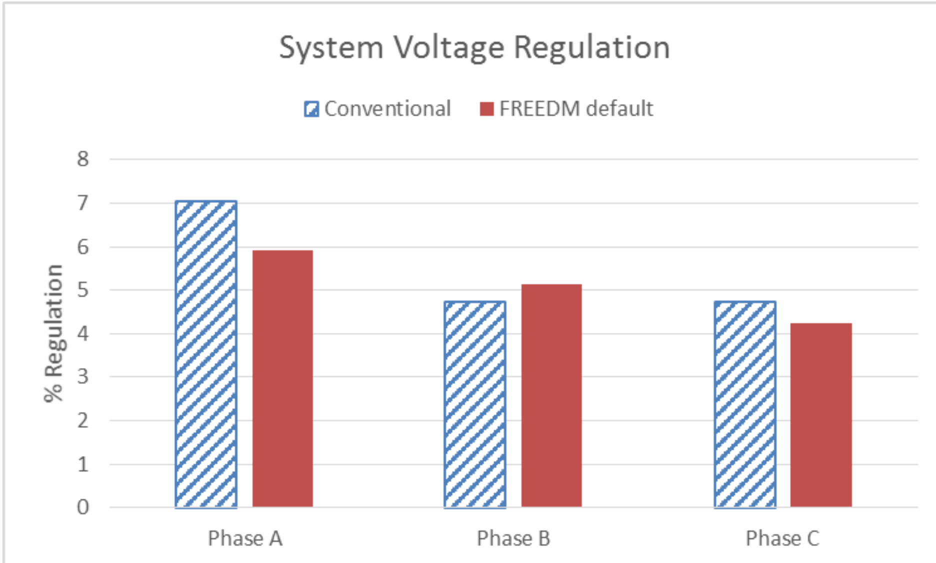

Fig. 2.32 Feeder voltage regulation under peak load condition

4. Voltage Unbalance

Since the IEEE 34 nodes system is also a highly unbalanced system, we need to investigate how the FREEDM VVC influences the voltage unbalance at each node.

From the simulation result shown in Fig. 2.33, we can see that both the conventional VVC and the FREEDM VVC can reduce the VU at each node. The VUI under conventional control is 0.0264 p.u., under FREEDM default control is 0.0222 p.u.. The FREEDM VVC reduces VUI by 15.87 % compared with the conventional control.

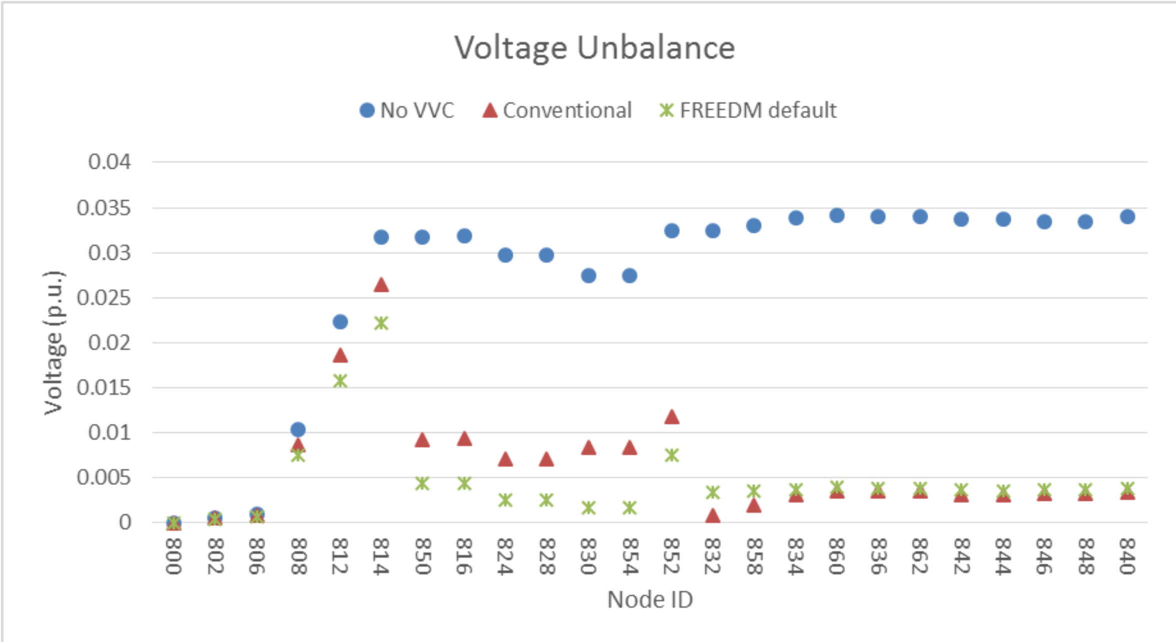

Fig. 2.33 Voltage unbalance under peak load condition

Case 3:

In this case, a 24-hour simulation is conducted to explore if the FREEDM VVC is still effective when load varies during a day and there is no PV penetration.

The 24-hour simulation results are as follows:

1. Voltage Profile

From the simulation results, both control schemes successfully keep the voltages within the range 0.95-1.05 p.u. in spite of the load variation during a day. Under FREEDM default control, the minimum voltage is 0.9676 pu at Node 852 in phase C at 18:00. Under conventional control, the minimum voltage is 0.9614 p.u. at Node 852 in phase C at 18:30.

The maximum voltage is 1.05 p.u at the substation in both cases. The 24-hour voltage profile at Node 852 is shown in Fig 2.34.

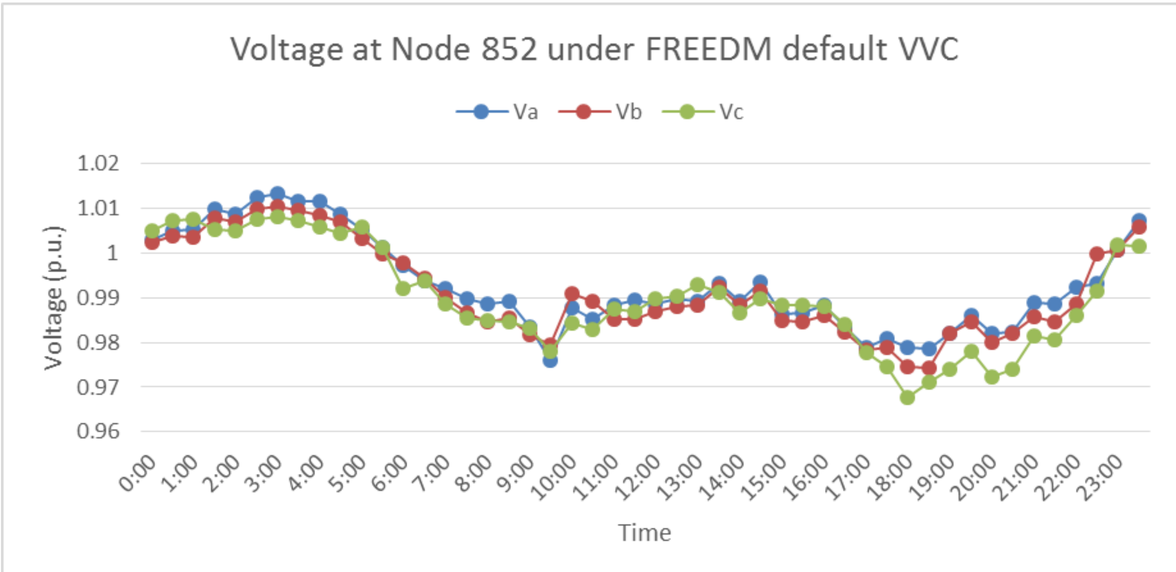

Fig. 2.34 Voltage at Node 852 during a day without PV penetration

2. Power Loss and Energy Loss

As shown in Fig. 2.35, under FREEDM default control, the 24-hour power loss ranges from 28.92kW at 3:00 to 183.769kW at 18:30, with a loss percentage range of 4.52%-12.28% respectively. Under conventional control the power loss is always higher during a day, which indicates that the FREEDM VVC mitigates the issue of power loss better. In Fig. 2.35, the power loss shows the same pattern as the load condition of the system, which verifies that as the load goes up the power loss increases. From, Tab. 2.13, under FREEDM default control, the energy loss is 2263.181kWh for a day, which is less than 2505.465kWh under conventional control. The sum of both primary-side and secondary-side energy loss is

2761.690 kWh under conventional VVC, and 3033.079 kWh under FREEDM default control. Thus, the FREEDM default control can reduce primary-side energy loss, but it increases the total loss on both primary and secondary sides.

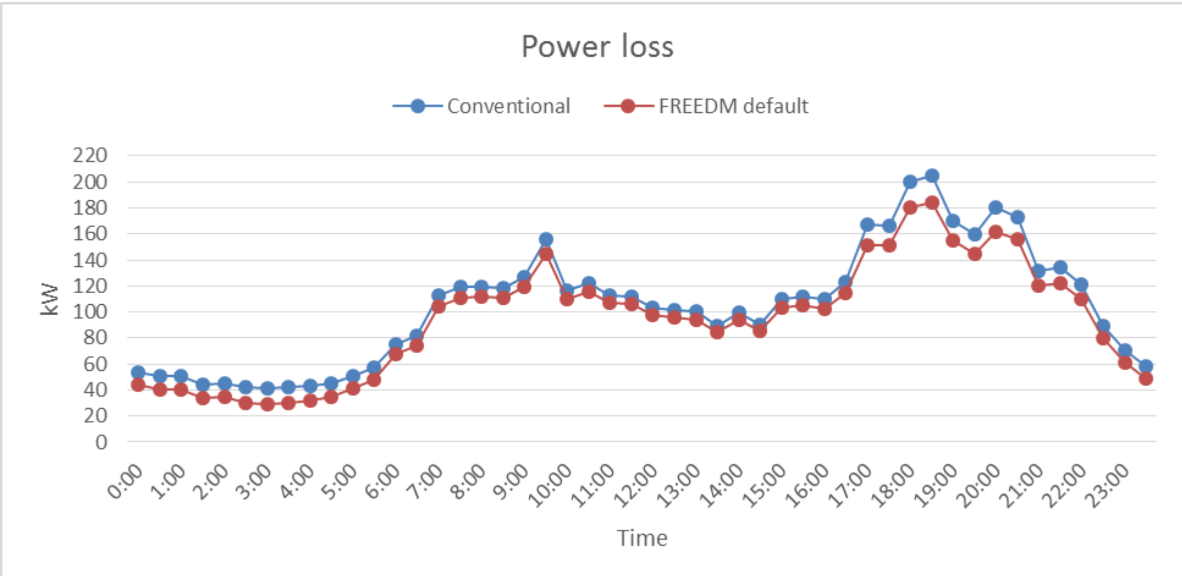

Fig. 2.35 Power loss during a day without PV penetration

Tab. 2.13 Daily energy loss without PV penetration

	Conventional	FREEDM default
Energy loss for one day (kWh)	2505.465	2263.181
Energy loss percentage (%)	9.762289	8.818252

3. Voltage Regulation

In the results of 24-hour simulation, for Phase A, the maximum voltage regulations in both control cases occur are under peak load condition, at 18:30, 7.03% under conventional VVC, 5.91% under FREEDM default VVC. For Phase B the maximum %Regulation under conventional control is 5.09% at 9:30 AM, while in FREEDM default control case the maximum %Regulation is 5.12% at 18:30, slightly more than the value under conventional control. For Phase C, the maximum %Regulation under conventional control is 4.72% at 18:30, while in FREEDM default control case the maximum %Regulation in the same phase occurs at 18:00 with a value of 4.58%. A comparison of maximum %Regulation at each phase during 24 hours is shown in Fig. 2.36. The VRI under conventional control is 7.03%, under FREEDM control is 5.91%. The FREEDM VVC reduce the VRI by 15.97%.

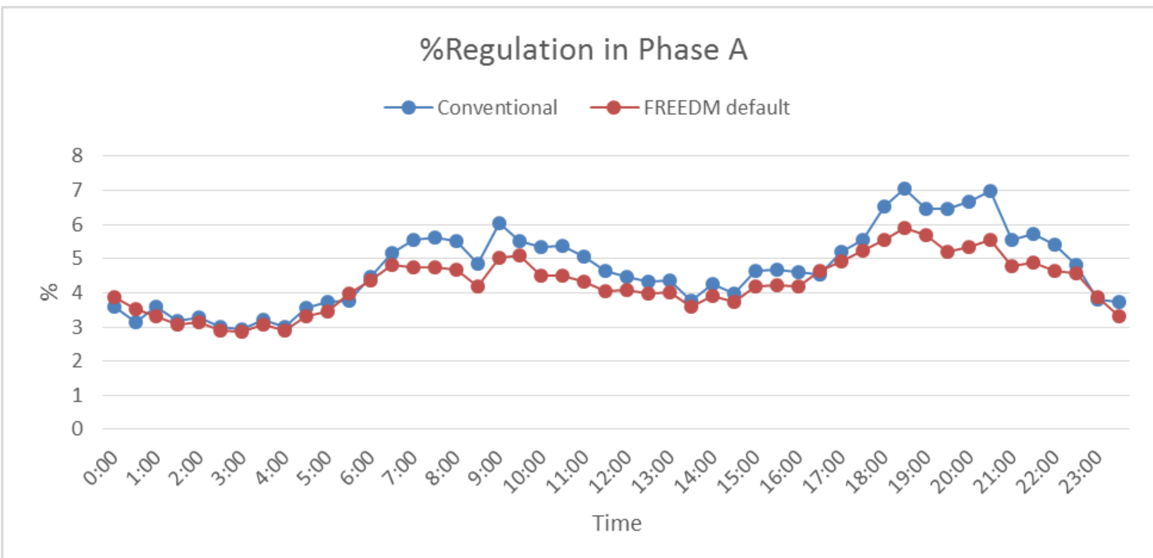

Fig. 2.36 (a)

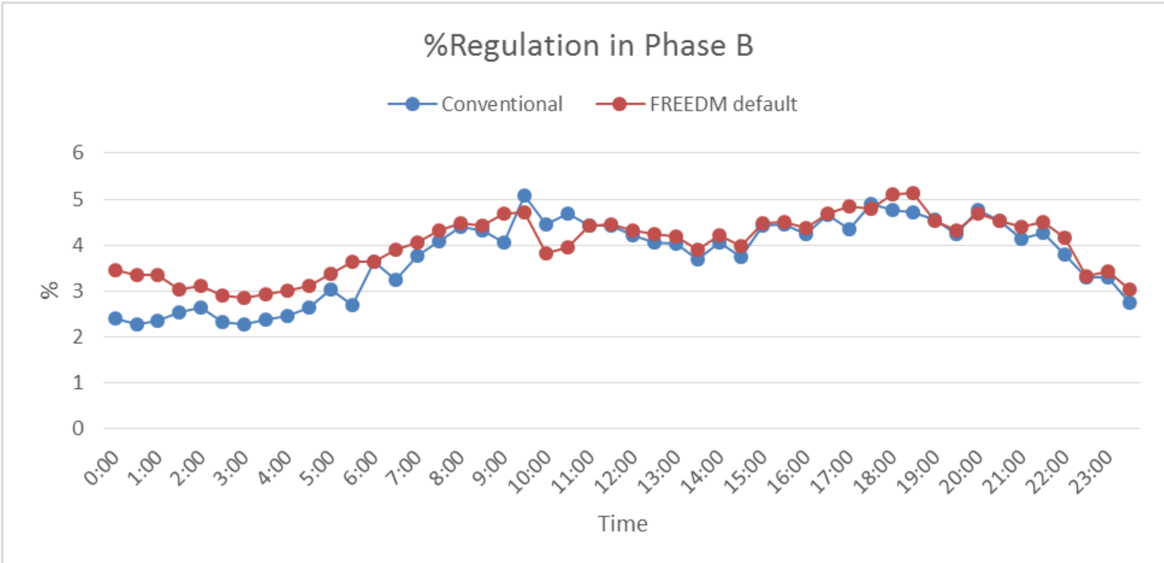

Fig. 2.36 (b)

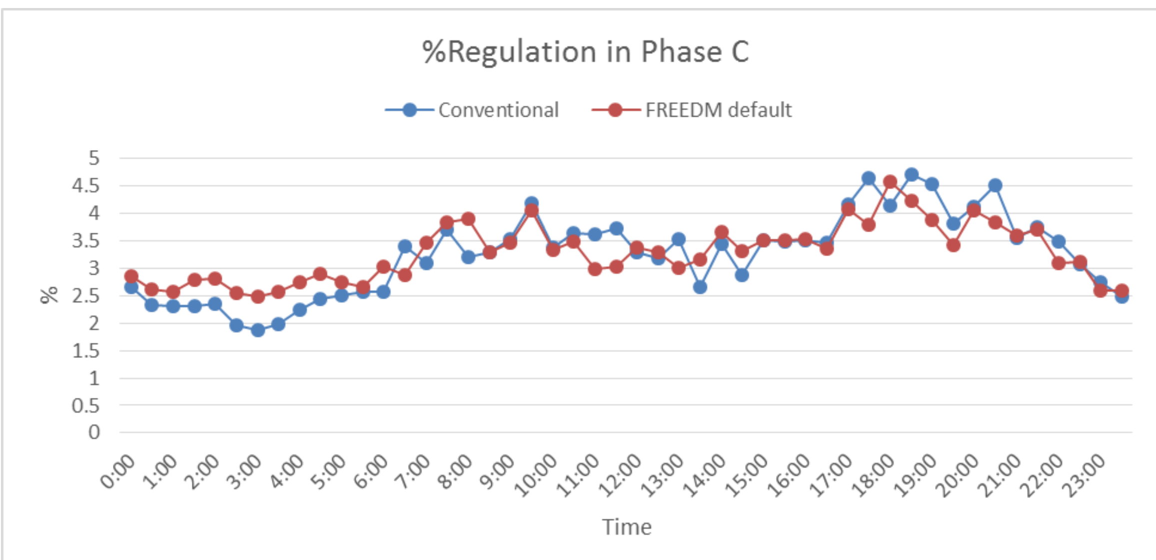

Fig. 2.36 (c)

Fig. 2.36 The system voltage regulation profile during a day without PV penetration

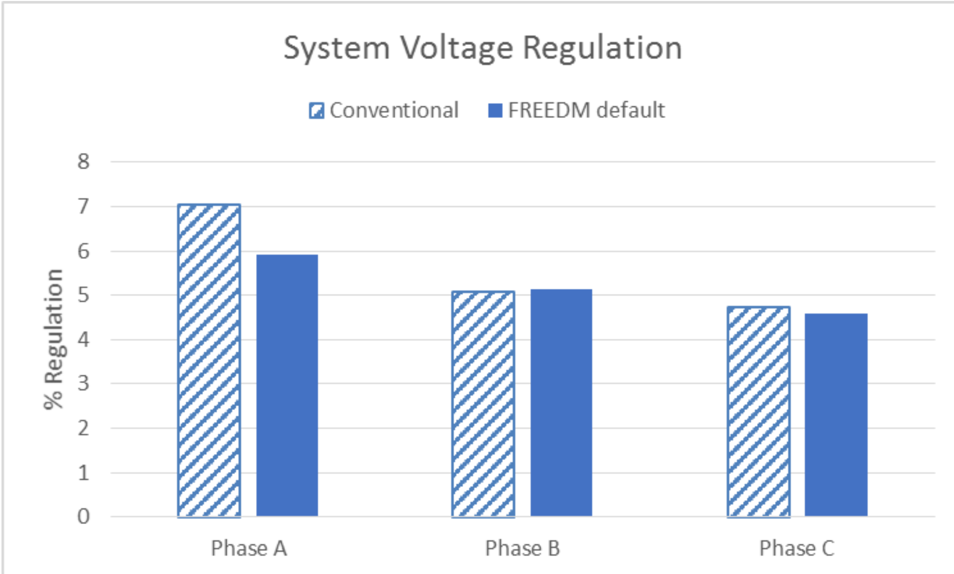

Fig. 2.37 System voltage regulation per phase during a day without PV penetration

4. Voltage Unbalance

From the 24-hour simulation results, for some nodes the voltage unbalance under the FREEDM default control is always less than that under the conventional control. Such phenomenon at Node 814 is shown in Fig. 2.38. However, for other nodes the voltage unbalance under the FREEDM default control is not always less than that under the conventional control, as illustrated in Fig.2.39. The VUI is 0.0284 p.u. in conventional control case and 0.0222 p.u. in FREEDN default control case. The FREEDM default control reduce the VUI by 21.8%. Other voltage unbalance indices are shown in Tab. 2.14

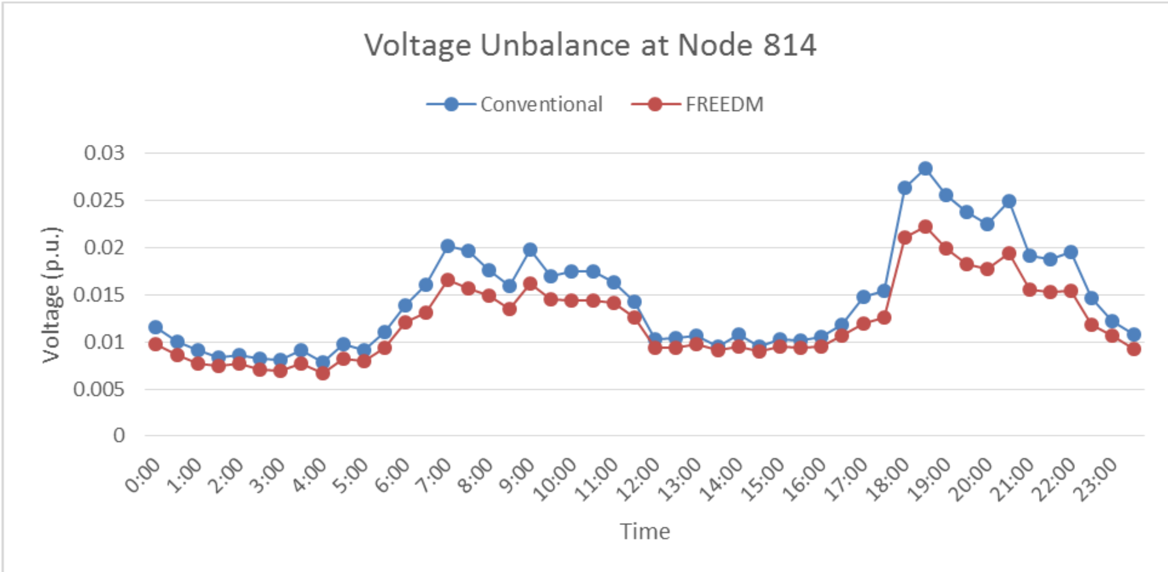

Fig. 2.38 Voltage unbalance at Node 814 during a day without PV penetration

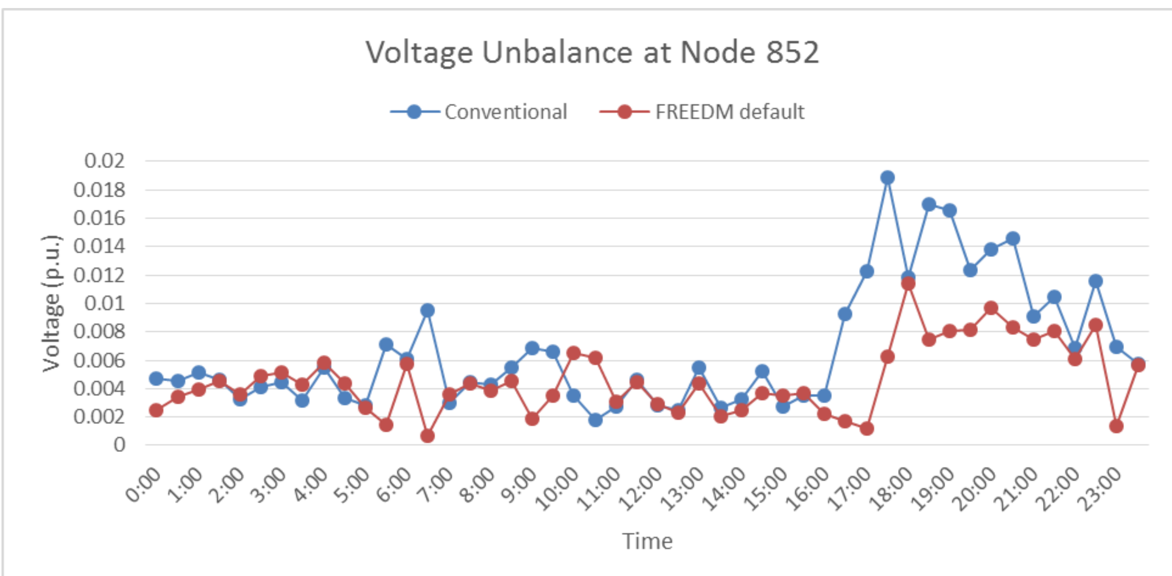

Fig. 2.39 Voltage unbalance at Node 852 during a day without PV penetration

Tab. 2.14 Voltage Unbalance Index of Notional Feeder for zero PV case

	VVC	VUI	%PVUR Index	%VUF Index
Zero PV	Conventional	0.02842	1.45710	0.77464
	FREEDM default	0.02224	1.17134	0.67934

5. Voltage Variation

The voltage Variations (VVs) at each node, under different VVC are shown in Fig. 2.40. Under the FREEDM default VVC, the VVs at each node during a day is always less than those under the conventional VVC. The maximum VVI under FREEDM control is 0.0420 p.u., under conventional control is 0.0573 p.u., shown as in the table below. The FREEDM default control reduces the maximum VVI by 26.70%. As to the voltage variations on the secondary-side, at each node with SST the VV is zero, since the SST can regulate the secondary-side voltage constant [8]. In conventional distribution systems, in which traditional distribution transformers are used, the voltage variations on the secondary-side is the same as those on the primary-side.

The histogram of primary-side voltages under conventional VVC are shown in Fig. 2.41. The histogram of primary-side voltages under FREEDM default VVC are shown in Fig. 2.42.

Tab. 2.15 VVI comparison with no PV penetration

Control	VVI_a	VVI_b	VVI_c	Max(VVI)
Conventional	0.0573	0.0443	0.057	0.0573
FREEDM default	0.0420	0.0361	0.0405	0.0420

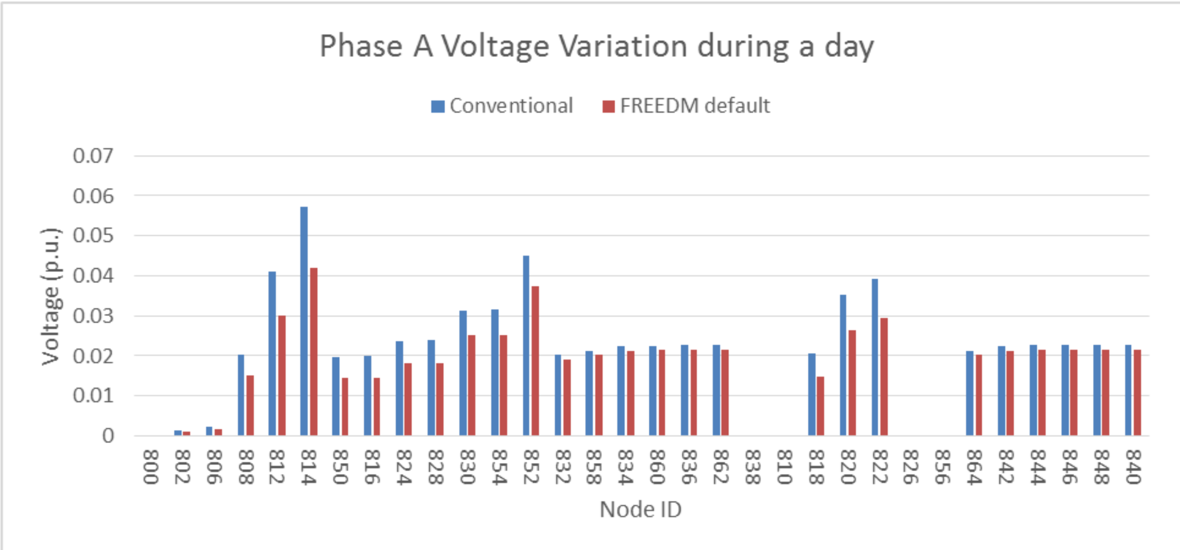

Fig. 2.40 (a)

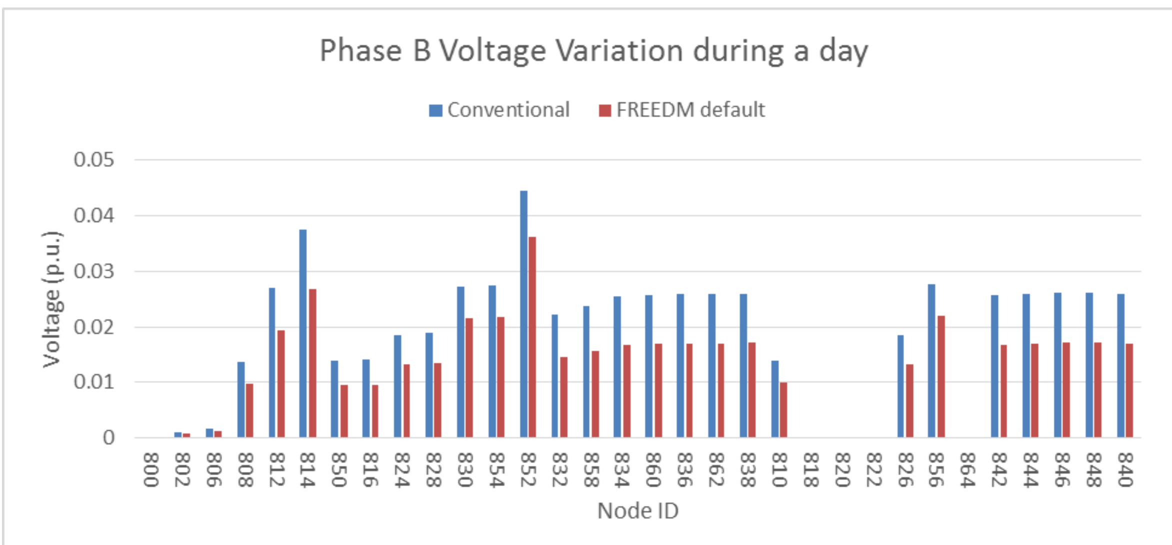

Fig. 2.40 (b)

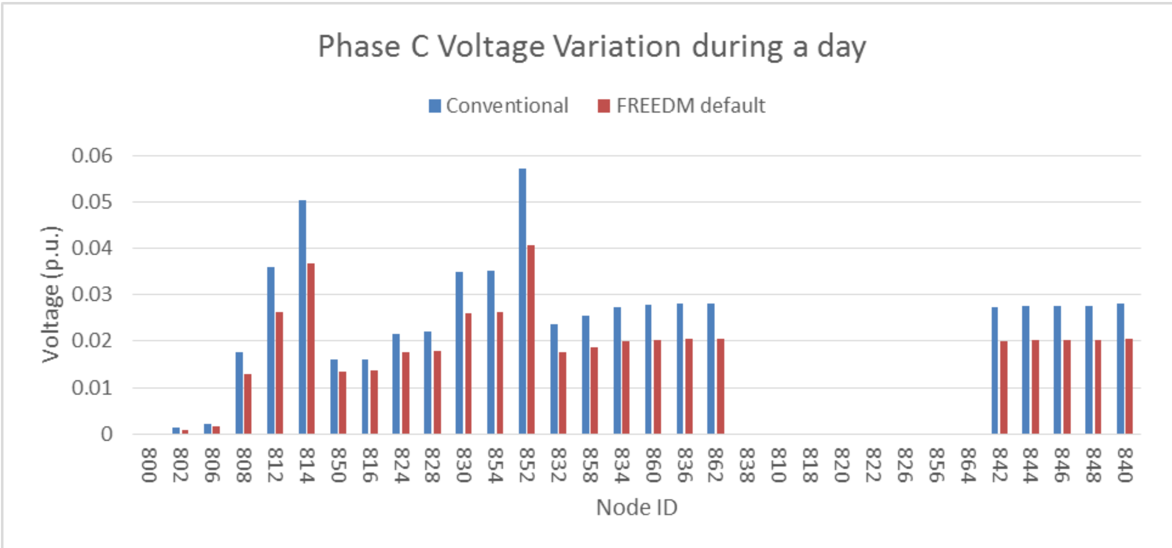

Fig. 2.40 (c)

Fig. 2.40 Voltage Variation without PV penetration

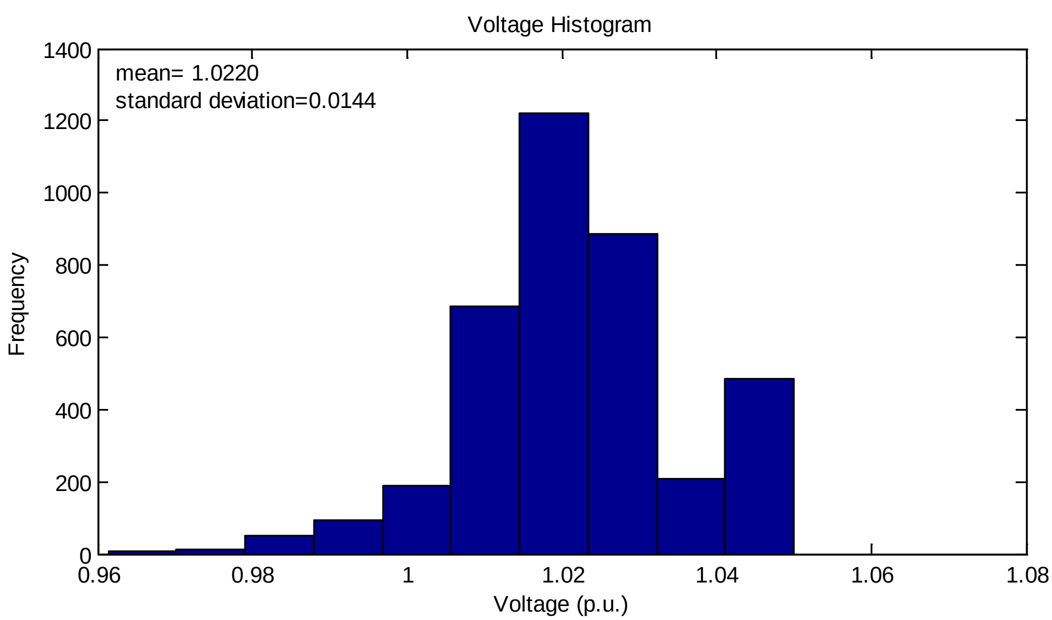

Fig. 2.41 Histogram of voltages on the primary-side of the IEEE 34 feeder under conventional VVC (zero PV)

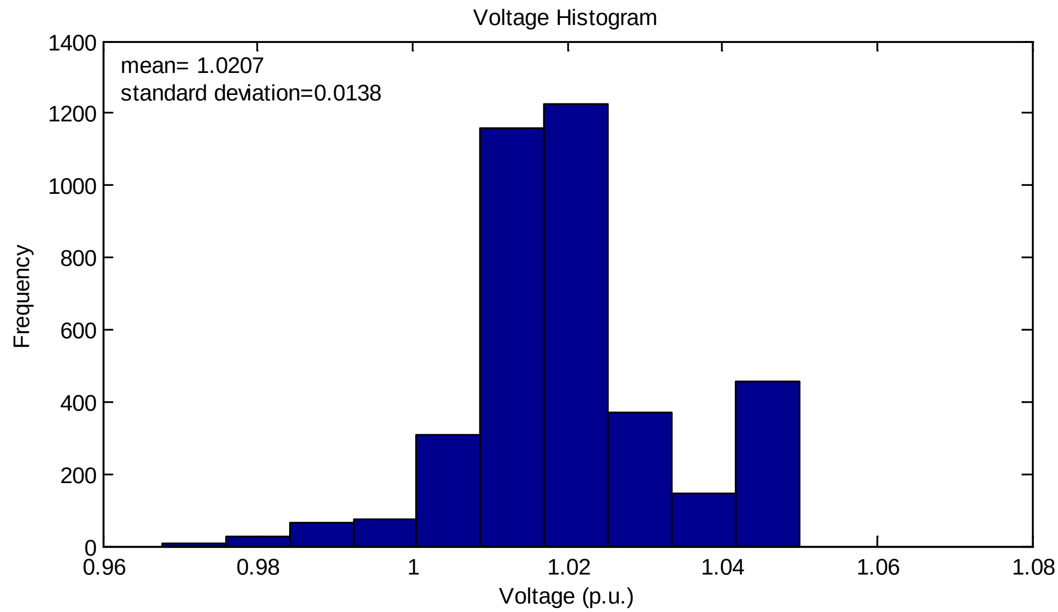

Fig. 2.42 Histogram of voltages on the primary-side of the IEEE 34 feeder under FREEDM default VVC (zero PV)

6. Voltage Regulator Tap Change

Voltage regulators change tap positions corresponding to the load variations during a day, Fig. 2.43 shows the tap positons of the two voltage regulators under both control scheme during a day. The Voltage Regulator Tap Change of the two voltage regulators are shown in Tab.2.12. For either voltage regulator, the tap position changes under FREEDM control is always less or equal to those under the conventional default control. The VRTCI of those two voltage regulators has the same trend, as shown in Tab.2.17.

The number of operations of the two VRs are shown in Tab. 2.17.

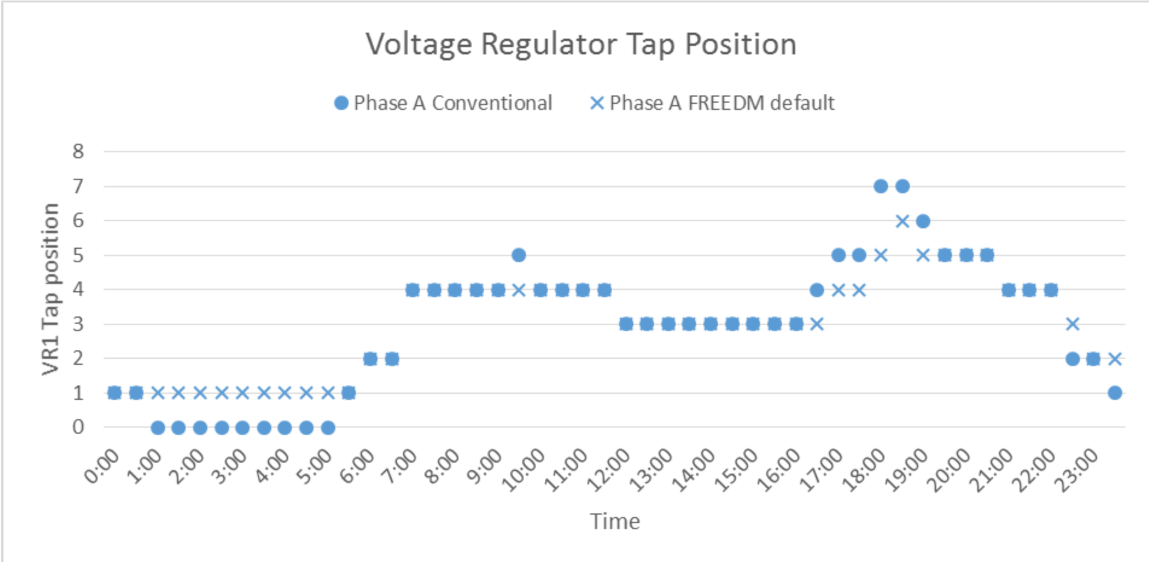

Fig. 2.43 (a) VR1

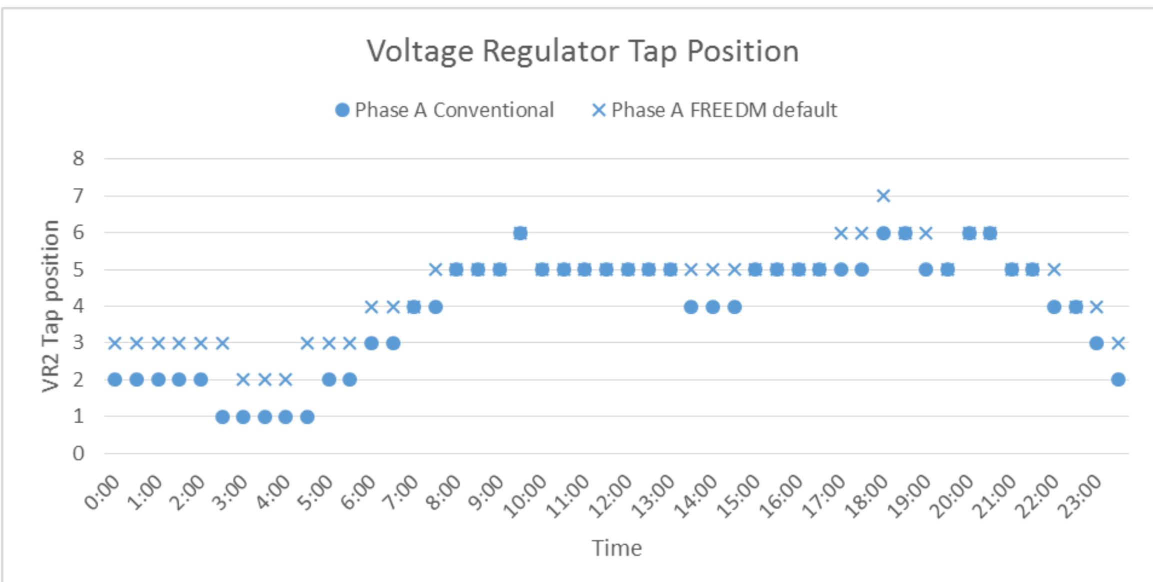

Fig. 2.43 (b)VR2

Fig. 2.43 Phase A tap positions of the two VRs during a day without PV penetration

Tab. 2.16 Tap change of the VRs during a day without PV penetration

VRTC	VVC	Phase A	Phase B	Phase C	VRTCI
VR1	Conventional	7	5	6	7
	FREEDM default	5	3	5	5
VR2	Conventional	5	4	6	6
	FREEDM default	5	4	4	5

Tab. 2.17 Number of operations of the VRs during a day without PV penetration

#Operations	VVC	Phase A	Phase B	Phase C	#Op Index
VR1	Conventional	16	13	14	16
	FREEDM default	9	7	15	15
VR2	Conventional	17	15	17	17
	FREEDM default	13	11	10	13

High PV Penetration

Since there is no PV output during the peak load time, 18:30, and the tap positions of the two voltage regulators remain the same as those in Case 3. Therefore, all simulations under the peak load condition have the same results with Case 3. For the system with PV connected, the FREEDM VCC is still effective under peak load condition.

Case 4:

In this case, a 24-hour simulation is conducted to explore if the FREEDM VVC is still effective when there is high PV penetration in the system.

The corresponding simulation results are as follows.

1. Voltage Profile

Under the conventional control, primary-side voltages ranges from 0.9614p.u. to 1.0628p.u.. The maximum voltage occurs at Node 814 in Phase C at noon. Under the FREEDM default control, primary-side voltages ranges from 0.9676p.u. to 1.0604p.u.. The maximum voltage occurs at Node 814 in Phase C at noon as well. In both cases, the system suffers voltage violations. The regulating points of the two voltage regulators are both downstream of the voltage regulators. However, Node 814 is located upstream of the voltage regulators, and Node 800 is regulated at 1.05 p.u. by the LTC at substation. At noon the PV generation exceeds the load, resulting in reverse power flow. When power goes from Node 814 to Node 800, the voltage at Node 814 will be higher than the voltage at Node 800, thus violating the upper voltage limit. The 24-hour Phase C voltage profile at Node 814 is shown in Fig. 2.44.

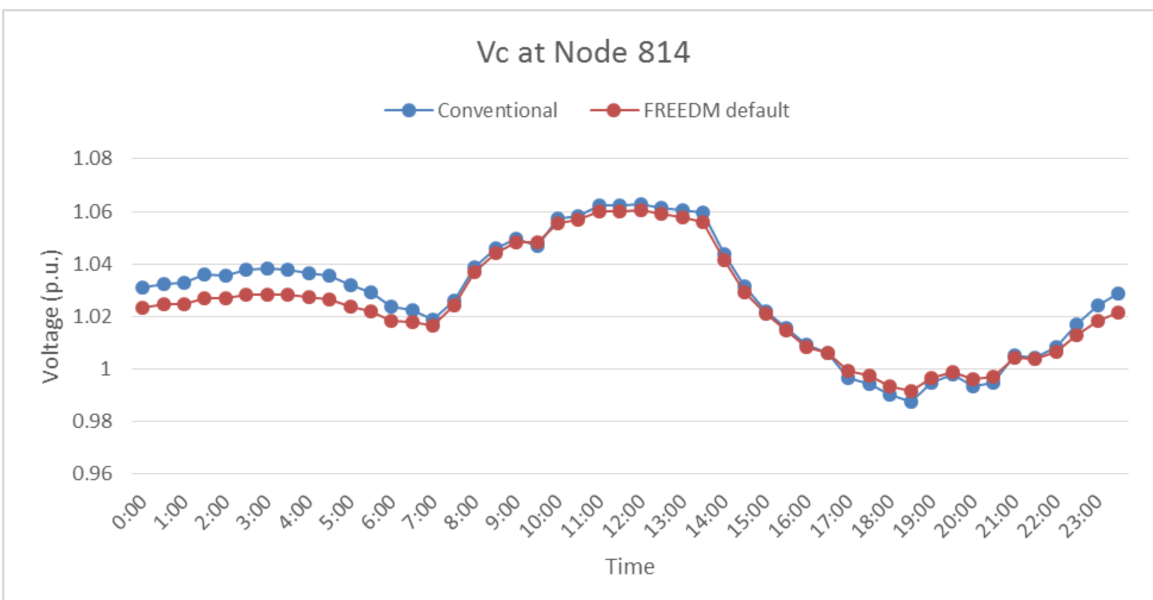

Fig. 2.44 Phase C voltage profile at Node 814 with high PV penetration

2. Power Loss and Energy Loss

As shown in Fig. 2.45, under FREEDM default control, the 24-hour power loss ranges from 3.82kW at 13:30 to 204.12kW at 18:30, with a loss percentage range of 0.37%-12.28% respectively. Under conventional control the power loss is always higher during a day, which indicates the FREEDM VVC mitigates the issue of power loss better. Under FREEDM default control, the primary-side energy loss is 1500.725kWh for a day, which is less than 1726.457kWh under conventional control. The sum of both primary-side and secondary-side energy loss is 1913.175 kWh under conventional VVC, and 2061.774 kWh under FREEDM default control. Thus, the FREEDM default control can reduce primary-side energy loss, but it increases the total loss on both primary and secondary sides.

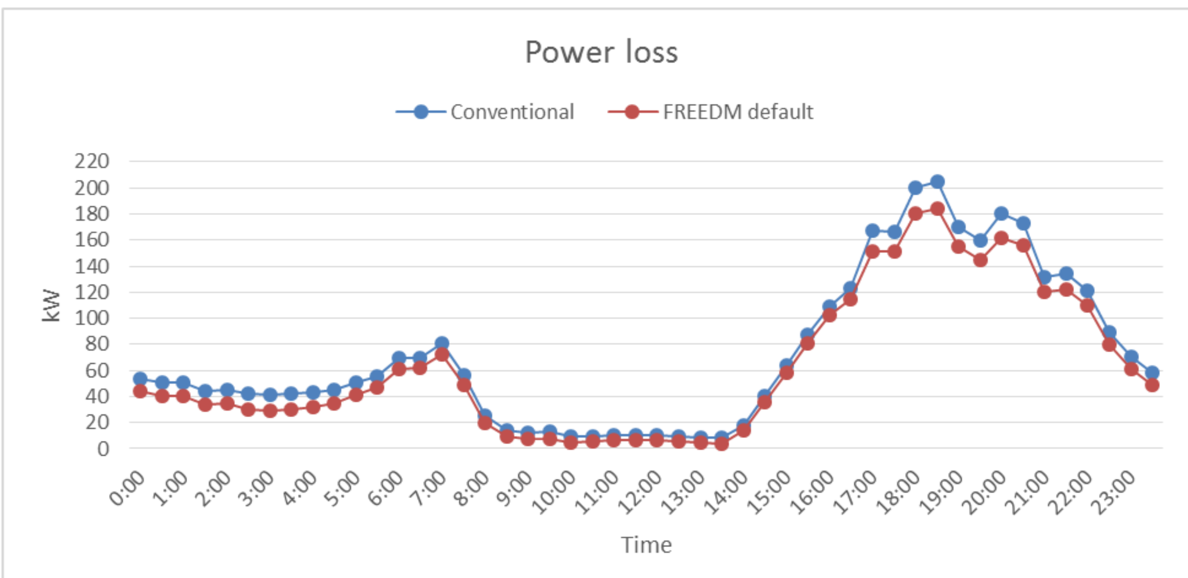

Fig. 2.45 Power loss during a day with high PV penetration

Tab. 2.18 Daily energy loss with high PV penetration

	Conventional	FREEDM default
Energy loss for one day (kWh)	1726.457131	1500.724528
Energy loss percentage (%)	6.726963311	5.847419353

3. Voltage Regulation

In the results of 24-hour simulation, for Phase A, the maximum voltage regulations in both control cases occur under peak load condition, at 18:30, 7.03% under conventional VVC, 5.91% under FREEDM default VVC. For Phase B the maximum %Regulation under conventional control is 4.91% at 17:30, while in FREEDM default control case the maximum %Regulation is 5.12% at 18:30. For Phase C, the maximum %Regulation under conventional control is 4.72% at 18:30, while in FREEDM default control case the maximum %Regulation in the same phase occurs at 18:00 with a value of 4.58%. A comparison of maximum %Regulation at each phases during 24 hours is shown in Fig. 2.46. The VRI has the same results as the system with zero PV penetration. The FREEDM VVC still reduces the VRI by 15.97% if the PV penetration is high.

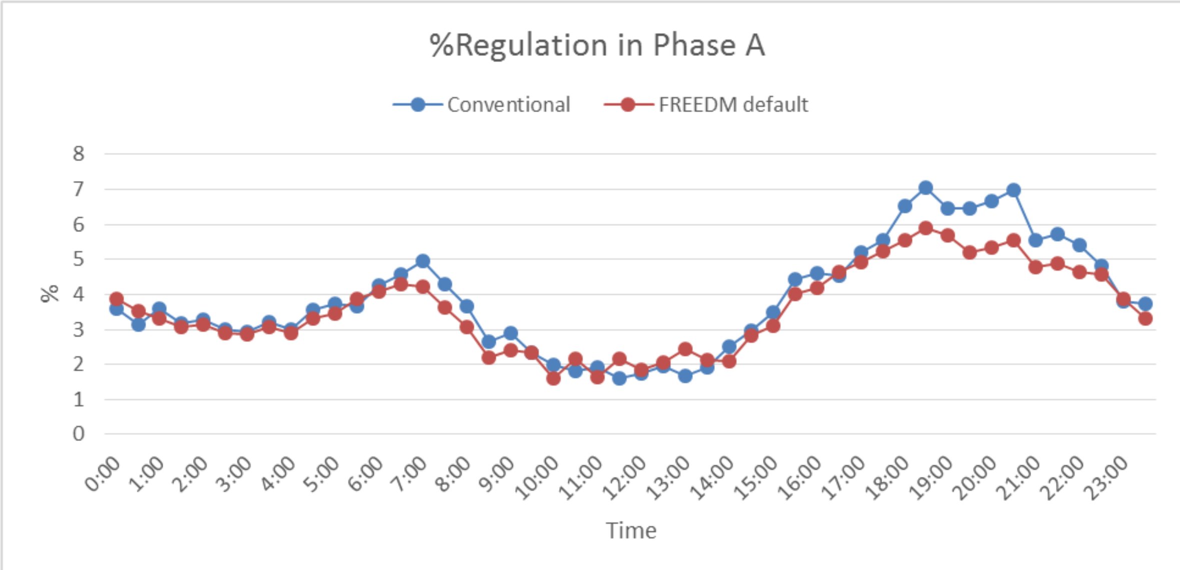

Fig. 2.46 (a)

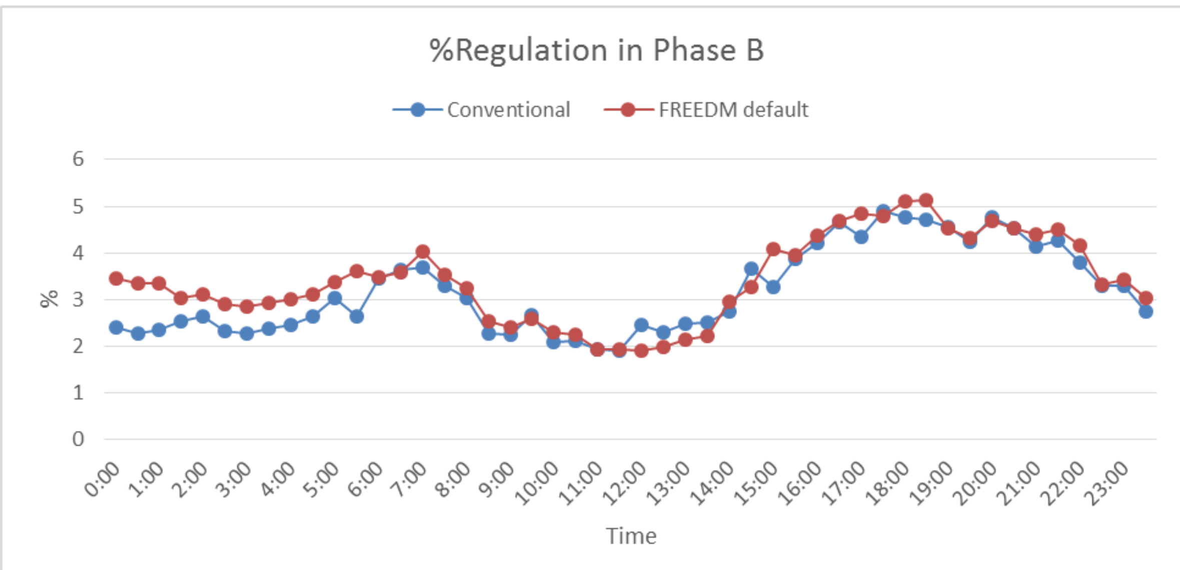

Fig. 2.46 (b)

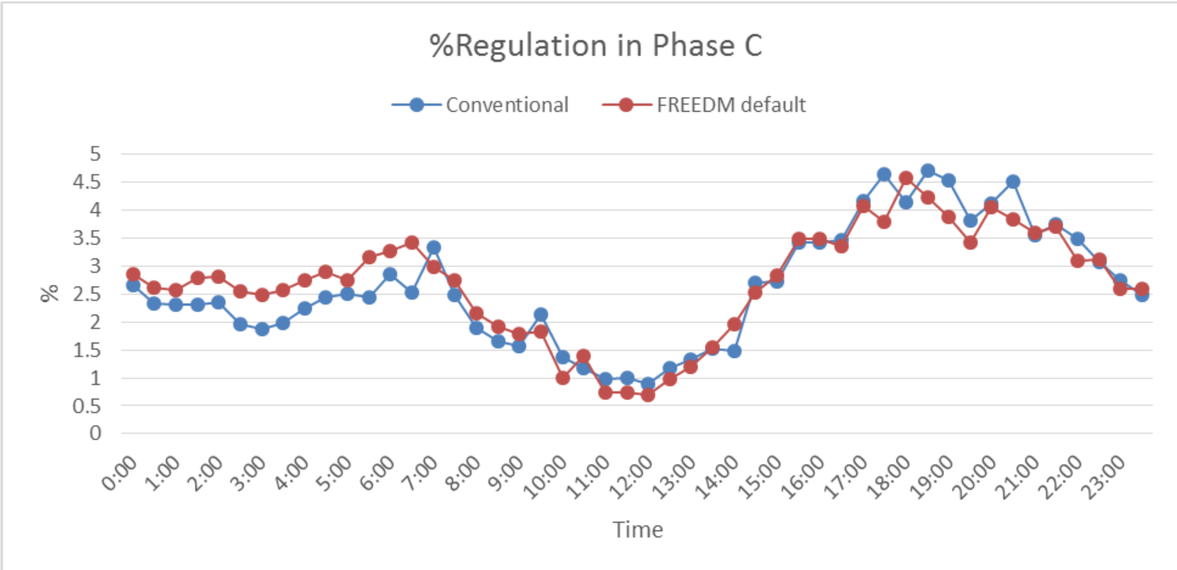

Fig. 2.46 (c)

Fig. 2.46 The system voltage regulation profile during a day with high PV penetration

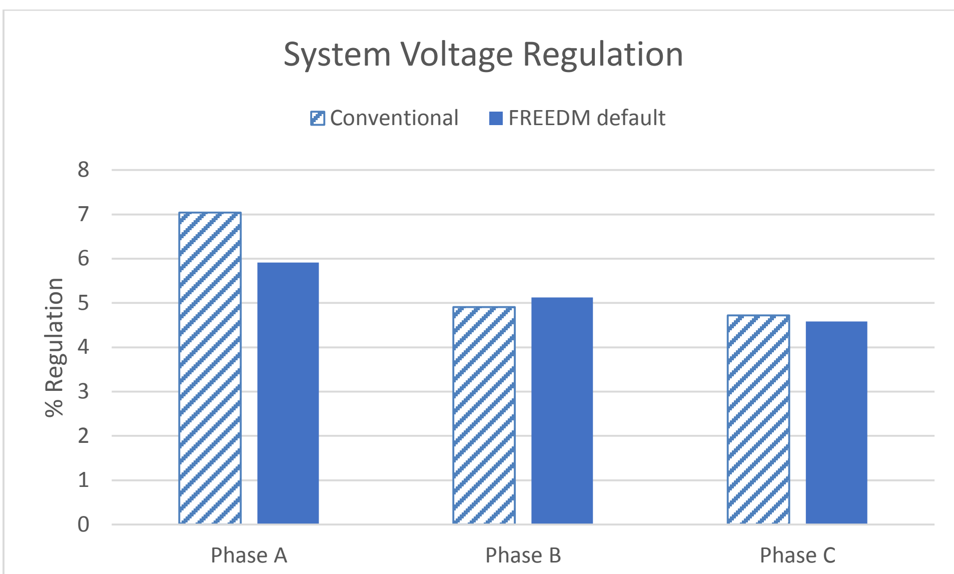

Fig. 2.47 System voltage regulation per phase during a day with high PV penetration

4. Voltage Unbalance

From the 24-hour simulation results, for all the nodes, the voltage unbalance under the FREEDM default control is not always less than that under the conventional control. Such phenomenon at Node 814 and Node 852 is shown in Fig. 2.48. However, VUIs are the same as the results of zero-PV penetration case. The VUI is 0.0284 p.u. in conventional control case and 0.0222 p.u. in FREEDM default control case. The FREEDM default control reduces the VUI by 21.8%. Other voltage unbalance indices are shown in Tab. 2.19

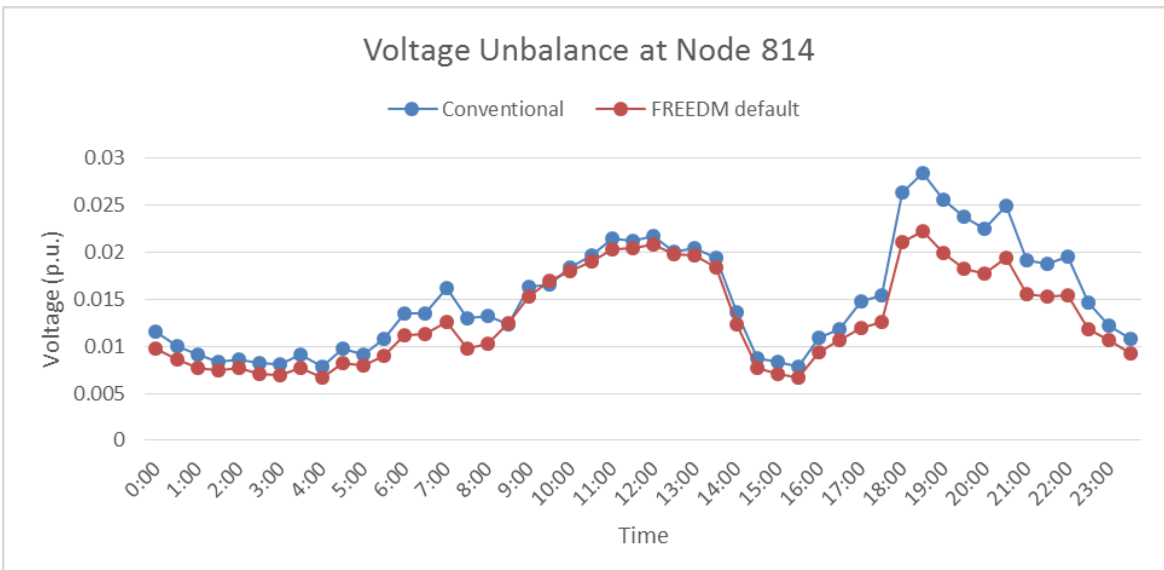

Fig. 2.48 (a) Voltage unbalance at Node 814 during a day with high PV penetration

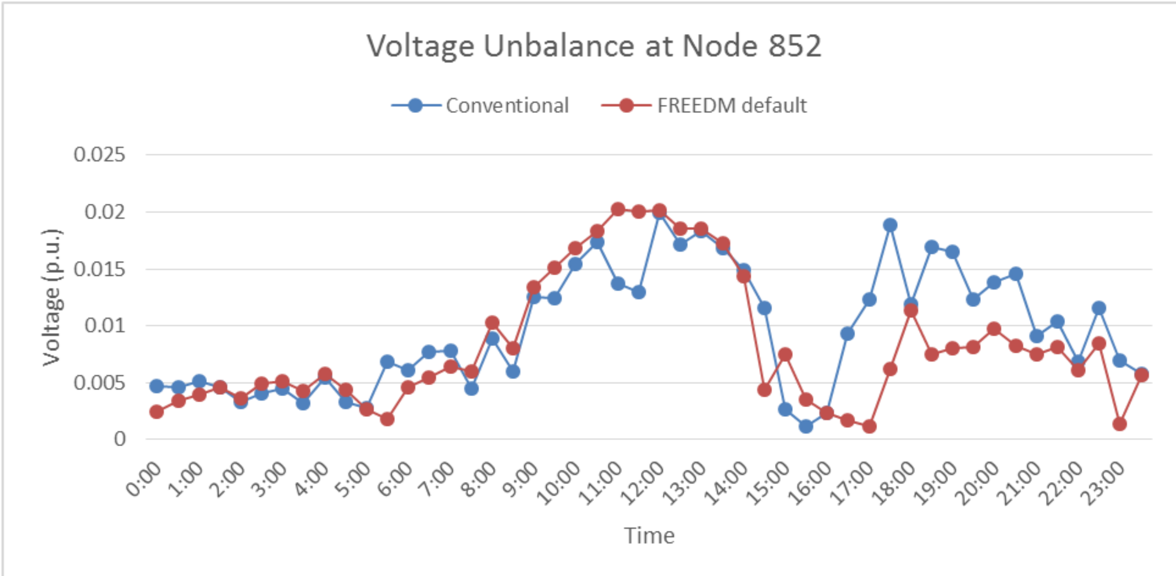

Fig. 2.48 (b) Voltage unbalance at Node 814 during a day with high PV penetration

Tab. 2.19 Voltage Unbalance Index of Notional Feeder for high PV case

	VVC	VUI	%PVUR Index	%VUF Index
High PV	Conventional	0.02842	1.45710	0.77464
	FREEDM default	0.02224	1.27064	0.72597

5. Voltage Variation

The voltage Variations (VVs) at each node, under different VVC are shown in Fig. 2.49. Different from the results of case3 (the zero-PV penetration case), under the FREEDM default VVC, the VVs at some nodes during a day are always less than those under the conventional VVC. But for other nodes, such as Node 852, under the FREEDM default VVC, the VVs in certain phase are higher than that under the conventional VVC. However, the maximum VVI under FREEDM control is 0.0812 p.u., while under conventional control is 0.08423 p.u., shown as in Tab. 2.20. The FREEDM default control still reduces the maximum VVI, but with a smaller reduction of 3.56%.

As to the voltage variations on the secondary-side, at each node with SST the VV is zero, since the SST can regulate the secondary-side voltage constant [8]. In conventional distribution systems, in which traditional distribution transformers are used, the voltage variations on the secondary-side are the same as those on the primary-side.

The histogram of primary-side voltages under conventional VVC is shown in Fig. 2.50. The histogram of primary-side voltages under FREEDM default VVC is shown in Fig. 2.51.

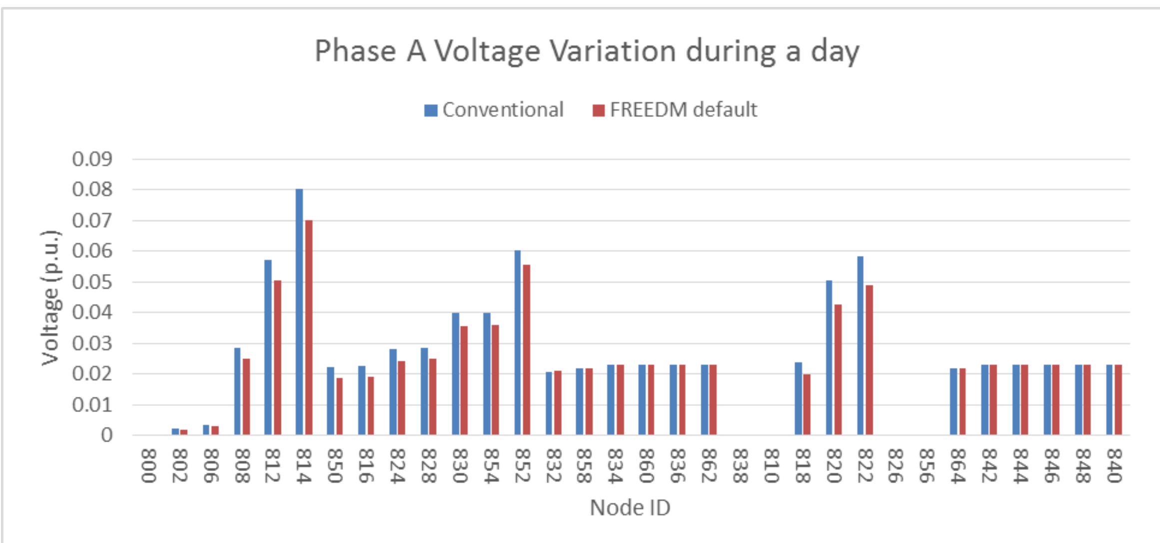

Fig. 2.49 (a)

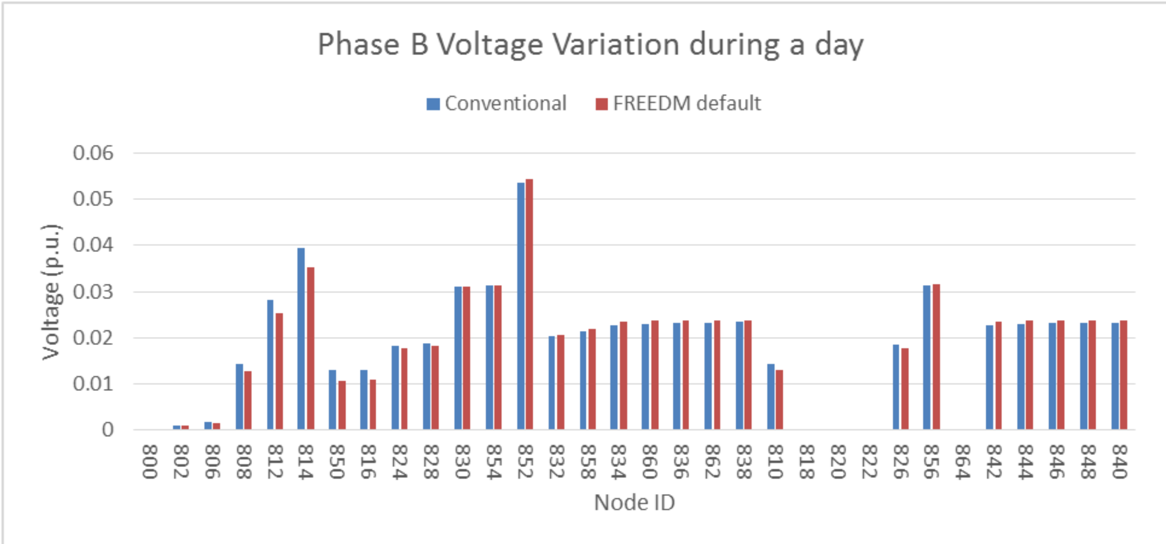

Fig. 2.49 (b)

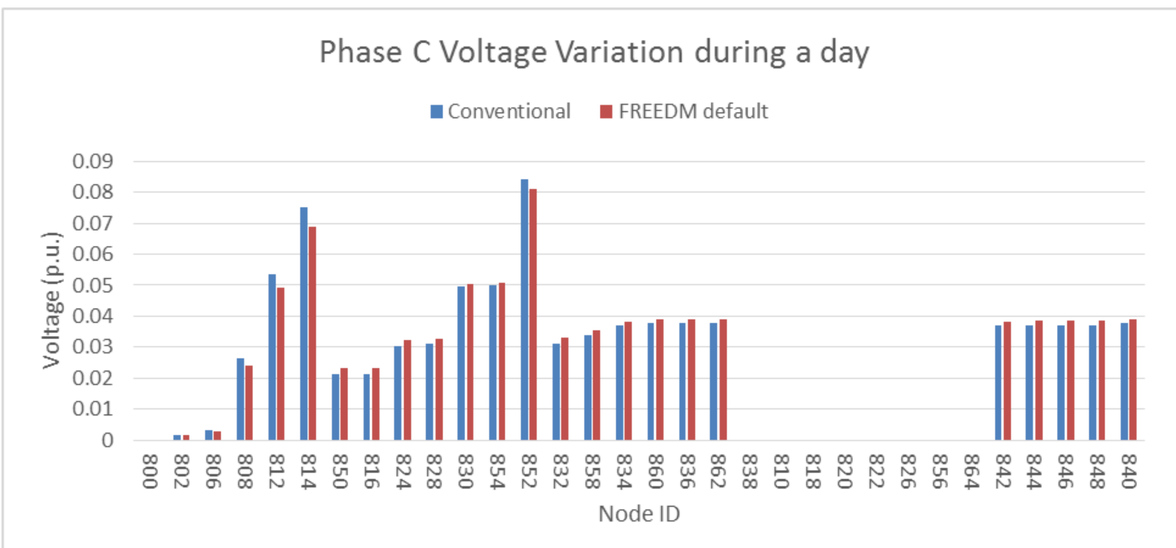

Fig. 2.49 (c)

Fig. 2.49 Voltage Variation with high PV penetration

Tab. 2.20 VVI comparison with high PV penetration

Control	VVI_a	VVI_b	VVI_c	Max(VVI)
Conventional	0.0801	0.0536	0.0842	0.0842
FREEDM default	0.0702	0.0543	0.0812	0.0812

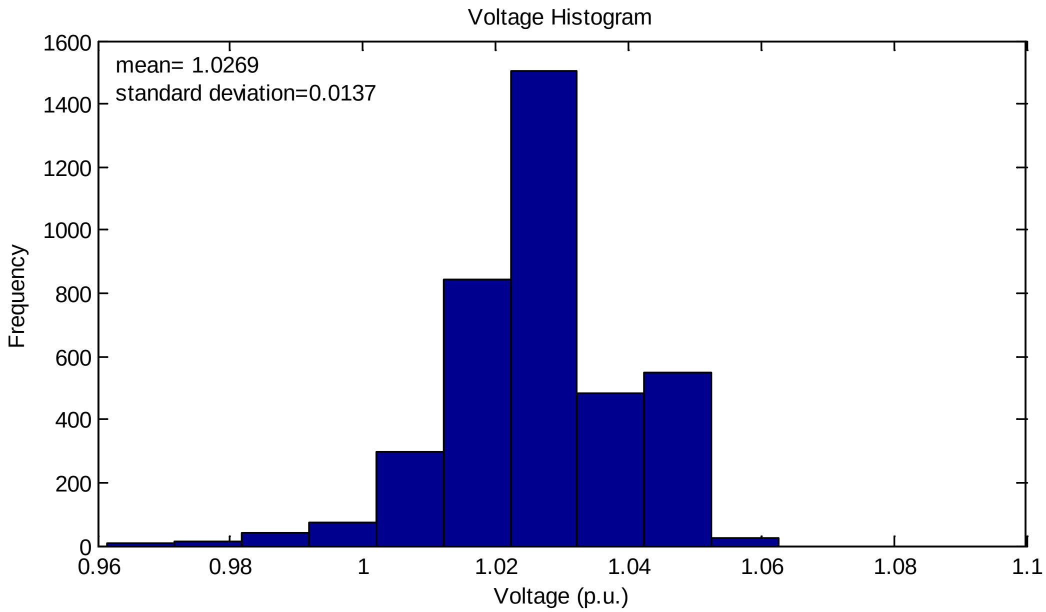

Fig. 2.50 Histogram of voltages on the primary-side of the IEEE 34 feeder under conventional VVC (high PV)

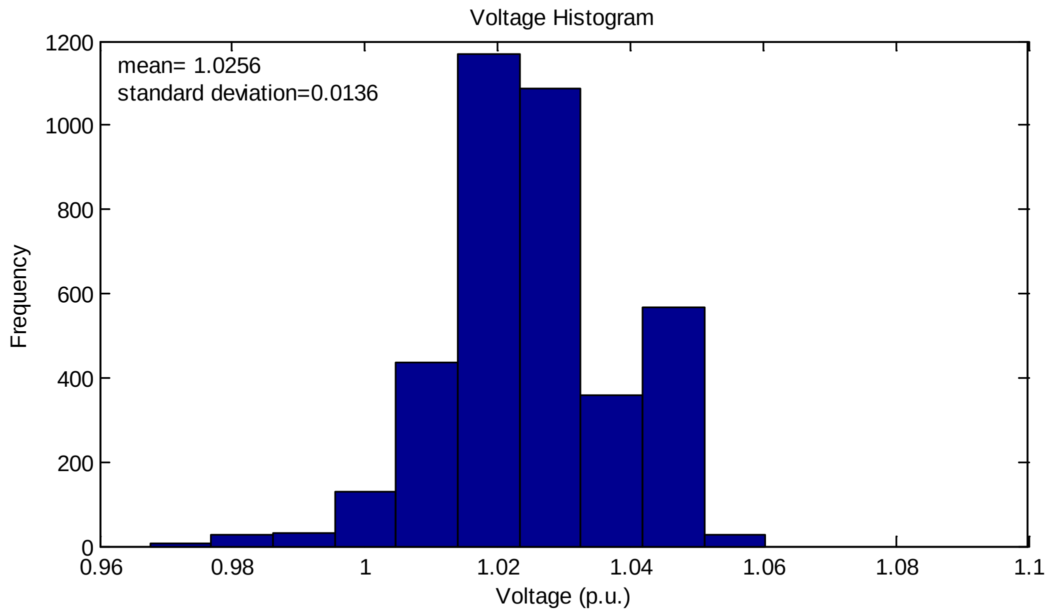

Fig. 2.51 Histogram of voltages on the primary-side of the IEEE 34 feeder under FREEDM default VVC (high PV)

6. Voltage Regulator Tap Change

Fig 2.52 shows the tap positons of the two voltage regulators under both control schemes, during a day. The Voltage Regulator Tap Change of the two voltage regulators are shown in Tab.2.21. For either voltage regulator, under FREEDM control the tap position changes are always less than those under the conventional default control. The VRTCIs of those two voltage regulators have the same trend, as shown in Tab.2.21. From this point, the FREEDM default VVC can still reduce the device cost when there is high PV penetration in the system. The number of operations of the two VRs are shown in Tab. 2.22.

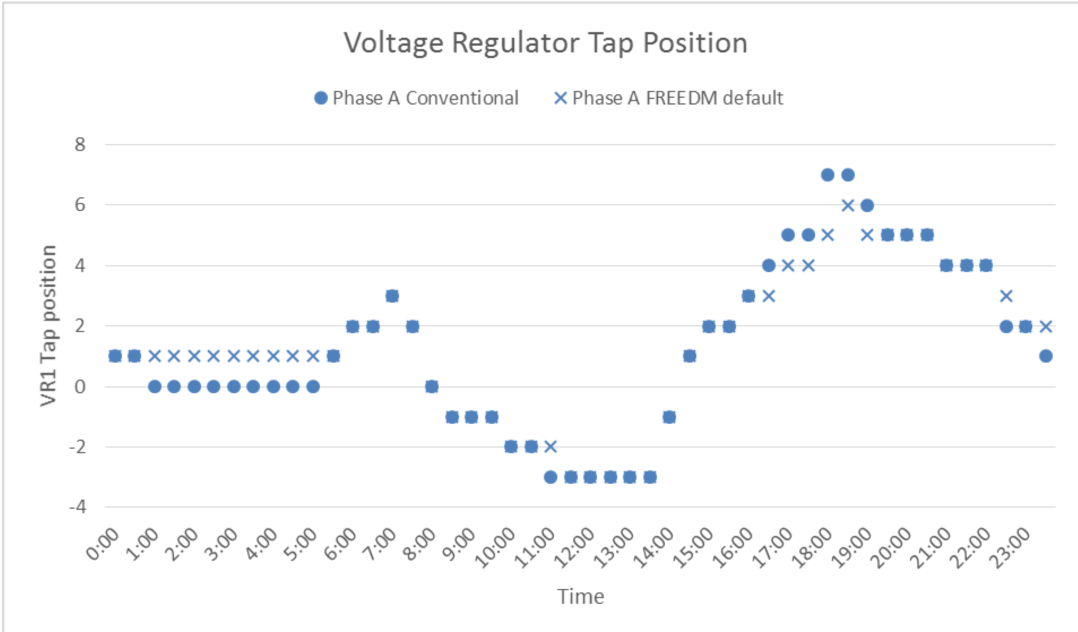

Fig. 2.52 (a)

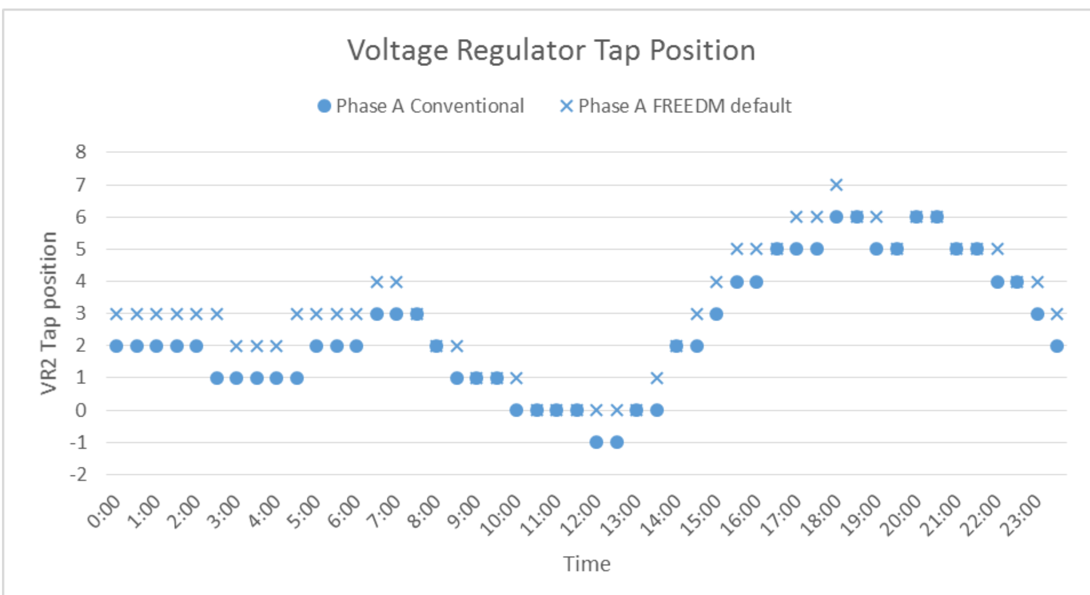

Fig. 2.52 (b)

Fig. 2.52 Phase A tap positions of the two VRs during a day with high PV penetration

Tab. 2.21 Tap change of the VRs during a high-PV day

VRTC	VVC	Phase A	Phase B	Phase C	VRTCI
VR1	Conventional	10	6	9	10
	FREEDM default	9	4	8	9
VR2	Conventional	7	6	9	9
	FREEDM default	7	6	8	8

Tab. 2.22 Number of operations of the VRs during a high-PV day

#Operations	VVC	Phase A	Phase B	Phase C	#Op Index
VR1	Conventional	22	15	18	22
	FREEDM default	17	9	19	19
VR2	Conventional	20	17	21	21
	FREEDM default	19	15	16	19

2.4.2 Summary

1. The primary-side voltages in the system can be regulated within the recommended service voltage range of 0.95-1.05 p.u. (range A by ANSI C84.1) under both the conventional and FREEDM default control schemes. But when there is high PV penetration in the system, the voltages violates the upper limit under both Volt/Var control schemes.

2. Under peak load condition, the primary-side power loss under the conventional control is 204.93kW; with the FREEDM default control the power loss is 183.77kW. A reduction of 10.33% is achieved. In a zero-PV day, the primary-side energy loss under conventional control is 2505.5kWh, under FREEDM default control is 2263.2kWh. The FREEDM default control reduces the primary-side energy loss by 9.67%. In a high-PV day, the primary-side energy loss under the conventional control is 1726.5kWh, under FREEDM default control is 1500.7kWh. A reduction of 13.07% is achieved. When considering the

secondary-side loss, the FREEDM VVC has more total energy loss than the conventional control.

3. The FREEDM default control can reduce the voltage regulation of the feeder. The VRI under conventional control is 7.03%, under FREEDM control is 5.91%. A reduction of 15.97% is achieved by the FREEDM default control scheme.

4. The FREEDM default control greatly reduces the voltage unbalance of the system. The VUI is 0.0652 p.u. under the FREEDM default control, and 0.0416 p.u. under conventional control. A reduction of 36.2% is achieved by the FREEDM default control scheme.

5. The FREEDM default control also reduces the voltage variation on the primary-side under different operating conditions during a day. In a zero-PV day, the maximum VVI among three phases is 0.0573 p.u. under FREEDM default control, and 0.0420 p.u. under conventional control. The FREEDM default control scheme achieves a voltage variation reduction of 26.70%. In a high-PV day, the maximum VVI among three phases is 0.0842 p.u. under FREEDM default control, and 0.0812 p.u. under conventional control. The FREEDM default control scheme achieves a voltage variation reduction of 3.56%. Besides, the FREEDM control guarantees a zero voltage variation on the secondary-side.

6. The FREEDM default control always has less VRTC for each phase than those under conventional control, thus less control cost for the voltage regulators.

Chapter 3 Alternative Volt/Var Control Schemes for FREEDM Systems

The objectives of Volt/Var control includes maintaining the voltages within acceptable limits, reducing power and energy loss, and reducing voltage unbalance and variation. The most common methods of Volt/Var Control are direct voltage regulation and Var compensation. The load tap changer (LTC) and voltage regulator (VR) are such devices that can regulate voltage directly like a transformer. Also for Var compensation, SSTs can be used to provide reactive power support in FREEDM Systems. Thus alternative VVC schemes can be designed for the FREEDM systems by utilizing these two methods.

The following subsections illustrate the adoption of these two methods for a given system.

3.1 Option I: Var Compensation for Volt/Var Control on FREEDM systems

This option uses only the Var compensation provide by SSTs on a FREEDM system. As illustrated in previous chapter, SSTs operating at unity power factor alone provide a good voltage profile for feeders with moderate voltage drop. In such cases, SSTs can provide extra voltage boost when needed, and that may be enough to keep the voltages within limits.

Under FREEDM default control, the control variable Q_{inj}, also the reactive power injected at each node is zero. With the increasing reactive power provided by SST the effectiveness of Volt/Var control can be improved. This can be justified by the following two simulations.

Case 1: Var Compensation on the FREEDM Notional Feeder

In this case, the Q_{inj} from SSTs on the FREEDM Notional Feeder is changed from 0 to -50 kVar under peak load condition. The LTC at substation still regulate the voltage at Node 0 at 1.0 p.u..

Tab. 3.1-3.3 show the simulation results under peak load condition. These results show that as Q_{inj} increases, the voltages at the nodes is boosted along the feeder, as expected, shown in Fig. 3.1. Fig. 3.2 shows the %Regulation of Node 9.

Tab. 3.1 Simulation results for Case 1.1

Case 1.1: $Q_{inj} = -5kVar$				
Node ID	Va	Vb	Vc	
0	1	1	1	
1	0.983509	1.002017	0.986139	
2	0.980886	1.000762	0.987764	
3	0.980823	1.000158	0.98823	
4	0.981063	1.00003	0.988075	
5	0.97905	1.006035	0.975749	
6	0.977962	1.00619	0.966693	
7	0.977934	1.003381	0.962034	
8	0.977873	1.003205	0.961746	
9	0.977535	1.002981	0.961463	Total
Psub (kW)	3140.88	2427.136	2481.347	8049.363
Qsub (kVar)	240.3677	62.38758	89.98993	392.7453
Pload (kW)	3083.85	2433.54	2405.48	7922.87
Ploss (kW)	57.02978	-6.40408	75.86709	126.4928
Loss percentage				1.5966%

Tab. 3.2 Simulation results for Case 1.2

Case 1.2: $Q_{inj} = -20kVar$				
Node ID	Va	Vb	Vc	
0	1	1	1	
1	0.984916	1.003813	0.988118	
2	0.982381	1.002821	0.990049	
3	0.982319	1.002376	0.990718	
4	0.982607	1.002296	0.99061	
5	0.981029	1.008386	0.978318	
6	0.980464	1.009058	0.96981	
7	0.980804	1.006623	0.965534	
8	0.980763	1.006467	0.965266	
9	0.980461	1.006278	0.965019	Total
Psub (kW)	3143.315	2426.456	2479.281	8049.052
Qsub (kVar)	119.0954	-70.2148	-47.481	1.399573
Pload (kW)	3083.85	2433.54	2405.48	7922.87
Ploss (kW)	59.46505	-7.08432	73.80138	126.1821
Loss percentage				1.5926%

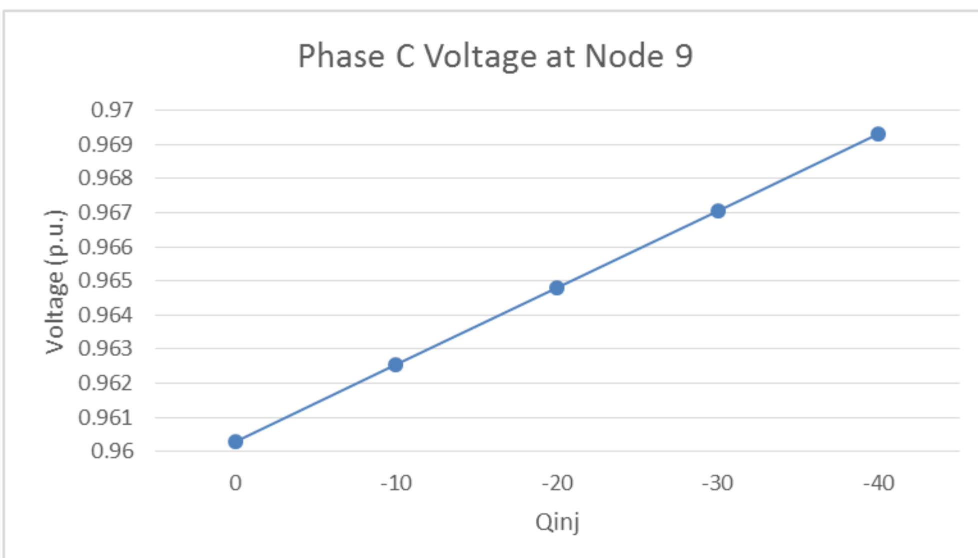

Fig. 3.1 Phase C voltage at Node 9

Tab. 3.3 Simulation results for Case 1.3

Case 1.3: $Q_{inj} = -50kVar$				
Node ID	Va	Vb	Vc	
0	1	1	1	
1	0.987713	1.007378	0.992037	
2	0.985354	1.006908	0.994579	
3	0.985293	1.006778	0.995648	
4	0.985678	1.006795	0.995637	
5	0.984961	1.013049	0.983408	
6	0.985432	1.014747	0.975979	
7	0.986503	1.013053	0.972461	
8	0.986502	1.012938	0.972235	
9	0.986272	1.012819	0.972059	Total
Psub	3148.511	2425.781	2475.584	8049.876
Qsub	-121.804	-333.396	-320.042	-775.242
Pload	3083.85	2433.54	2405.48	7922.87
loss	64.66075	-7.75911	70.10388	127.0055
Loss percentage				1.6030%

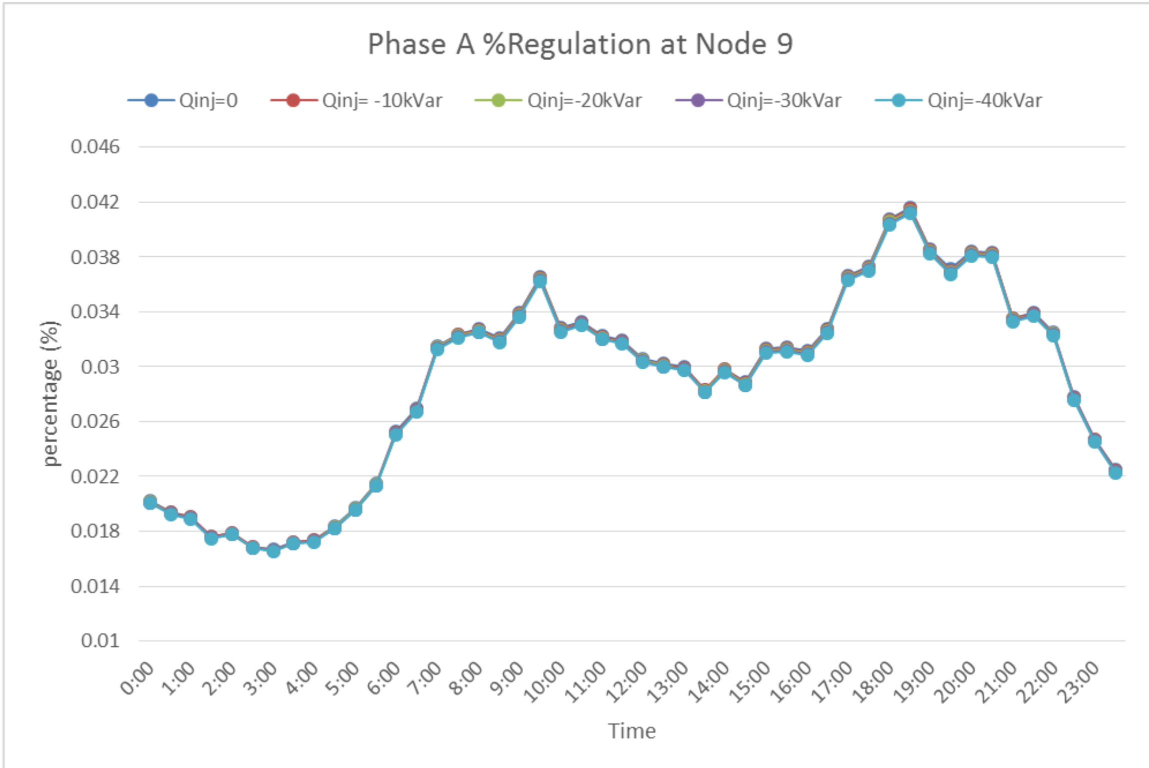

Fig. 3.2 Phase A %Regulation at Node 9 during a day without PV penetration

As to power loss, the loss percentage goes down from 1.597% to 1.593% as Q_{inj} goes from -5kVar to -20kVar. But it then increases to 1.603% as Q_{inj} goes to -50kVar. The absolute value of power loss also decreases first then increases as SSTs provide more reactive power. Simulations for Q_{inj} ranges from 0 to -50kVar, with a gap of 5kVar are all conducted. The respective results are seen in Fig. 3.3. From the graph, we can find some optimal value of Q_{inj} to achieve a minimal power loss.

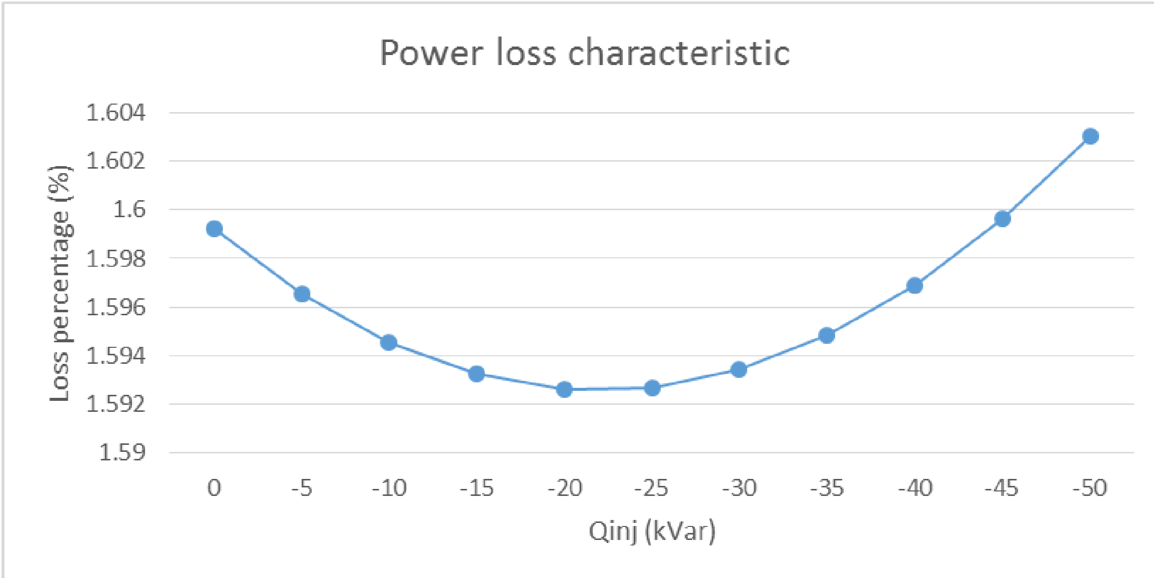

Fig. 3.3 Power loss characteristic with respect to Q_{inj}

In case 1, for the FREEDM notional feeder, we found that Node 9 always has the most Voltage Unbalance and Voltage Variation. Although we change Q_{inj} from 0 to -40kVar, there is little change of voltage unbalance and variation as shown in Fig. 3.4 and Fig. 3.5. It seems that we can design an alternative VVC scheme by just increase the reactive power injected by SST in order to reduce power loss further.

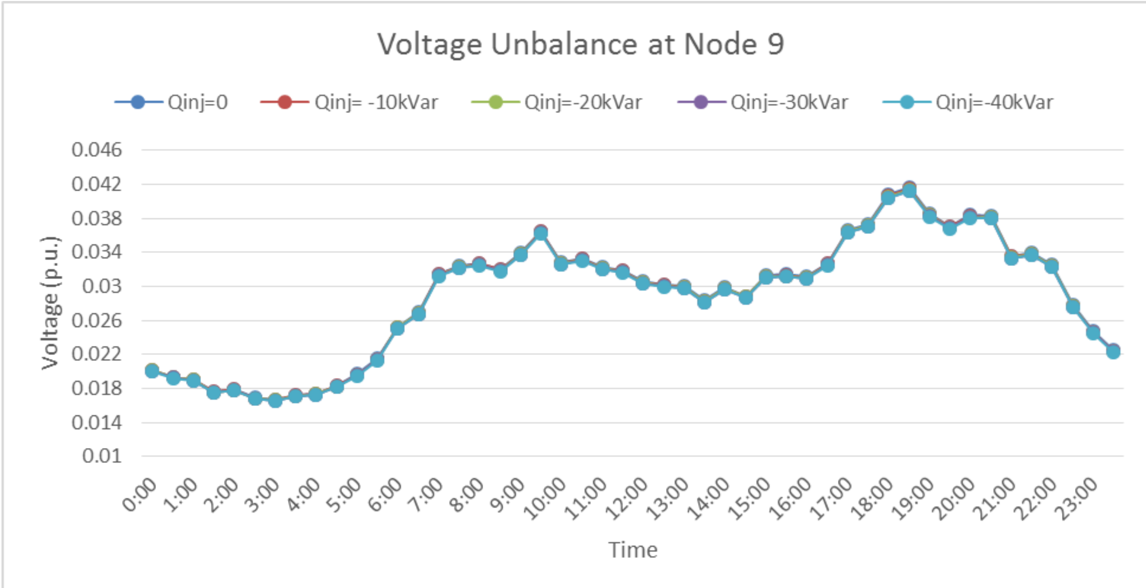

Fig. 3.4 Voltage unbalance at Node 9 for different Q_{inj}

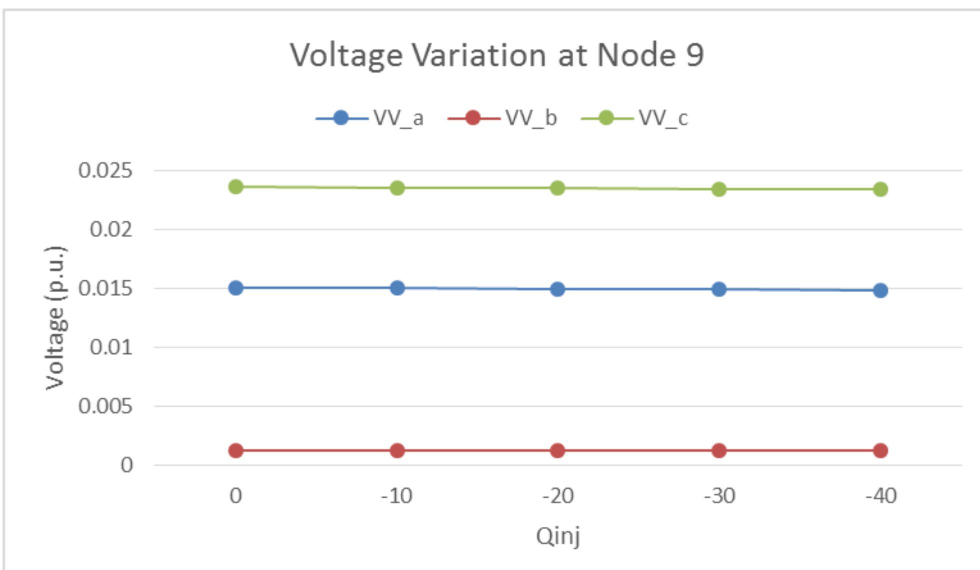

Fig. 3.5 Voltage variation at Node 9 for different Q_{inj}

Case 2: Var Compensation on the FRREDM IEEE 34 Nodes Feeder

In this case, the Q_{inj} on the FREEDM IEEE 34 Nodes Feeder is changed from 0 to -20 kVar under peak load condition. The LTC at substation still regulate the voltage at Node 800 at 1.05 p.u.. And the tap position of the two VRs are kept as in Case 2 of the FREEDM IEEE 34 Nodes Feeder.

Case 2.1: In this case, $Q_{inj} = -5kVar$ under peak load condition.

Case 2.2: In this case, $Q_{inj} = -10kVar$ under peak load condition.

Case 2.3: In this case, $Q_{inj} = -15kVar$ under peak load condition.

Case 2.4: In this case, $Q_{inj} = -20kVar$ under peak load condition.

As in previous case, increasing the Q_{inj} boosts the voltages on the feeder. Fig.3.6 shows the phase C voltage profiles at Node 852 with increasing Q_{inj}. In case 2.1, 2.2 and 2.3, all voltages are within the range 0.95 p.u.-1.05 p.u. In case 2.4, voltage at Node 832, Phase B exceeds 1.05 p.u., indicating that over Var injection by SSTs would result in voltage violation. . Among all feeder ends, Node 822 always has the maximum %Regulation as the change of Q_{inj}. %Regulation at Node 822 decreases as SSTs inject more reactive power, as illustrated in Fig. 3.7. Unlike the Notional Feeder, on which Q_{inj} has little influence on the voltage, in the IEEE 34 Nodes system Q_{inj} have certain effect on the voltage profile. Hence, we can design an alternative VVC scheme for the FREEDM IEEE 34 Nodes Feeder by increasing Q_{inj}.

As to power loss, the loss percentage goes down from 12.279% to 12.123% as Q_{inj} goes from 0kVar to -5kVar. But it then increases to 13.570% as Q_{inj} goes to -20kVar. This characteristic is shown in Fig. 3.8. The absolute value of power loss also decreases first then increases as SSTs provide more reactive power. From the graph, we can find some optimal value of Q_{inj} to achieve a minimal power loss.

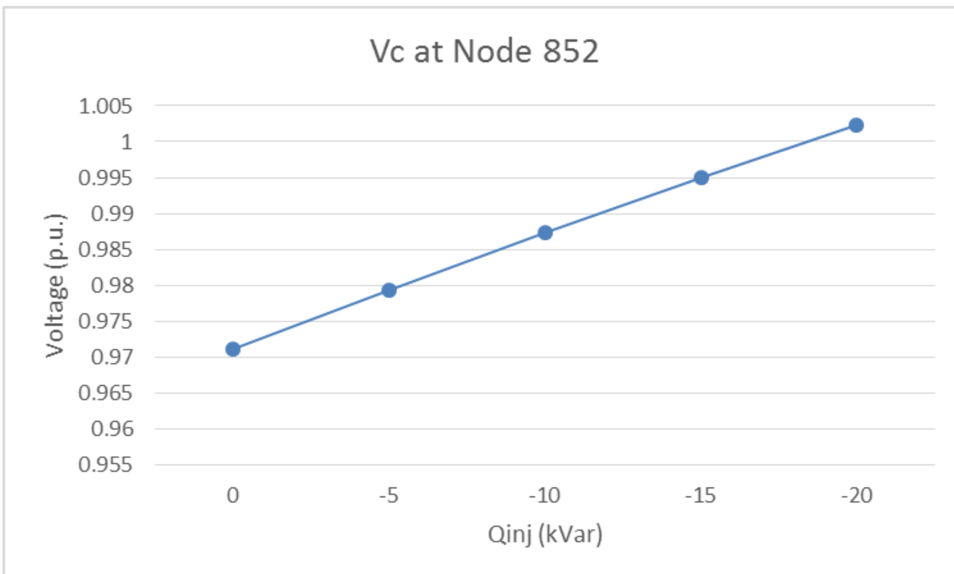

Fig. 3.6 Phase C voltage at Node 852 with respect to the change of Q_{inj}

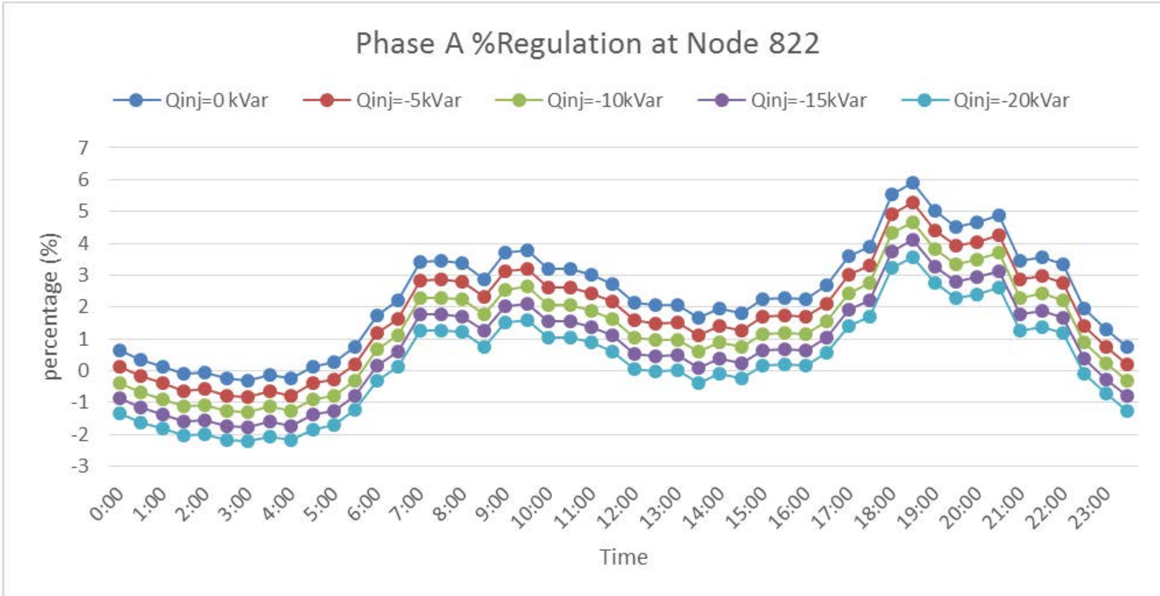

Fig. 3.7 Phase A %Regulation at Node 822 during a day without PV penetration

Although, from the results in Case 3 of FREEDM IEEE 34 Nodes Feeder, the maximum Voltage Unbalance does not always occurs at Node 814 during 24 hours, the VU at Node 814 is higher than most the VUs at other nodes. The VU characteristic at Node 814 with respect to the change of Q_{inj} are shown in Fig. 3.9. Fig.3.10 shows the daily profile of VU at Node 814. Fig. 3.11 shows the VV at Node 814. As SSTs inject more reactive power, the VU at Node 814 increases, while VV decreases slightly.

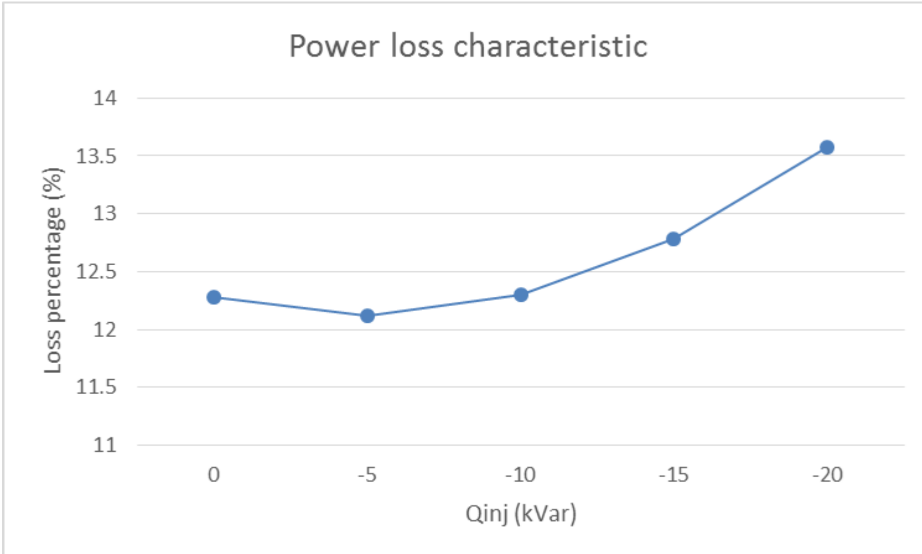

Fig. 3.8 Power loss characteristic with respect to Q_{inj}

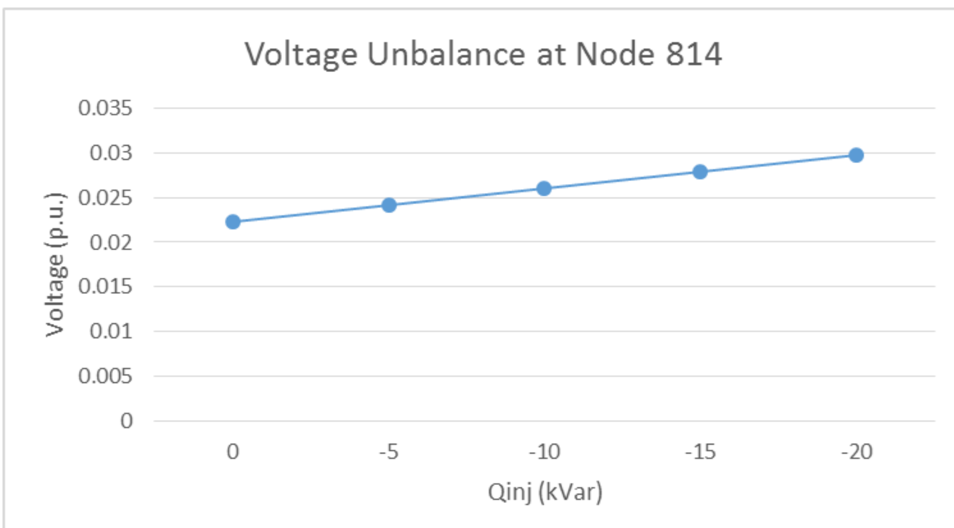

Fig. 3.9 Voltage Unbalance at Node 814 9 for different Q_{inj} under peak load condition

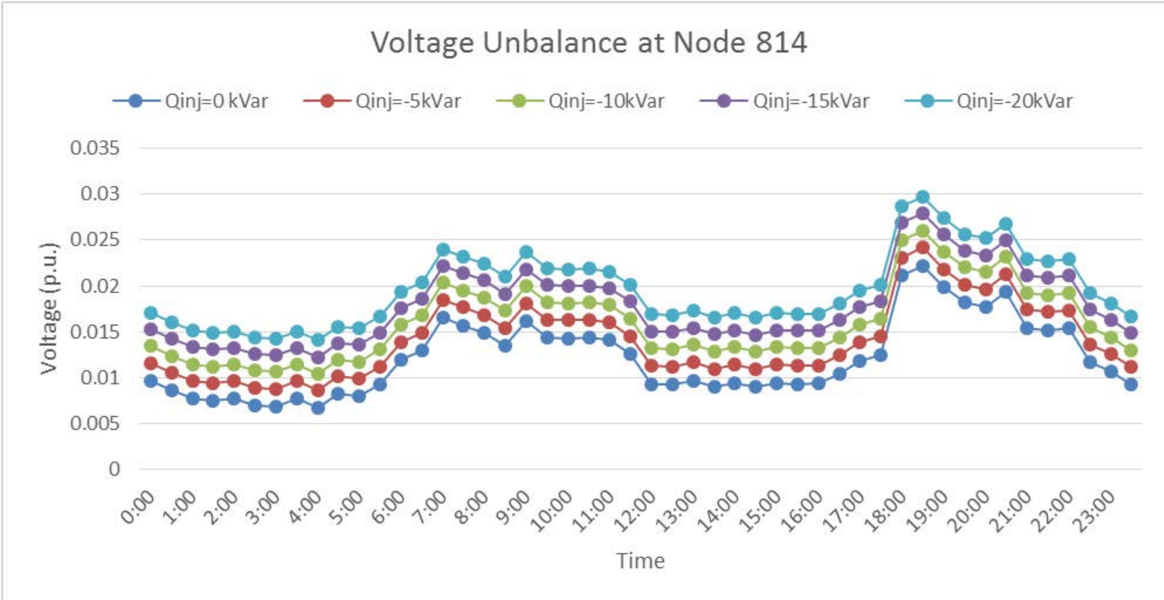

Fig. 3.10 Voltage Unbalance at Node 814 during a day without PV penetration

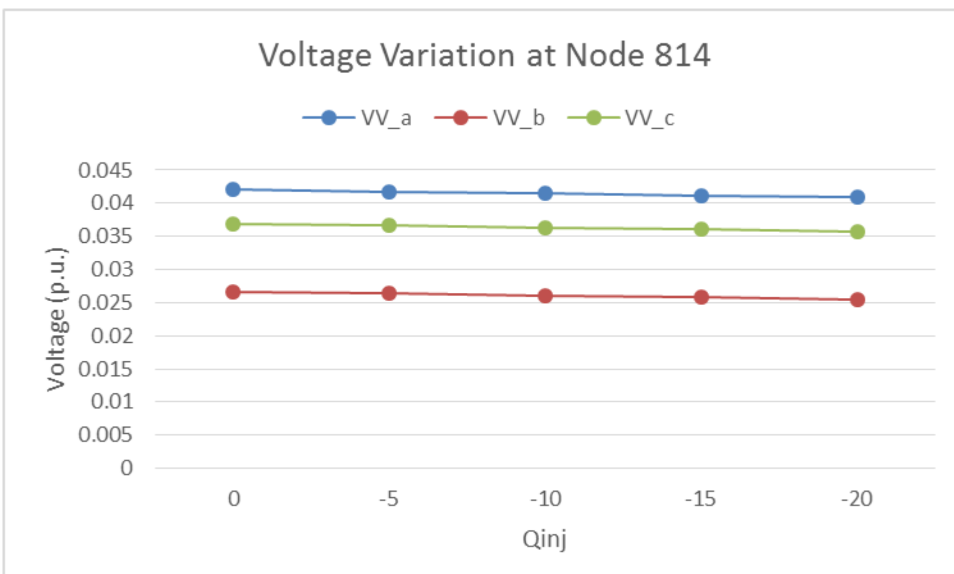

Fig. 3.11 Voltage variation at Node 814 for different Q_{inj}

Although increasing Q_{inj} can solve the voltage violation issue under heavy load condition, at noon when PV output is high the over reactive power generated by SSTs can raise the voltage, violating the upper limit. Fig. 3.12 shows such a case in which Q_{inj} = -15 kVar and voltage at 800 is regulated at 1.05 p.u.. Therefore, the LTC needs to be controlled to keep the source voltage at a lower value for high PV output condition. One simple way to solve this is to adjust the voltage at Node 800 based on the system equivalent load, similar as that in the conventional control for the Notional Feeder. Case 3, shown later in this chapter, illustrates a possible VVC scheme based on the control logic above.

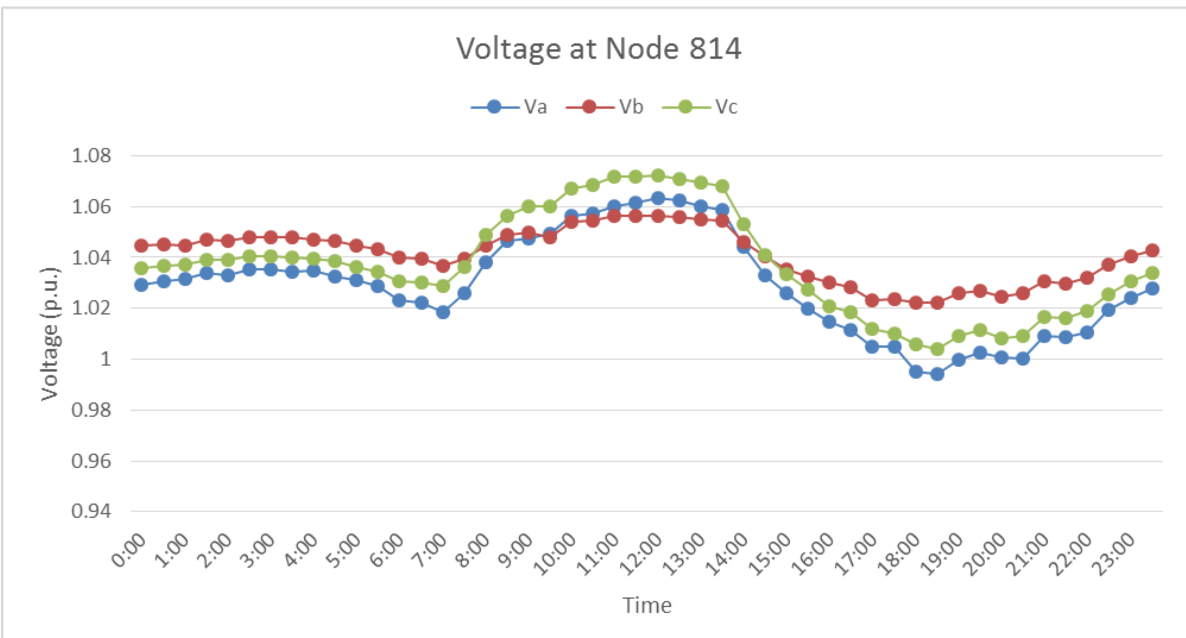

Fig. 3.12 Voltage profile at Node 814 with high PV penetration

3.2 Option II: Voltage Boost/Buck by VR

If voltages on a feeder get below the minimum limit, VRs can be placed along the feeder to raise the voltages. In the conventional VVC, a practical guideline is commonly followed for this purpose. According this guideline, the optimal location, if only one supplementary VR is applied, is approximately 30% of the entire line length from the source (for a uniformly loaded line). If one supplementary VR is not adequate to keep the voltage with the allowable range, two supplementary VRs can be applied in series on the line. Optimum locations for two voltage regulators in series on a line are approximately 20% and 50% of the entire line length from the source [14]. In case 4, a VR is placed at 30% length from the source. Since this scheme effectively maintains the voltages along the feeder within the acceptable range, we don't need a second supplementary VR.

3.3 Assessment of the Alternative VVC Schemes for FREEDM Systems

Assessment on the two test systems in previous sections indicate that while only Var compensation may be enough for the FREEDM Notional feeder. However, the FREEDM IEEE 34 Nodes test feeder utilizes both Var compensation and VR. The following subsections explore the effectiveness of these schemes.

3.3.1 Alternative VVC for FREEDM Notional Feeder

Assessment in Chapter 2, section 2.3.1 indicate that indeed the Var compensation provided by SSTs are enough for VVC on this test feeder, provided that the LTC at the substation keeps the substation bus voltage at 1.0 p.u.. Therefore, it’s not necessary to change the default control scheme.

3.3.2 Alternative VVC for FREEDM IEEE 34 Nodes Test Feeder

On the original test feeder, there are two VRs placed on the feeder, as Fig. 2.5 shows. However, since SSTs provide Var compensation in the FREEDM case, there may not need to use two VRs. To determine the number of VRs needed, the following cases have been considered:

Case 3: Option I – No Voltage Regulator

In this case, the control variable of SST is set to -15kVar. LTC keep the voltage at Node 800 at two different values, 1.0 p.u. and 1.05 p.u. If the system load is more than 0.8MW, voltage at Node 800 is regulated at 1.05 p.u., otherwise 1.0 p.u..

Case 4: Option II – One Voltage Regulator

In this case, the control variable of SST is set to 0 kVar, voltage at Node 800 is regulated in the same way as in Case 3. The VR is between Node 808 and 812 with a setting same as that in the FREEDM default control scheme.

Tab. 3.4 The maximum and minimum voltages during a typical day with different R and X setting

	R	X	V min	V max
Original setting	13.5	8	0.9596	1.0544
New setting	9.45	5.6	0.9529	1.05

Here the R and X setting of VR is different as the cases in Chapter 2. That's because higher R and X setting impede the VR taps to step back from heavy load tap positions when the load decreases. Voltage can violates the upper limit when the load goes down from heavy condition. Tab. 3.4 shows such simulation result of the maximum and minimum voltages during a typical day with different R and X setting. Therefore the new setting is adopted in this case.

Simulation results of Case 3 and Case 4 can be seen in the following assessment.

No PV penetration

1. Voltage Profile

Simulation results show that both alternative VVC schemes successfully keep the voltages within the range 0.95-1.05 p.u. in spite of the load variation during a day. In Case 3, the minimum voltage is 0.9557 pu at Node 836 in phase C at 18:30, as shown in Fig. 3.13, and the maximum voltage is 1.05 p.u.. In Case 4, the minimum voltage is 0.9529 p.u. at Node 840 in phase C at 17:00, as shown in Fig. 3.14. And the maximum voltage is 1.05 p.u..

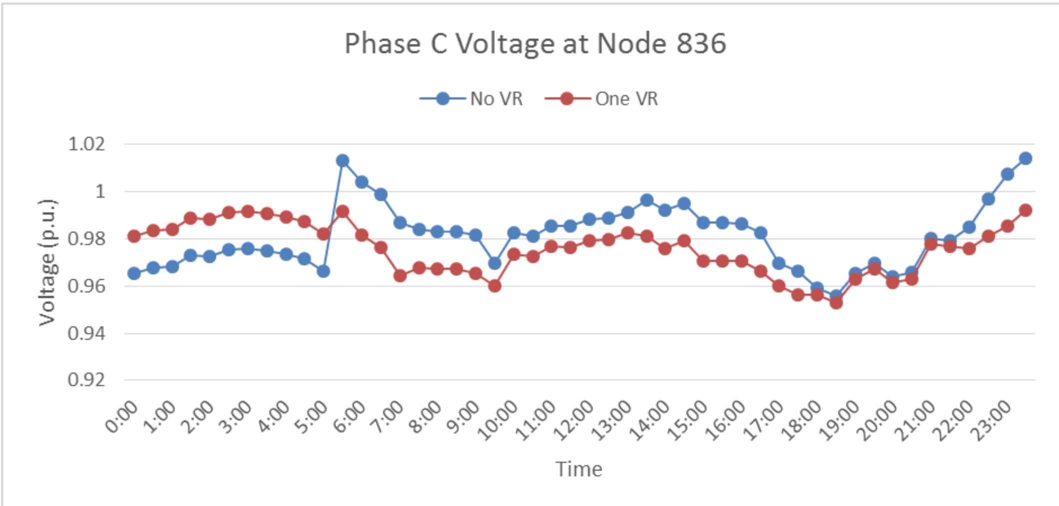

Fig. 3.13 Phase C voltage profile at Node 836 during a day without PV penetration

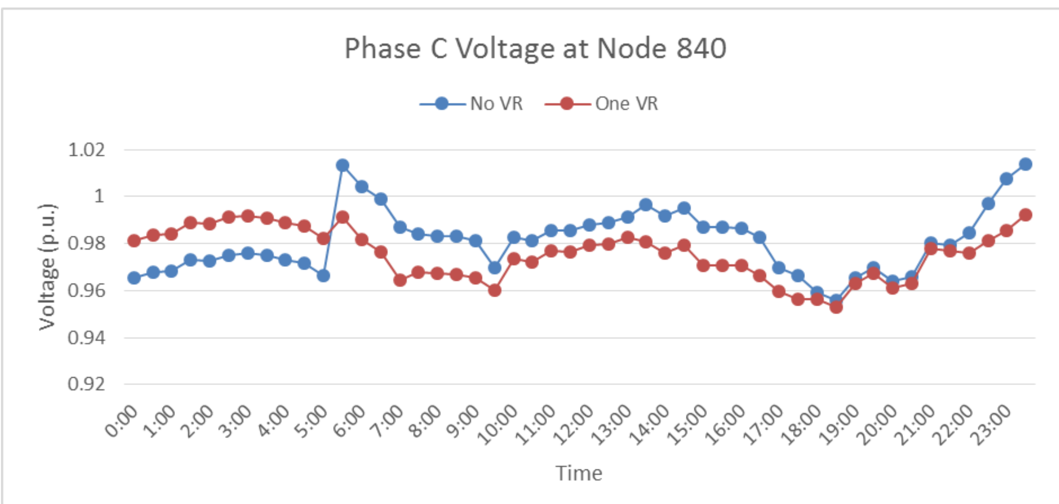

Fig. 3.14 Phase C voltage profile at Node 840 during a day without PV penetration

2. Power Loss and Energy Loss

As shown in Fig. 3.15, in Case 3, the 24-hour power loss ranges from 51.167kW at 3:00 to 201.944kW at 18:30, with a loss percentage range of 8.00%-13.49% respectively.

Tab. 3.5 Daily primary-side energy loss under alternative VVC without PV penetration

	Case 3 (no VR)	Case 4 (one VR)
Energy loss for one day (kWh)	2696.696865	2309.936129
Energy loss percentage (%)	10.50740302	9.000429441

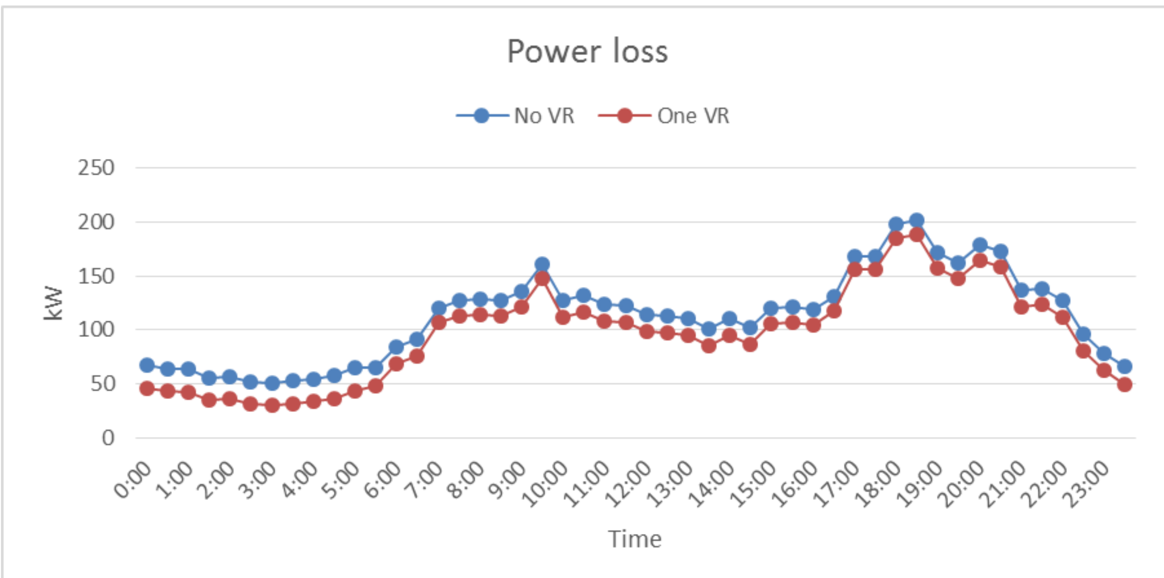

Fig. 3.15 Power loss under alternative VVC during a day without PV penetration

The corresponding daily primary-side energy loss is 2696.697 kWh, and the total energy loss on both primary and secondary sides is 3466.639 kWh. In Case 4, the 24-hour power loss ranges from 30.399kW at 3:00 to 188.375kW at 18:30, with a loss percentage range of 4.75%-12.59% respectively. The corresponding daily primary-side energy loss is 2309.936

kWh, and the total energy loss on both primary and secondary sides is 3079.878 kWh. Therefore, adding a VR can help to reduce energy loss for zero-PV days.

3. Voltage Regulation, Voltage Unbalance and Voltage Variation

The simulation results of %Regulation, VU and VV are seen in Tab. 3.6 and Tab. 3.7. From these results, Option II has less VUI, VVI and VRI than Option I.

Tab. 3.6 VRI and VV per phase under alternative VVC without PV penetration

		Phasd A	Phase B	Phase C
Case 3 (no VR)	VRIy	9.6367	7.1624	9.8701
	VVy	0.0547	0.05	0.0584
Case 4 (one VR)	VRIy	9.0976	9.3934	10.1949
	VVy	0.0505	0.05	0.05

Tab. 3.7 VRI, VUI and VVI under alternative VVC without PV penetration

	Case 3 (no VR)	Case 4 (one VR)
VRI	9.8701	10.1949
VUI	0.0284	0.0127
VVI	0.0584	0.0505

High PV penetration

1. Voltage Profile

Simulation results show that both alternative VVC schemes can successfully keep the voltages within the range 0.95-1.05 p.u. in spite of the load variation during a day. In either Case 3 or Case 4, the minimum and maximum voltages during a day are the same as those when there is no PV penetration. But the voltage profiles for the time with PV penetration are different with those under non-PV penetration condition. The phase C voltage profiles of Node 836 and Node 840 are seen in Fig. 3.16 and Fig. 3.17.

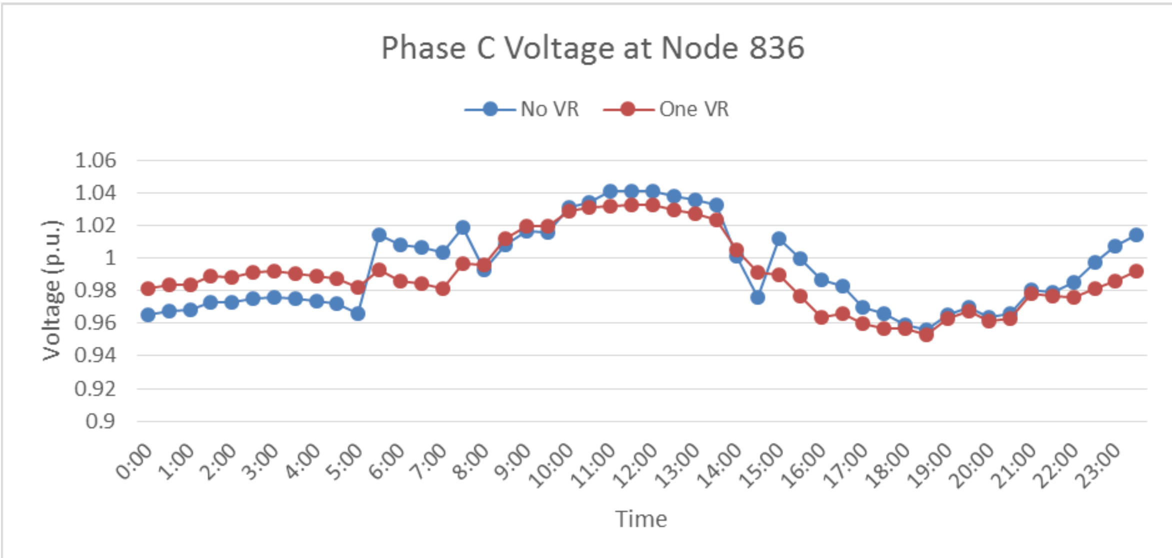

Fig. 3.16 Phase C voltage at Node 836 during a day with high PV penetration

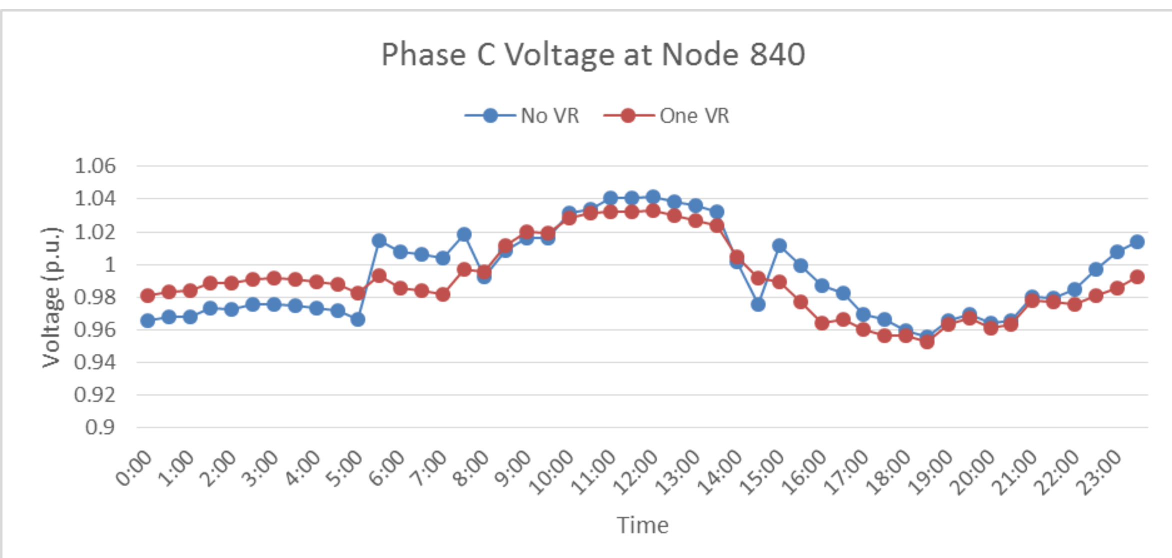

Fig. 3.17 Phase C voltage at Node 840 during a day with high PV penetration

2. Power Loss and Energy Loss

As shown in Fig. 3.18, in Case 3, the 24-hour power loss ranges from 23.344kW at 13:30 to 201.944kW at 18:30, with a loss percentage range of 2.01%-13.49% respectively. As shown in Tab. 3.7, the corresponding daily energy loss is 1960.312 kWh, and the total energy loss on both primary and secondary sides is 2521.415 kWh. In Case 4, the 24-hour power loss ranges from 3.987kW at 13:30 to 188.375kW at 18:30, with a loss percentage range of 0.38%-12.59% respectively. The corresponding daily energy loss is 1538.943kWh, and the total energy loss on both primary and secondary sides is 2100.047 kWh. Therefore, adding a VR can help to reduce energy loss for high-PV days.

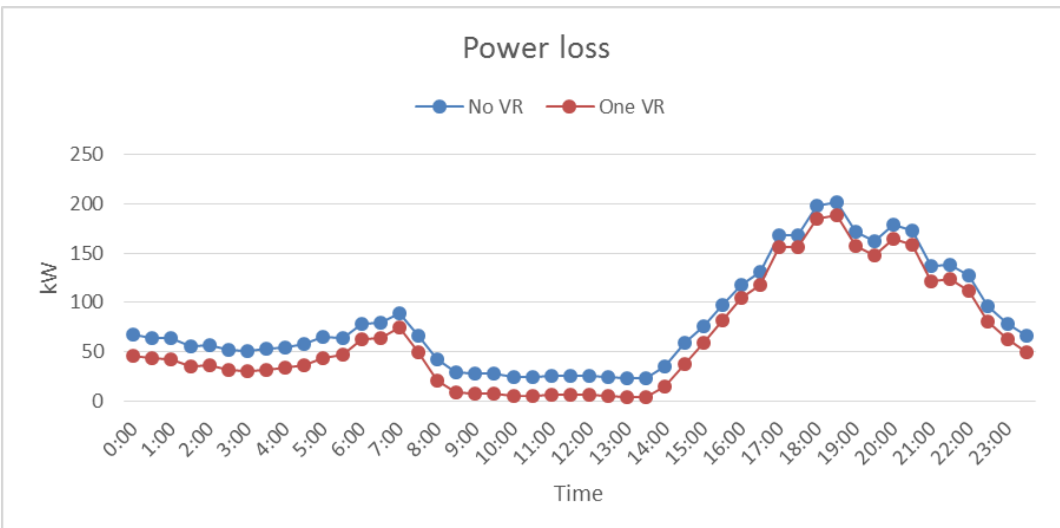

Fig. 3.18 Power loss under alternative VVC during a day with high PV penetration

Tab. 3.8 Daily energy loss under alternative VVC with high PV penetration

Energy loss for a day	Case 1 (no VR)	Case 2 (one VR)
Primary-side	1960.312 kWh	1538.943 kWh
Total	2521.415 kWh	2100.047 kWh

3. Voltage Regulation, Voltage Unbalance and Voltage Variation

The simulation results of %Regulation, VU and VV are seen in Tab. 3.9 and Tab. 3.10.

From these results, Option II has less VUI, VVI and VRI than Option I.

Tab. 3.9 VRI and VV per phase under alternative VVC with high PV penetration

		Phasd A	Phase B	Phase C
Case 3 (no VR)	VRIy	9.6367	7.1624	9.8701
	VVy	0.0617	0.0559	0.0857
Case 4 (one VR)	VRIy	9.0976	9.3934	10.1949
	VVy	0.057	0.0541	0.0798

Tab. 3.10 VRI, VUI and VVI under alternative VVC with high PV penetration

	Case 3 (no VR)	Case 4 (one VR)
VRI	9.8701	10.1949
VUI	0.0304	0.025
VVI	0.0857	0.0798

3.4 Summary

1. Both alternative VVC schemes can maintain the primary-side voltages in the system within the recommended service voltage range of 0.95-1.05 p.u. (range A by ANSI C84.1).

2. For a typical day, with minimum PV penetration (zero output), the energy loss in Case 3 is 2696.697kWh, while in Case 4 is 2309.936kWh. The VVC in Case 4 reduces energy loss by 14.34%. With full PV penetration (peak PV generation at each node equals peak load), the energy loss in Case 3 is 1960.312kWh, while in Case 4 is 1538.943kWh. A reduction of 21.49% is achieved.

3. In Case 3 the VRI is 9.87%, while in Case 4 the VRI is 10.19%. The alternative VVC in Case 4 increase the VRI a little bit.

4. Adding a VR reduces the voltage unbalance of the system. For a typical day with minimum PV penetration, the VUI in Case 3 is 0.0284 p.u., while in Case 4 is 0.0127 p.u.. A reduction of 55.28% is achieved the VVC in Case 4. With full PV penetration, the VUI in Case 3 is 0.0304 p.u., while in Case 4 is 0.0250 p.u.. A reduction of 17.76% is achieved by the VVC in Case 4.

5. Adding a VR reduces the voltage variation under different operating conditions during a day. For a typical day with minimum PV penetration, the maximum VVI among three phases is 0.0584 p.u. in Case 3, and 0.0505 p.u. in Case 4. The VVC in Case 4 achieves a voltage variation reduction of 13.53%. With full PV penetration, the maximum VVI among three phases in Case 3 is 0.0857 p.u., in Case 4 is 0.0798 p.u.. A reduction of 6.88% is achieved by adding a VR.

From the results above, a brief conclusion about the pros and cons of the two options can be drawn, shown as in Tab.3.11.

Tab. 3.11 Pros and cons of Option I and II for FREEDM Systems

	Pros	Cons
Option I	Voltages meet the requirement. Less VVC devices involved, thus more economic.	More energy loss. More voltage variation. The unbalance is more severe than choosing option II.
Option II	Voltages meet the requirement. Less energy loss. Less voltage variation. Balance three phase voltage better.	Other devices involved, thus more expensive.

Chapter 4 Conclusions and Future Work

4.1 Conclusions

The main contribution of this work include:

- Six metrics are adopted to assess Volt/Var Control schemes. The simulation results indicate that the FREEDM VVC has the advantage of reducing the primary-side power and energy loss, reducing the voltage unbalance and reducing the voltage variations. Besides, the FREEDM VVC can also reduce the tap change of VRs, which increases the lifetime of a VR thus reducing the cost of replacing a VR.
- Alternative VVC schemes are proposed based on the two options, Var compensation alone and adding voltage regulator. Simulation results indicate that adding a voltage regulator to FREEDM VVC schemes can reduce power and energy loss, voltage unbalance and voltage variation. But we may not need a VR in FREEDM systems. Simple practical guidelines can be followed to design a VVC scheme for FREEDM IEEE 34 Nodes system.

4.2 Future Work

In this work, all loads are modeled as constant power load, but in an actually distribution system the characteristic for each load can be constant impedance as well. It is necessary to investigate how much the load model difference would influence the effectiveness of VVC schemes.

In Chapter 3, two alternative FREEDM VVC schemes are proposed. Although adding VR can improve the performance of the FREEDM VVC, further economic assessment is needed for the tradeoff between the control performance and the cost of VVC schemes.

In the FREEDM default control scheme, Q_{inj} for each SST is set to zero. From Fig. 3.3 and Fig. 3.8, we can find some Q_{inj} to reduce power loss further and guarantee the desired voltage profile at the same time.

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APPENDICES

Appendix I: System information of the FREEDM Notional Feeder

Base Value

Base voltage along the main distribution feeder is 12kV, so per-phase base voltage is 6.9282 kV. Choose base capacity to be 10MVA, the following table shows all the base values that are used in the Residential Notional System.

Tab. A-1: Base value for Residential Notional System

	3-phase	per-phase
Vbase(kV)	12	6.9282
Sbase(MVA)		10
Zbase		4.8

Loads

Residential Notional System is a three phase unbalanced distribution feeder. The following is the load data in the Residential Notional System.

Line sections:

The original system line data is providing in Tab. A-3.

Divide all the resistance and inductance by its corresponding line length, it is clear that all the lines are of the same type. The line's positive/zero resistance and inductance per kilometer is show in the table below.

Tab. A-2 :Load data for Residential Notional System

load #	PL A(kW)	IQL A (kVAR)	PL B(kW)	IQL B (kVAR)	PL C(kW)	IQL C (kVAR)
Ld1	57.75	81.62	165.55	110.11	112.42	66.99
Ld2	532.07	273.35	734.83	364.99	338.8	173.25
Ld3	0	0	141	68	14.63	7.7
Ld4	20.02	10.01	10.01	1.54	85.47	43.12
Ld5	651.42	332.64	171.71	80.08	100.1	56.98
Ld6	544.39	278.74	56.98	29.26	254.1	120.12
Ld7	145.53	74.69	112.42	57.75	245.63	120.12
Ld8	597.52	304.92	510.51	253.33	733.81	386.54
Ld9	535.15	272.58	530.53	261.8	520.52	264.88
Ld10	32.725	28.028	25.564	26.334	50.743	34.804
Ld11	455.84	189.651	715.176	325.094	841.841	353.661
Ld12	235.081	112.959	207.438	98.945	196.119	93.709
Ld13	319.396	145.222	317.856	141.603	95.326	39.578
Ld14	15.862	8.701	0	0	0	0
Ld15	357.665	168.553	207.207	105.798	59.598	35.266
Ld16	499.576	232.617	424.424	187.957	846.461	364.133
Ld17	168.938	55.363	608.839	271.887	227.227	87.549

Tab. A-3 Line data for Residential Notional System

Line	R1 (ohm)	R0 (ohm)	L1 (H)	L0 (H)	C1 (F)	C0 (F)	Length (km)
1	0.1502	0.8004	0.0017	0.0067	1E-15	1E-15	7.141
2	0.0618	0.3294	0.0007	0.0027	1E-15	1E-15	2.939
3	0.0546	0.2910	0.0006	0.0024	1E-15	1E-15	2.596
4	0.0366	0.1949	0.0004	0.0016	1E-15	1E-15	1.739
5	0.0851	0.4536	0.0009	0.0038	1E-15	1E-15	4.047
6	0.0978	0.5209	0.0011	0.0043	1E-15	1E-15	4.647
7	0.0919	0.4898	0.0010	0.0041	1E-15	1E-15	4.37
8	0.0075	0.0399	0.0001	0.0003	1E-15	1E-15	0.356
9	0.0261	0.1389	0.0003	0.0012	1E-15	1E-15	1.239
10	0.0711	0.3786	0.0008	0.0032	1E-15	1E-15	3.378
11	0.0476	0.2534	0.0005	0.0021	1E-15	1E-15	2.261
12	0.0050	0.0268	0.0001	0.0002	1E-15	1E-15	0.239
13	0.0439	0.2342	0.0005	0.0019	1E-15	1E-15	2.089
14	0.1197	0.6379	0.0013	0.0053	1E-15	1E-15	5.6913
15	0.0593	0.3160	0.0007	0.0026	1E-15	1E-15	2.819
16	0.0186	0.0990	0.0002	0.0008	1E-15	1E-15	0.883
17	0.0667	0.3553	0.0007	0.0030	1E-15	1E-15	3.17

Tab. A-4 Line type parameter for Residential Notional System

R1 (ohm/km)	R0 (ohm/km)	L1 (H/km)	L0 (H/km)
0.021035	0.112089	0.000234	0.000933

Substation Transformer

The substation transformer data of Residential Notional System is shown in the table below.

The rated voltage of substation transformer is 69kV/12kV.

Tab. A-5 Substation transformer information for Residential Notional System

substation voltage	69kV/12kV
transformer capacity	30MVA
transformer winding type	delta/wye
transformer impedance	0.19
neutral reactor	0.315 Ω

Appendix II: System information of the FREEDM IEEE 34 Nodes Feeder

Base Values

Base voltage along the main distribution feeder is 24.9kV, so per-phase base voltage is 14.2760 kV. Choose base capacity to be 10MVA, and then the following table shows all the base values that are used.

Tab. A-6 Base values for IEEE 34 System

	3-phase	per-phase
Vbase(kV)	24.9	14.3760217
Sbase(MVA)		10
Zbase		20.667

Loads

As stated before, instead of using "spot" loads and "distributed" loads, all the loads are represented as Y connection at the corresponding nodes. Tab. A-7 shows the aggregated load data in the IEEE 34 node system.

Line sections

There are 6 types of line in IEEE 34 node system: 300, 301, 302, 303, 304, and 200. The Tab. A-8 shows the line impedance and susceptance for each type.

Where type 300, 301, 302, 303, 304 work under 24.9kV voltage level. Type 300, 301 are 3-phase distribution lines, but type 302, 303, 304 are single phase conductor, where type 302 is connected to phase A, type 303 and 304 are connected to phase B. The following chart gives the sending and receiving node that each line is connected to, line length and line type.

Tab. A-7 Load data for IEEE 34 System

#	connected to	P_a	Q_a	P_b	Q_b	P_c	Q_c
1	806	0	0	29.68113	15.20609	24.68113	13.98744
2	824	0	0	5	1.976126	0	0
3	828	0	0	0	0	4	2.049261
4	830	15.78584	7.483107	8.78584	4.50112	23.56004	9.311525
5	858	7	2.981988	2	1.02463	6	3.073891
6	834	4	2.049261	15	8.096142	13	7.016657
7	860	33.80166	22.60137	37.70643	24.60184	125.2391	69.44614
8	836	29.86535	15.30047	10	5.933652	41.7307	21.37927
9	838	0	0	27.68113	14.18146	0	0
10	810	0	0	15.97307	8.183246	0	0
11	820	33.67336	17.25137	0	0	0	0
12	822	134.1921	68.74865	0	0	0	0
13	826	0	0	39.36226	20.16588	0	0
14	856	0	0	4	2.049261	0	0
15	890	136.2363	69.79592	136.2363	69.79592	136.2363	69.79592
16	864	2	1.02463	0	0	0	0
17	844	81.43175	61.99582	75.68987	58.74174	75.68987	58.74174
18	846	0	0	24.68113	11.95362	19.68113	10.62275
19	848	12.44449	9.983986	28.28954	17.65809	12.44449	9.983986
20	840	25.94788	15.41121	29.89402	17.43288	8.028672	6.230929

Tab. A-8 Line type for IEEE 34 System

Tab. A-8 (a)

300			
Z=	1.3238+ 1.357i	0.2109 + 0.5965i	0.2051 + 0.4616i
	0.2109 + 0.5965i	1.3385+ 1.3313i	0.2124 + 0.5026i
	0.2051 + 0.4616i	0.2124 + 0.5026i	1.3266 + 1.3521i

Tab. A-8 (b)

301			
Z=	1.9157 + 1.4282i	0.2336 + 0.6431i	0.2273 + 0.5256i
	0.2336 + 0.6431i	1.9318 + 1.4094i	0.2352 + 0.5699i
	0.2273 + 0.5256i	0.2352 + 0.5699i	1.9188 + 1.4246i

Tab. A-8 (c)

301			
Z=	1.9157 + 1.4282i	0.2336 + 0.6431i	0.2273 + 0.5256i
	0.2336 + 0.6431i	1.9318 + 1.4094i	0.2352 + 0.5699i
	0.2273 + 0.5256i	0.2352 + 0.5699i	1.9188 + 1.4246i

Tab. A-8 (d)

303			
Z=	0+ 0i	0+ 0i	0+ 0i
	0+ 0i	2.7799 + 1.4804i	0+ 0i
	0+ 0i	0+ 0i	0+ 0i

Tab. A-8 (e)

304			
Z=	0+ 0i	0+ 0i	0+ 0i
	0+ 0i	1.9216 + 1.4213i	0+ 0i
	0+ 0i	0+ 0i	0+ 0i

Tab. A-9 Line parameters for IEEE 34 System

#	From	To	Length	Type	#	From	To	Length	Type
1	800	802	2580	300	17	834	860	2020	301
2	802	806	1730	300	18	834	842	280	301
3	806	808	32230	300	19	836	840	860	301
4	808	810	5804	303	20	836	862	280	301
5	808	812	37500	300	21	842	844	1350	301
6	812	814	29730	300	22	844	846	3640	301
7	814	850	1	VR	23	846	848	530	301
8	816	818	1710	302	24	850	816	310	301
9	816	824	10210	301	25	852	832	1	VR
10	818	820	48150	302	26	854	856	23330	303
11	820	822	13740	302	27	854	852	36830	301
12	824	826	3030	303	28	858	864	1620	303
13	824	828	840	301	29	858	834	5830	301
14	828	830	20440	301	30	860	836	2680	301
15	830	854	520	301	31	862	838	4860	304
16	832	858	4900	301	32	888	890	10560	300

Voltage Regulator and Transformer

There are two VRs in the system, connected between node 814 and 850, 852 and 832. And they are modeled as LTC transformer with three different taps that can work independently for three phases. The impedance of VR is chosen to be the same as shown in Tab. A-10.

Tab. A-10 The impedance of VR

Z=	0.004+0.03i	0+ 0i	0+ 0i
	0.00	0.004+0.03i	0+ 0i
	0+ 0i	0+ 0i	0.004+0.03i

There are two types of transformer in the original IEEE 34 node system. The rated voltage of substation transformer is 69kV/24.9kV, and for transformer 832 is 24.9kV/4.16 kV. The impedances of these two transformers are shown in Tab. A-11.

Tab. A-11 Transformer parameters for IEEE 34 System (a) substation transformer (b) distribution transformer

Tab. A-11 (a)

Z=	2.48+19.84i	0+ 0i	0+ 0i
	0.00	2.48+19.84i	0+ 0i
	0+ 0i	0+ 0i	2.48+19.84i

Tab. A-11 (b)

Z=	0.057+ 0.1224i	0+ 0i	0+ 0i
	0+ 0i	0.057+ 0.1224i	0+ 0i
	0+ 0i	0+ 0i	0.057+ 0.1224i

Appendix III: Voltage Regulator Control Logic

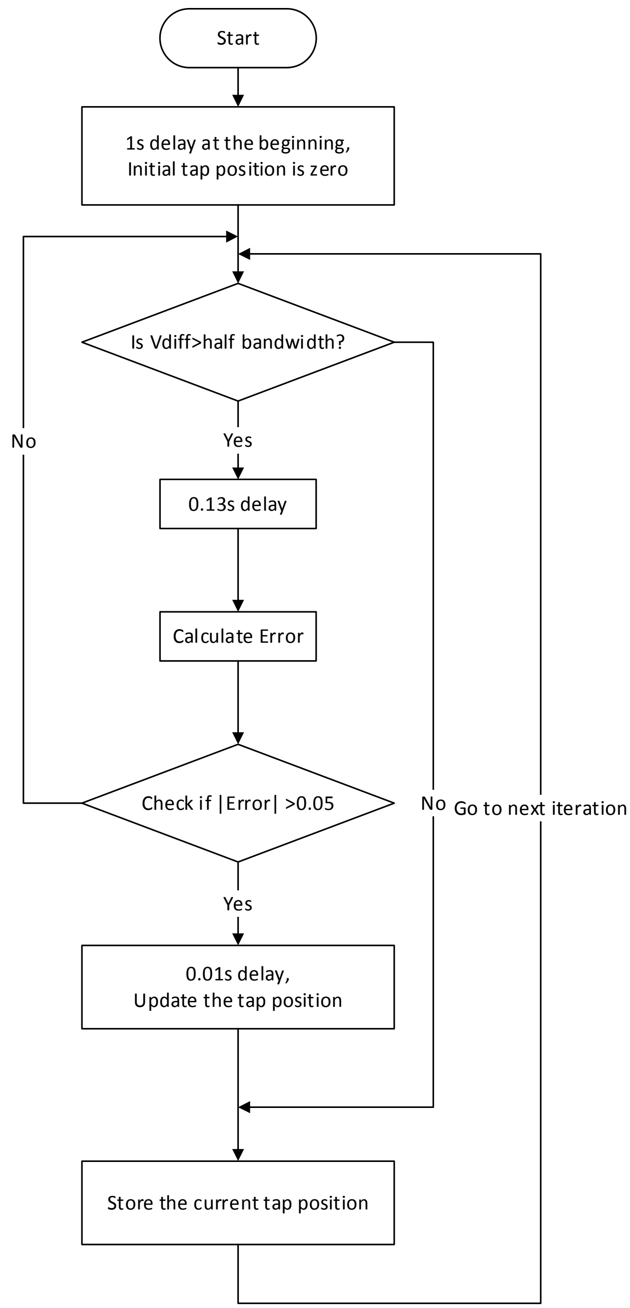

Fig. A-1 (a)

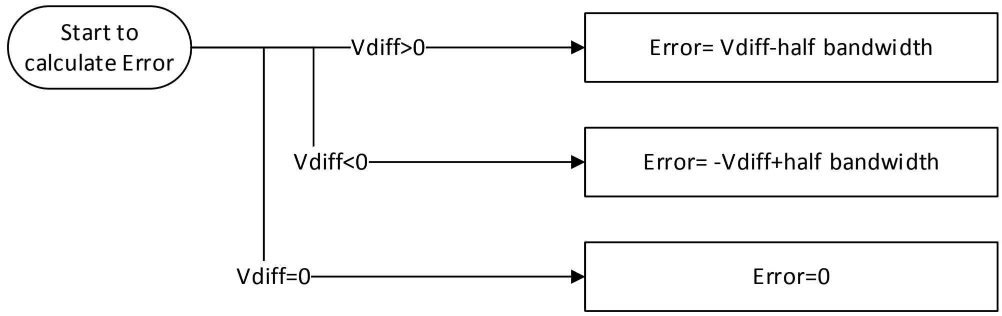

Fig. A-1 (b)

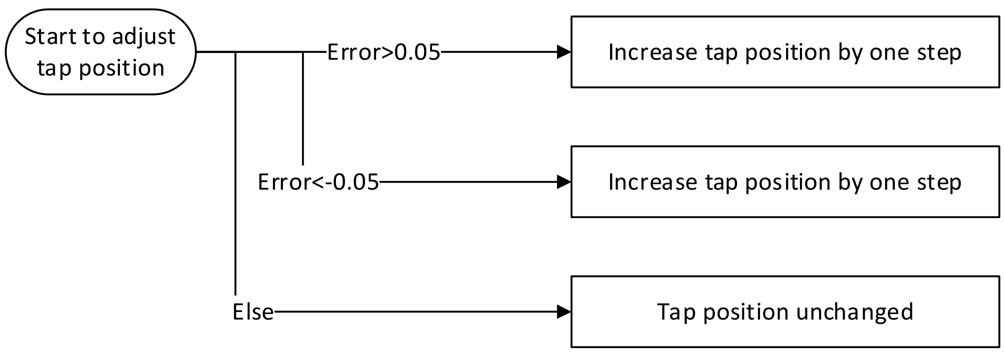

Fig. A-1 (c)

Fig. A-1 The control logic of the voltage regulator in this thesis