ABSTRACT

ZHANG, WENBO. Fast Volt - VAR Control on PV Dominated Distribution Systems. (Under the direction of Mesut E Baran).

Voltage Regulation is a fundamental operating requirement of all electric distribution systems. Volt- VAR control aims at maintaining the voltages on a distribution feeder within acceptable limits during all load conditions. PVs are becoming widely used in some distribution systems. Since high penetration level of PV may adversely affect current distribution system, steps must be taken to mitigate their impacts.

This thesis investigates the voltage issues of high penetration level of PV on traditional power distribution systems and then proposes a new dynamic VAR compensator to address and improve the system voltage performance. Dynamic VAR compensator is a new type of Static VAR Compensator. The study involves simulating a prototype 34 node distribution feeder with high penetration of PVs on PSCAD. Then, case studies have been conducted on this system to investigate and demonstrate the volt –VAR issues on this system. The second part of the thesis consists of case studies which investigates and assesses the use of DVC to address the voltage regulation challenges on the prototype system.

The simulations show that DVC can help reduce operations of voltage regulator. If DVC is used to replace all Volt – VAR control devices, it can provide a flatter voltage profile. In PV dominated distribution system, DVC has a fast response to voltage change which can prevent voltage drop caused by cloud. DVC can also help address high voltage violation in high penetration level of PV. In summary, DVC could serve the voltage regulator and capacitor functions in a distribution system and even has a better performance.

Fast Volt - VAR Control on PV Dominated
Distribution Systems

by
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BIOGRAPHY

Wenbo Zhang was born on July 27th 1988 in Dalian, Liaoning, China. She spent her early childhood in Dalian, her hometown. And then she spent about three year finishing her Bachelor of Engineering degree in Optical Engineering from Zhejiang University. In 2010, she joined North Carolina State University to pursue Master of Science in Electrical Engineering under the guidance of Dr. Mesut E Baran.

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My heartfelt thanks my parents Qiujuan Wang and Peijie Zhang, whose love has always supported me throughout my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

Voltage regulation is a fundamental operating requirement of all electric distribution systems. Volt-VAR control (VVC) aims to maintain the voltages on a distribution feeder within acceptable limits during all load conditions. In traditional systems, the most common VVC methods are direct voltage regulation and reactive power compensation. Voltage Regulators (VRs) and Capacitor Bank (CAPs) are conventional devices used in the distribution systems. VRs are typically placed at the substation and the CAPs are placed along the feeder.

1.1 Background

ANSI C84.1 [1] specifies the range of both service voltage and utilization voltage. Generally, utilities need to keep the service voltage within acceptable limits; the utilization voltage then follows automatically. Figure 1.1 shows the 120V voltage level ANSI C84.1 recommended service and utilization voltage limits. Table 1.1 clearly shows the voltage range of service and utilization. When the voltage drops to range B, corrective measures shall be undertaken within a reasonable time to improve voltages to go back to Range A [1].

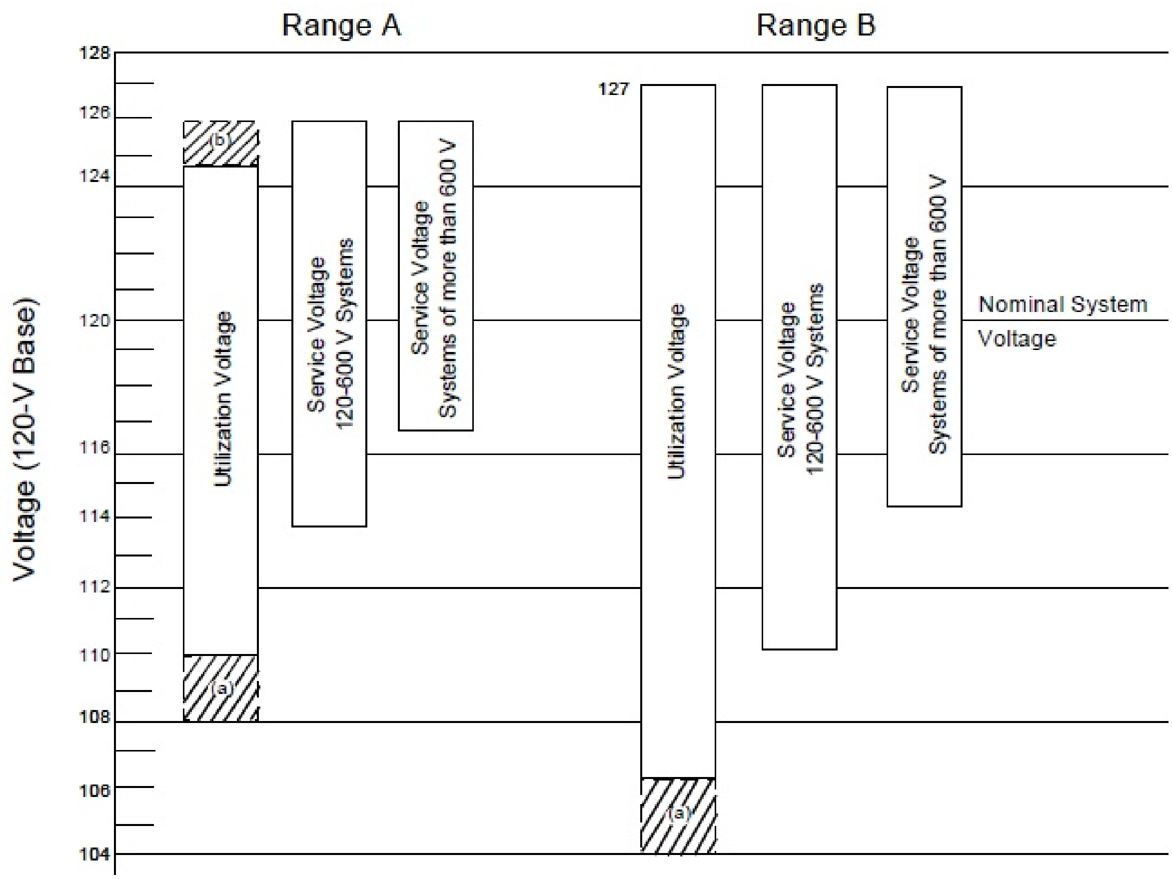


Figure 1.1 ANSI C84.1 Voltage range for 120V voltage level [1]

Table 1.1 Voltage range for 120V voltage level

	Service		Utilization	
	Min	Max	Min	Max
Range A (Normal)	-5%	5%	-8.30%	4.20%
Range B(Emergency)	-8.30%	5.80%	-11.70%	5.80%

1.1.1 Conventional Volt-VAR Control

In a traditional distribution system, as shown (Figure 1.2), without Volt-VAR control devices, the typical voltage profile under peak load decreases gradually along the feeder.

Under heavy load conditions, the node farthest from the substation may have low-voltage violation (Figure 1.3). In order to fix this problem, we need to manually raise the source voltage (Figure 1.4), though this will cause other problems at light load (Figure 1.5). So Volt-VAR control is needed to deal with all possible normal operation conditions, [2].

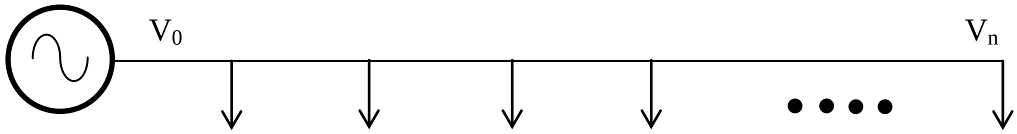


Figure 1.2 Traditional Distribution System

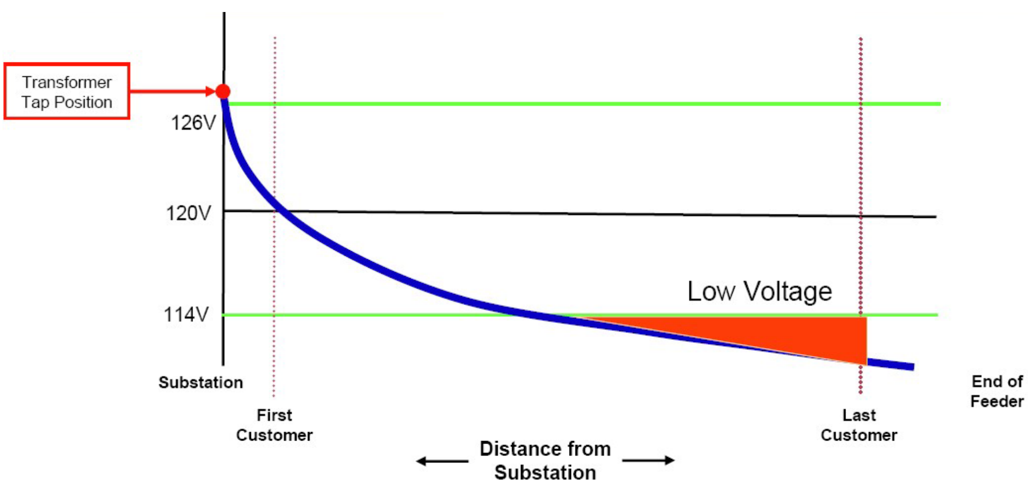


Figure 1.3 Without Volt-VAR Control under peak load

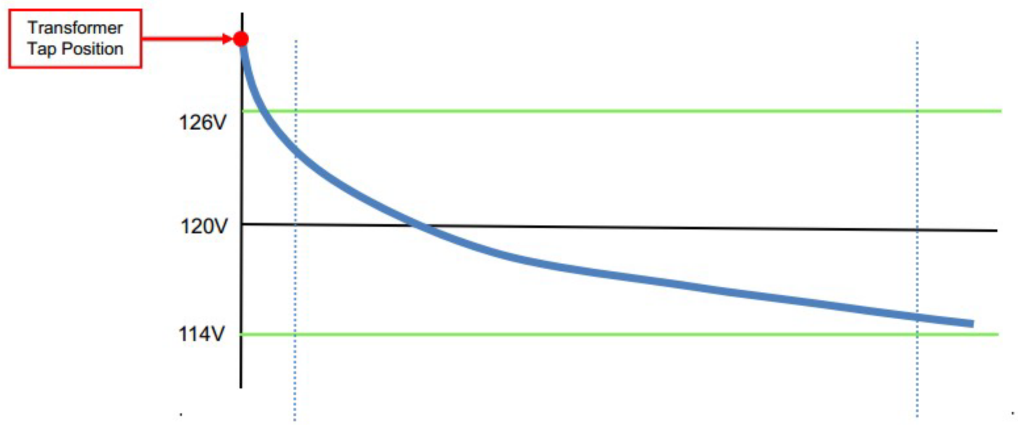


Figure 1.4 After raising the source voltage under peak load

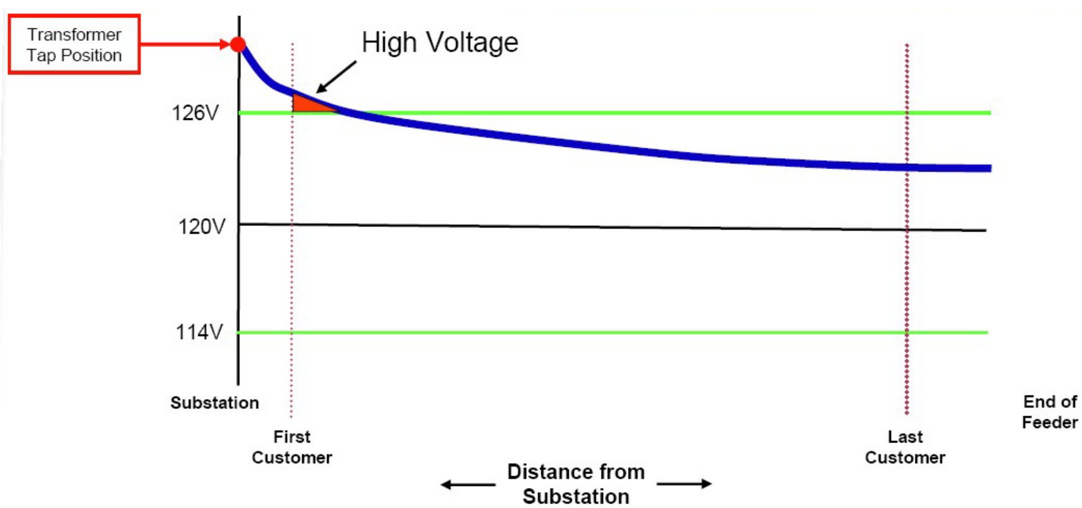


Figure 1.5 Without Volt-VAR Control under light load after raising setting voltage

The most common devices used in conventional Volt-VAR control are voltage regulators (VRs) and capacity banks (CAP). VRs adjust the voltage at the substation or along the feeder. It raises and drops the voltage profile on the whole feeder. CAPs are used to further raise the feeder voltage by offsetting the reactive power demand of the load if the voltage gets too low down the feeder. Conventional control schemes of VRs and CAPs are simple local measurement based schemes. Figure 1.6 illustrates the typical application of these two kinds of devices.

Figure 1.6 Voltage Regulators and Capacitor banks used on a distribution feeder

a) Voltage Regulator Control

VRs use local measurements of current and voltage to adjust the voltage at its terminals by changing its tap position. The VR is controlled by a VR relay and has two control options. The first option is regulating the voltage at its terminals. The second option is regulating a remote point down the feeder, which is achieved through a “line drop compensation” device that estimates voltage at the remote target point using voltage and current measurements,[3].

b) Capacitor Bank Control

The reactive power of the load can be supplied by the substation or by capacitors. Installed capacitors can offset the reactive power demand of the load and consequently reduce the current and boost the voltage. Capacitors can be either fixed or switched. Fixed capacitors provide the minimum voltage boost needed during normal loading. Switched capacitors provide the extra voltage boost needed during heavy load conditions. Switched capacitors are thus switched off during light load conditions to prevent overvoltage conditions and to avoid power loss due to excessive reactive power compensation. Two main problems still may exist in practical applications. First problem is that capacitors often switched in chunks, instead of varying continuously followed load demand. Second problem is as reactive power is a function of voltage squared, reactive power supplied by capacitors goes lower when the voltage is low, but that is when more reactive power is needed,[4].Usually very simple schemes are used to switch on or off the CAPs such as time of the day or voltage levels.

c) Coordination of VR and CAP

One of the main challenges of local control schemes is the difficulty of coordinating the control between the VRs and CAPs. With the recent efforts towards extending SCADA at distribution feeder level, it is becoming possible to coordinate the operation of these devices. Figure 1.7 illustrates the voltage profile in a conventional system with voltage regulator and switched capacitor.

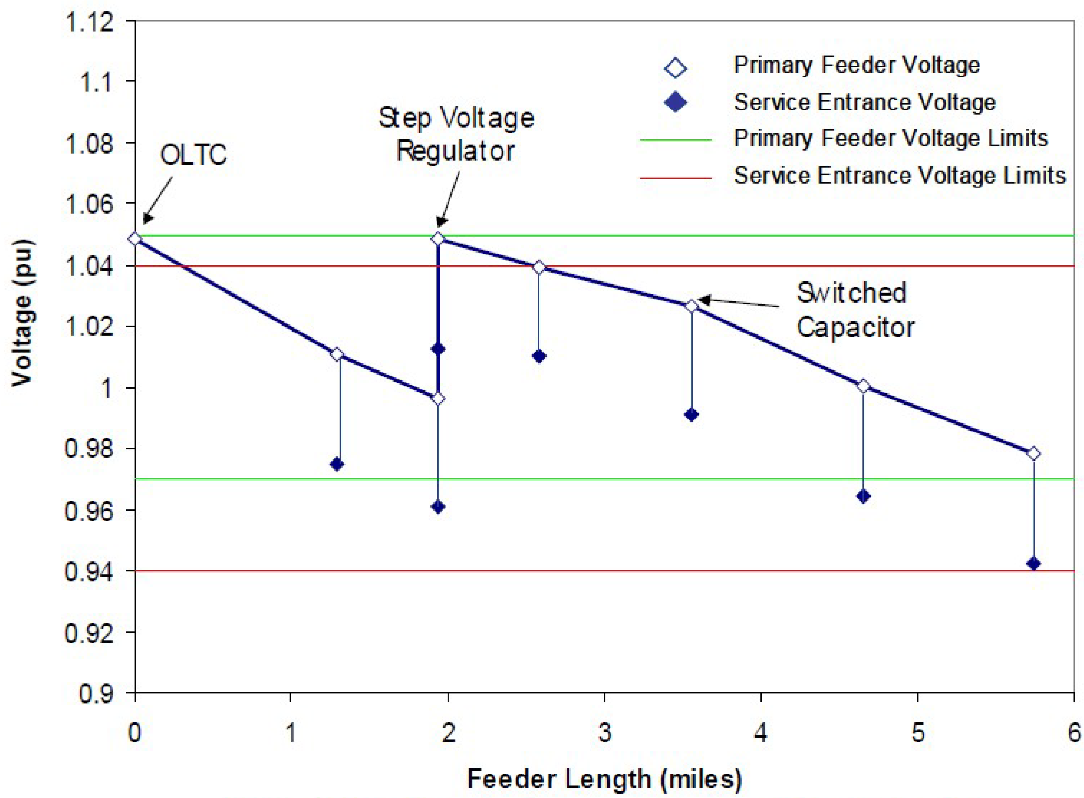


Figure 1.7 Voltage profile with voltage regulator and Capacitor[4]

1.1.2 Photovoltaics

Recently, driven by raised average temperature and environmental destruction, Renewable Portfolio Standards (RPS) have been proposed in several countries [5]. Australia passed Renewable Energy (Electricity) Act in 2000. China proposed a renewable energy target in 2006 and modified it in 2009. The European Union adopted the Directive on Electricity Production from Renewable Energy sources in 2001. In America, many states have passed RPS programs with various different targets. For example, California’s target is to reach 33% of total power generation by 2020 and North Carolina’s target is 12.5% by 2021[5]. Right now wind, biomass and hydropower are the predominant resources used by most states to meet the requirement of RPS, while more and more states established a solar set-aside into the RPS, stipulating the percentage of energy from solar photovoltaics (PVs) at overall renewable energy. This kind of bills incentivizes the market for solar PVs, especially for grid-connected applications. Furthermore, most of the new PVs are installed in distributed grid and working as distributed generations. PVs are encouraged for environmental reasons, but we must note that PVs may adversely affect the existing distribution system. Utilities and power system operators need to consider the potential impact of high penetration levels of PVs on traditional distribution power systems and prepare robust measures to mitigate these impacts.

Traditional distribution systems were designed to operate in a radial fashion that supplies power from substation to loads, PV interconnections need to be studied to determine the potential impacts and propose more useful mitigation measures. PV has intermittent resource characteristic that varies the output power and requires inverters to convert dc to ac power, which may lead to more challenges given the volatile and uncontrollable nature of its primary resource,[6].

PVs have several impacts on planning and operation of distribution systems and interfere with traditional protection and control schemes. The most significant effects are on voltage profiles (voltage rise and voltage unbalance), operation, maintenance and life-time of voltage control and regulation equipment such as Load Tap Changers (LTCs) and switched CAPs, power flow, electric losses, power factor, and power quality. The effects vary in severity as a function of the penetration level and location of PV, [7].

Voltage rise leads to high voltage violation [8]. Based on BS EN 50160, which is the standard in Europe to gauge voltage acceptability, under normal operating conditions, all 10 minutes mean voltage should be less than 253V, while in Figure 1.8 for the 50% PV case, there is a probability of voltages exceeding 253V which is not acceptable, [9]. Figure 1.9 shows low and moderate penetration levels of PV may reduce power system losses but high penetration level of PV may lead to increase of power losses.

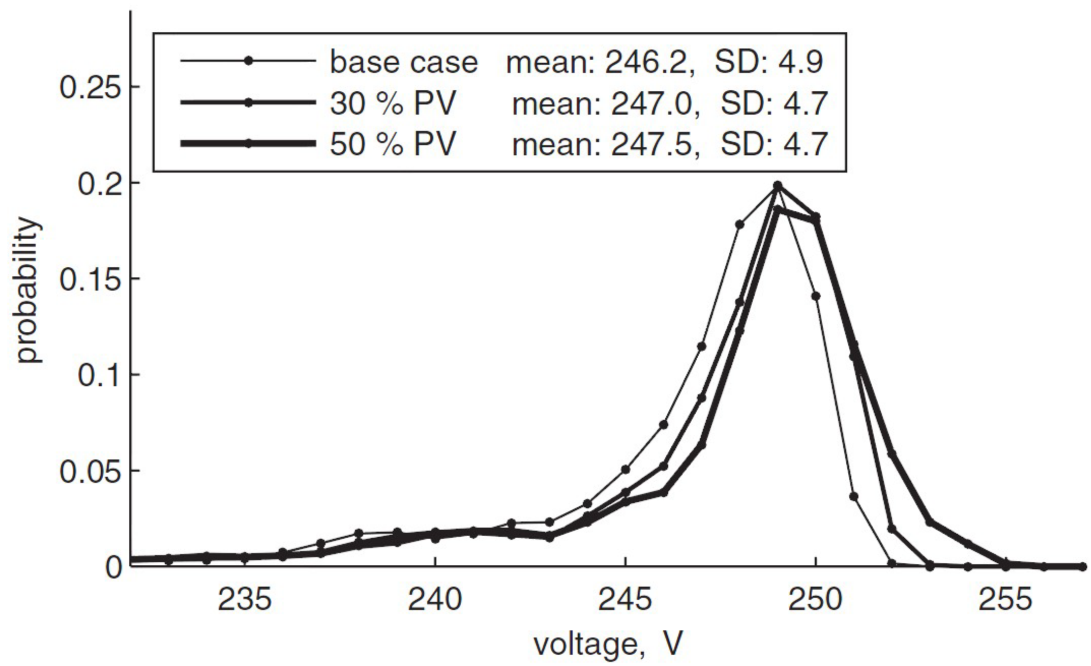


Figure 1.8 Probability distributions of ten-minute-average voltages at all LV customer connection points in summer[8]

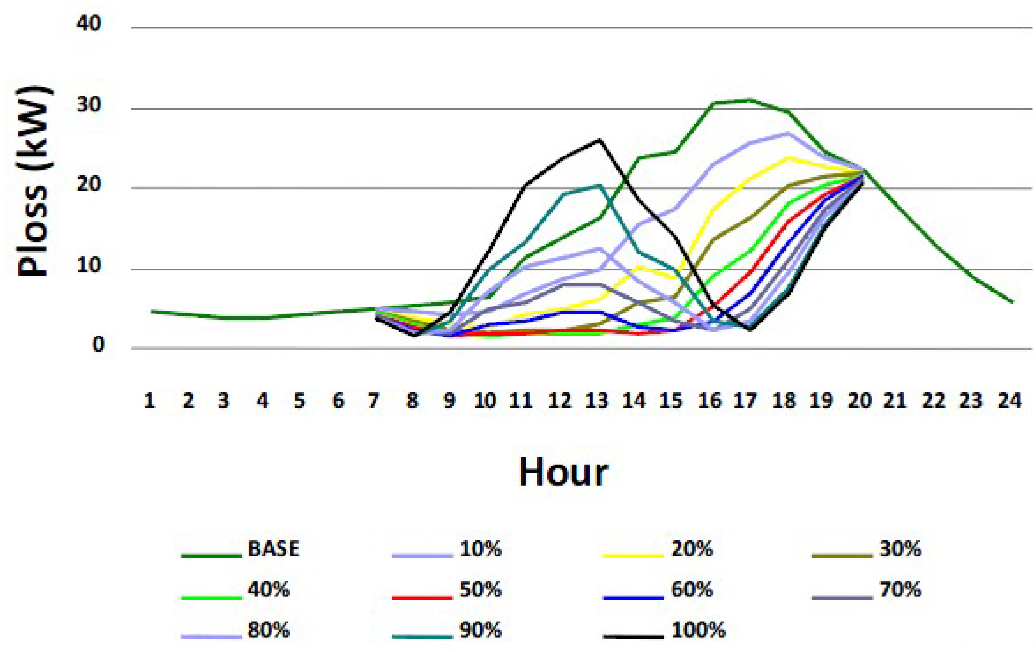


Figure 1.9 Feeder Losses as a function of PV penetration level for two real distribution feeders [9]

1.2 Proposed Approach

The aims of this thesis are to assess the impacts of high penetration levels of PV on conventional Volt-VAR control schemes in distribution system, and to investigate adopting a new dynamic VAR compensator for improving Volt-VAR control.

The study consists of the following steps:

1. Simulate a prototype traditional distribution system with conventional Volt-VAR control devices as the base case.
2. Assess impacts of high penetration levels of PV on the prototype system
3. Model and apply DVC on the prototype system
4. Investigate the performance of DVC to address the impacts of high penetration levels of PV.

1.3 Organization

This thesis is organized as follows. In Chapter 2, conventional Volt-VAR control device for traditional distribution system is assessed. This establishes a base-case for the following chapters. Chapter 3 investigates the impact of integrating high penetration PV on the distribution system with traditional control devices. In Chapter 4, a new fast Volt-VAR compensator – Dynamic VAR Compensator is implemented in the system and its performance is assessed for both traditional system and the system with high PV penetration.

1.4 Glossary

PSCAD	Power System Computer Aided Design is powerful simulation software. It has a powerful library of variable simulation model including electric machines, FACTS devices, transmission lines and cables.
PV	Solar Photovoltaic
VR	Voltage Regulator
DVC	Dynamic VAR Compensator
LDC	Line Drop Compensator

CHAPTER 2
CONVENTIONAL VOLT-VAR CONTROL SCHEME

The objective of this chapter is to investigate the effectiveness of conventional volt-VAR schemes outlined in Chapter 1. A prototype feeder is selected and implemented on PSCAD. The feeder's primary circuit is modeled in detail, lines are represented in detail with equivalent circuits with mutual inductance terms, and loads are presented on a phase basis as constant impedances. This system will also be the base case for the following work.

2.1 Prototype Feeder

2.1.1 Distribution Feeder Model

IEEE 34 node test system is a traditional distribution system located in Arizona, composed of many unbalanced "distributed" and "spot" loads. This system was modeled on PSCAD. A single line diagram of the feeder is shown in Figure 2.1.

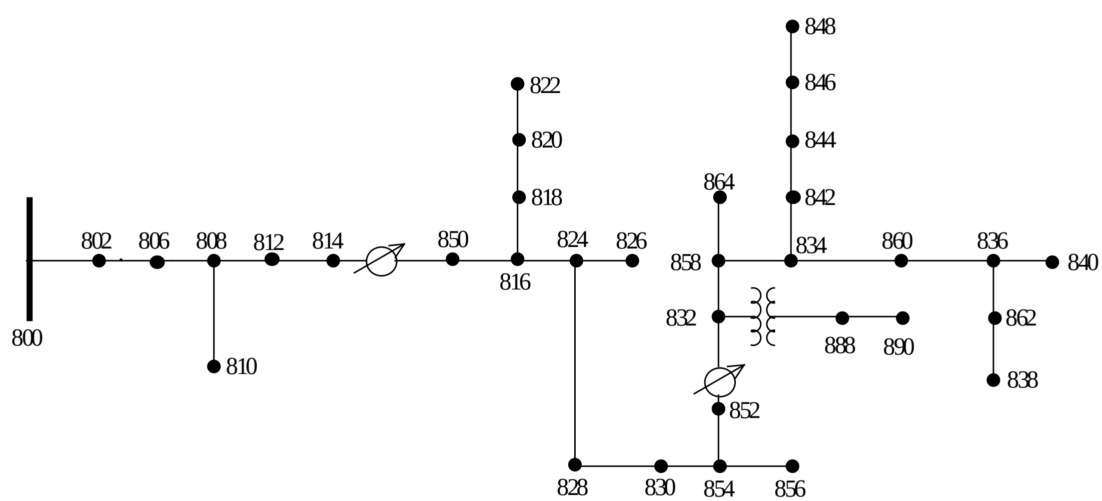


Figure 2.1 Prototype System

The system is radial and supplied by a medium-voltage transformer with a LTC installed. We assume the voltage at node 800 is constantly equal to 1.05 pu. The distribution system includes a main feeder and several laterals. There are 30 distributed loads and 6 spot loads ranging from 2 kW to 150 kW. The total load is 1769 kW. Fixed capacitors are installed at node 844 and node 848. The total rated reactive power injection is 750 kVAR. Two voltage regulators are installed, with one between nodes 814 and 850, and another between nodes 852 and 832 (Figure 2.1). The main feeder voltage is 24.9kV. A transformer is located between node 832 and node 888 steps down the primary voltage from 24.9 kV to 4.16kV.

2.1.2 Component Models

i) Primary circuit

There are 5 feeder configurations. Three of them are three-phase lines and the other two are single phase lines. One transformer and two capacitors are installed in the feeder. The parameters are shown in Table 2.1.

Table 2.1 Feeder Voltage Device

Type	From	To	Rating
Transformer	832	888	500kVA
capacitor1	844		300kVAr
capacitor2	848		450kVAr

ii) Load

Loads were modeled as constant resistance loads (Np = Nq = 2). All loads are connected at the end of the line.

iii) Voltage Regulators

The voltage regulators are modeled as tap-changing transformers with LDC incorporated in the controllers. The LDC is illustrated in Figure 2.2. The LDC measures the local voltage and current, and then calculates the voltage regulating point (V_{VRR}) by transferring the measurements to a low-voltage circuit.

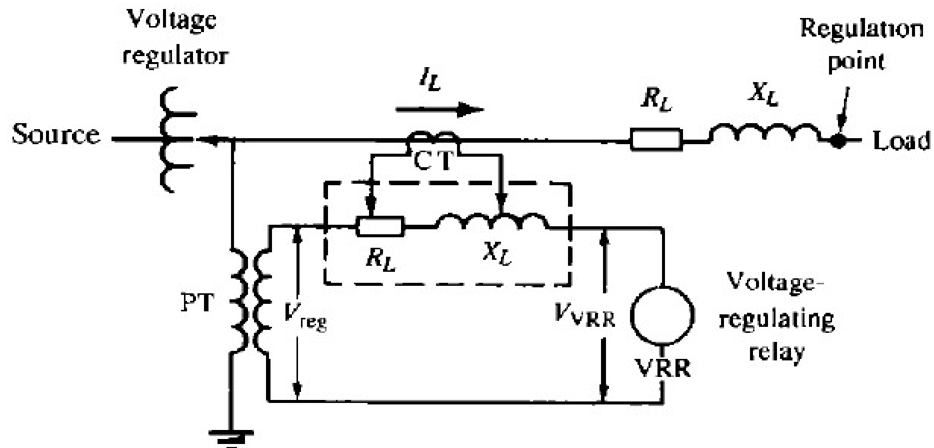


Figure 2.2 Line-Drop Compensator circuit

Voltage-regulating relay (VRR) is used to control tap changes. As illustrated in Figure 2.2, this relay has the following three basic settings that control tap changes:

- **Setting voltage:** The desired output of the regulator. It is also called the set point or band-center.
- **Bandwidth (BW):** Voltage regulator 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_{RR} with the set point, if the difference between V_{RR} and set voltage exceeds half of the BW, the timer starts counting. When the timer reaches TD, it sends a signal to move taps up or down.

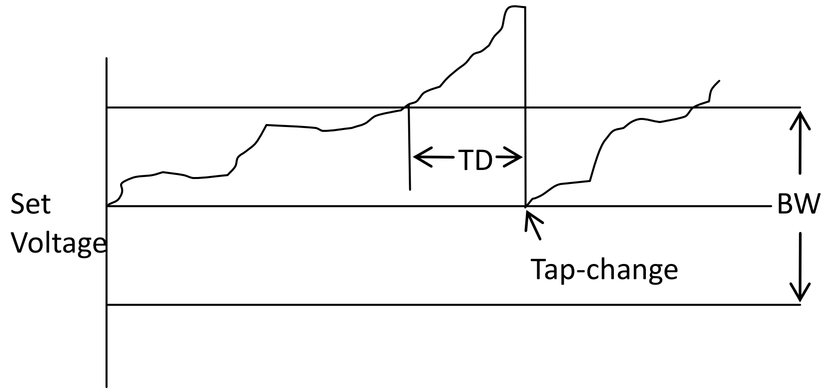


Figure 2.3 VR control based on the set voltage, bandwidth and time delay

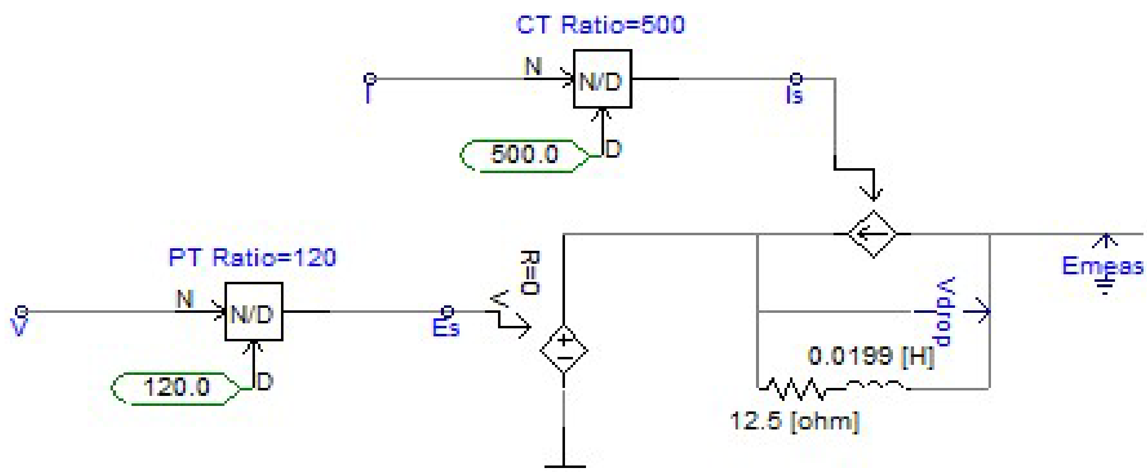


Figure 2.4 Voltage Regulation Line Drop Compensator Circuit in PSCAD

In this way, VRs calculate the voltage at a remote node by measuring local voltage and current and regulate the voltage to a preset reference voltage by changing the turn ratio of the transformer. In Figure 2.4, V and I represent local voltage and current measurements. E_{meas} represents the voltage of the regulating point and is used to determine how to change tap position. When there is reverse power flow in the grid, the current cross the impedance flows from right side to left side, so E_{meas} will be higher than E_s. While under the normal power flow conditions, the current cross the impedance flows from the left side to the right side, so E_{meas} will lower than E_s. Under both condition E_{meas} is presented the voltage of regulating point. So the LDC could work in bidirectional mode which ensures that VRs could work under reverse power flow when high penetration level PV installed in the system.

The VRs typically have 32 tap positions (±16) which correspond to a range of ±10% of transformer rated voltage. In other words, each step is 0.625% of the rated voltage. The tap changer is a mechanical device. Typically, the time needed to move from one position to the next is 1 – 2s. In large power systems, especially for those with long feeder systems, more than one VR is installed. An improper TD setting will result in unnecessary tap changes, which may shorten the life-time of the VR. The most common way to make them coordinated is to set a longer time delay for the VRs which are further from substation or are in lower voltage networks. The first VR's time delay should be from 30 to 60s,[10], and further ones could range from 30 to 120s. The main parameters of VRs for the prototype system are listed in Table 2.2.

Table 2.2 Voltage Regulator Parameters

	Location	PT Ratio	CT Rating	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

2.2 Conventional Volt-VAR Control Study

The simulation runs under peak load condition with no VRs in the system. Figure 2.5 shows the voltage profile. Most nodes are under low-voltage violation.

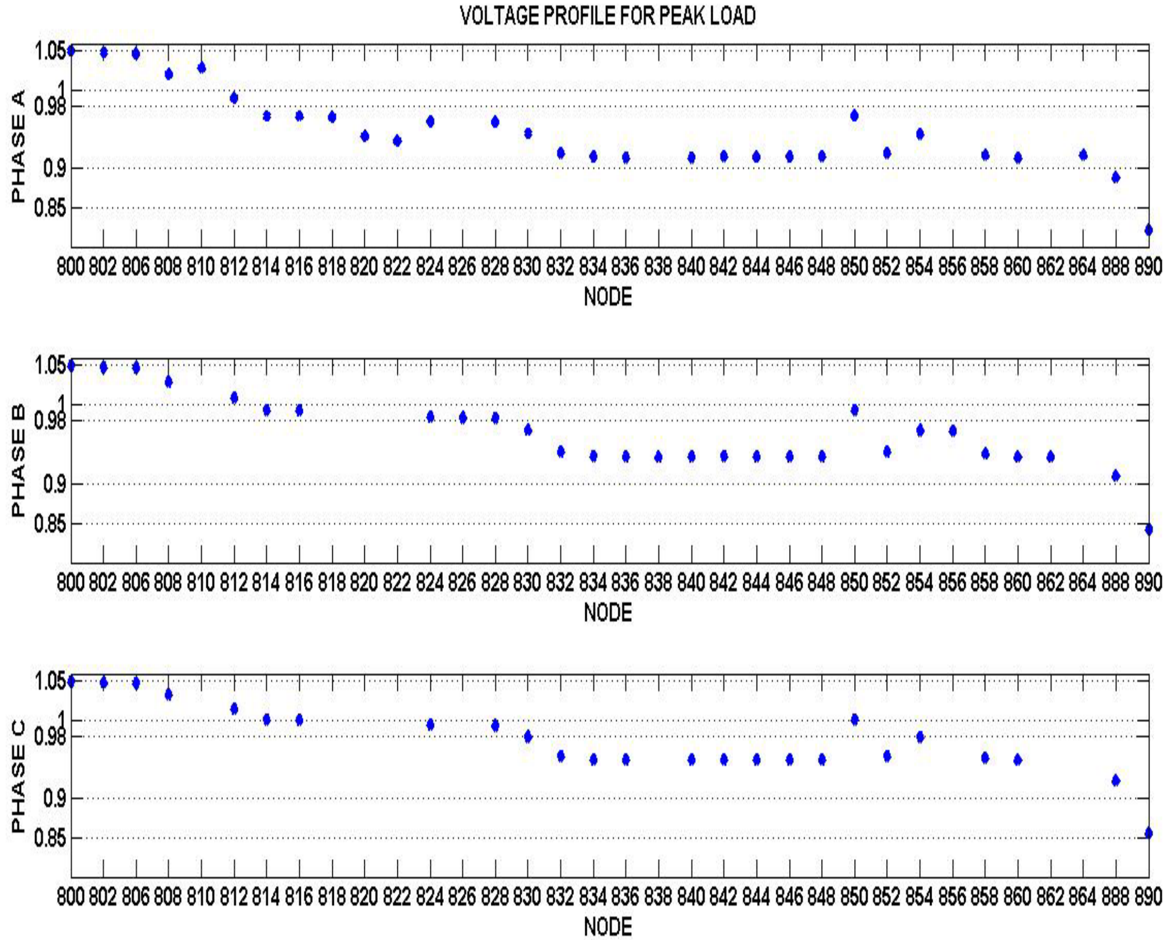


Figure 2.5 Voltage Profile of no VRs at Peak Load

Next, the prototype system under peak load with voltage regulators is simulated to see how voltage regulators work in distribution system. Figure 2.6 shows the voltage profile and Figure 2.7 shows the voltage profile comparison at peak load. Most voltages are higher than limit (0.97 pu). Although voltage at node 890 was boosted from around 0.85pu to 0.94pu, it still has voltage violation which we will try to solve by using DVC and PV in the following chapters.

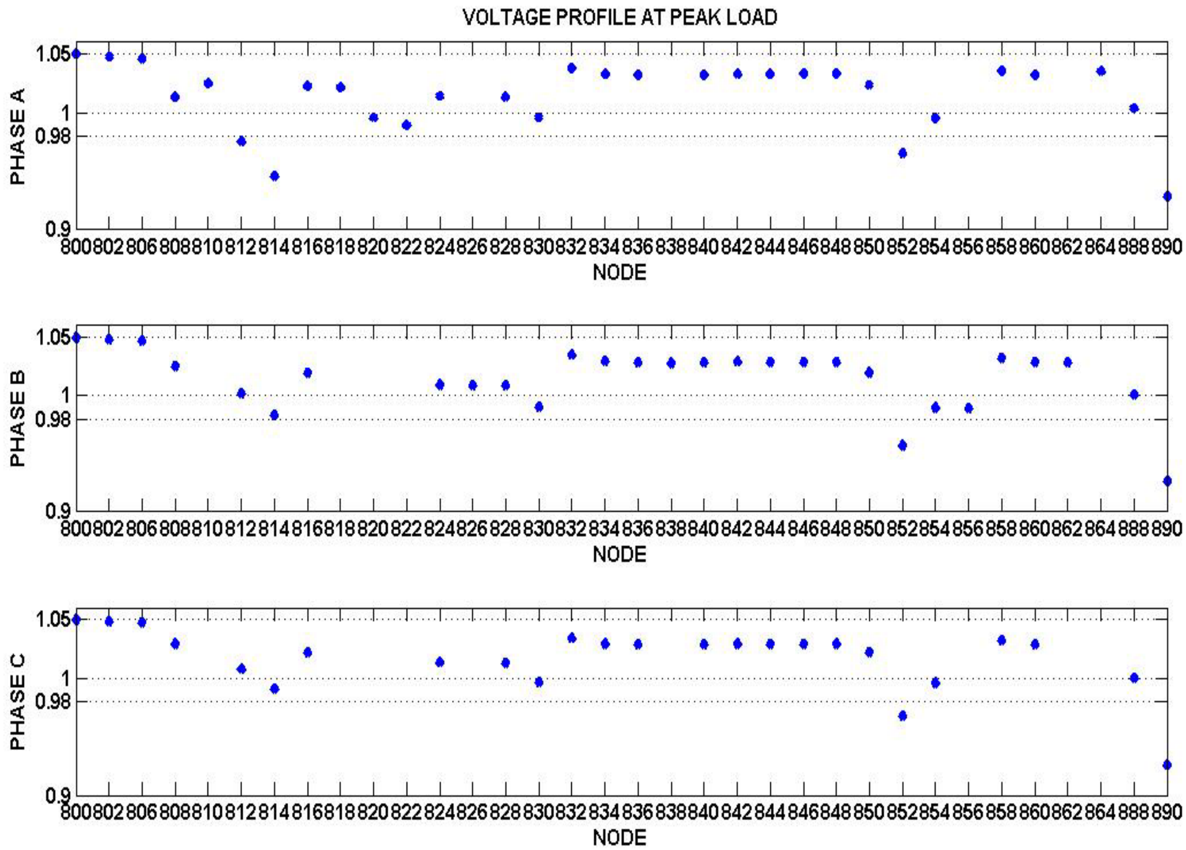


Figure 2.6 Voltage Profile with VRs at Peak Load

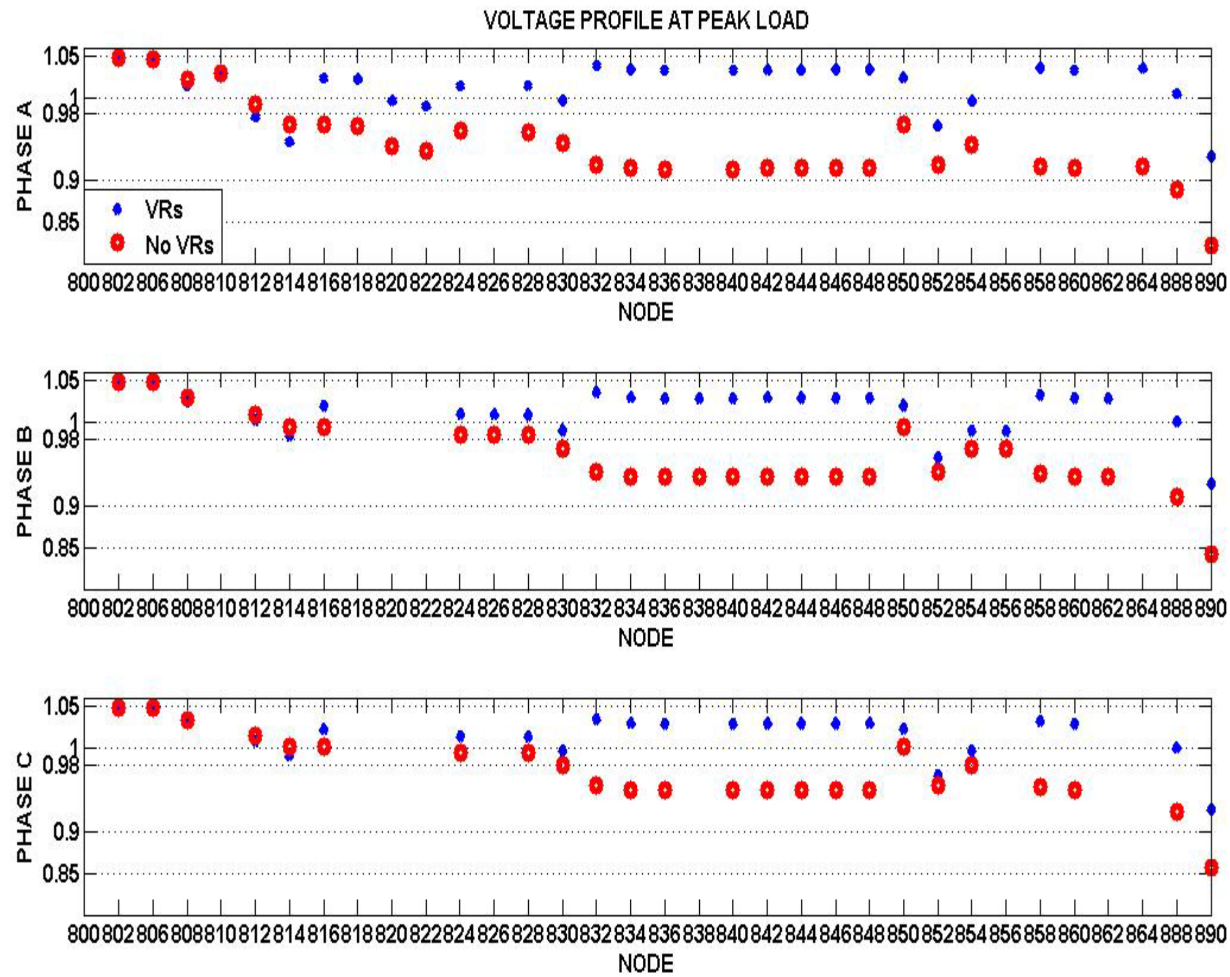


Figure 2.7 Voltage Profile comparison at Peak Load

Figure 2.8 clearly shows the functionality of VRs in the system. At node 850 and 832, the voltage boost to a presetting value and enables the nodes farther down the feeder to have no voltage issues. Table 2.3 shows the tap position.

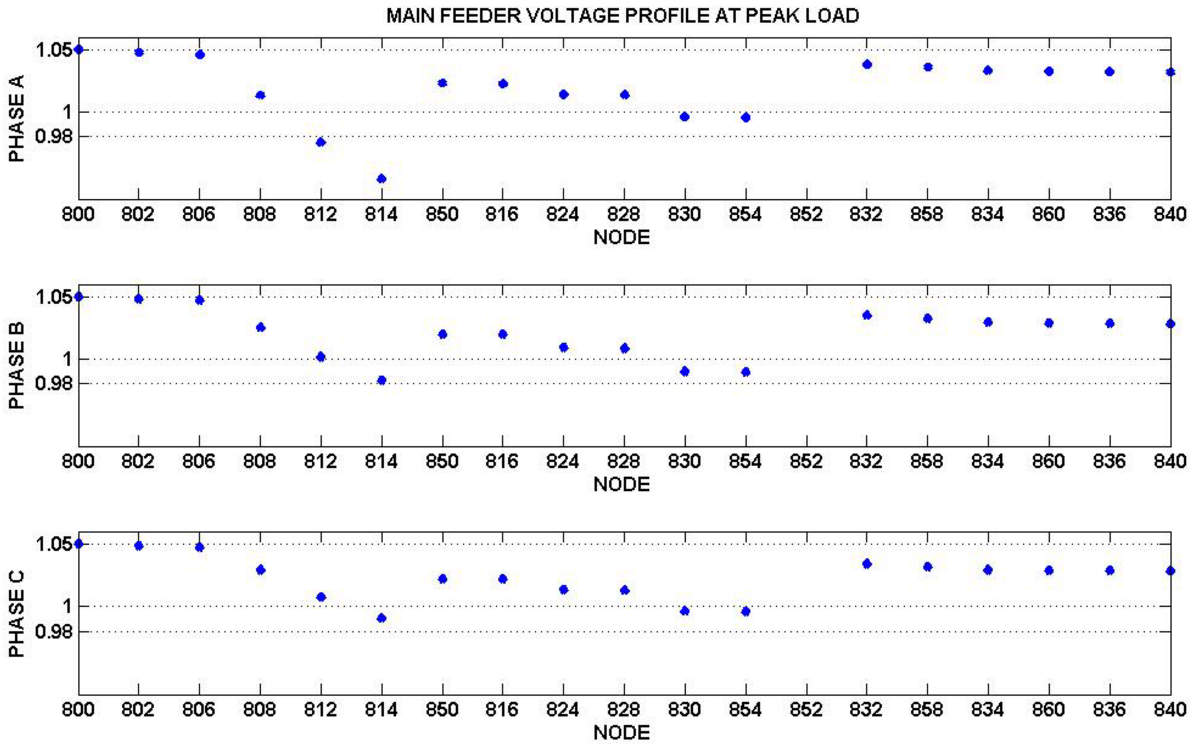


Figure 2.8 Main Feeder Voltage Profile at Peak Load

Table 2.3 Tap Position

	PHASE A	PHASE B	PHASE C
VR1	13	6	5
VR2	12	13	11

In order to see how the devices change within 24 hours, the simulation is run with daily variation load (shown in Figure 2.9). The load profile provides power and reactive power every half hour. In the simulation, the load change time is scaled to 2s. And the start-up time is 5s.

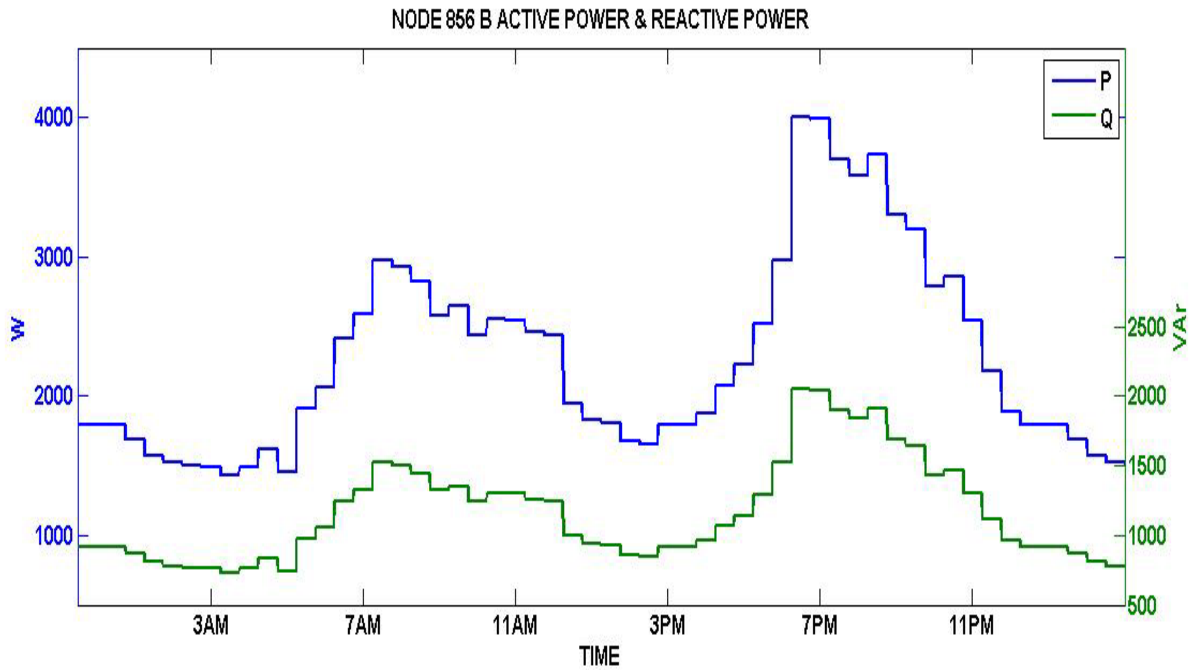


Figure 2.9 Daily Load Profile at Node 856

As shown in Figure 2.10, 10:30 AM has a high load demand, and the voltage is low. In order to boost the voltage the tap needs to rise to a high position as Figure 2.11 shown. It also can be seen that the tap increase step-by-step following the load demand from around 7:00 AM.

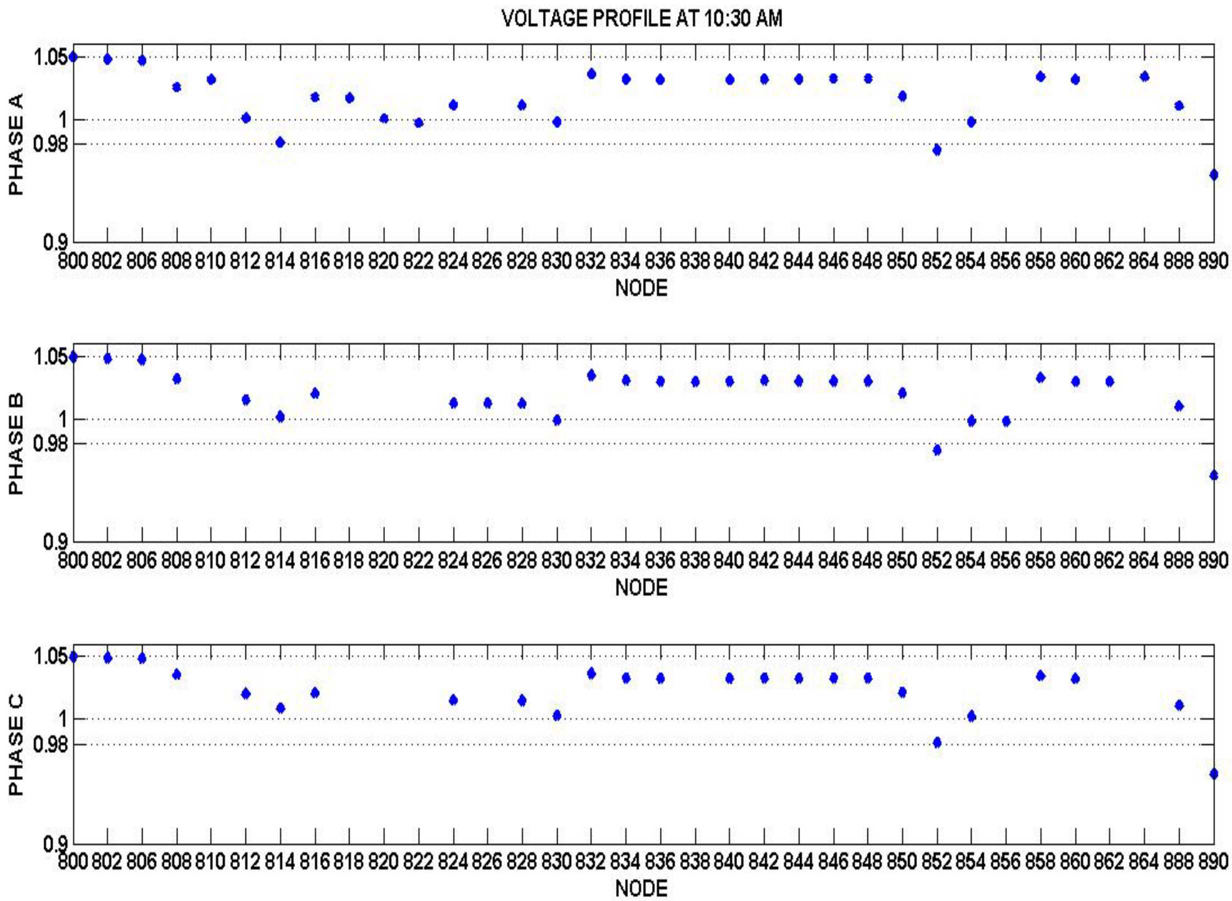
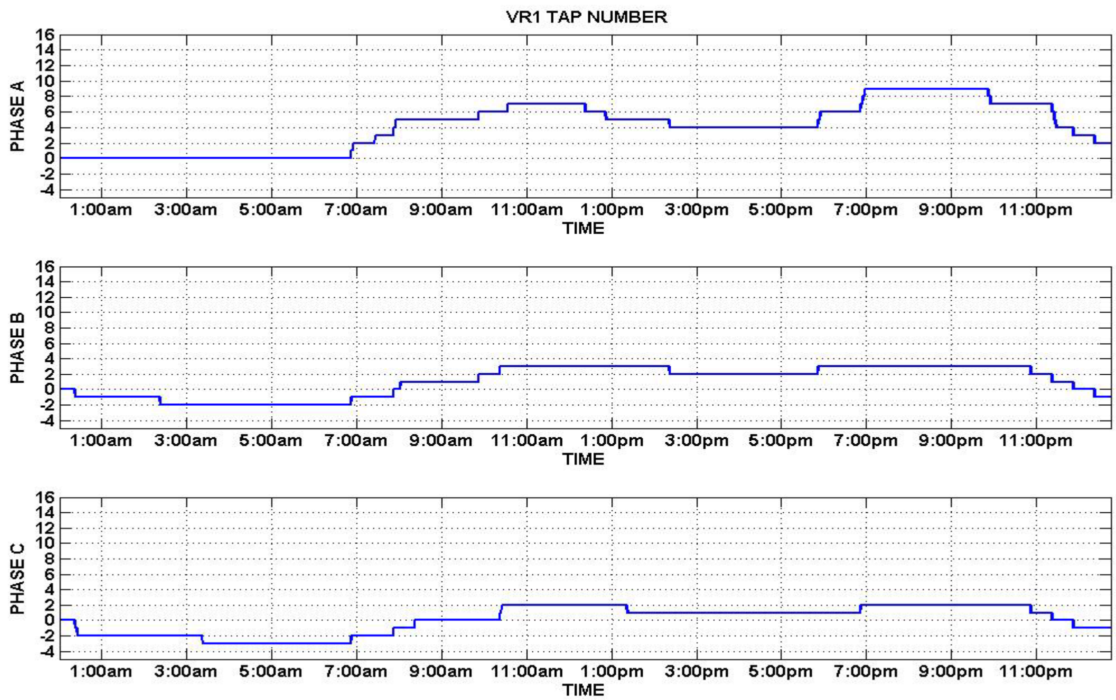
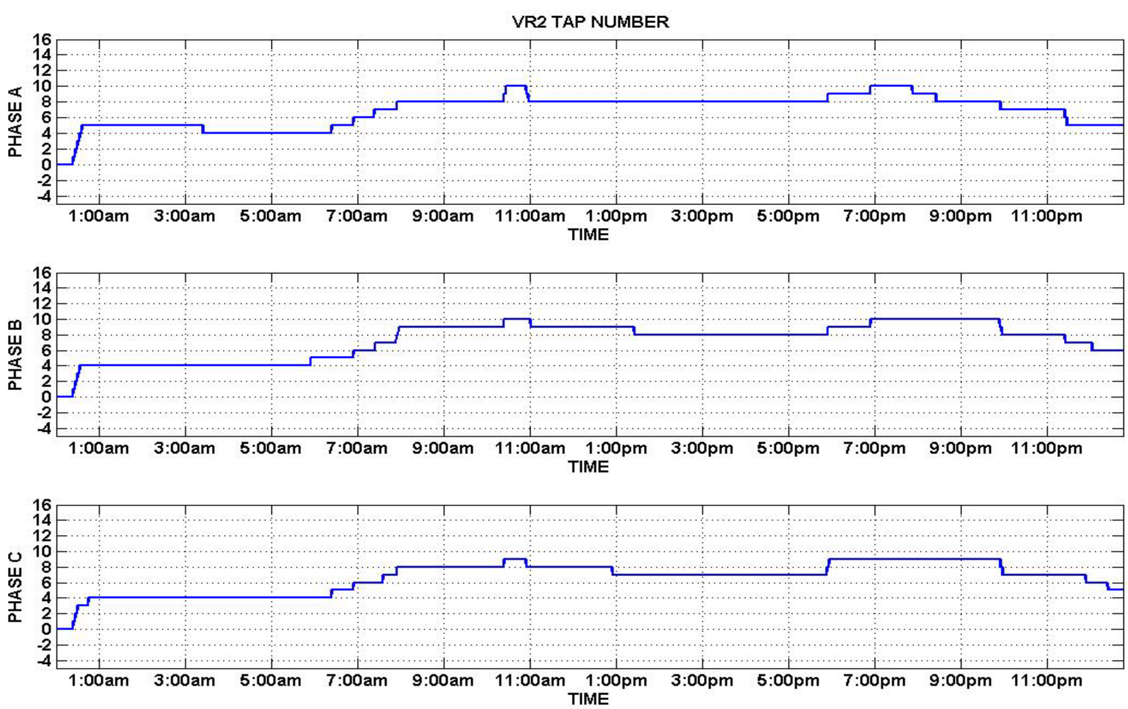


Figure 2.10 Voltage Profile at 10:30 AM



(a)



(b)

Figure 2.11 (a) Voltage Regulator 1 Tap Position (b) Voltage Regulator 2 Tap Position

At 3:00PM the load demand is considered low and the voltage is relatively high. Figure 2.12 shows there is no low voltage violation in the system. The lowest voltage in the system is node 890 which is near 0.98pu. However there may be high voltage violation. In Figure 2.13, we clearly see the functionality of the automatic control scheme. When the voltage increase exceeds 1.05pu, the VRs will drop the tap position to drag the voltage back into the acceptable limits. In order to have a view of voltage changes during the whole day, Figure 2.14 shows the voltage profile range of each node.

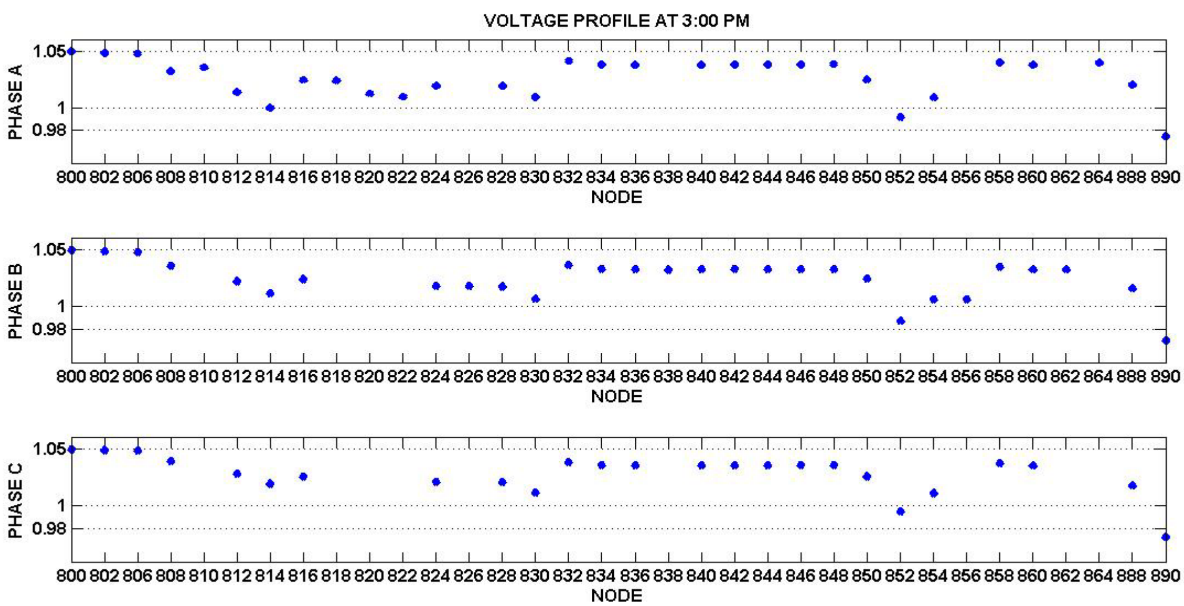


Figure 2.12 Voltage Profile at 3:00 PM

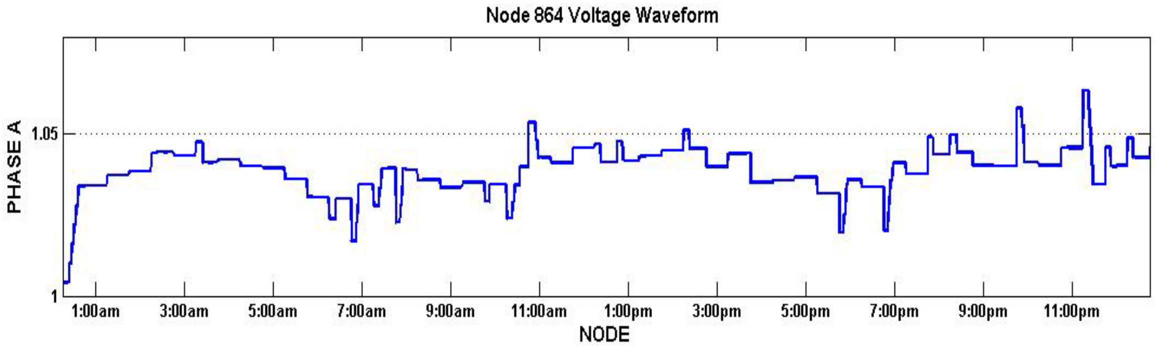


Figure 2.13 Voltage Waveform at node 864

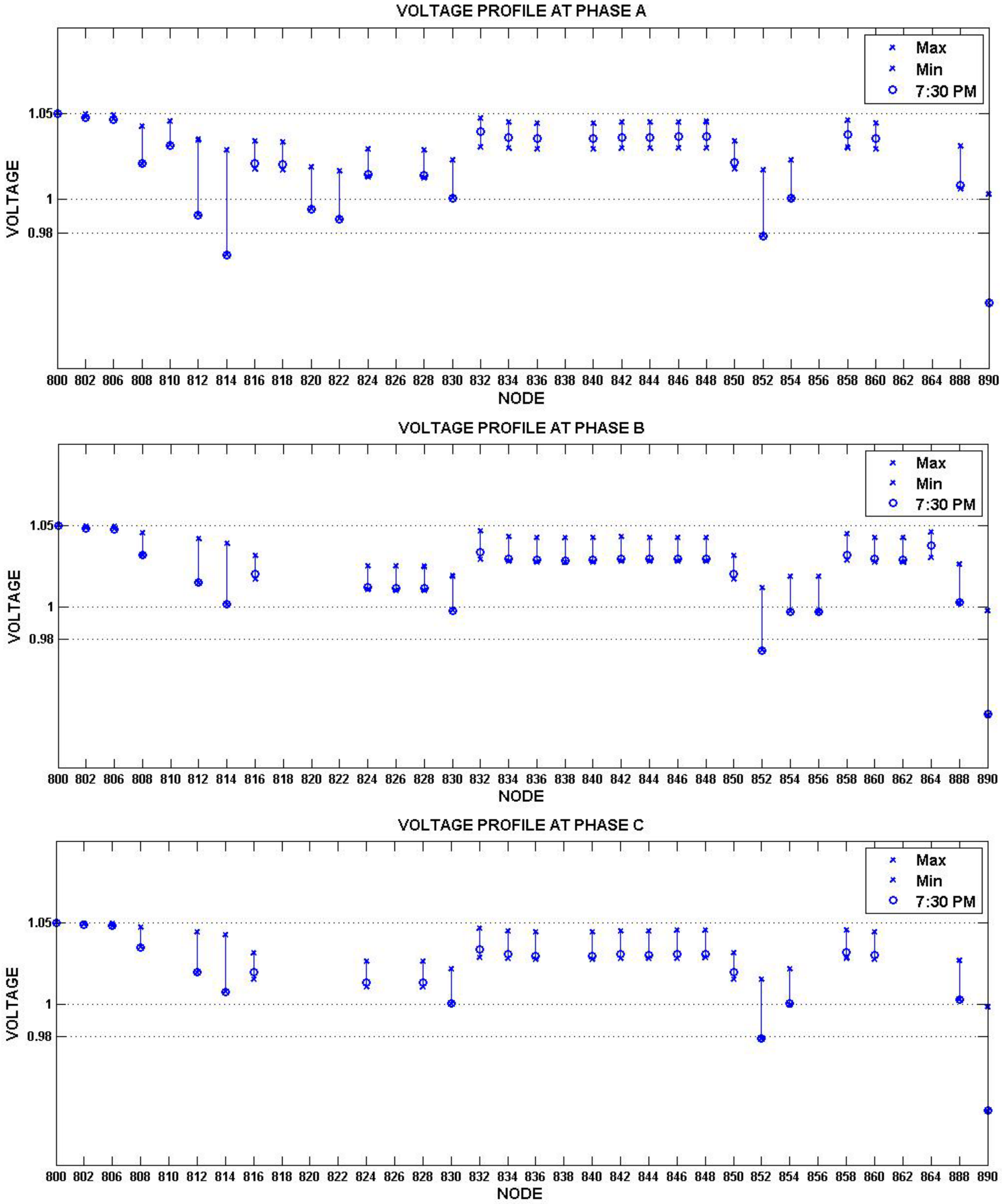


Figure 2.14 Feeder Voltage Profile variation

CHAPTER 3
PV IMPACTS ON DISTRIBUTION SYSTEM

The main goal of this chapter is to investigate the voltage related issues that arise when a considerable amount of distributed generation (DG) is installed on a distribution feeder. An increased amount of DG may have a significant impact on distribution system [5][6][7][8]. The main concerns identified involve reverse power flow, voltage rise, voltage unbalance, voltage fluctuation, improper VR operation, and increased power loss.

- <u>Reverse power flow:</u>

High penetration levels of PV can offset the feeder loads and the direction of power flow will be reversed from loads to neighbors or even to the substation. This situation is called reverse power flow. As distribution feeders are designed for unidirectional power flows, reverse power flow can negatively affect operation of line voltage regulators, particularly of the Line Drop Compensation (LDC), [11]. Furthermore, if substations have reverse power flow, the voltages and loading limits of some transformers may be affected.

- <u>Voltage Rise:</u>

PV integration can modify feeder voltage profile and raise the voltage close to the location of PVs. When high penetration level of PV is connected in a lightly loaded system, the voltage rise will be significant. If switched capacitor banks are on when the output of PV is maximal or if there are many fixed capacitor banks in the system, this voltage rise will lead to voltage violations on utility planning limits and industry standards.

- Voltage Fluctuations:

PV is an intermittent resource, therefore its varied output power lead to voltage variations which may cause power quality issues and complaints from customers. The severity of these voltage fluctuations must be assed to ensure that the system will not have voltage violation under any conditions.

- Voltage and current unbalance:

Single-phase high penetration PV may lead to significant voltage and current unbalance. For example, phase A has a PV installed and may experience reverse power flow, while phase B and phase C don't have PVs and have normal power flow. However, PV can also provide active power to the load and offset unbalances between different phases. So if all three phases have PVs installed, the voltage and current unbalance will be mitigated.

- Interaction with voltage-controlled capacitor banks, LTCs, and line voltage regulators:

Voltage rise and fluctuations both can cause frequent operation of LTCs, line VRs and voltage-controlled capacitor banks. At noon, PV systems provide a large amount of power into the system, which boosts the voltage and the voltage regulators move down the tap position to maintain all of the voltage limits. When the sun sets, no power is supplied by the PV system, the voltage regulators need move up tap positions to keep the voltage within limits. The higher number of operations increases maintenance and shortens the life-cycle of the equipment. In addition, frequent operations in turn can augment voltage fluctuations and affect power quality. Furthermore, voltage fluctuations may affect the implementation of advanced Volt-VAR Optimization (VVO) schemes and Conservation Voltage Reduction (CVR) approaches.

- Power Losses

Power system losses are proportional to the square of line current, so losses depend on the magnitude of feeder currents. For low and moderate penetration levels of PV, the magnitude of feeder currents will decrease, so power system line losses tend to decrease. For high penetration levels of PV, power system line losses tend to increase due to the reverse power flow which has larger magnitude of reverse direction currents. It is worth noting that these situations could happen within a single day. At noon, the load is light and the output of PV is maximal, so the line losses may increase. While during the late afternoon, the light isolation may decrease the penetration level of PV and decrease the power losses at the same time. Therefore we need to evaluate the average power losses instead of instantaneous losses. Voltage rise under high penetration levels of PV is also a reason to augment the high losses situation, because distribution transformer core losses are proportional to nodal voltage.

3.1 PV Impacts Studies

To investigate these issues, the prototype feeder shown in Figure 2.1 with detailed PV models is used. It is assumed that this is a residential feeder and some of the customers have installed photovoltaic (PV) systems on their rooftops. To simulate these PV systems, a typical grid connected PV system, shown in Figure 3.1, has been simulated. This system consists of a PV array with maximum power point tracking connected to a DC-DC converter and a DC-AC inverter to connect the system to the 240 AC supply. The model has been adopted from Colorado model [13].

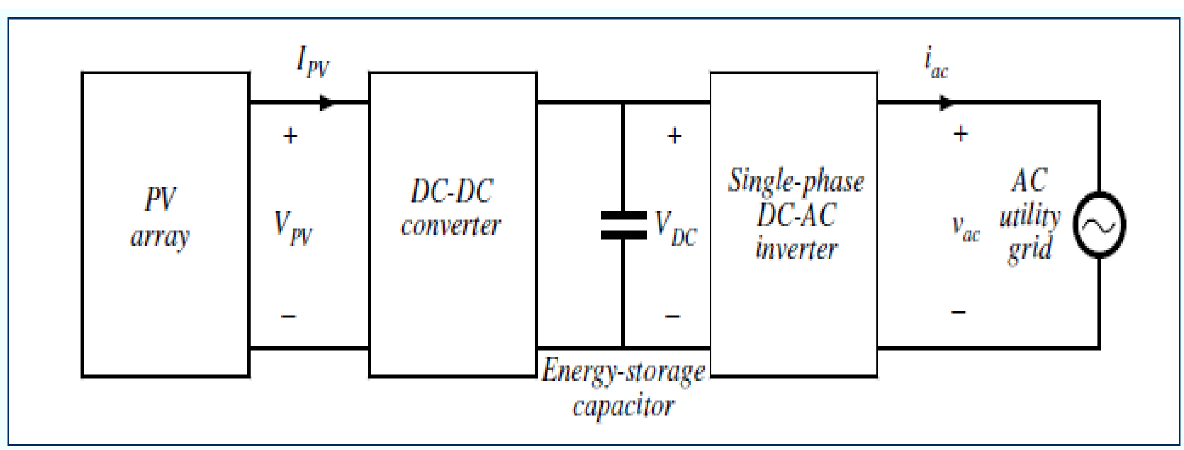


Figure 3.1 Main components of a residential PV system

The main objectives of the PV impact studies are to investigate steady-state and dynamic impacts previously discussed,[6]. The steady-state impact study is implemented by using distribution software analysis. The time-varied load and PV output are run with batch processes from which we determine the worst-case scenarios. The range of the time-varied data could be 8,760 hours of the year, 24 hours of the day, or half-hour intervals during a single day. The dynamic impacts study conducted with a more detailed model and simulating the worst-case scenarios identified in the steady-state study, [6].

A. Steady-state impact study

Steady-state impact study can be conducted on both local and system-wide scopes [5]. Localized studies focus more on the impact of utility-scale PVs and mitigations on a specific feeder of a substation. System-wide studies address impacts of medium-scale or small-scale PVs on the overall utility power distribution systems, [6]. In these studies, the location, timeline and number of PVs are uncertain. Generally, studies may be targeted to comparing feeder voltage profiles, active and reactive power flows, distribution losses and operation of control devices (like LTCs, line voltage regulators and switched capacitors) before and after PV integration, [9]. These studies should be conducted over 8760 hours of the year to incorporate monthly and seasonal variation in load and PV generation. If this is not feasible due to the limitations of running time or data, a simplified study could be done for 30-min intervals over a 24 hour period.

B. Dynamic-state impact study

Dynamic-state impact studies focus on the effects of fast-varying output power caused by PV intermittency, which may be a result of clouding or sudden disconnection (faults or repair) and connection of PVs. Accidental islanding of PV is also of main concern in the study, as it may lead to significant temporary overvoltage (TOV). The study also needs to analyze the impacts of PV integration on voltage transients and power quality and PV behavior during faults and system dynamics. This kind of simulation should be implemented on second- or sub-second-based PV output profiles that can show the potential power quality impacts.

3.2 Case Studies

Based on these guidelines, we developed two case studies for the PV impact study. Case I is focused on the steady- state impact of PV and normal operation of conventional Volt-VAR control devices. Case II is a cloud impact case study. Both static load and dynamic load will be used in the second case.

3.2.1 Case I

In this case, the main goal is to investigate the voltage-related issues that will happen when high penetration levels of PV system are installed in a distribution system. A modified prototype (Figure 2.1) is used.

It is assumed that five large load nodes on the feeder have installed PV systems. Table 3.1 shows the nodes and the size of the PVs at these nodes. Note that in this case it is assumed that PV capacity is about 70% of the maximum total load; hence, this case represents 70% PV penetration. Figure 3.2 shows the simulated power output profile of these PVs and the load profile during a day.

Table 3.1 PV systems placed on the prototype system

node	890	844	860	822	836
power	450	405	146	135	82
total	1218				
percentage	69%				

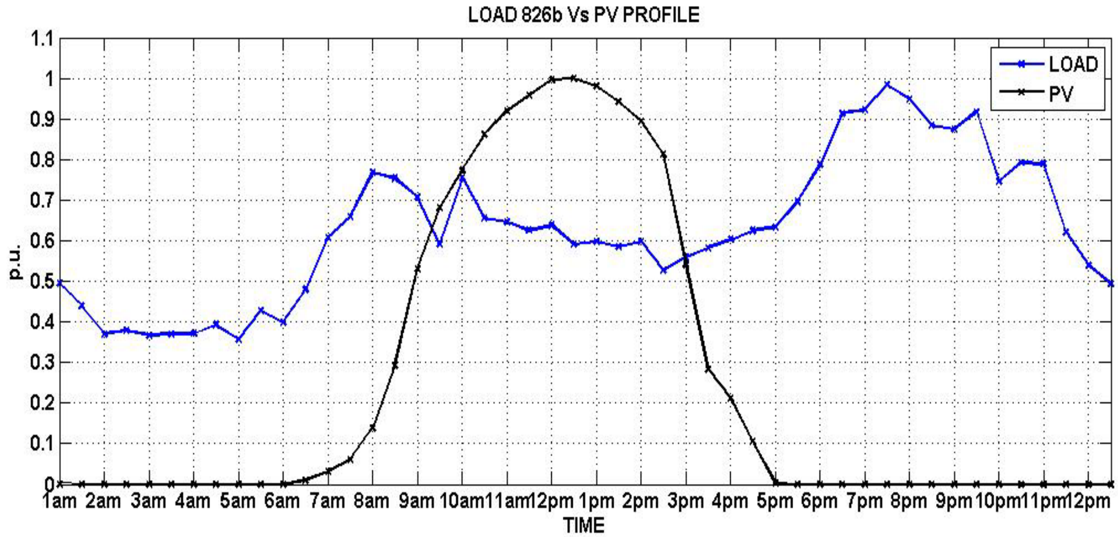


Figure 3.2 Normalized PV and Load profiles

3.2.1.1 Voltage Rise

Figure 3.3 show the voltages at node 890 both before and after the installation of PV systems. A maximum 0.07 pu (around 200V) rise is shown at noon. From the waveform we see that PV systems improve the voltage by boosting it into a better range. On a hot summer day, the peak load, which is mainly comprised of room air conditioners, appears at noon. PV systems could well improve the voltage profile. But when peak load happens at night, installing PV cannot solve the peak load low voltage violation problem.

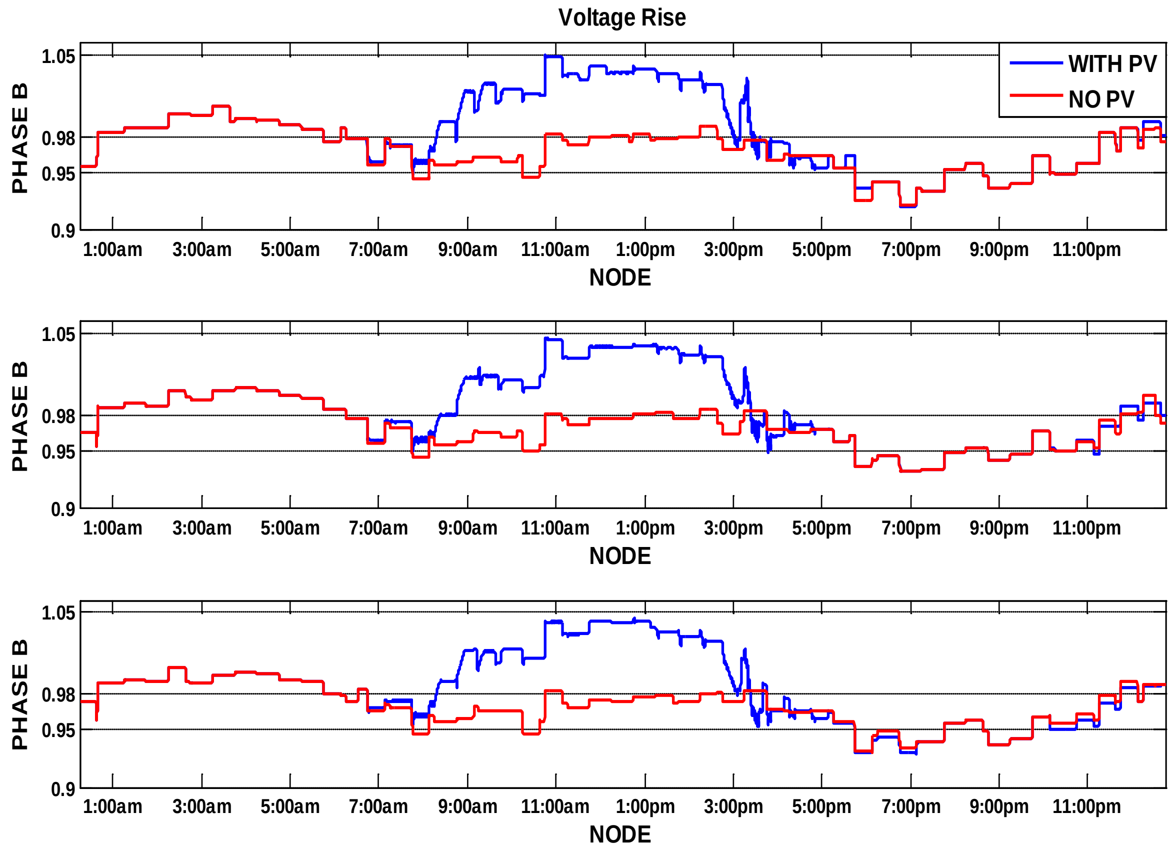


Figure 3.3 Voltage waveform comparison of before and after PV installation at node 890

Figure 3.4 shows the voltage profile along the entire feeder at noon, when PV power output is at maximum value. The voltages are flatter than when PVs are not installed. However, the voltages at node 812 and node 814 phase A suffer a high voltage violation. Voltage rise caused by PV system installation may lead to this high voltage violation problem.

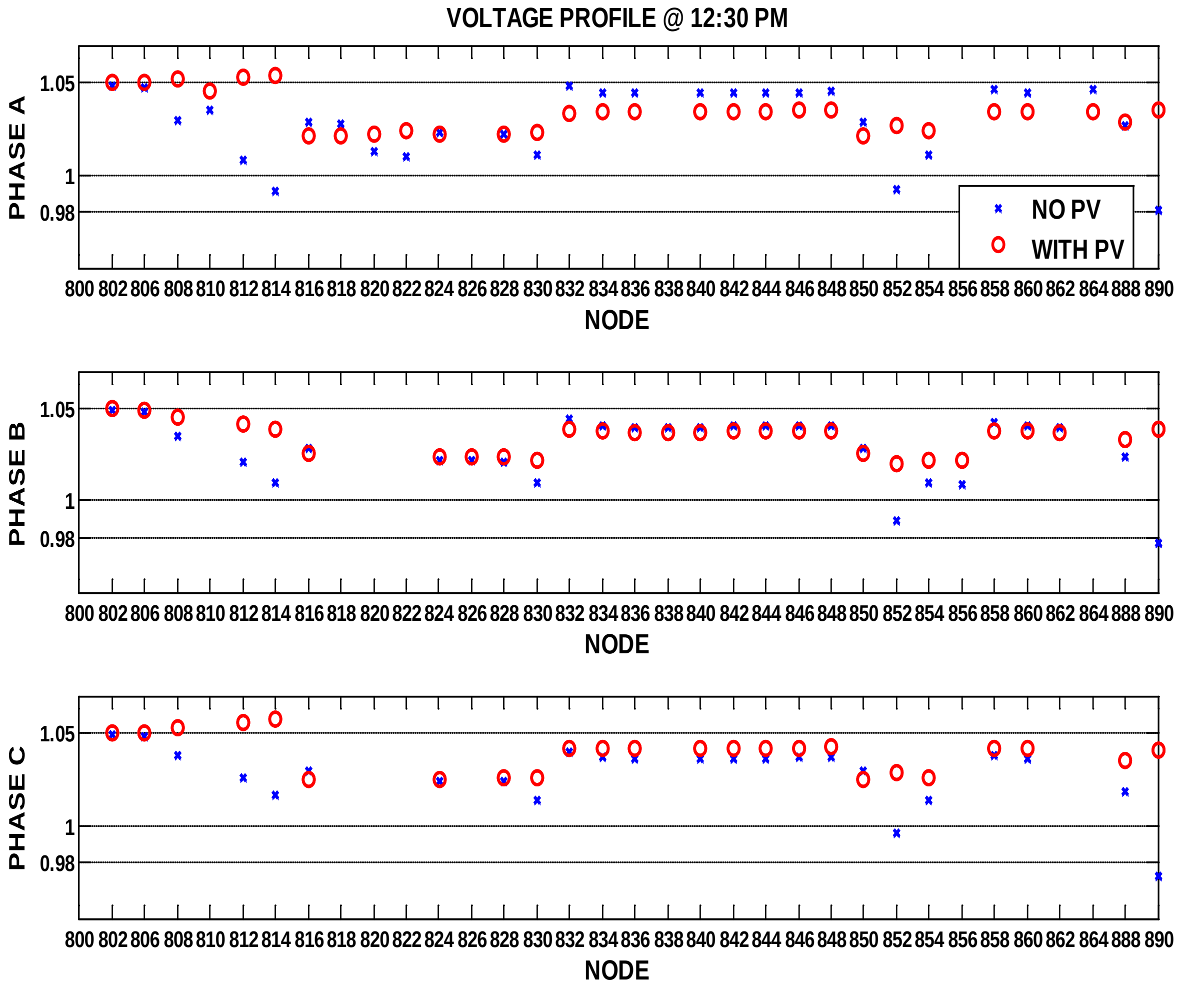


Figure 3.4 Voltage profile comparison of before and after PV installation at 12:30 PM

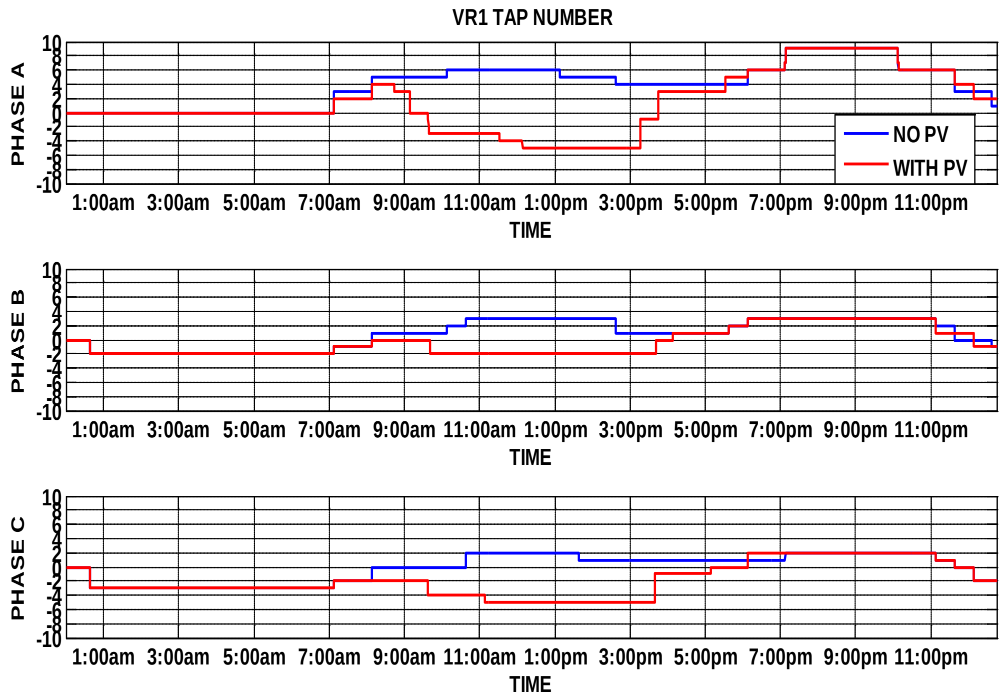
3.2.1.2Interaction with line voltage regulators

a) Frequent operation

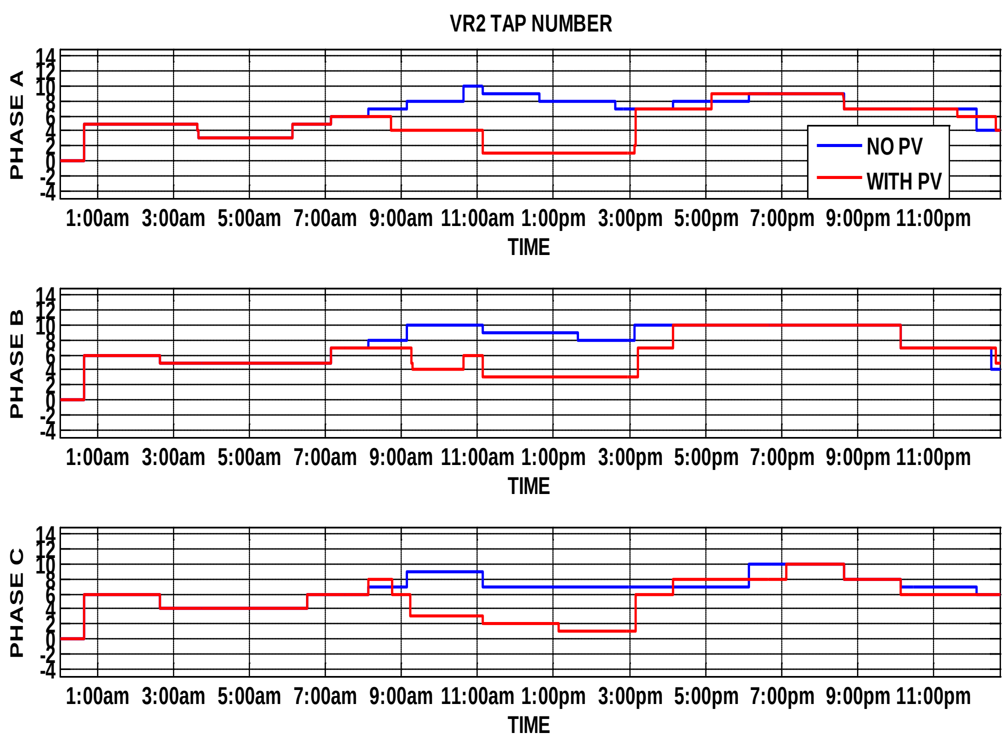
Voltage rise can cause frequent operation of line voltage regulators. Tap positions are shown in Figure 3.5. The number of operations is shown in Table 3.2. At noon, PV systems boost the voltage and the VRs need to lower the tap position to pull back the higher voltage. As the insolation decreases, the tap position increases. These increased movements increase the maintenance and shorten the life-cycle of VRs.

Table 3.2 numbers of operations of both Voltage Regulators

	VR 1			VR2		
	PHASE A	PHASE B	PHASE C	PHASE A	PHASE B	PHASE C
NO PV	21	13	11	19	16	16
WITH PV	34	13	15	22	23	26
Raise Percentage (%)	61.90	0	36.36	15.79	43.75	62.5



(a)



(b)

Figure 3.5 (a)-(b) VR tap operation profile

b) Improper operation

As improper VR operation only happens under reverse power flow conditions, we focus on two points around noon: 10:30 AM and 12:30 PM. A separate unidirectional mode Voltage regulator was built as a comparison simulation. Figure 3.6 shows the tap number as a function of time. Tap changes are slower with the unidirectional mode than with bidirectional mode. If the feeder suffers a voltage violation, slower changes may lead to longer violation time. Phase C also shows an improper VR operation. As illustrated in Figure 3.7, with the conventional mode, the calculated voltage at remote points is always larger than the voltage where the VR is located. While, with the actual conditions, reverse power flow makes the voltage rise along the feeder, so the voltages at remote point should be higher. In this case the voltage drop between local voltages and remote voltages is not significant. Thus there is no serious improper VR operation happens. However Figure 3.8 shows a more extreme case. If the actual voltage is higher than upper limits while calculated voltage is still smaller than lower limits, the conventional VR will increase the tap number to boost the voltage. This improper operation increases the severity of the voltage violation.

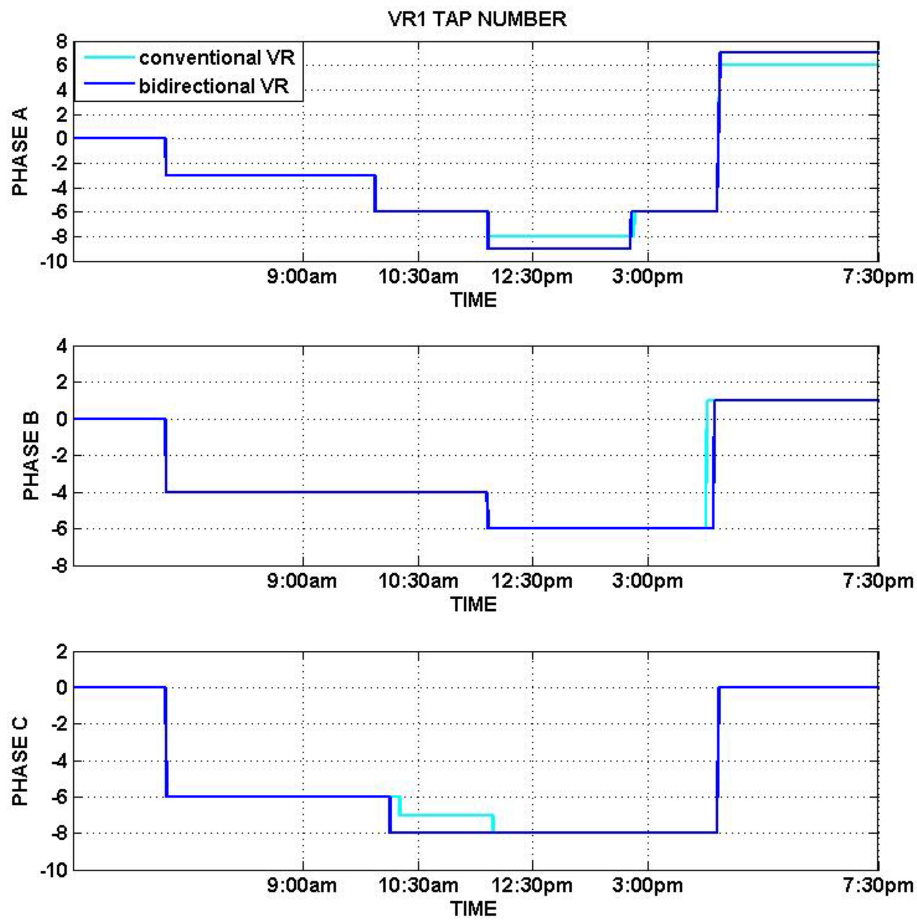


Figure 3.6 Voltage Regulator Tap Number

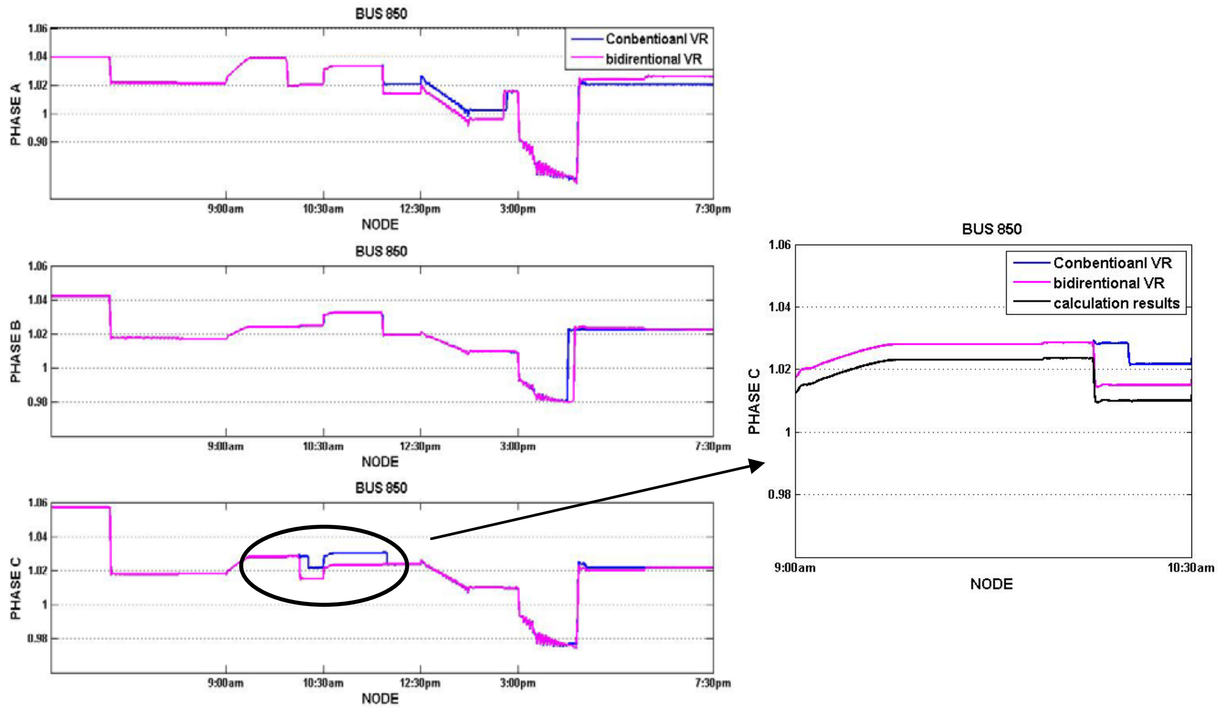


Figure 3.7 Voltage Profile at Node 850

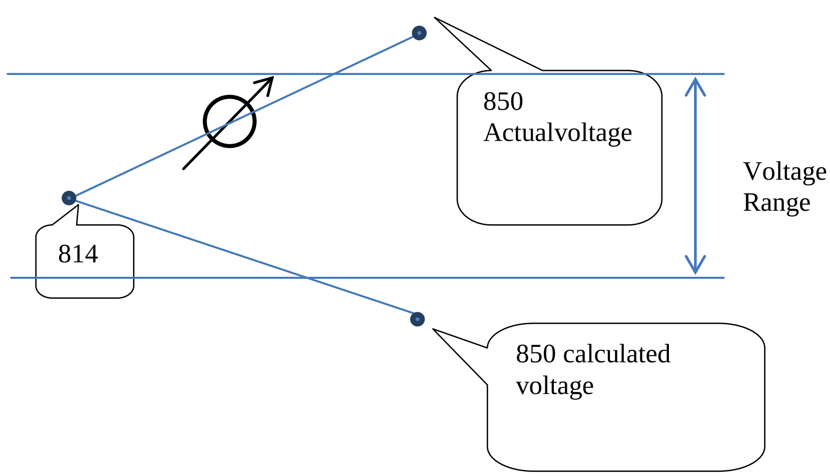


Figure 3.8 Conventional VR

3.2.1.3 Power Loss

Power system losses are proportional to the square of line current, so power losses decrease when power supplied by PV systems increases and the current magnitude decreases as shown in Figure 3.9. However we need to notice that power losses between 10:00AM to 3:00PM are the same. This is because as the penetration levels of PV increase, it may lead to reverse power flow with a large magnitude of reverse current, in high power losses. In our study case, when PVs reach their maximum power output at around 12:00PM, the reverse current increases losses (Figure 3.10). If we increase the penetration level of PV systems, it may lead to larger power loss than without PV installation.

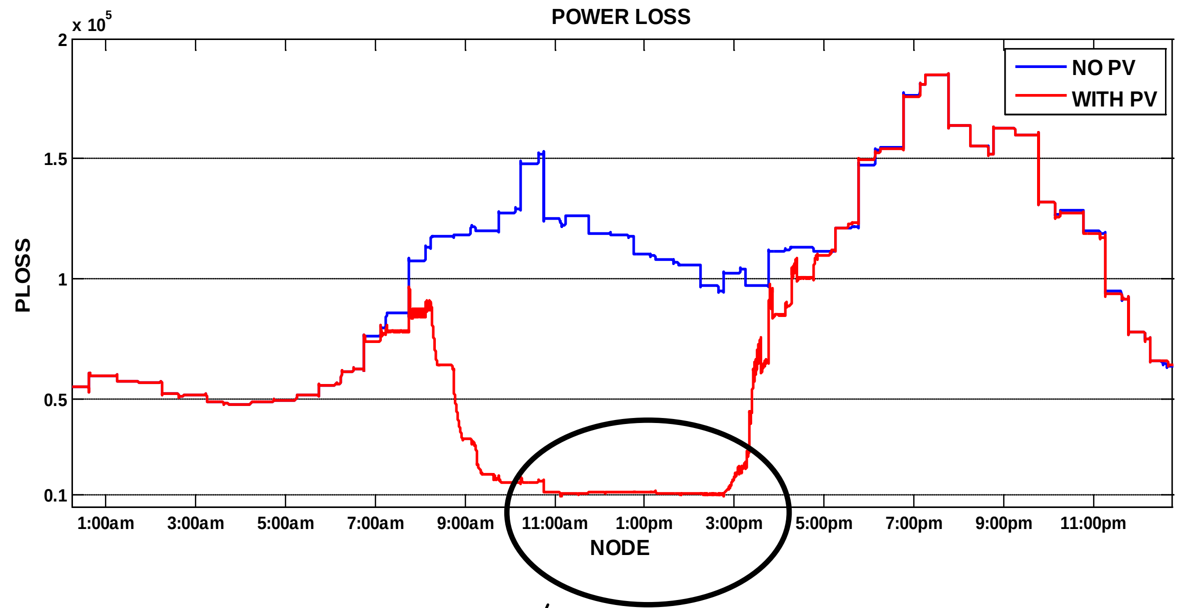


Figure 3.9 Power loss comparison

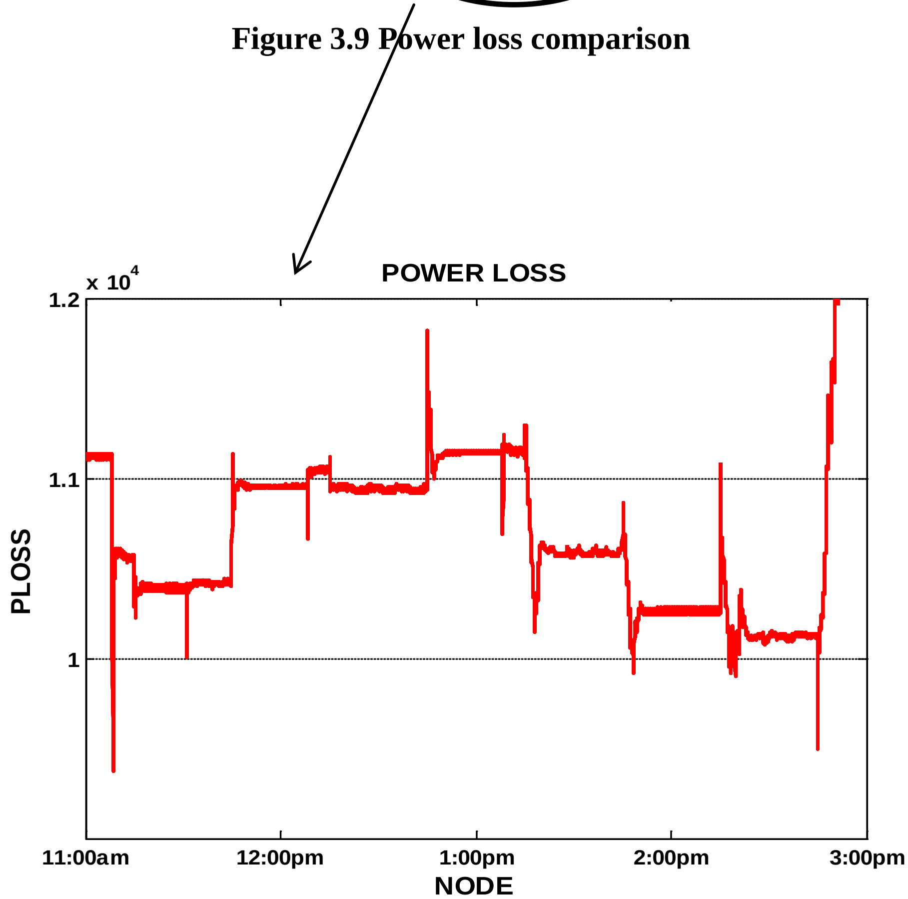


Figure 3.10 Power loss with PV installation

3.2.1.4 Voltage Unbalance

Three phase PV systems could improve the voltage unbalance. For each node, Equation (3-1) is used to calculate voltage unbalance.

$$V_{(unbanlance)} = V_{imax} - V_{imin} \tag{3-1}$$

Where i represents Phase A, B or C. As Figure 3.11 shows, the maximum voltage difference between three phase decrease from 0.025pu to 0.0197pu and at most of the nodes, the voltage difference decreases slightly.

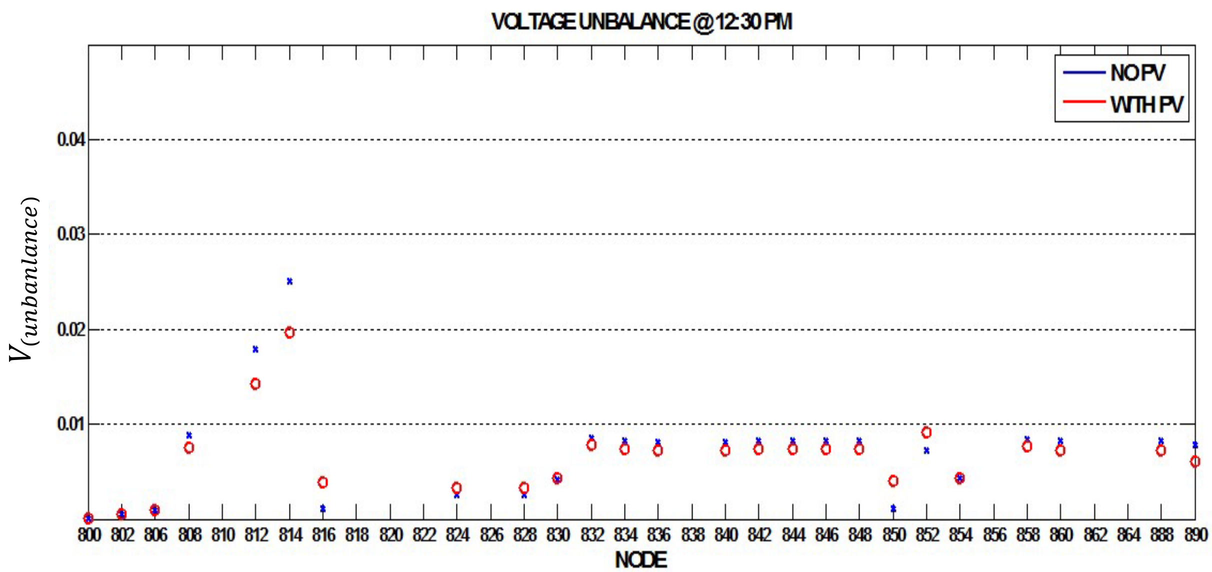


Figure 3.11 Voltage unbalance comparison at 12:30PM

3.2.2 Case II

3.2.2.1 Cloud Impact with Static Load

As we mentioned before, the tap position in the voltage regulator is kept in a relatively low position at noon. If clouds sweep over this network within a short period of time, PV power contribution will drop quickly. Although the VR can observe a voltage decrease, the LTC controller will not response immediately due to time delay, so the voltage drop will remain for a short time. Because the voltage drop is a function of distance from the substation, the voltages at some remote nodes may have already suffered unacceptably low voltage.

The cloud transient is simulated by a decrease in solar irradiation from 1000 to 70 W/m^2 over a 20s period of time from 80 to 100s as shown in Figure 3.12,[10].The PV active power output follows the solar radiation.

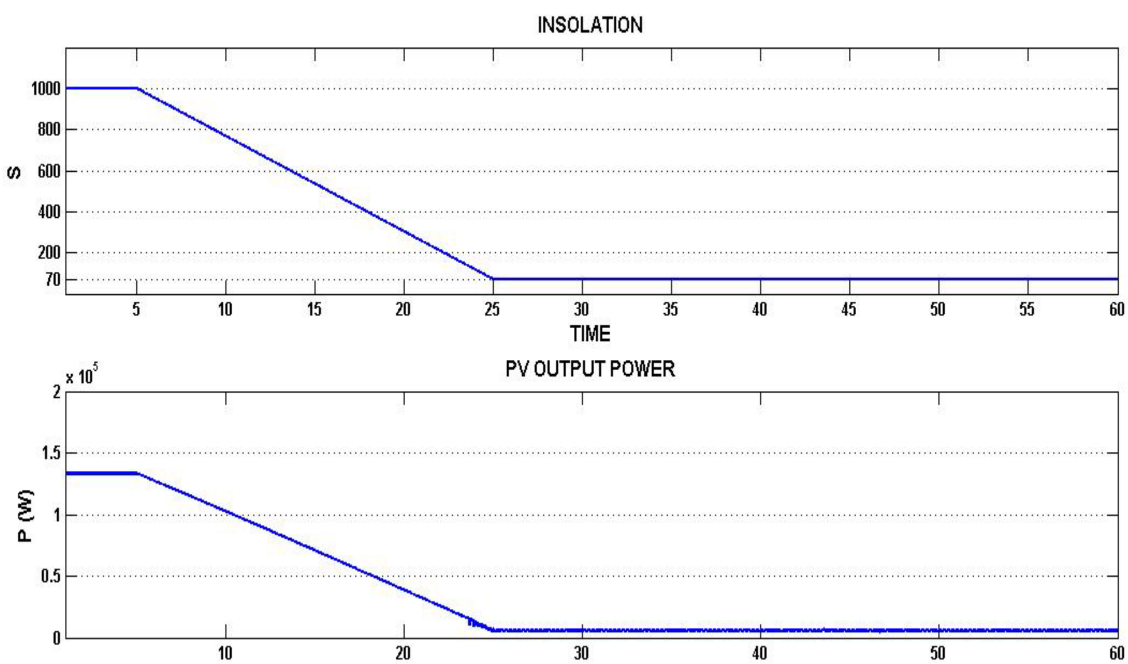


Figure 3.12 PV power changes with sun irradiation

Figure 3.13 show the voltage profile for the cloud impact. In this case, phase A has the worst voltage profile and the voltage at node 890 is most severely affected by cloud coverage. Figure 3.14 shows the voltage profile at node 890. Following cloud cover, the voltage at node 890 drop down to 0.89 pu which exceeds the low-voltage limits for 15s and then comes back within limits after 30s.

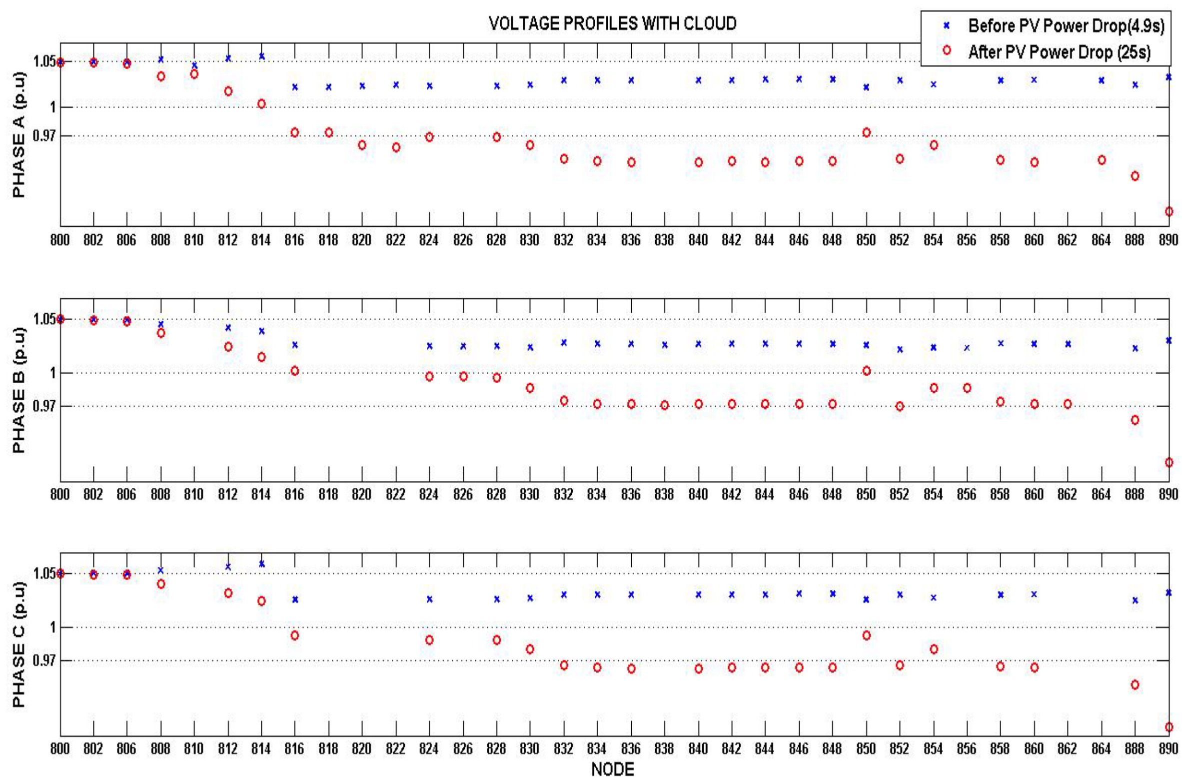


Figure 3.13 Voltage Profiles with cloud

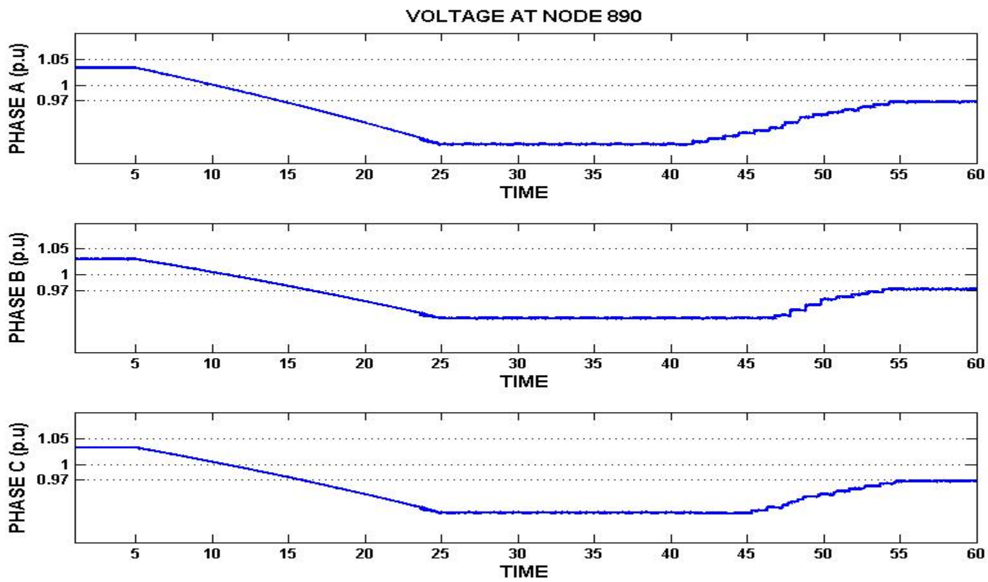


Figure 3.14 Service voltage of Node 890

3.2.2.2 Cloud Impact with Dynamic Load

a) 70% penetration

In this case, dynamic load models are implemented in the simulation. We adopt 50% resistive loads and 50% small induction motor loads in the system. A squirrel cage induction machine (shown in Figure 3.15) is implemented as a dynamic load. The loading torque is assumed to be about 0.45 pu at noon and the stalling voltage is around 0.95pu. When one motor starts to stall, it will draw more current, which may cause a lower voltage. But after the speed goes down to zero, the motor will be disconnected from the grid and the total load will decrease, which may lead a voltage jump in the grid.

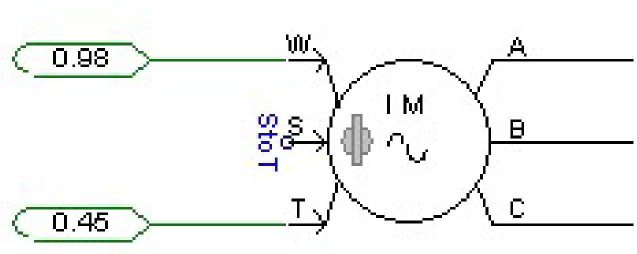


Figure 3.15 Induction Motor in the system

At about 5 s when the whole system has already reached steady state, the clouds begin to cover the PV panels in the system and the output of the PV begins to fall. The voltage also drops as Figure 3.16 - Figure 3.18 show. Figure 3.16 and Figure 3.17 show voltage profile of the nodes with motor connected. Figure 3.18 shows the voltage profile of the node at the end of the main feeder. From these figures, we can see two voltage jumps at around 15s and 22s, which means two motors stall in the simulation. The steady state voltage at node 860 is about 1.03 pu. However, when the motor begins to stall, the large current that motor draws from the grid causes the voltage to drop to 0.95 pu (Figure 3.16). Figure 3.19 shows the speed of all four motors in the system.

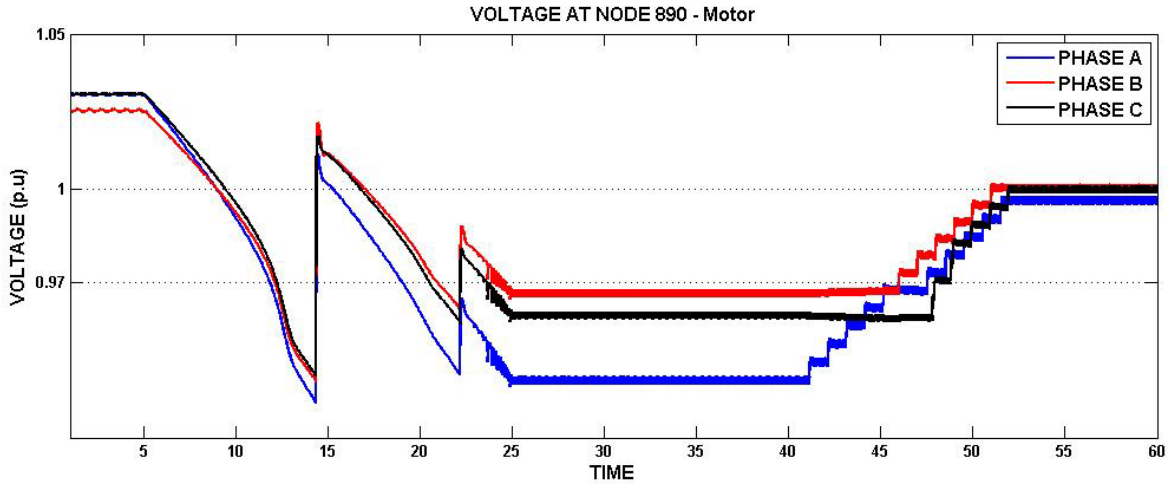


Figure 3.16 Voltage Variation at node 890

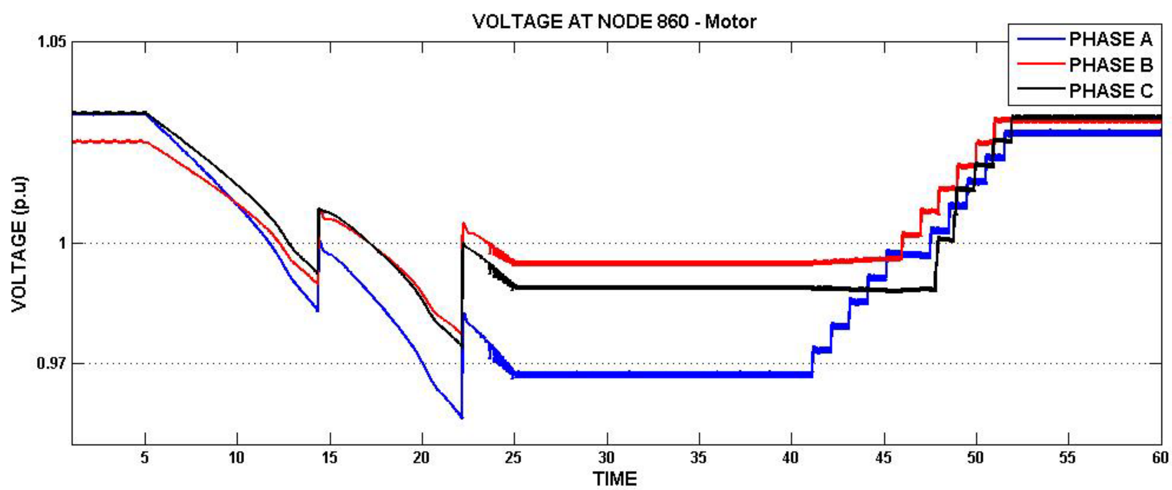


Figure 3.17 Voltage Variation at node 860

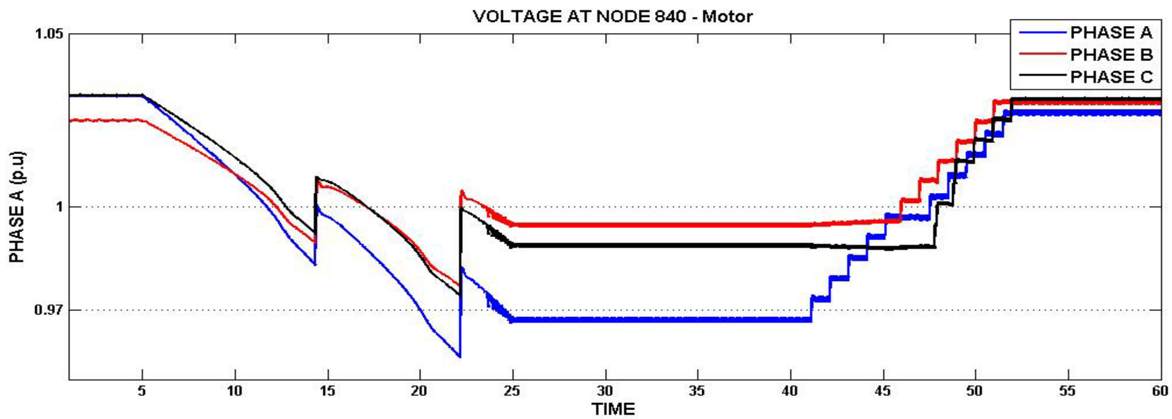


Figure 3.18 Voltage Variation at node 840

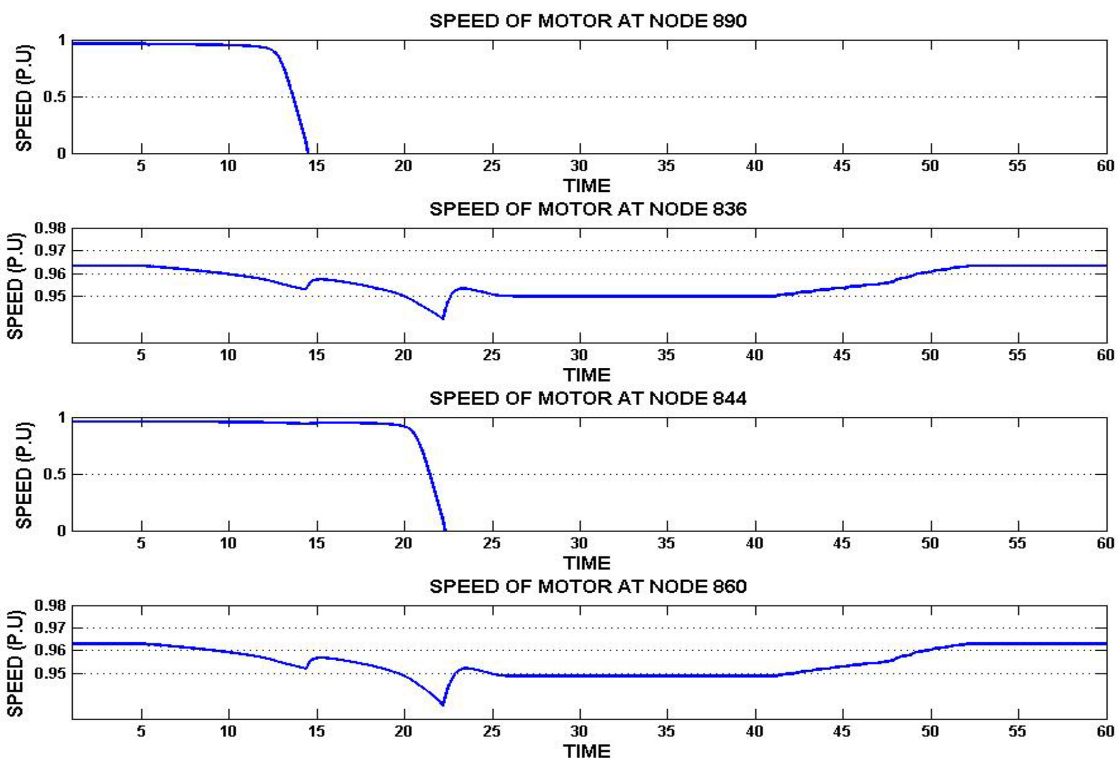


Figure 3.19 Speed of Motors in the system

From Figure 3.19, we can see that motor 890 begins to stall at 12s and motor 844 begins to stall at around 20s. Although the other two motors have a very low speed at 22s, they do not stall and the speeds of these two motors come back to normal after voltage regulator acts.

Figure 3.20 – Figure 3.21 show more clearly the behavior of induction motors in the simulation. At around 15s the motor at node 890 stops, which means the residential device stops working because of cloud cover. This serious problem will cause custom complaints. So in the following chapter, we attempt to use DVC to maintain the voltage and keep the all the motors working during cloud cover.

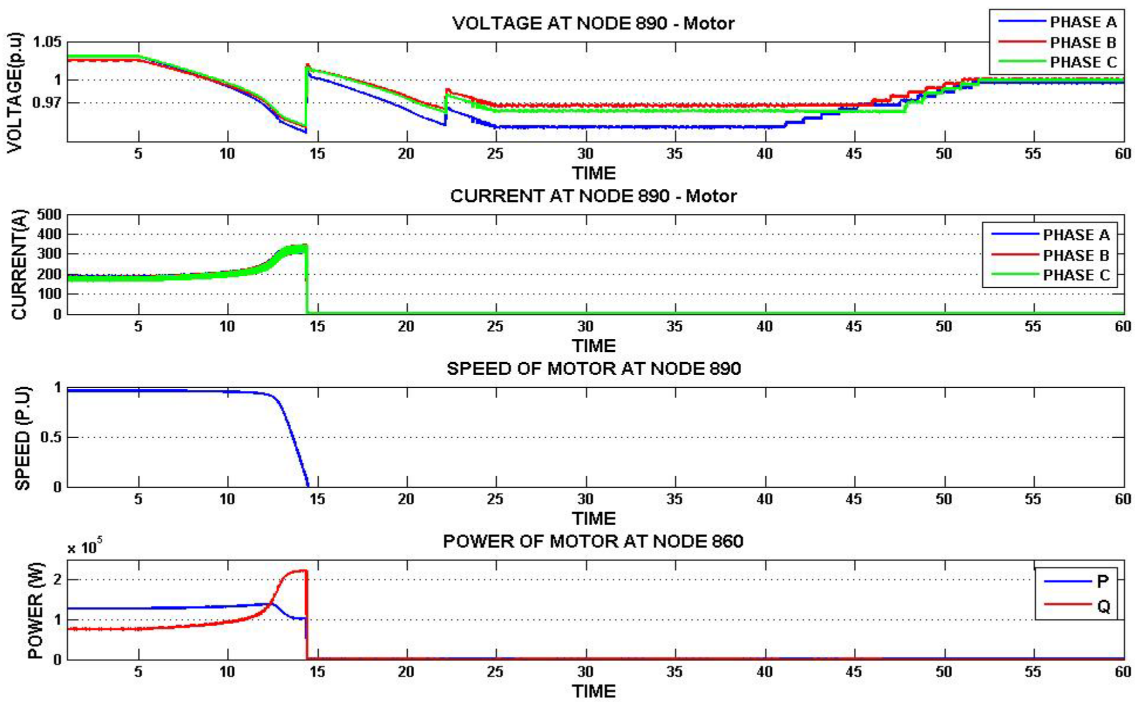


Figure 3.20 Motor Behavior at node 890

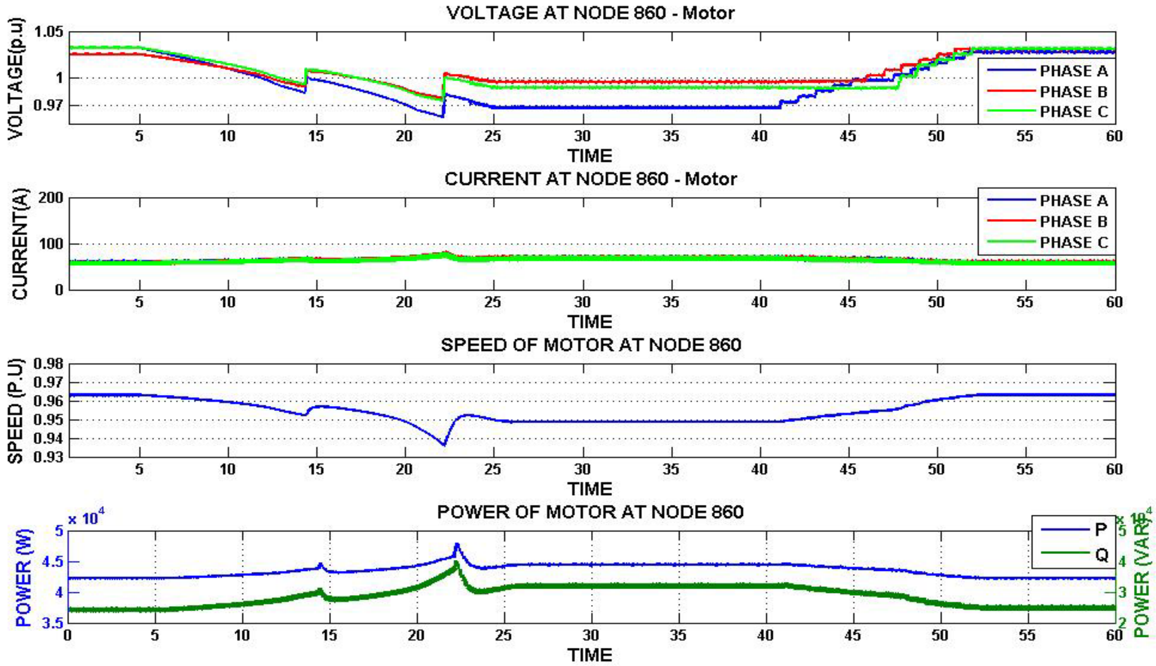


Figure 3.21 Motor Behavior at node 860

b) Low Penetration (5%)

In the previous section, with 70% penetration of PV, two motors stop working during cloud cover. That proves that high penetration level of PV can cause induction motor stall. This case is to determine the maximum PV penetration which will not affect the induction motor working.

First I reduced the penetration from 70% to 50% and 30%, the motors stalled. I kept reducing the penetration level of PV until 5%. Motors work continuously during cloud cover period with 5% penetration of PV. The new power outputs of PVs are listed in Table 3.3. When the penetration of PV increases, the VR's tap position decreases (Table 3.4) and the voltage after cloud covers the PV also decreases (Table 3.5).

Table 3.3 PV systems placed on the prototype system

node	890	844	860	822	836
power(kW)	22.5	40.5	14.6	6.75	8.2
total (kW)	92.55				
percentage	5%				

Table 3.4 VR2 Tap Position under Different PV Penetration

	Phase A	Phase B	Phase C
30%	6	6	4
10%	7	7	4
5%	7	7	5
No PV	7	9	6

Table 3.5 Voltage Comparison at node 890 after cloud covers all of the PVs

	Phase A	Phase B	Phase C
30%	3175	3170	3172
10%	3197	3202	3202
5%	3269	3255	3272
No PV	3295	3298	3300

Figure 3.22 shows that four motors are all work during the cloud cover period and the speed doesn't change much. Figure 3.23 shows the behavior of motor at node 890 which stops working in the previous section. We can see with 5% penetration level of PV, although there is still low voltage violation, it keeps working during the cloud cover period. If we expect PV doesn't affect the devices' working, the maximum penetration level of PV is 5%.

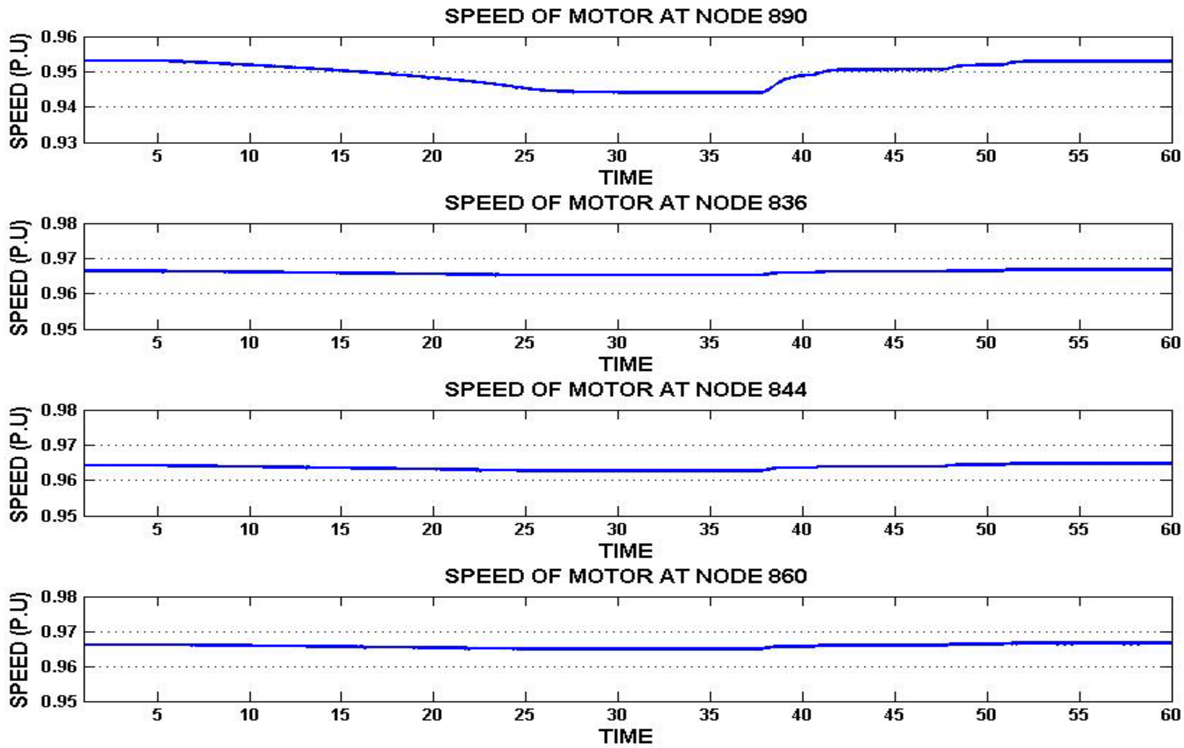


Figure 3.22 Speed of four motors

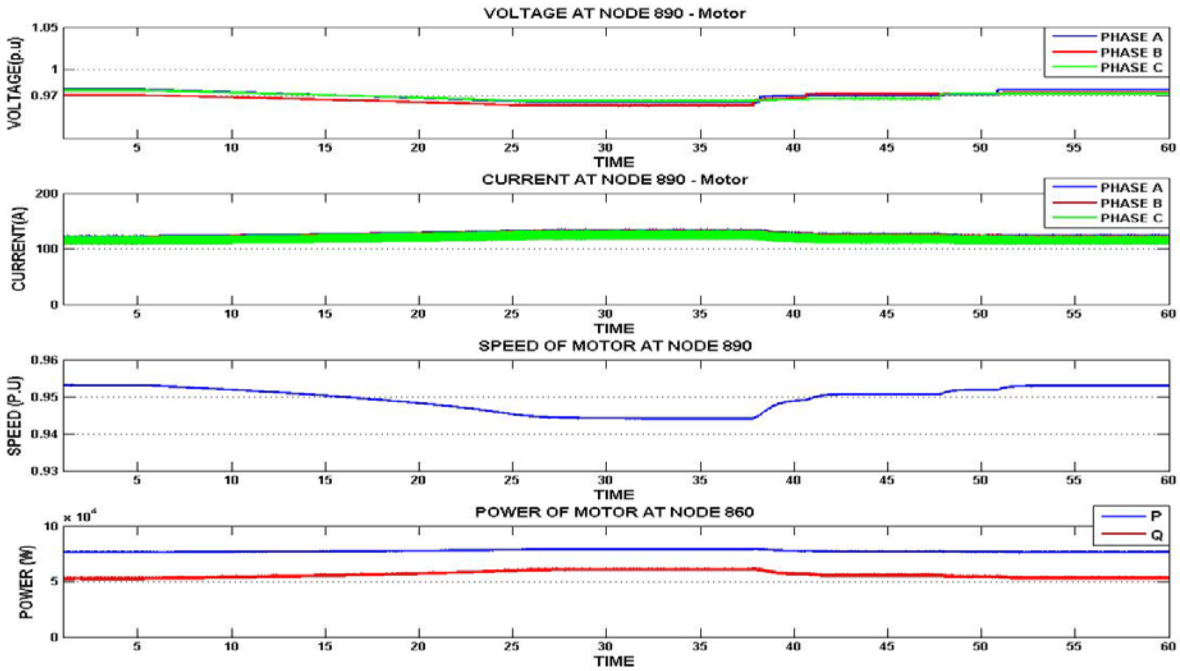


Figure 3.23 Motor Behavior at node 860

CHAPTER 4

DYNAMIC VAR COMPENSATOR

As shown in the previous chapter, voltage problems like high voltage violation or frequent operation of control devices caused by high penetration level of PV needs some viable solution. Dynamic VAR Compensator is a new type of Static VAR Compensator, with its own advantages. Usually, DVC is smooth and can continuously adjust reactive power [12],[14]. DVC can help solve the reactive compensation problem for many different transmission or distribution applications. Figure 4.1 illustrates the usual place where DVC installed, which is similar to capacitors. In this work, DVC is used to address voltage problems in a distribution system.

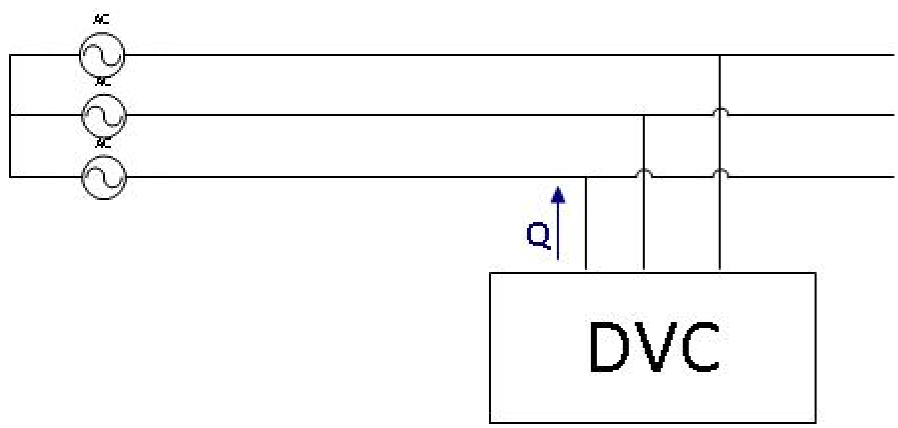


Figure 4.1 DVC installed in the grid

Figure 4.2 shows the circuit of voltage source converter based DVC. As it has a very long simulation time, it cannot be used for power-system-level simulation. So an average dynamic model with controlled voltage and current sources on both AC input and DC output is used.

Figure 4.3 shows the model used in this thesis. The DC output voltage and voltage on the grid are two input reference of controller. The controller calculates three phase voltage and sends it back to the three phase controlled voltage sources.

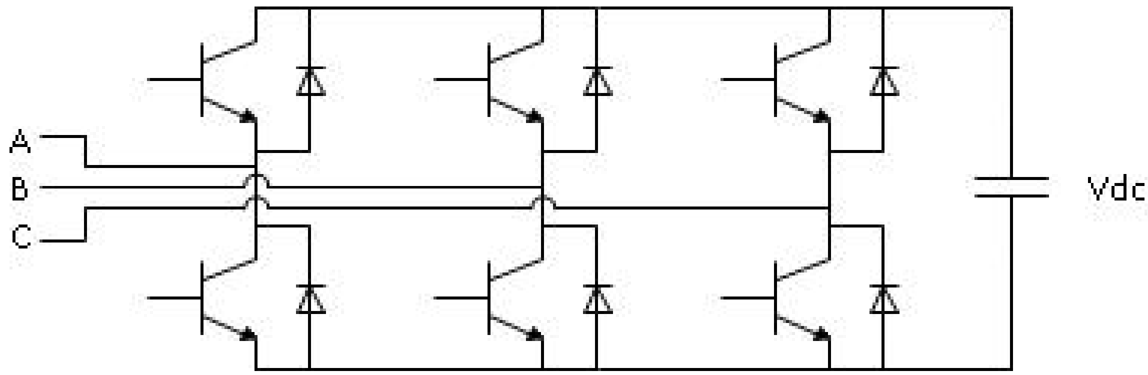


Figure 4.2 Circuit of Voltage Source Converter

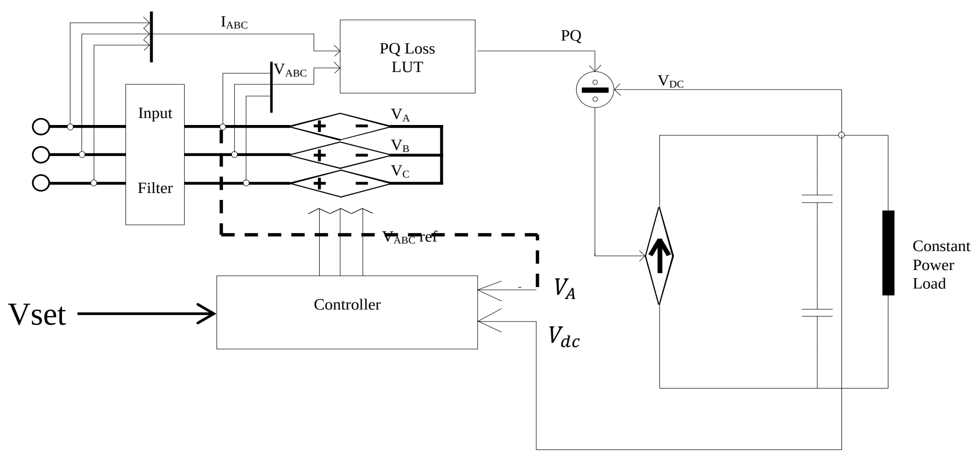


Figure 4.3 DVC Average Model

Figure 4.4 shows an equivalent DVC model in PSCAD, this model is made by Ankan De[15]. RYB is represented as an electric node which is connected to grid. A control signal is sent by the DVC controller to a1, a2 and a3. The controller is shown in Figure 4.5.

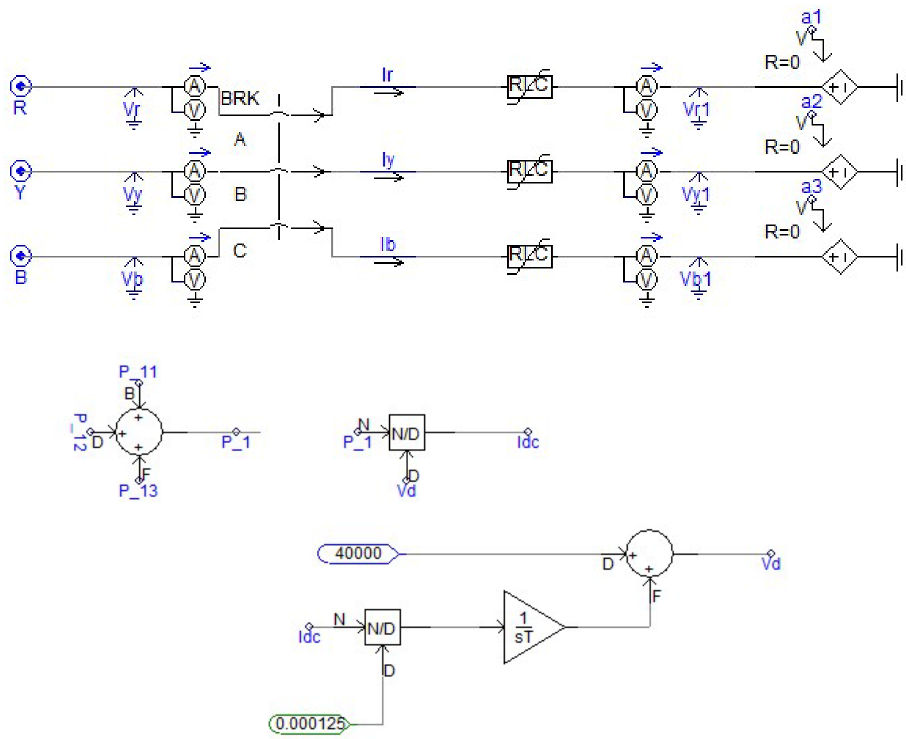


Figure 4.4 DVC equivalent circuit

The voltage at phase A and dc voltage are two inputs of the controller. The voltage reference could be preset in the controller. By adjusting the abc control signal which is three phase voltage of controlled voltage source in the DVC model, the controller keep the voltage at phase A equal to some preset voltage reference.

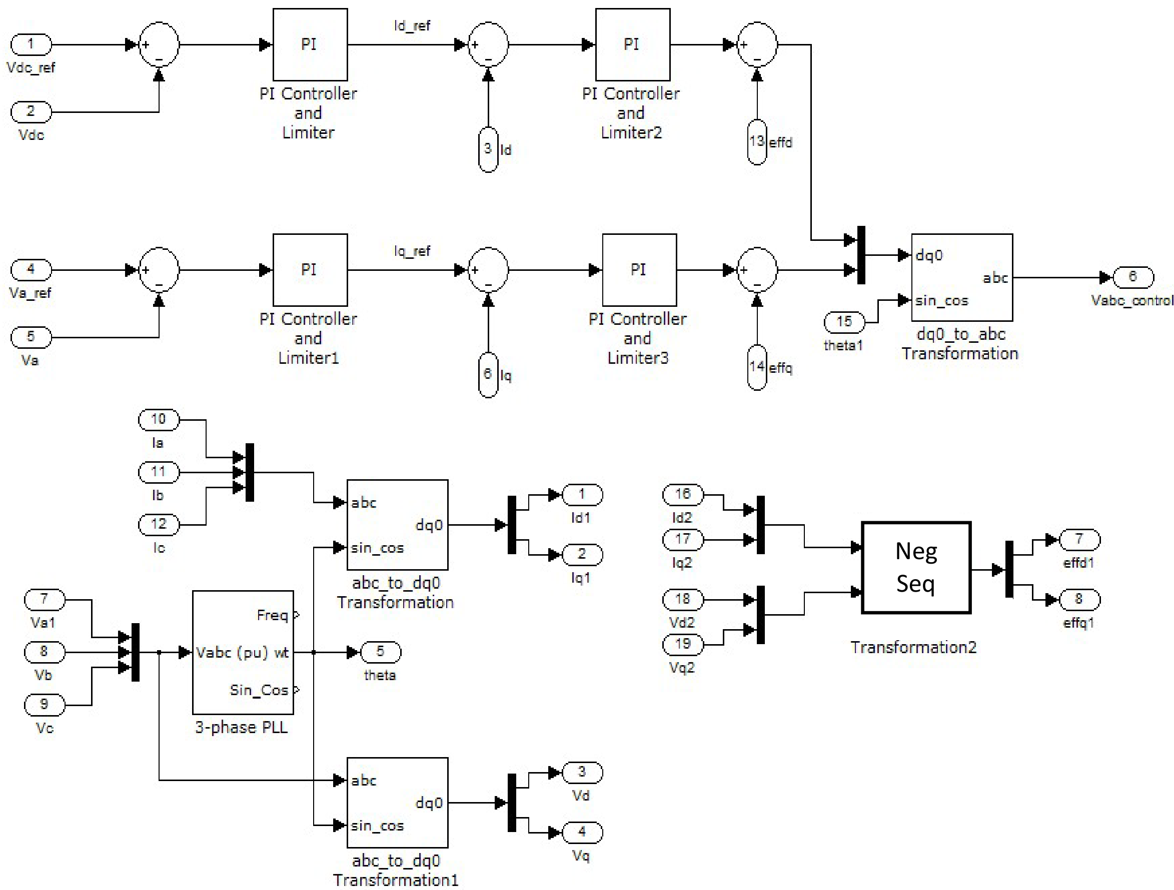


Figure 4.5 DVC Control Scheme

Case Studies

The goal is to investigate the DVC's performance when used as a Volt-VAR control device in the distribution system, and to determine whether it can help address the voltage problem in the system with a high penetration of PV. First, we integrate DVC into the conventional system to see whether it can replace voltage regulators and capacitors. Second, we use it in the system with high penetration of PV to see whether it can address the problem caused by the PV. Lastly, we use DVC to achieve flat voltage function to prepare a flatter voltage profile, which is required for Conservation Voltage Reduction.

4.1 Conventional System

4.1.1 Case 1: DVCs replace Voltage Regulators

In this case, we use DVC to replace two voltage regulators (at 814 and 852). With a line drop compensator integrated, VRs regulate two remote nodes, which are located around node 850 and node 832. Thus we put DVCs at node 850 and node 832 to verify whether they can realize the functionality of voltage regulators.

In order to regulate voltage at a preset value, we use the closed-loop control mode as shown in Figure 4.5. In this mode, we set a reference voltage value and regulate one phase voltage to this presetting. Figure 4.6 shows the main feeder voltage profile comparison between the system with DVCs and the system with VRs under peak load condition.

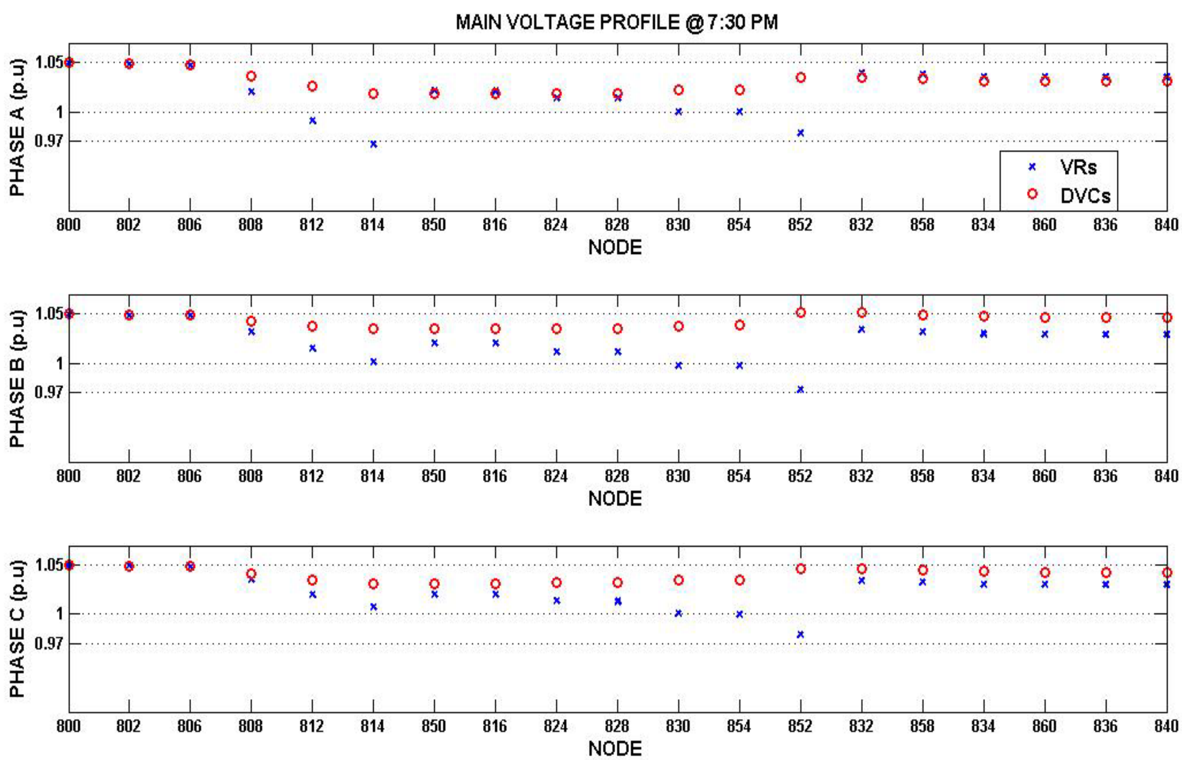


Figure 4.6 Voltage profile along the main feeder under peak load condition

Three-phase DVCs can only regulate one phase voltage at a preset value. In this case, the DVC regulates voltage at phase A. The reason is phase A has the lowest voltage among the three phases and if we regulate a different phase, the lateral connected to phase A (node 818, 820 and 822) will suffer a low voltage violation. From the Figure 4.7, we can see that at node 832 and 850, both VRs and DVCs boost the voltage to a preset value. As we mentioned in base case, voltage at node 814 and node 852 which are the nodes just in front of the voltage regulator, have a low voltage violation. As there is no load connected to these notes, this is not of much concern. But this is a disadvantage of using the VRs. However, DVC avoids this disadvantage and gives us a flatter voltage profile.

Figure 4.7 shows the voltage profile for every node under peak load condition. It shows us that node 890 still has a voltage violation issue. Figure 4.8 shows the comparison of voltage waveforms at node 850 where the DVC is located. The DVC can regulate the voltage exactly equal to a preset value, while the VR can only regulate the voltage within a small range.

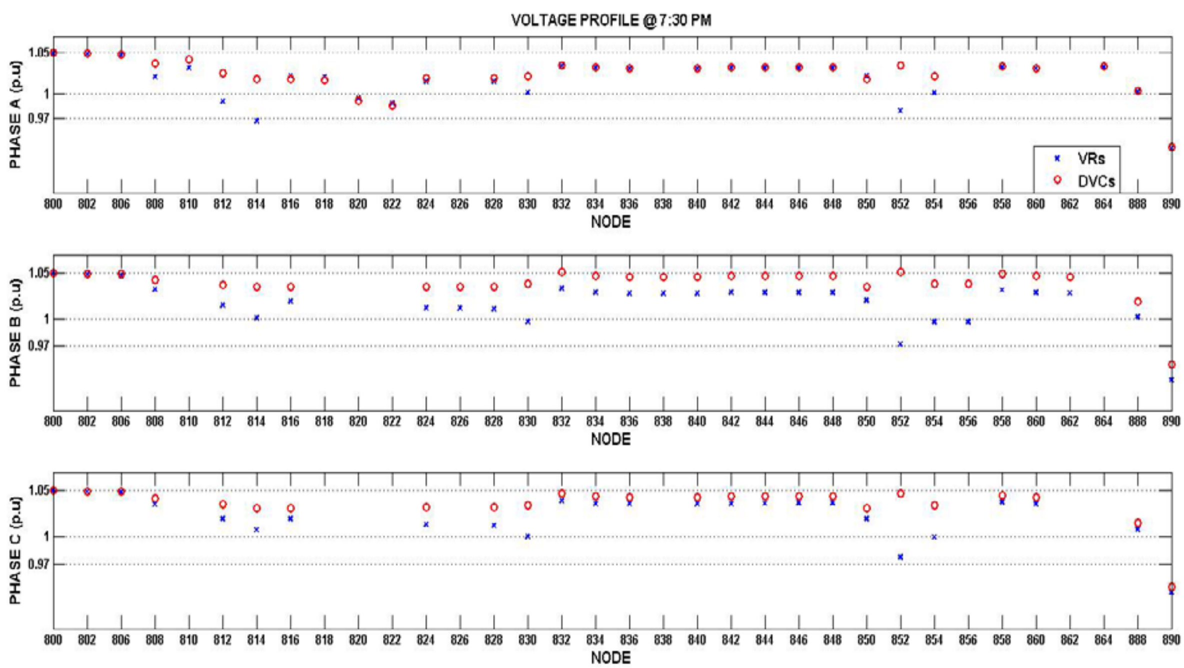


Figure 4.7 Voltage Profile Comparison under peak load condition

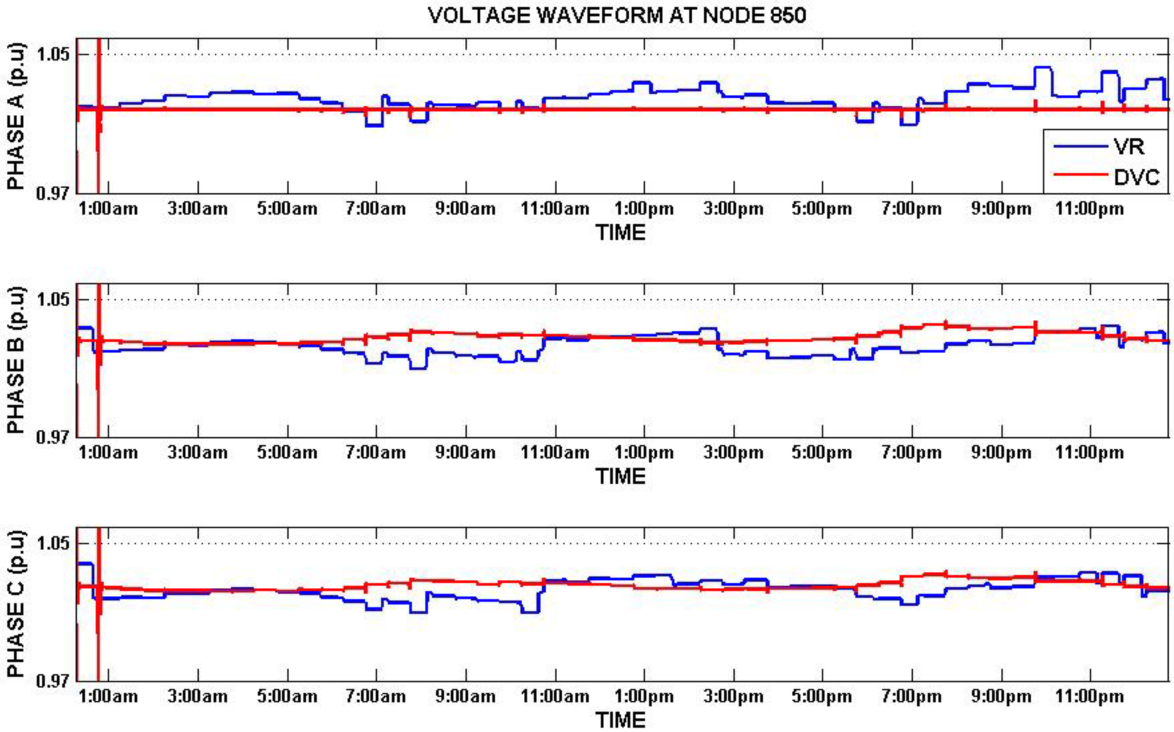


Figure 4.8 Voltage Waveform Comparison at node 850

In order to quantify how well DVC helps flatten the voltage, we need to check the voltage drop (VD) along the feeder at the nodes where loads are connected.

$$\boldsymbol{VD} = (\boldsymbol{V_{load}})_{\boldsymbol{max}} - (\boldsymbol{V_{load}})_{\boldsymbol{min}} \tag{4-1}$$

Figure 4.9 shows the VD comparison between the two DVCs in this test case and the two VRs in the Base Case. As we can see, DVC can improve the voltage drop. Table 4.1 summarizes the largest VD on each phase. From the figure and the table, we see that DVCs reduce voltage drop along the feeder.

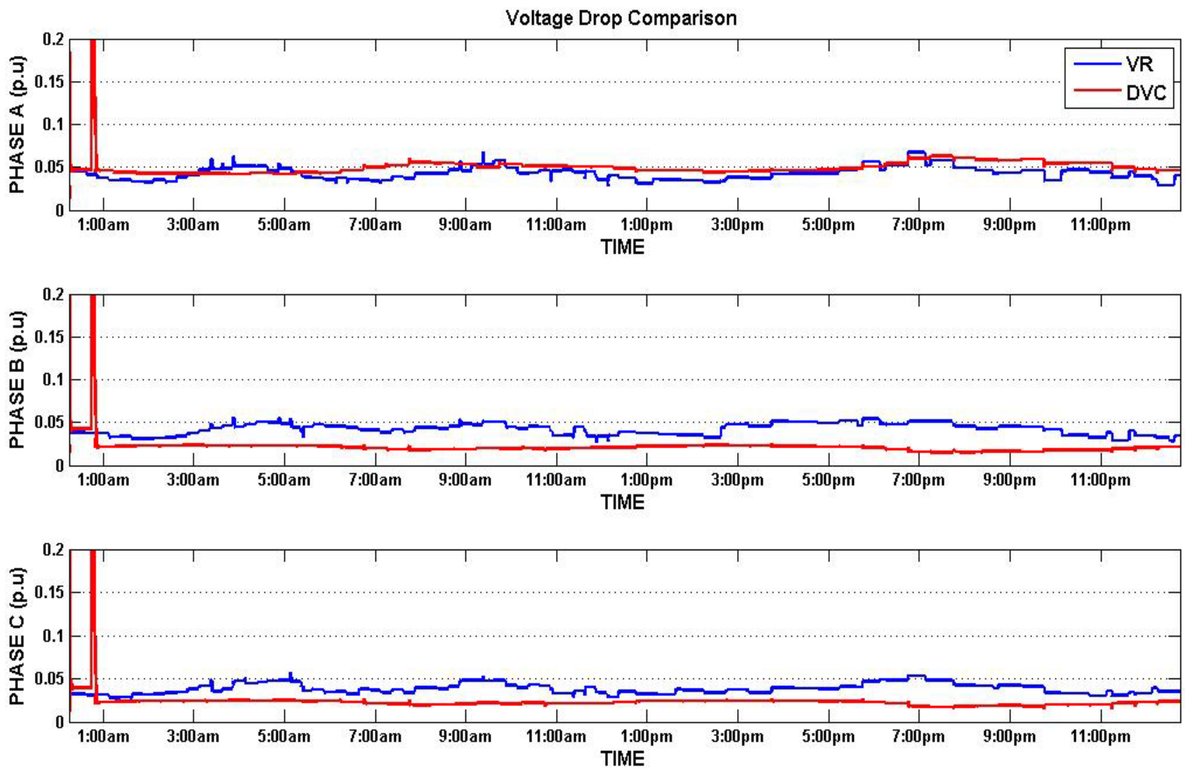


Figure 4.9 Voltage Drop Waveform Comparisons

Table 4.1 Voltage Drop Comparison

	PHASE A (P.U)	PHASE B (P.U)	PHASE C (P.U)
BASE	0.068	0.056	0.057
CASE 1	0.062	0.022	0.024

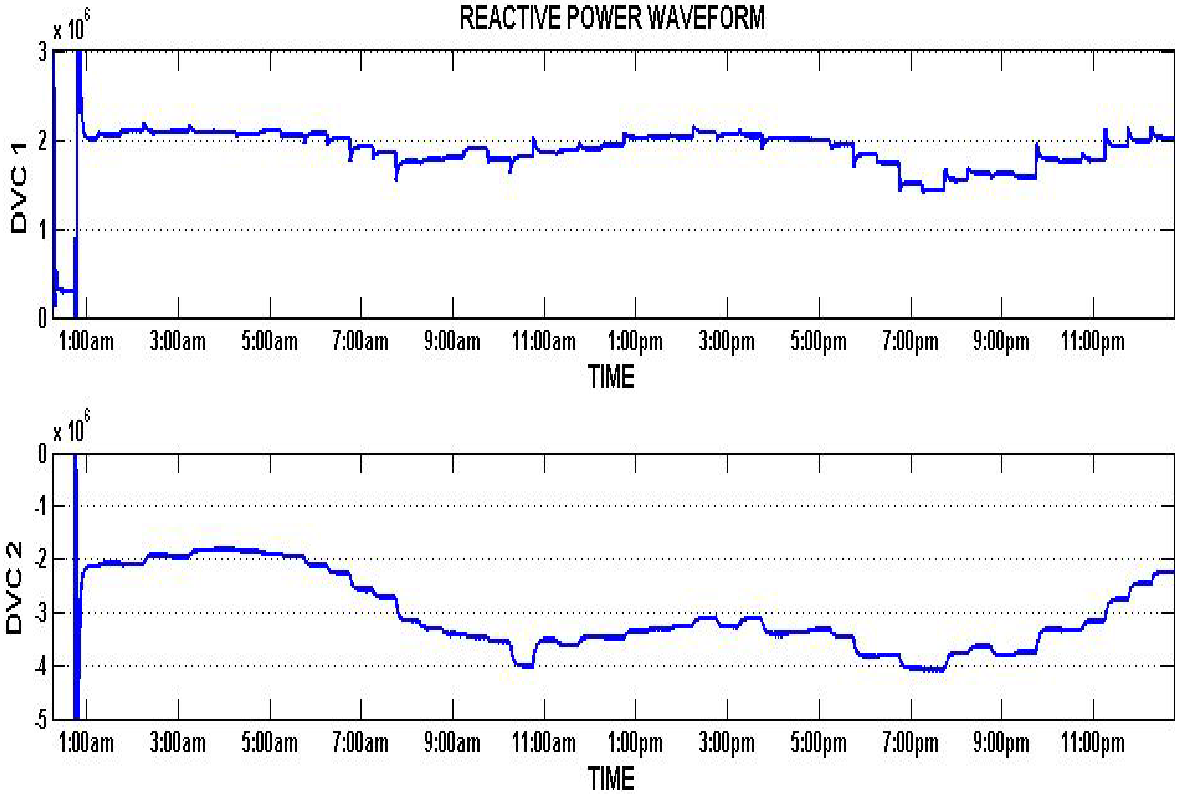


Figure 4.10 Reactive Power Profile of 2 DVCs

Figure 4.10 shows the Profile of Q injection. In the simulation, there is no limit on DVC sizes. Usually in this thesis negative numbers mean injection and positive numbers mean absorption of reactive power in the profile figures. So from the simulation we can determine that the sizes of the two DVCs are 2.27 MVAR inductive and 4.47 MVAR capacitive with a 10% margin. The second DVC generates reactive power into the system to boost the voltage to preset voltage, while the first DVC absorbs reactive power from the system to drag the voltage down. Thus DVC can work on capacitive mode or inductive mode.

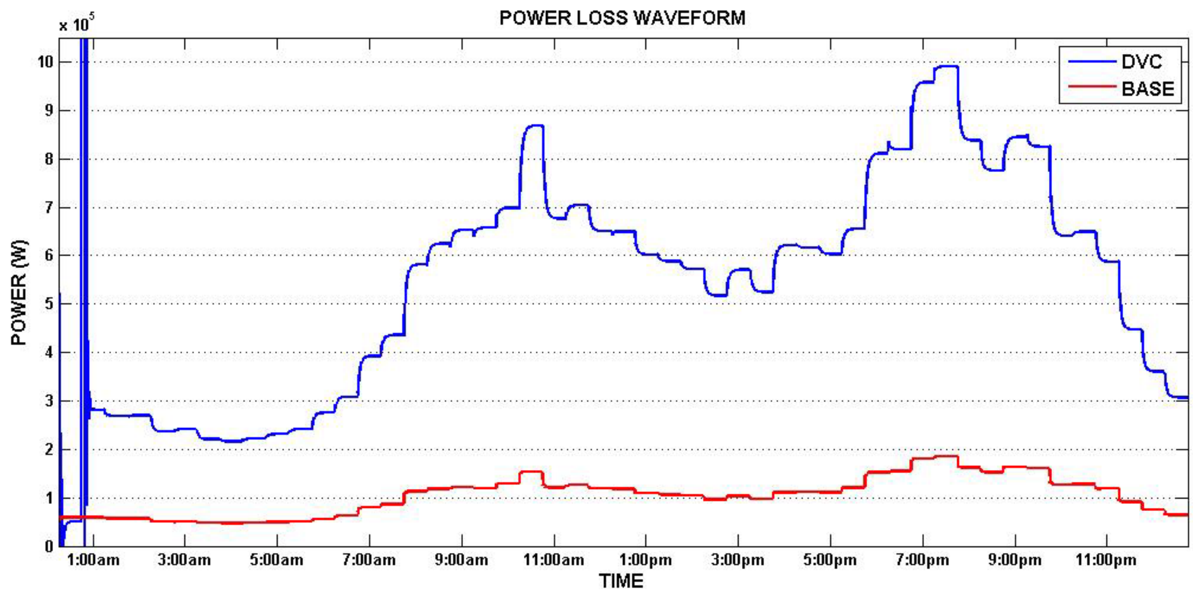


Figure 4.11 Power Loss Waveform Comparison

Figure 4.11 shows the power loss comparison. As the Q injection of DVC is too large and it already exceeds the Q requirement of the system. Thus the power loss in the system is much higher than the base case. As the voltage drop along the feeder reduces, we could lower the voltage setting in the DVC to reduce the power loss. As shown in Figure 4.7, there is a lateral node 818 - node 822 connected in phase A which has the lowest voltage (around 0.98pu) so we cannot lower the first DVC's setting. For the second DVC, we could reduce the setting by 0.045pu. The new settings of two DVCs are shown in Table 4.2.

Table 4.2 Voltage setting in DVCs

	V previou setting	V setting
DVC 1	20704 (1.018p.u)	20704 (1.018p.u)
DVC 2	21043 (1.035p.u)	20127 (0.99p.u)

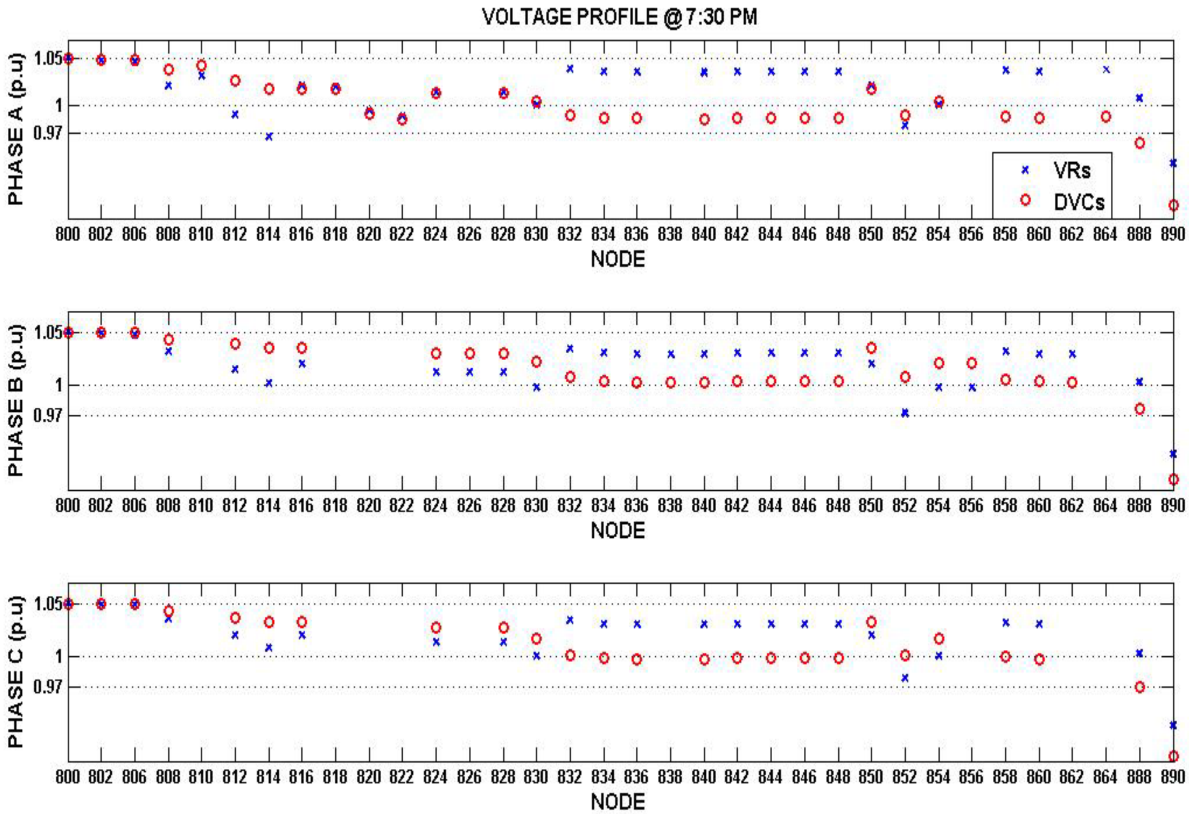


Figure 4.12 Voltage Profile under new setting condition at 7:30 PM (Peak Load)

The voltage profile with new voltage setting in the DVC is shown in Figure 4.12. Although the setting of second DVC drops down, the voltages at load connected node except node 890 are all within acceptable limits.

As the voltage drops down, the DVC only needs to generate a small amount of reactive power to boost the voltage. Figure 4.13 shows the Q injection of two DVCs. The first DVC generates about 0.68 MVAR (previously it was absorbing 2.06 MVAR) and the second DVC generates about 0.63 MVAR (previously this was 4.07 MVAR) at night and absorb 1 MVAR from the system in the morning. Figure 4.14 shows the power loss in the new setting condition. Compared with the previous setting condition, power loss is reduced from about 1

MW to 0.22 MW. However, the voltage drop (shown in Figure 4.15) increases during light load condition, slightly decreases in the heavy load condition.

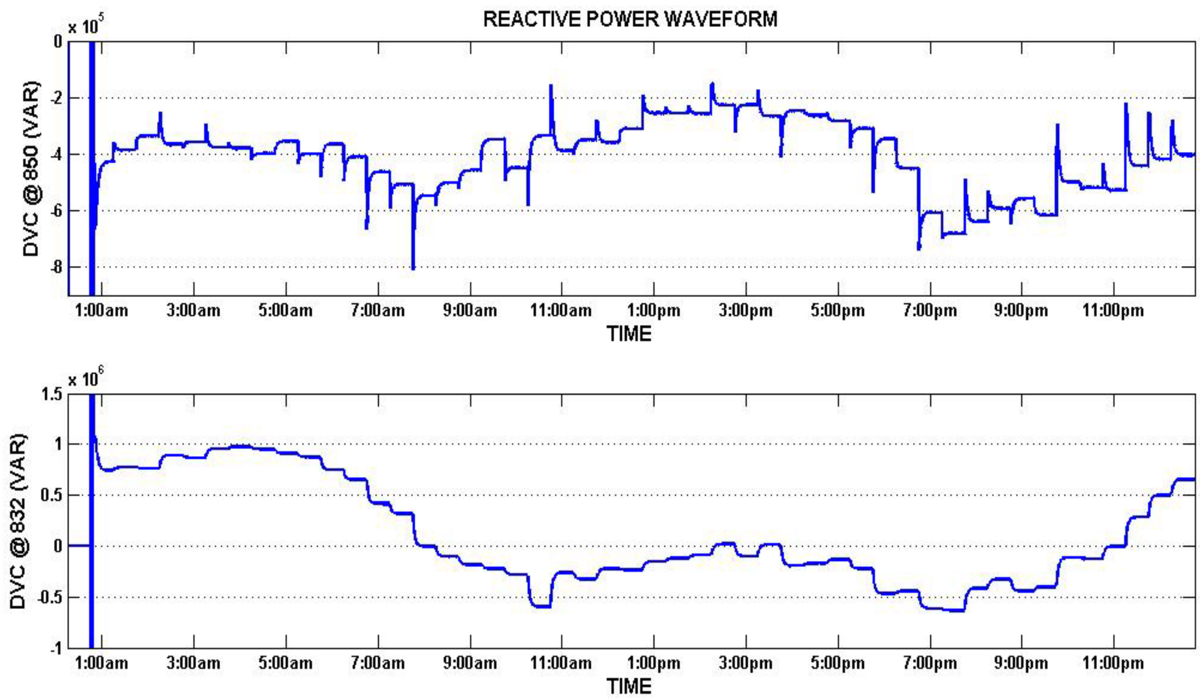


Figure 4.13 Q injections of two DVCs under new setting condition

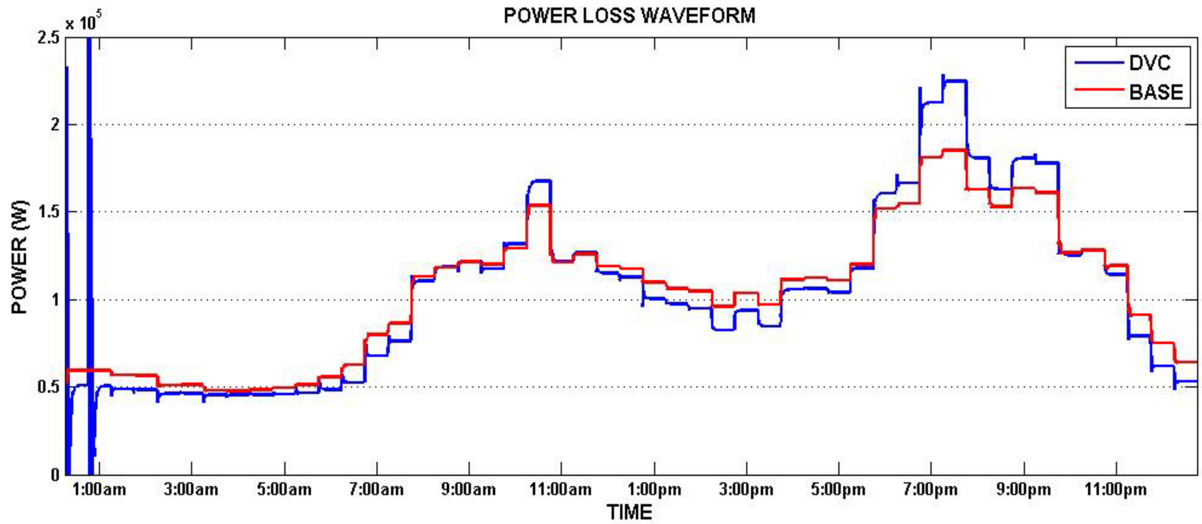


Figure 4.14 Power Loss Waveform Comparisons under new setting condition

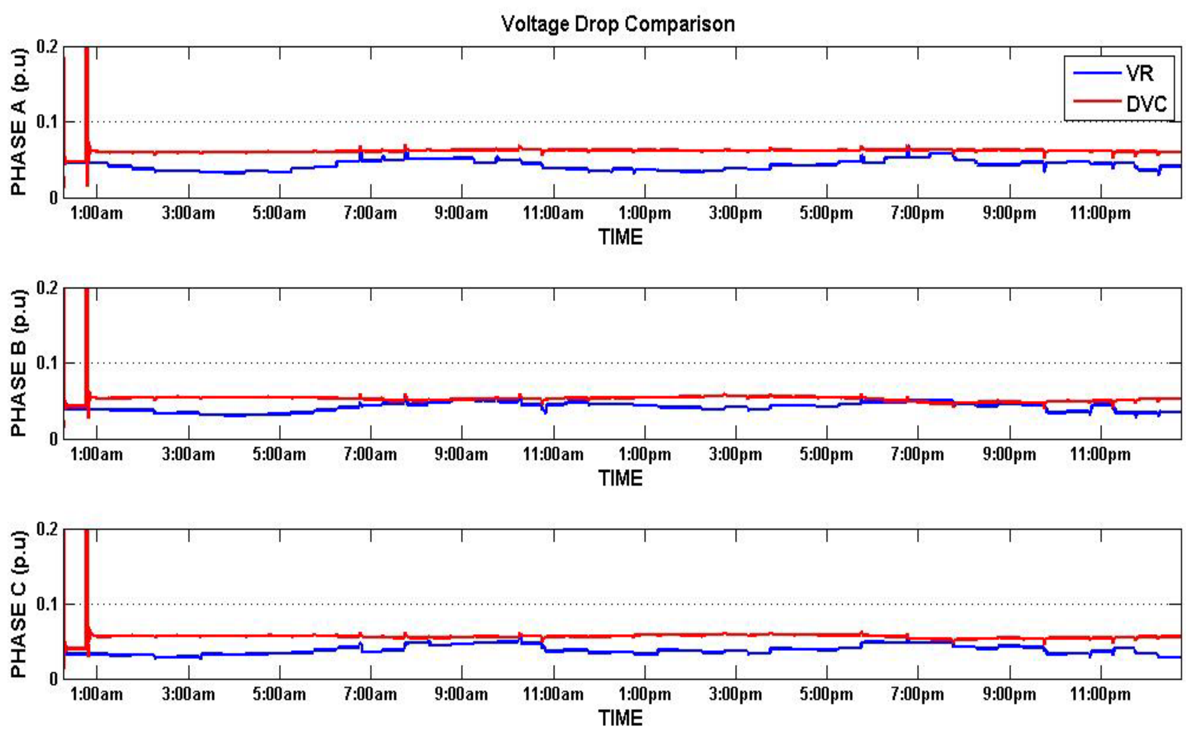


Figure 4.15 Voltage Drop Comparison under new setting condition

Our goal is to maintain all of the voltages within limit. Both settings could achieve this goal. With second settings, we can minimize system power loss, but the system has slightly larger voltage drop along the feeder. In other words, we could decrease the reference in DVC to a relatively lower value to reduce power loss in the system, as long as all the voltages at load connected nodes are within the limits.

4.1.2 Case 2: DVC at node 890

In this case, DVC is used to fix the low voltage violation at node 890 and eliminate the tow capacitors in the system. As we mentioned in the base case, node 890 has the worst case of voltage violation, so we integrate DVC at node 890 to see whether it can help address the voltage issue and maintain all the voltage within acceptable limits. We also remove the capacitors at node 844 and node 848 to see whether DVC will still maintain the voltages.

There are two ways to control DVC. One is to use Iq_ref input mode, and the other is closed-loop control mode. We choose to use closed-loop control mode. In this mode, grid voltage is the feedback in DVC controller. Figure 4.16 shows the voltage waveform at node 890 under the closed-loop control scheme.

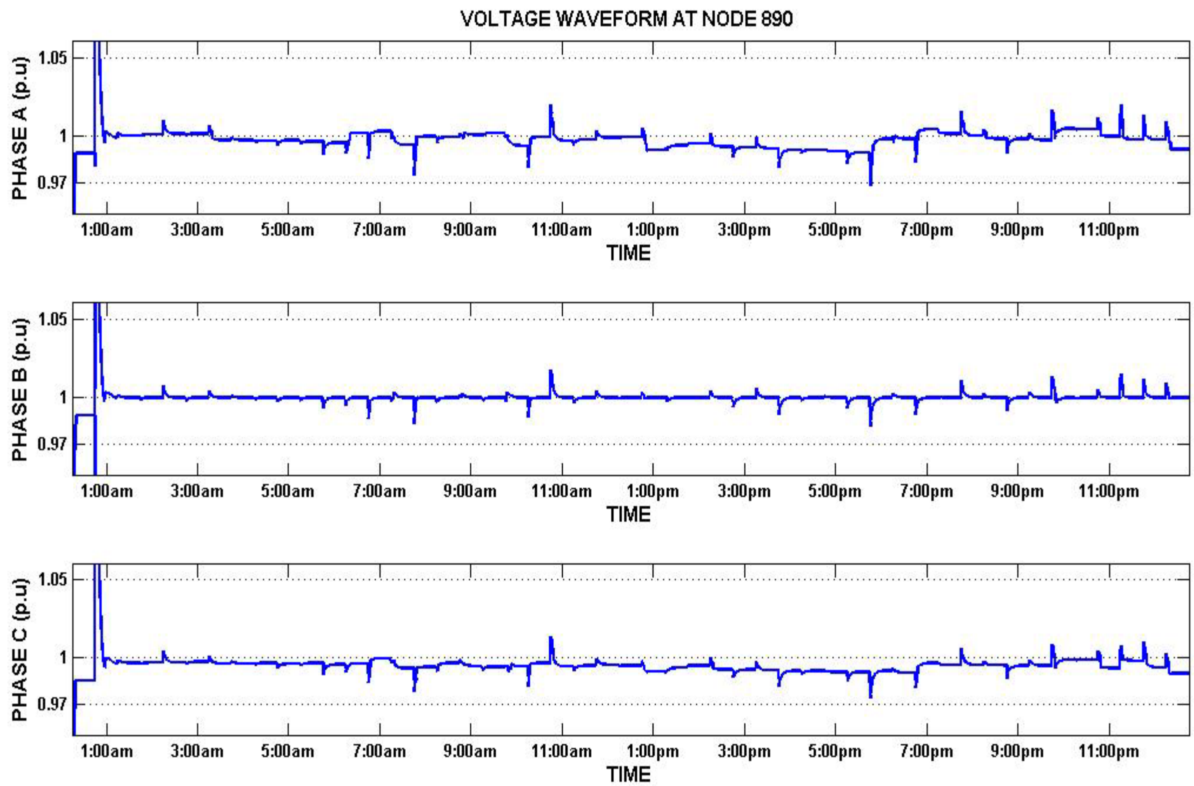


Figure 4.16 Voltage Waveform at node 890 with closed loop control scheme

Figure 4.17 shows the voltage profile under peak load condition. As we can see, only node 812, node 814 and node 852 have low voltage violation and these three nodes have no load connected. Thus DVC at node 890 could address the voltage issue at node 890 and also can eliminate the two capacitors in base case.

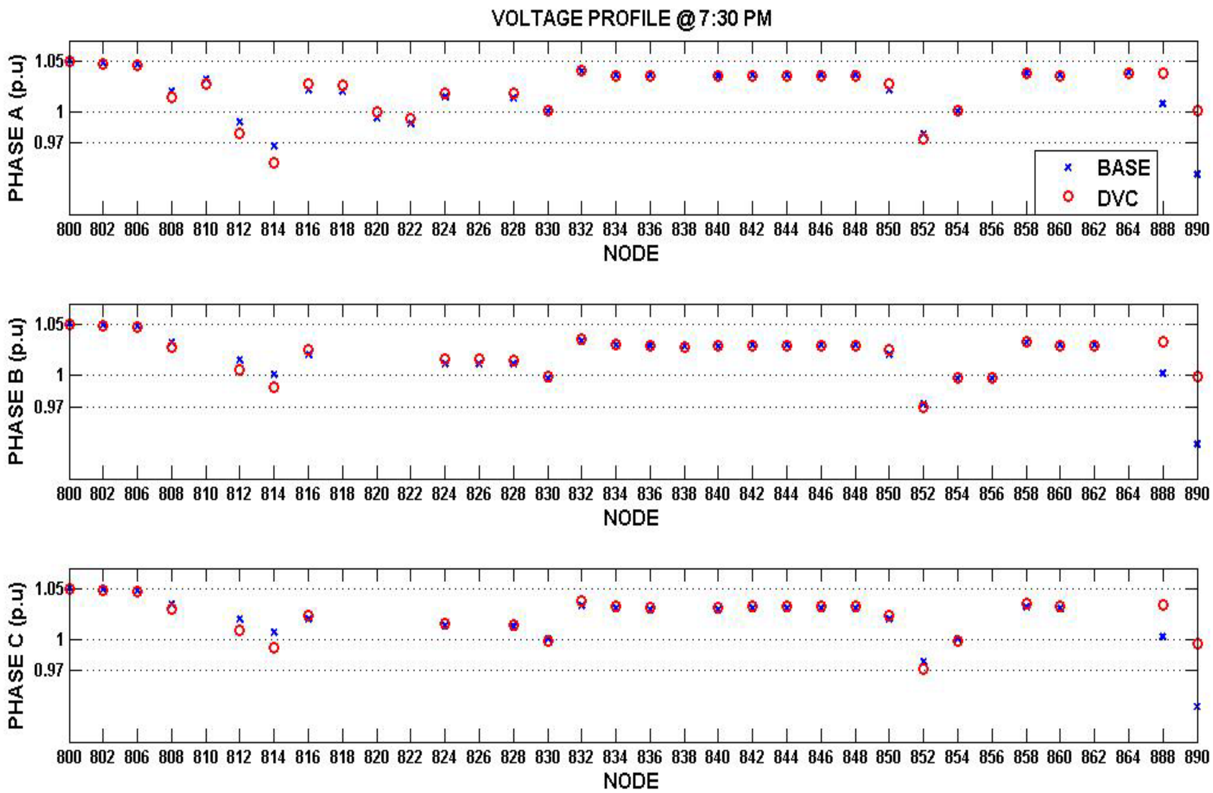


Figure 4.17 Voltage Profile under Peak Load Condition

Figure 4.18 shows reactive power provided by DVC. It varies along with the load change. The size of DVC is 0.45 MVAR. During the high load in the morning and peak load at night, DVC generate a large amount of reactive power to inject into the system, while in the afternoon during light load, DVC injects a small amount of reactive power into the system. The variable amount of reactive power maintains the voltage at node 890 at 1pu throughout day.

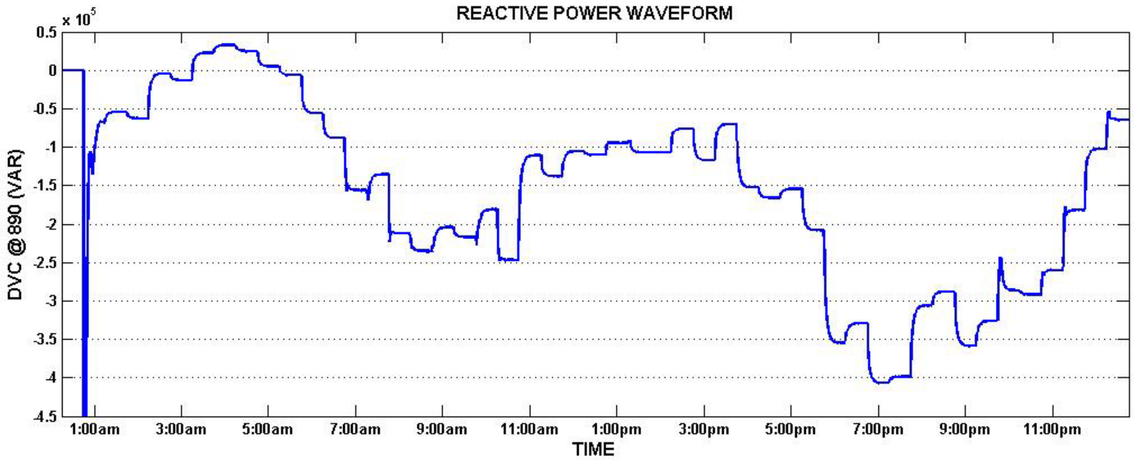
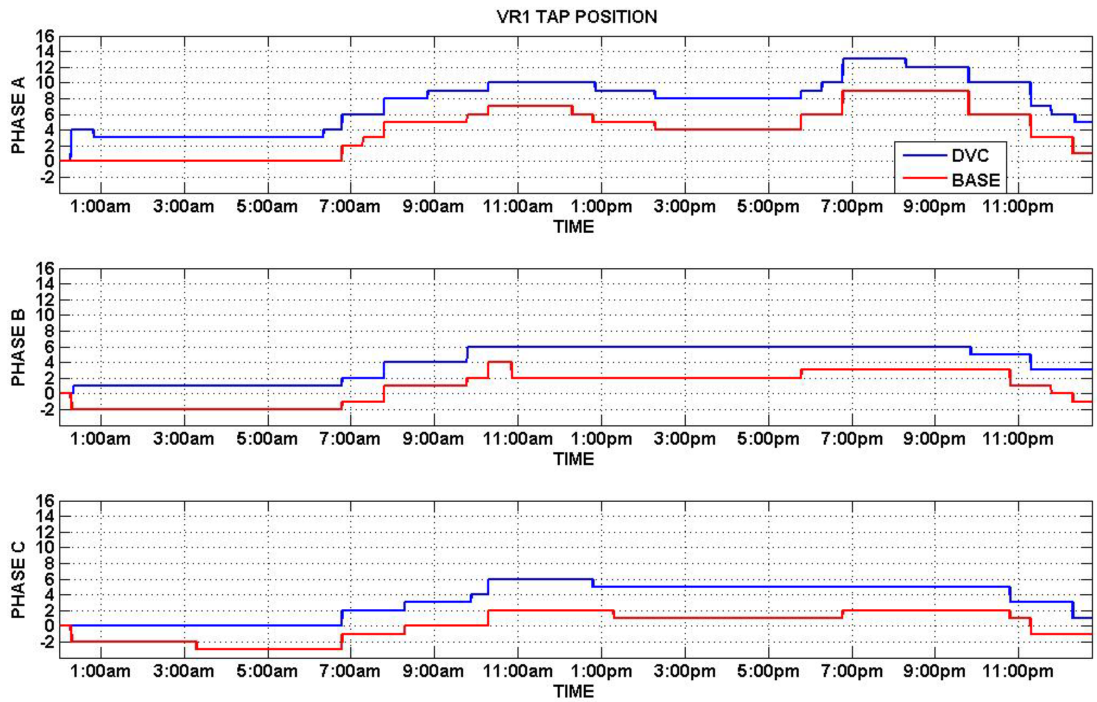
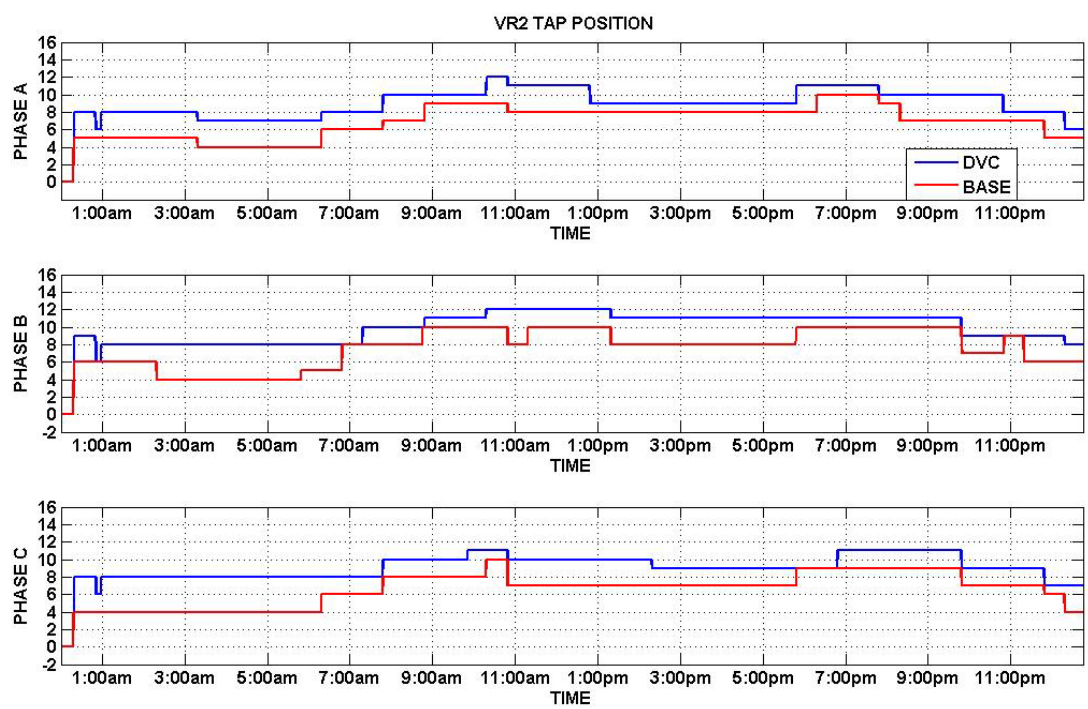


Figure 4.18 Reactive Power Waveform of DVC

Figure 4.19 shows the tap position comparison and Table 4.3summaries the number of operations in two cases. As the table shows, the DVC reduces the number of operations. This could help reduce the maintenance cost and increase the lifetime of the voltage regulating devices.



(a)



(b)

Figure 4.19 (a) – (b)Voltage Regulator Tap Position Comparison

Table 4.3 Numbers of operations of two Voltage Regulators

	PHASE A		PHASE B		PHASE C	
	CAP	DVC	CAP	DVC	CAP	DVC
VR1	23	22	13	8	11	11
VR2	14	16	24	8	16	11

Figure 4.20 shows the power loss in the system. The voltage in this case is higher than base case, so the power loss is also higher than base case. As DVC solves the low voltage issue, the voltage drop improves a little (Figure 4.21).

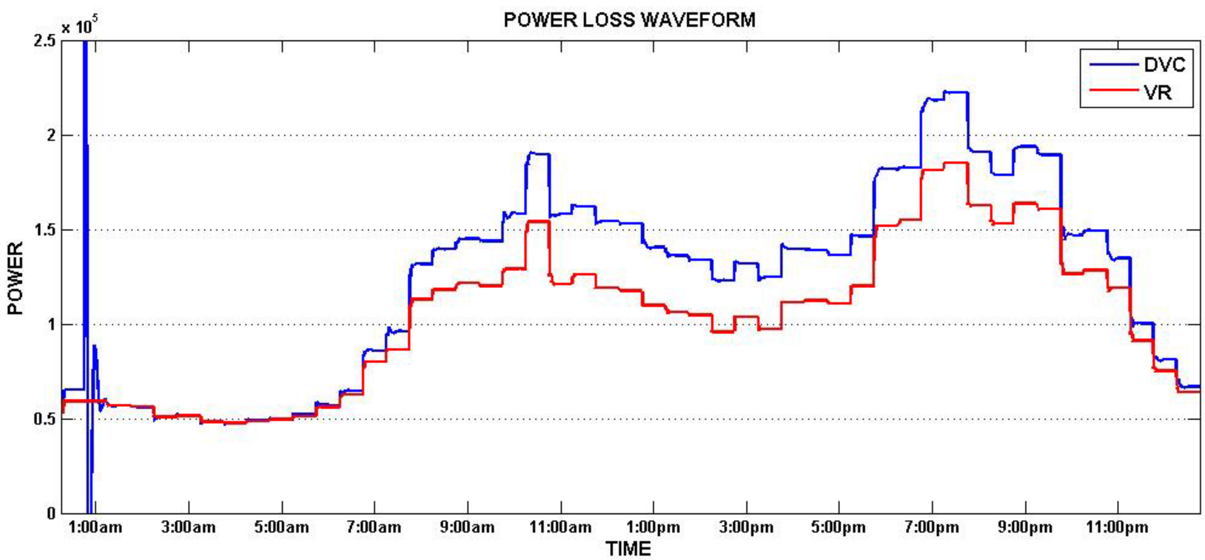


Figure 4.20 Power Loss Waveform Comparison

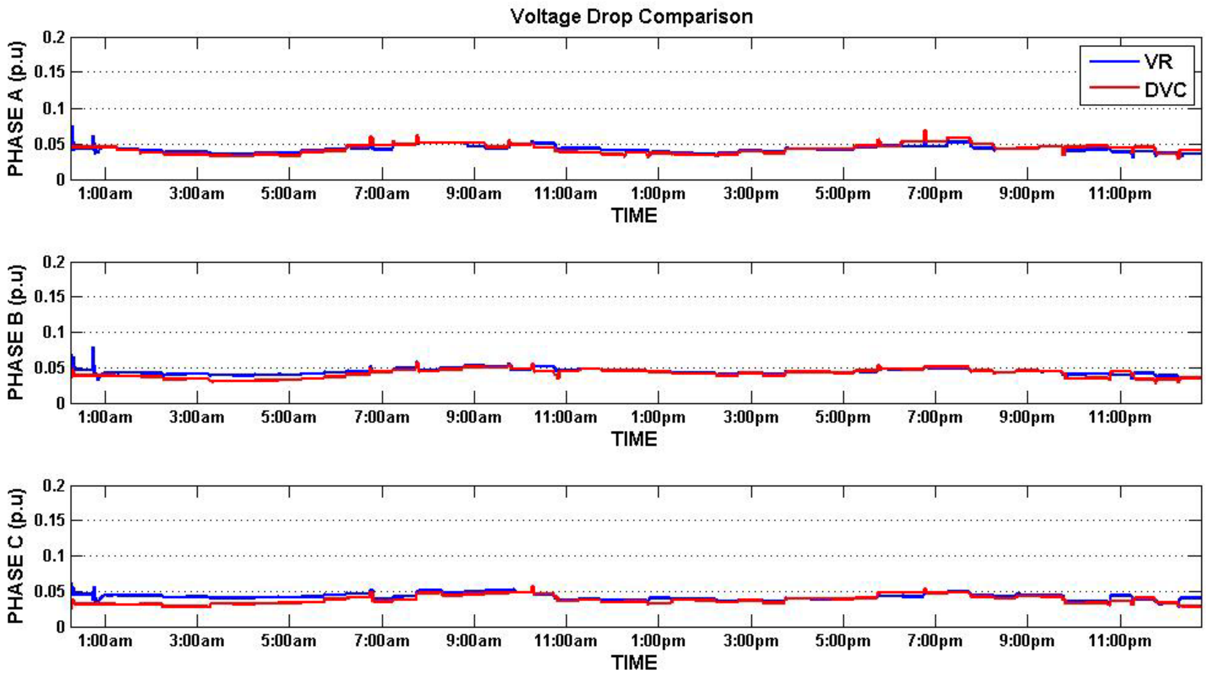


Figure 4.21 Voltage Drop Comparisons

4.1.3 Case 3: Three DVCs

Based on the previous two cases, we consider using three DVCs in the system to replace all of the conventional Volt-Var control devices. In this case, we replace the two VRs at node 814 and node 852 and the capacitors at node 844 and node 848 with three DVCs located at node 850, node 832 and node 890.

As we can see in Figure 4.22, all the voltages are within acceptable limits. Node 890 which was a concern in the previous cases also has no voltage violation. The voltage profile looks flatter than the base case.

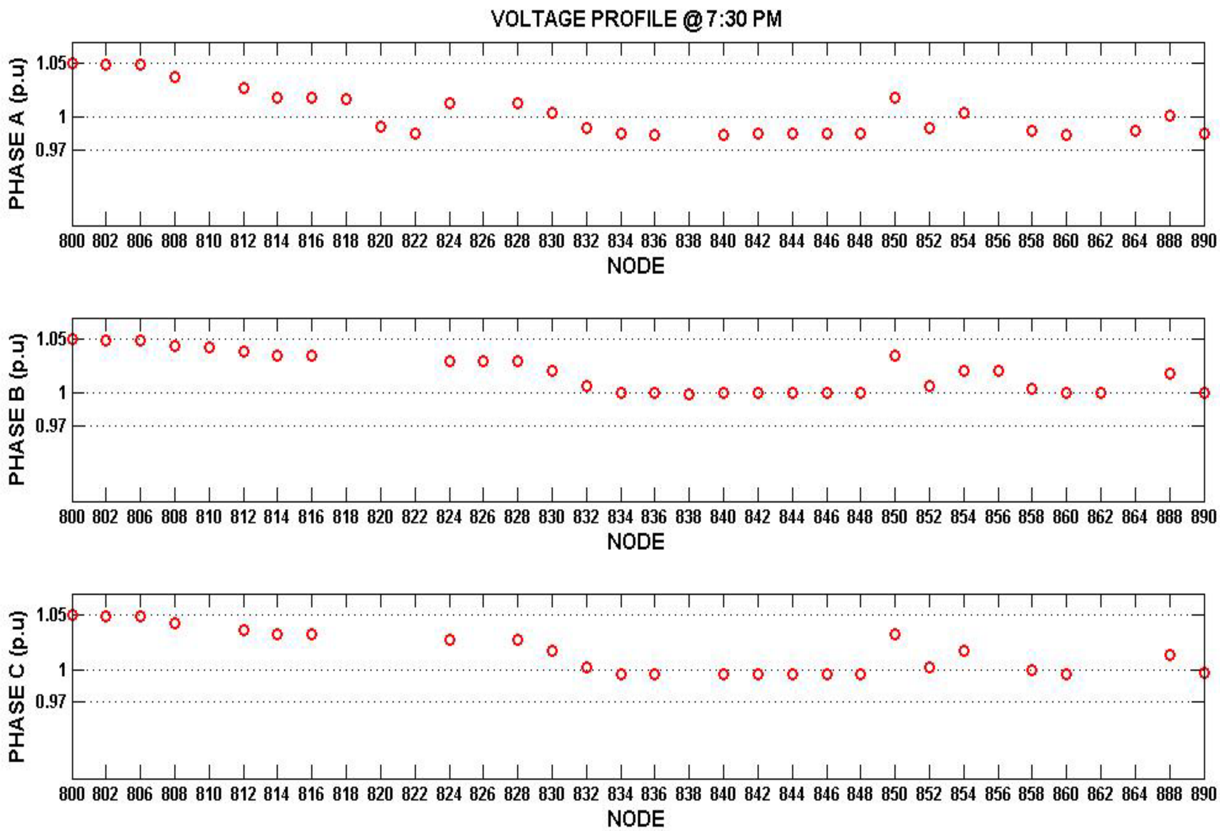


Figure 4.22 Voltage Profile for 3 DVC under Peak Load Condition (7:30PM)

Figure 4.23 shows the reactive power waveform of the three DVCs. The sizes of these three DVCs are 0.65 MVAR, 1 MVAR and 0.61 MVAR. Table 4.4summarizes the reactive power needed by the DVCs at peak load for the three cases we have discussed.

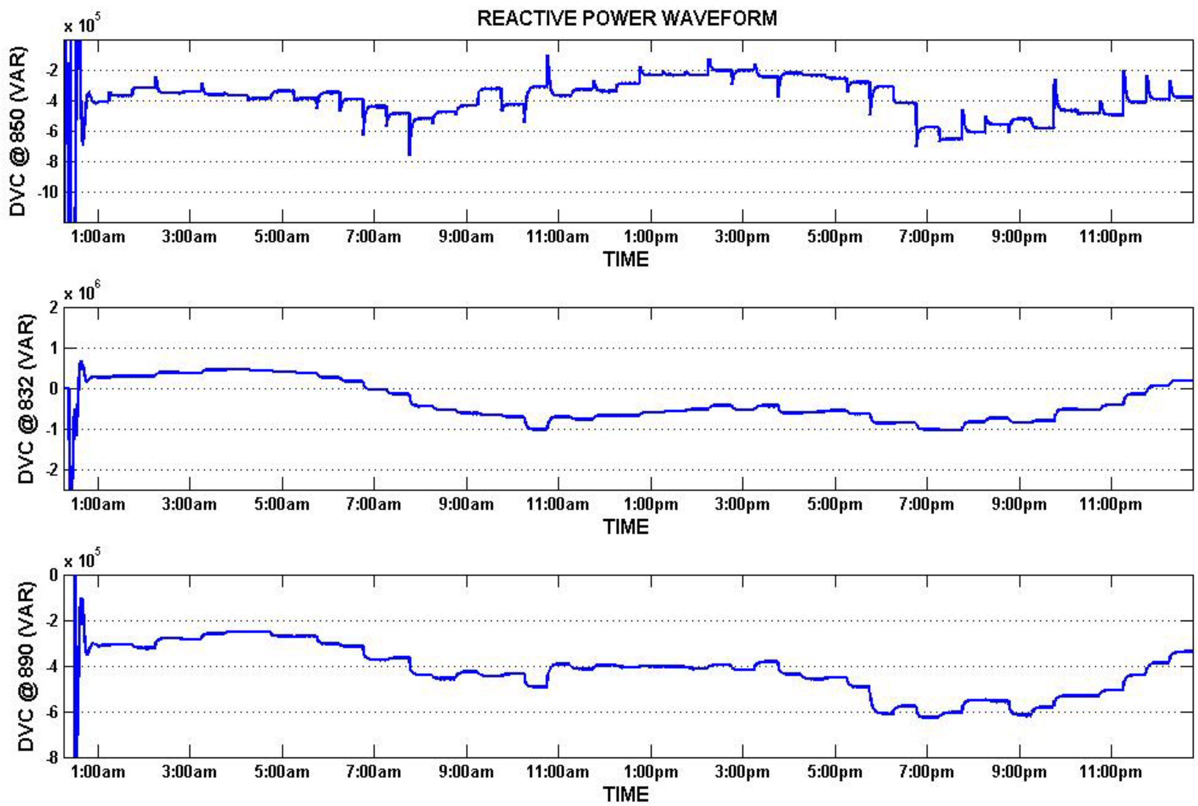


Figure 4.23 Reactive Power Waveform of 3 DVCs

Table 4.4 reactive power of DVCs at peak load

	DVC @ 850 (MVAR)	DVC @832 (MVAR)	DVC @ 890 (MVAR)
Case 1	0.68	0.63	
Case 2			0.45
Case 3	0.65	1	0.61

Comparing Case 2 and Case 3, the DVC at node 890 in Case 3 needs more Q injection to keep voltage at node 890 at 1 pu. Node 890 is closer to the second voltage regulator. In Case2, the voltage at node 832 is about 1.035pu, while in Case3, the voltage at node 832 is

0.99 pu. So DVC needs to provide more reactive power to boost the voltage in Case3. Comparing Case 1 and Case3, adding the third DVC could slightly reduce the size of the previous DVCs. As DVC at node 890 eliminates the two capacitors in the system, the other two DVC should provide more reactive power to compensate the reactive power provided by capacitors in the base case.

Figure 4.24 shows the power loss comparisons of base case and Case 3 with three DVCs. As the voltages in DVC case are higher than base case, the power loss is also higher.

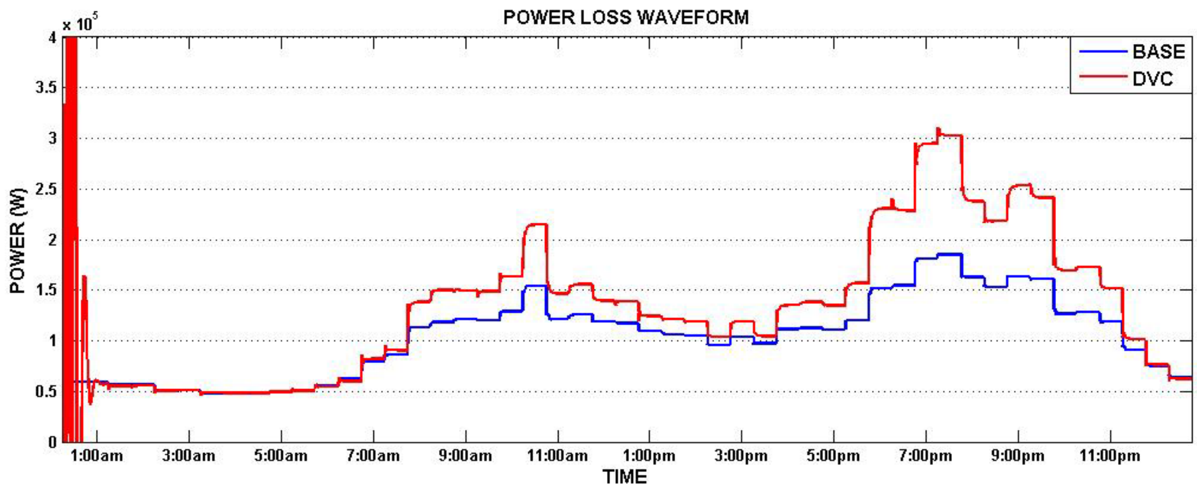


Figure 4.24 Power Loss Waveform Comparisons

DVCs could completely replace all conventional Volt-VAR control devices in the distribution system. With the proper settings of DVC, we could get a better voltage profile while requiring less maintenance.

4.2 DVC on system with PVs

4.2.1 Case 1: 2 DVCs

With PVs integrated into the system, we will determine how DVCs can address the problems discussed in Chapter 3.

Figure 4.25–Figure 4.27 show the comparison of the system voltage profile at three different point of time: 10:30 AM (high load), 12:30 PM (Peak PV output) and 7:30 PM (Peak load).

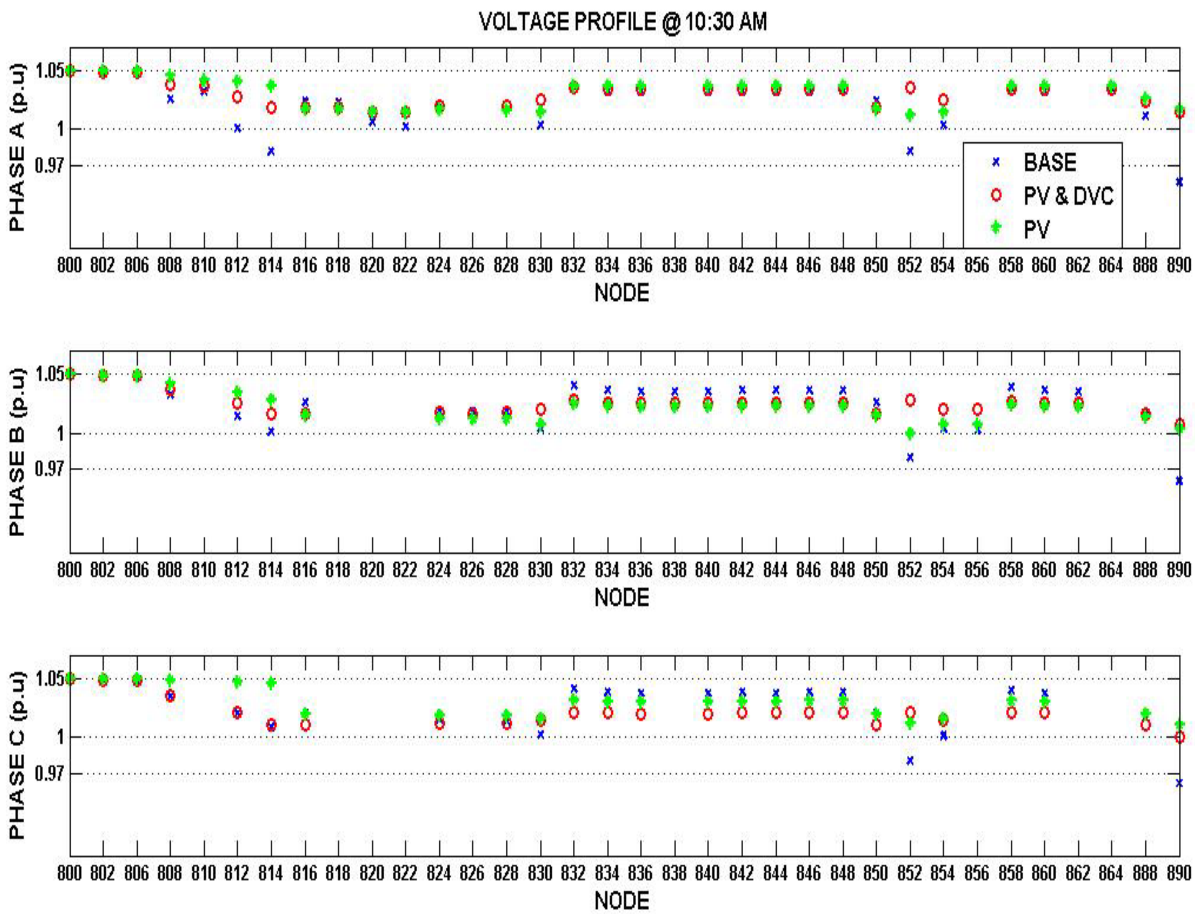


Figure 4.25 Voltage Profile Comparison at 10:30 AM (high load)

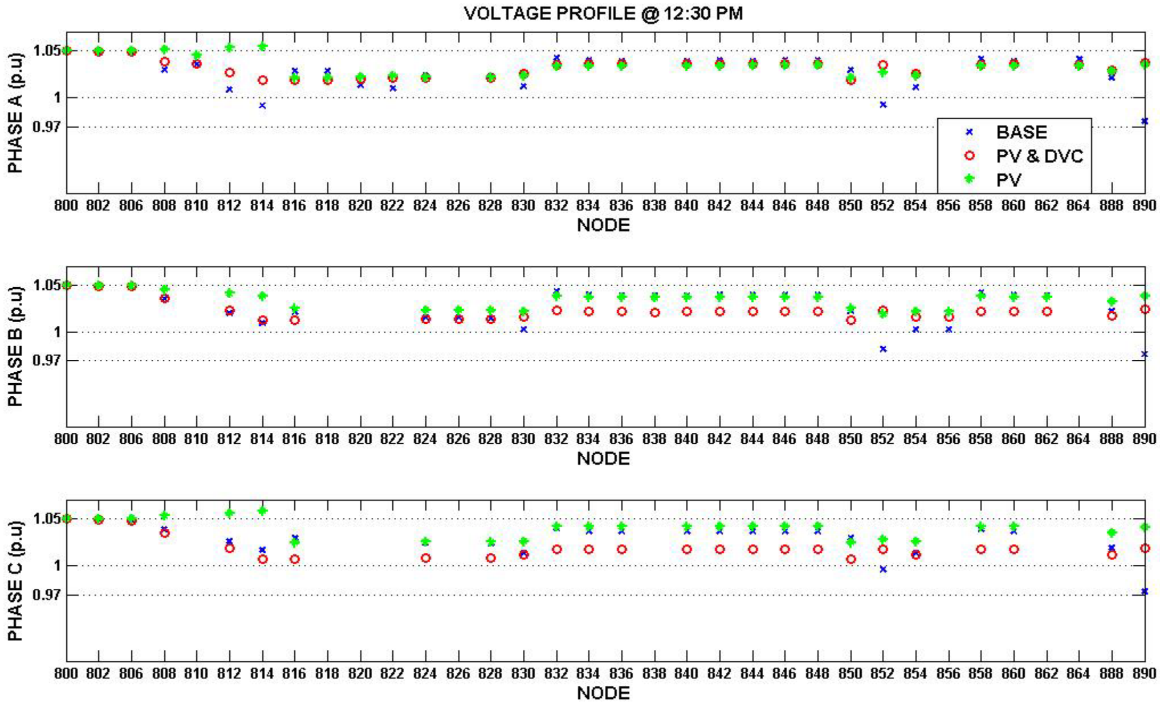


Figure 4.26 Voltage Profile Comparisons at 12:30 PM (Peak PV)

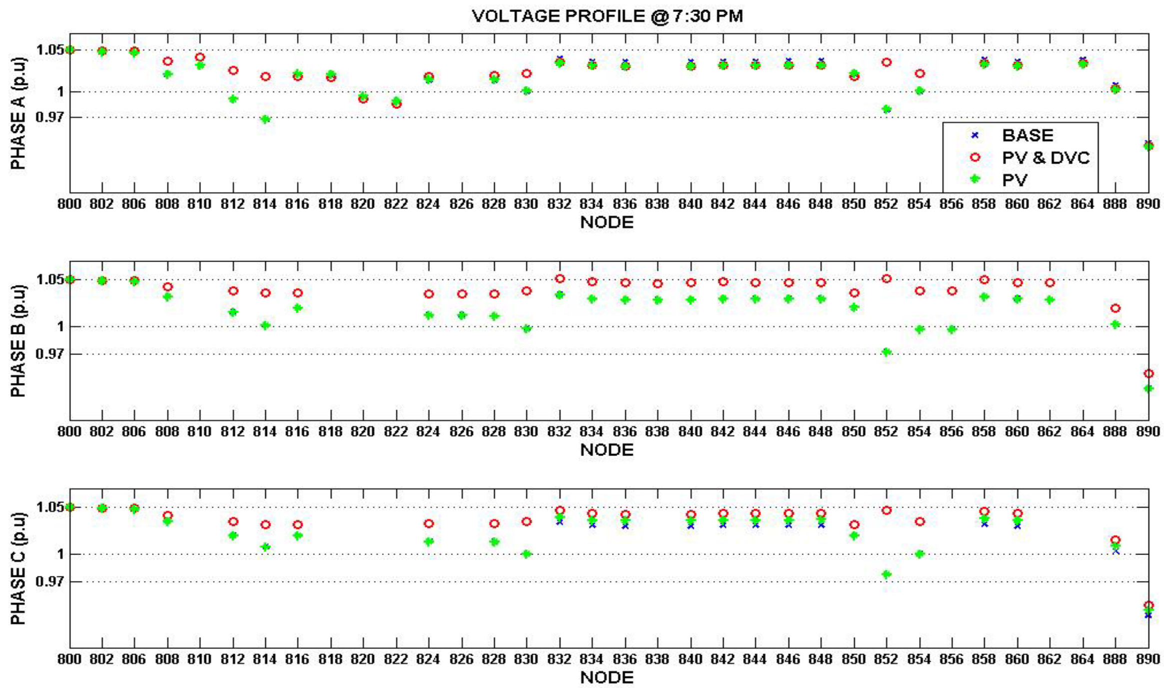


Figure 4.27 Voltage Profile Comparison at 7:30 PM (Peak load)

As Figure 4.26 shows, with PV integrated, the voltages gave high voltage violation, while after using DVCs instead of VRs in the system, the voltages all stay within the acceptable limits. Thus the voltage rise problem could be solved with DVC.

DVC could also help reduce the voltage drop along the feeder (Figure 4.28).PV helps reduce the voltage drop in the daytime, but will not help at night. DVC could reduce the voltage drop at night.

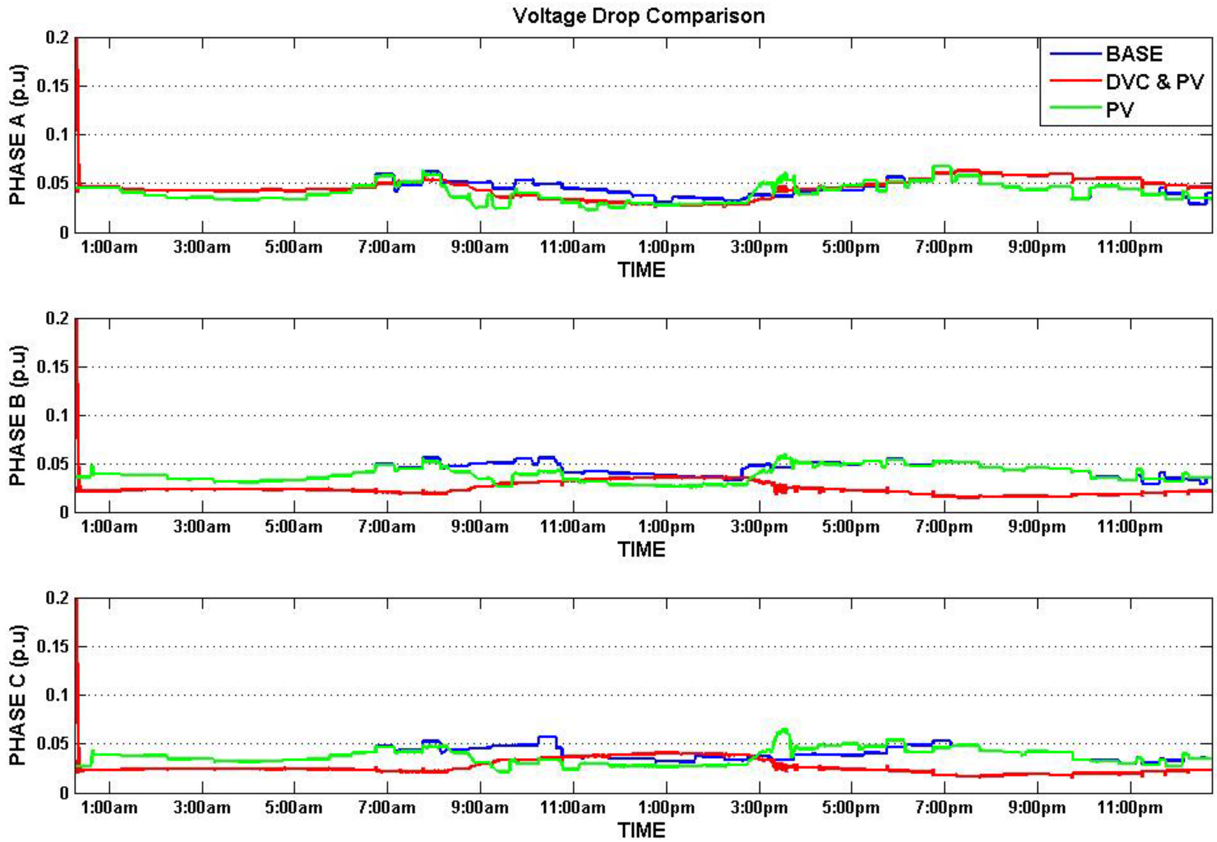


Figure 4.28 Voltage Drop Comparisons

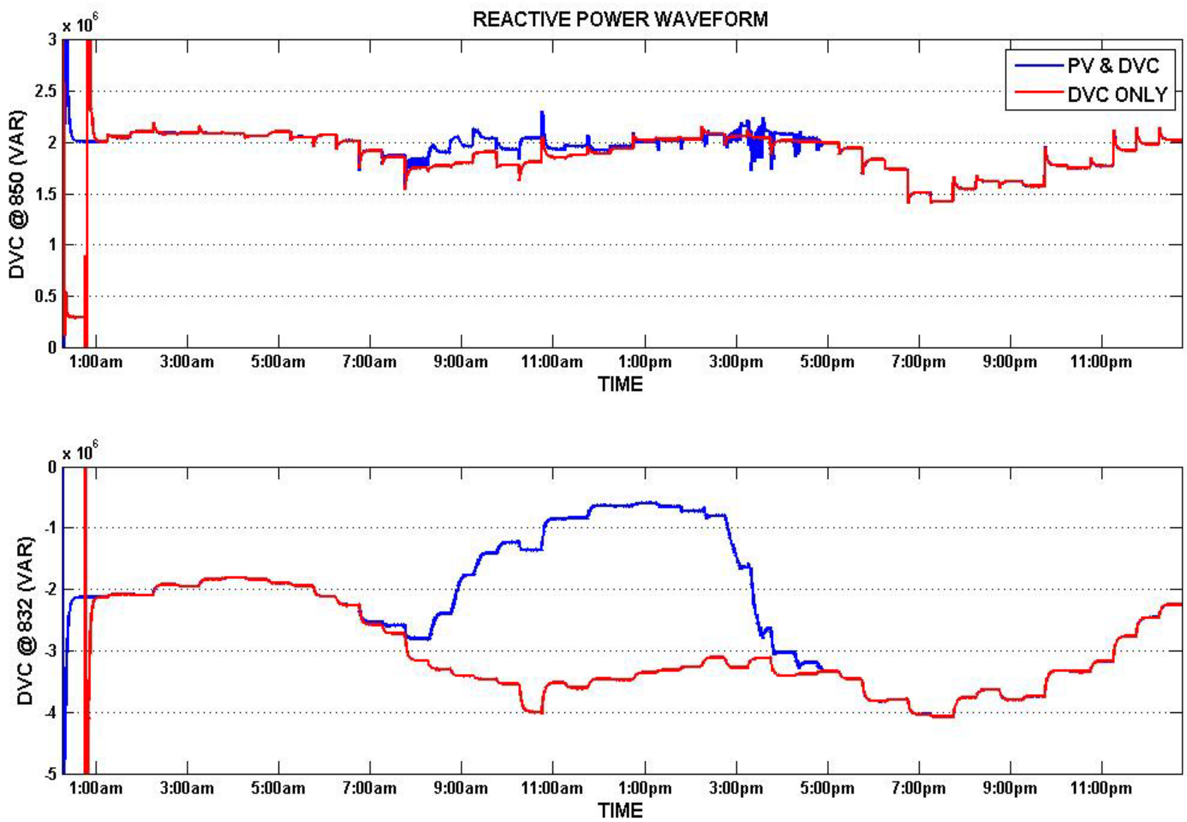


Figure 4.29 Reactive Power Profile Comparisons

Figure 4.29 shows the Q injection Profile comparisons. With PV integrated, there is not much change for the first DVC as it is near substation, so the voltage is not affect much by the PV. While for the second DVC, the Q injection needed by the grid is reduced during the day time from 3.5 MVAR to only 0.5 MVAR. However peak load is around 7:30 PM when there is no PV, so the size of the device cannot be changed from 4.5 MVAR.

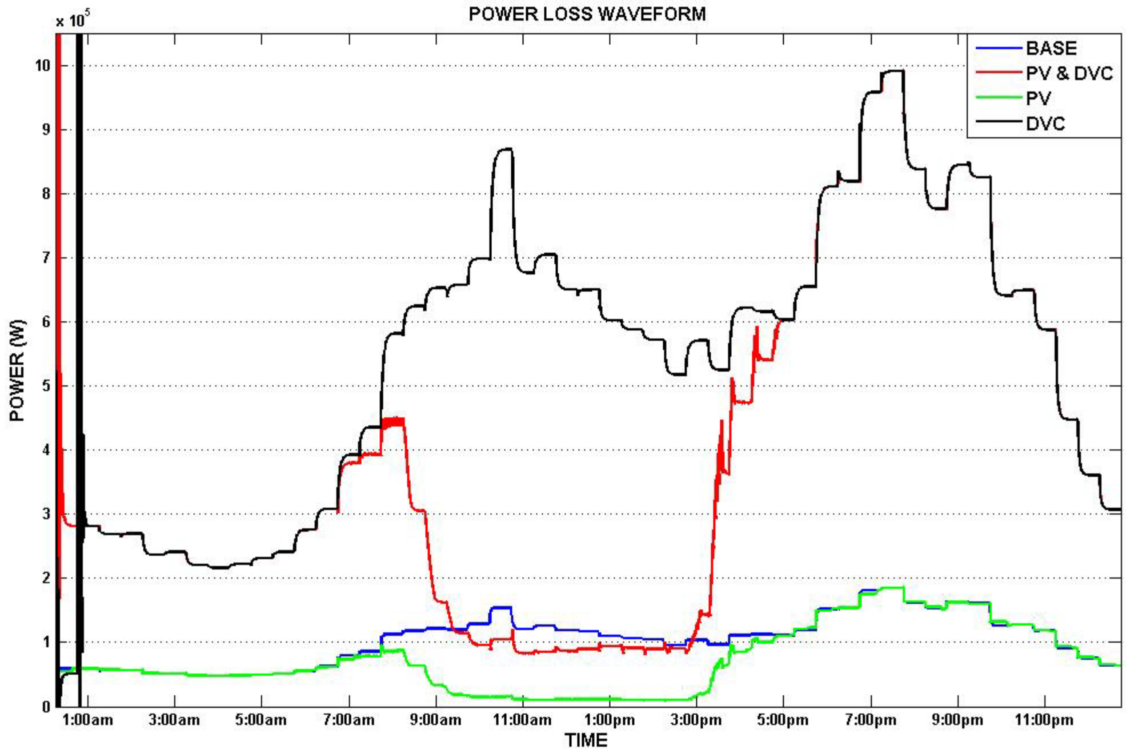


Figure 4.30 Power Loss Waveform Comparisons

Figure 4.30 shows the power loss comparison. Using DVC replace Voltage Regulator will increase the power losses in the system, while adding PV into the system could help reduce the power losses in the daytime. As we mentioned in Test Case 1, if we change the voltage setting to 0.99pu in second DVC, we could reduce the power loss to about 0.23 MW (shown in Figure 4.31). As we can see, the power loss increases a lot at noon. The reason is DVCs generate too much reactive power (shown in Figure 4.32) which increases the power loss. However, the voltage drop will increase a little especially in the daytime. As Figure 4.33 shows, without DVC the voltages stay around 1.05pu at noon, while with DVC the voltages stay around 0.98pu. That means the maximum voltage doesn't change and the minimum voltage drops. Based on the Equation (4-1), voltage drop will increase (Figure 4.34).

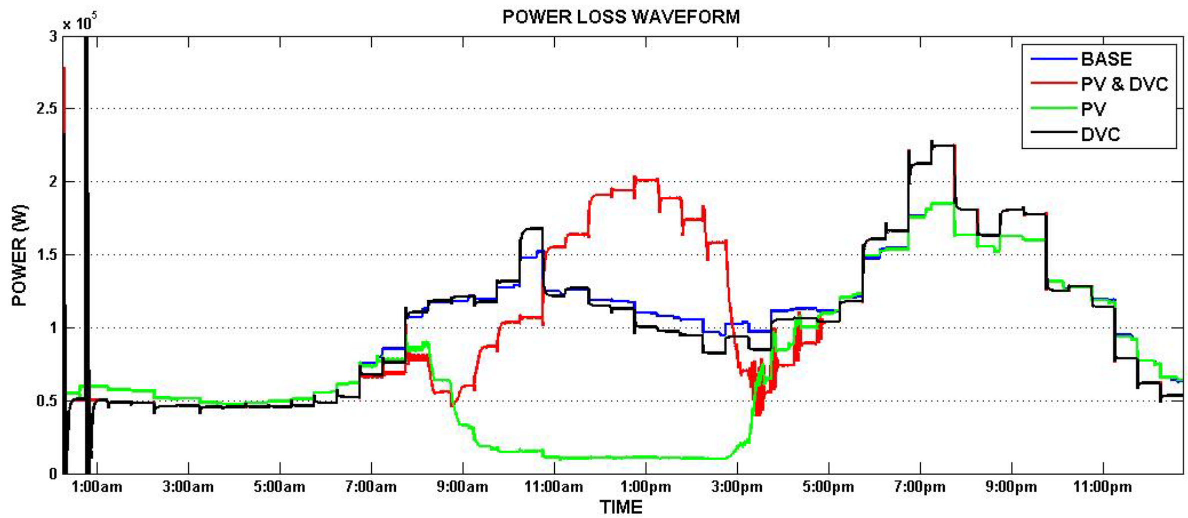


Figure 4.31 Power Loss Waveform Comparisons with lower voltage setting

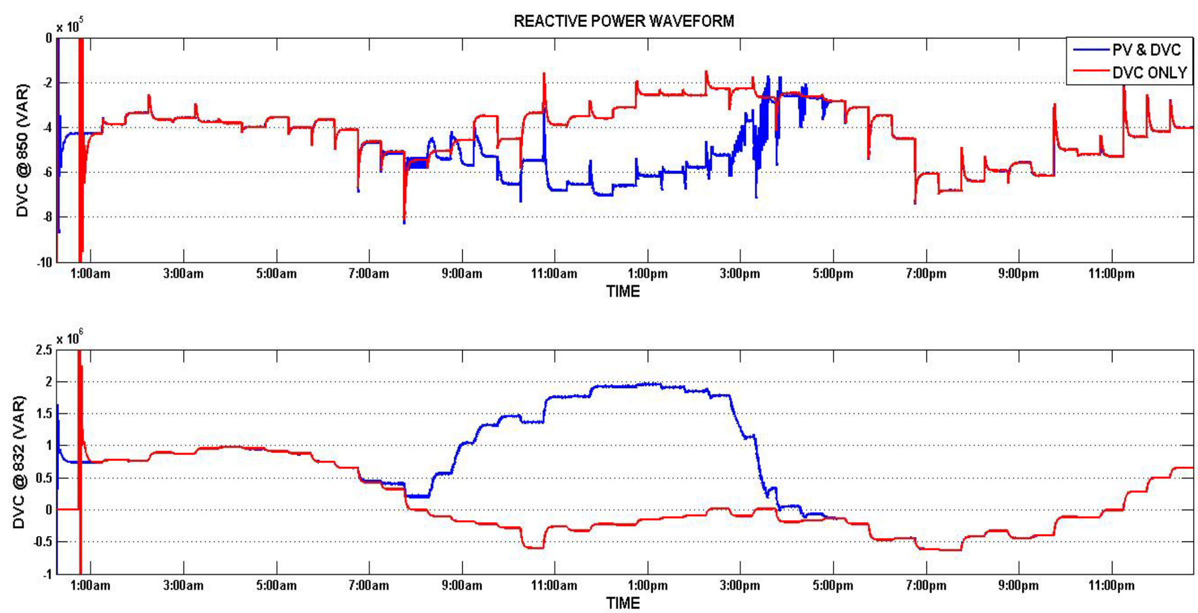


Figure 4.32 Reactive Power Waveform Comparisons

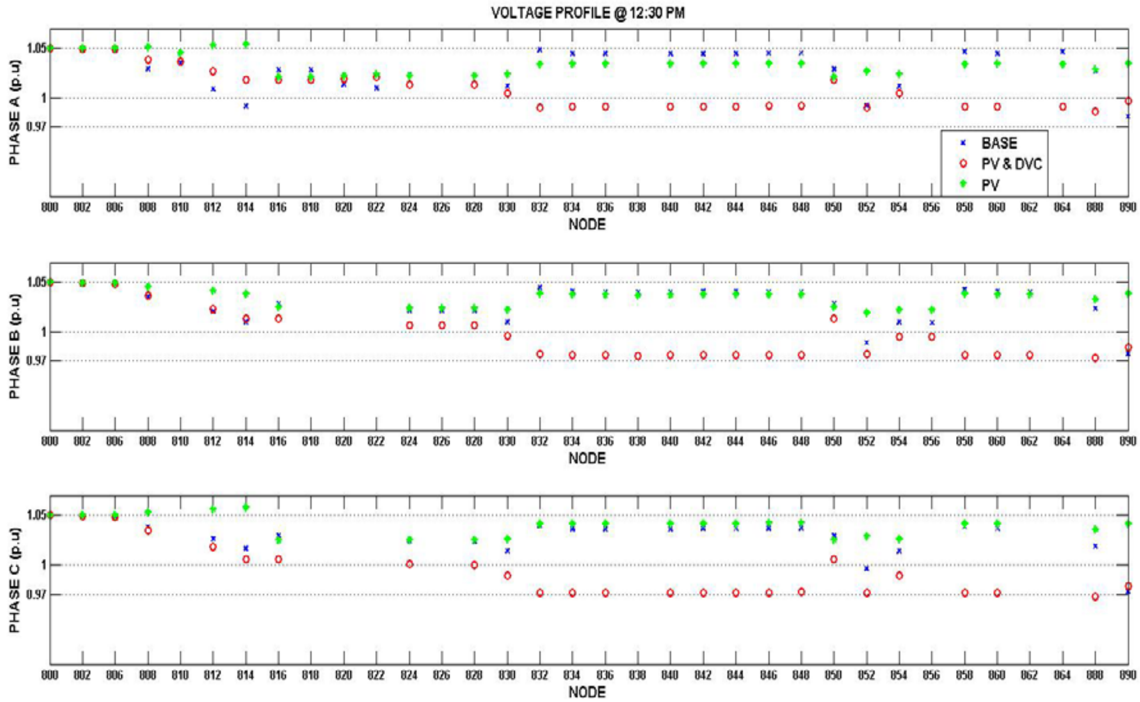


Figure 4.33 Voltage Profile Comparisons with new voltage setting at 12:30 PM (Peak PV)

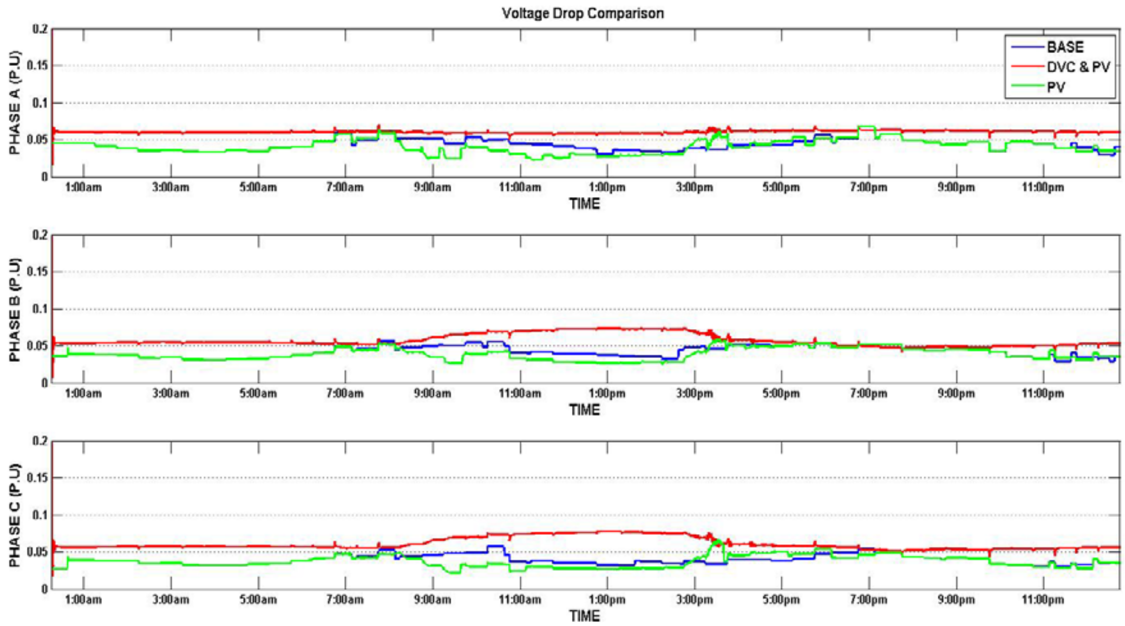


Figure 4.34 Voltage Drop Comparisons with new voltage setting

4.2.2 Case 2:1 DVC at node 890

This case shows how DVC helps improve the frequent operations problem caused by PV integration and solves the low voltage violation at node 890 at night.

Figure 4.35 shows the voltage profile comparisons under peak load conditions. The base case and PV case without DVC have the same results, as there is no PV output at night. The figure also shows that DVC solves the voltage issue at node 890.

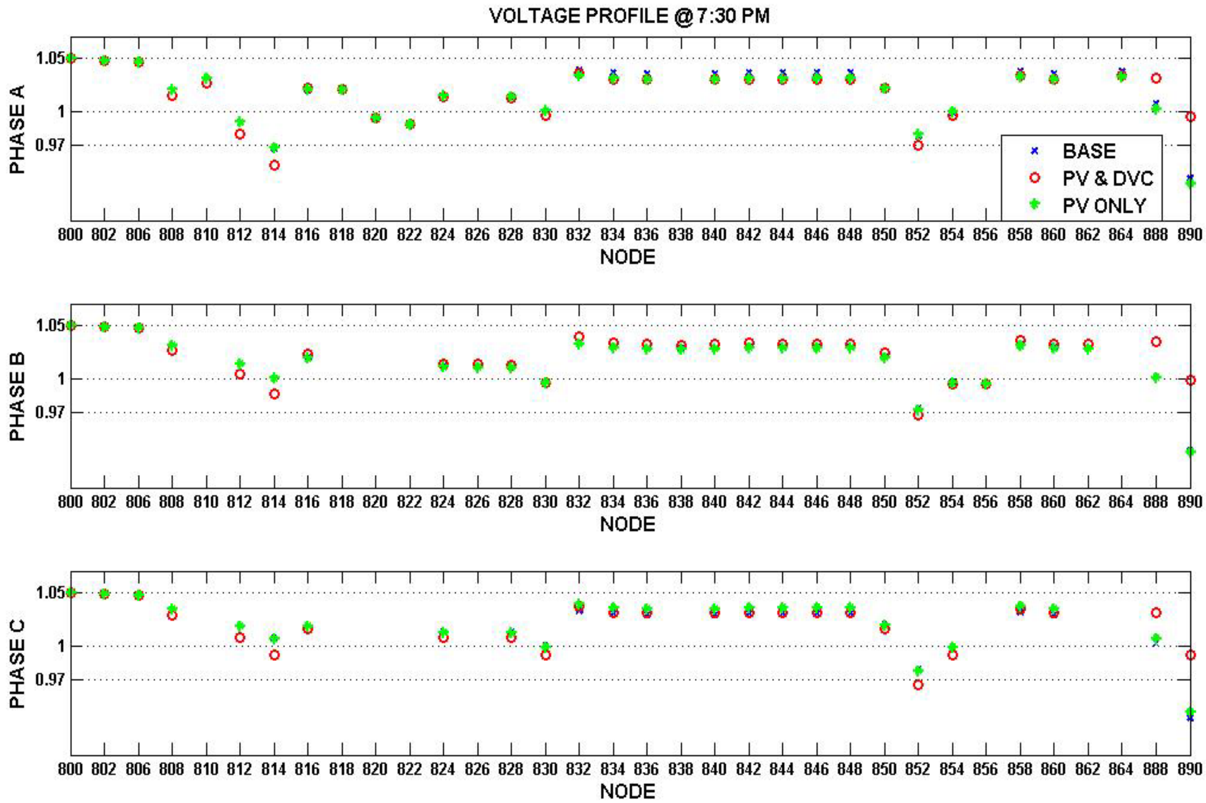
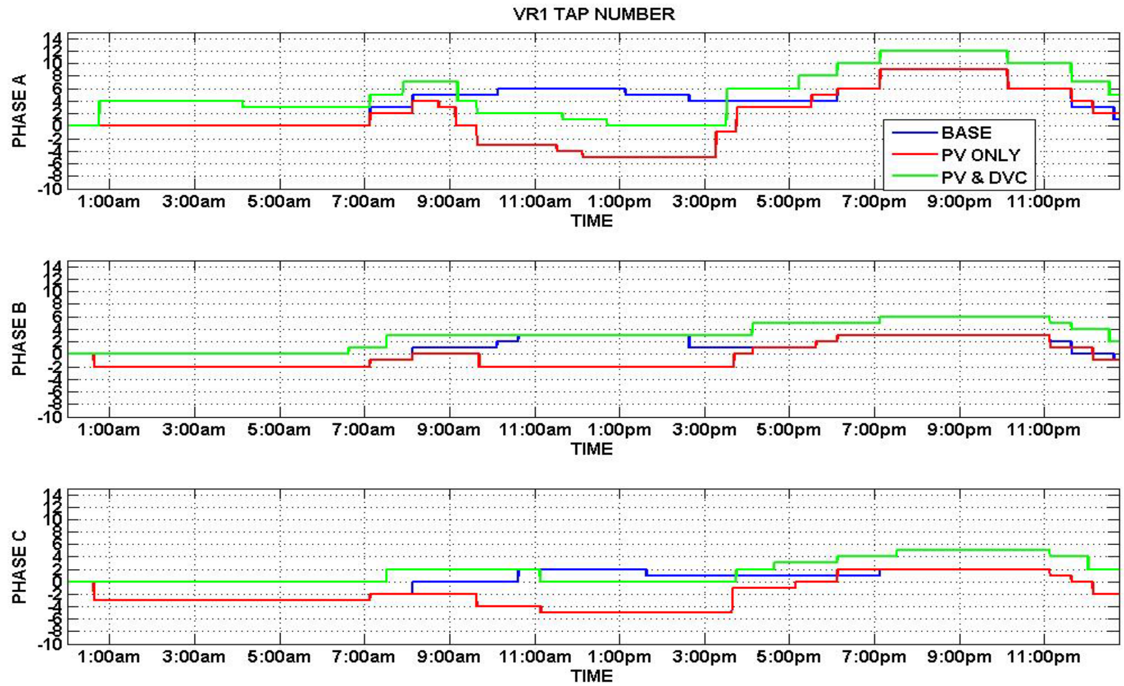


Figure 4.35 Voltage Profile Comparisons under Peak Load Condition

Figure 4.36 shows the tap position comparisons and Table 4.5 summaries the number of operations in three cases. High penetration of PVs may cause frequent operations of VRs which may increase the maintenance fee and shorten the life time of these devices. DVC could help reduce the operations.



(a)

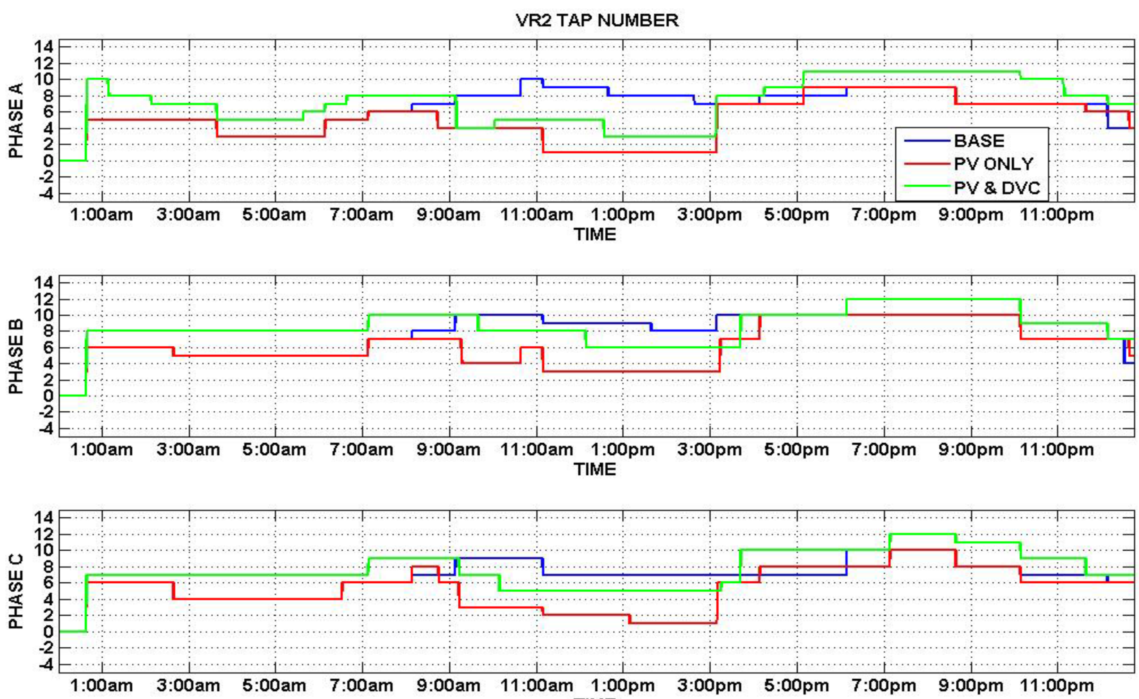


Figure 4.36 (a) – (b) Tap Position Comparisons

Table 4.5 Comparison of number of operations

		VR1	VR2
PHASE A	BASE	20	21
	PV	34	25
	DVC	31	25
PHASE B	BASE	13	16
	PV	13	23
	DVC	10	17
PHASE C	BASE	11	16
	PV	15	26
	DVC	12	18

Figure 4.37 shows the reactive power provided by DVC for with PV and without PV cases. In the day time, the voltage at node 890 is higher than 1 pu, so DVC works on inductive mode and absorb 0.3 MVAR from the grid to drag the voltage back to 1pu. At night, especially at around 7:30 PM which is peak load, the voltage is very low, so DVC works on capacitive mode and provide about 0.45 MVAR into the grid to boost the voltage to 1pu. Thus the size of DVC should be 0.45MVAR.

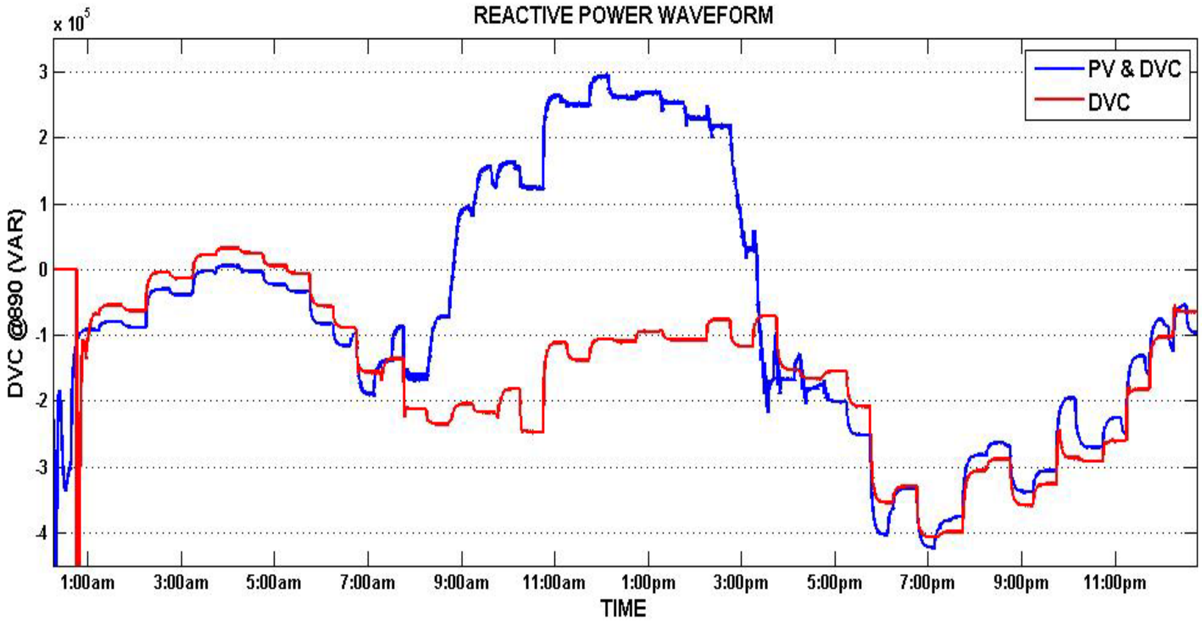


Figure 4.37 Reactive Power Waveform of DVC

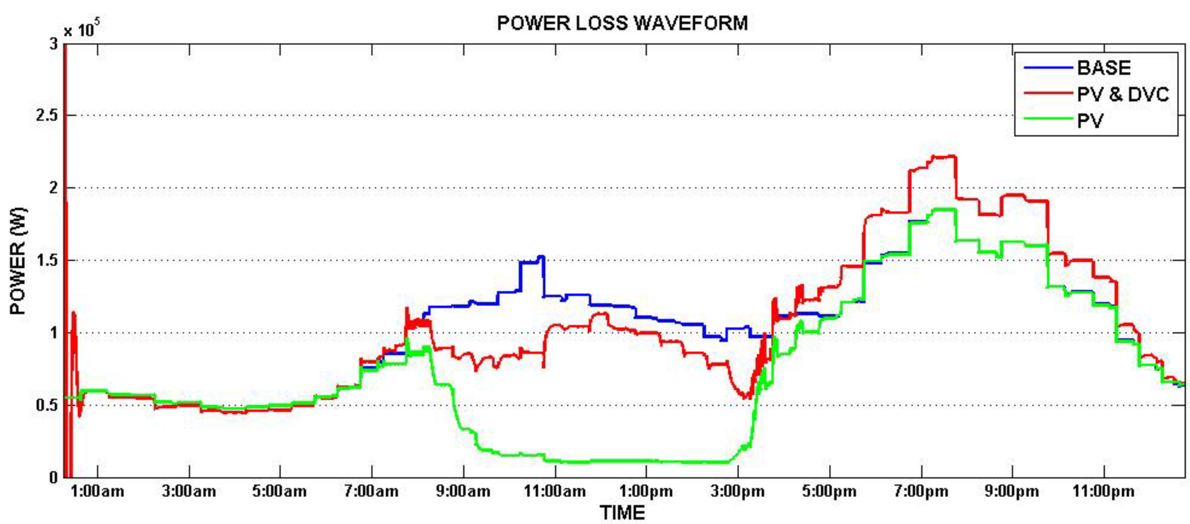


Figure 4.38 Power loss waveform Comparisons

Figure 4.38 shows the power loss waveform comparisons. DVC will increase the power loss, but as PVs reduce losses a lot in the day time, the power losses in the day time are still lower than the base case, while at night, the losses are higher than the base case.

4.2.3 Case 3: 3 DVCs

Combining Test Case 4 and Test Case 5 and we construct a system with three DVCs and 70% PV penetration. Figure 4.39 shows the voltage profile under peak load condition. All of the voltages are within acceptable limits. Figure 4.40 shows the voltage profile at phase A at noon (peak PV). In this figure, adding DVC in the system fixes the high voltage violation problem.

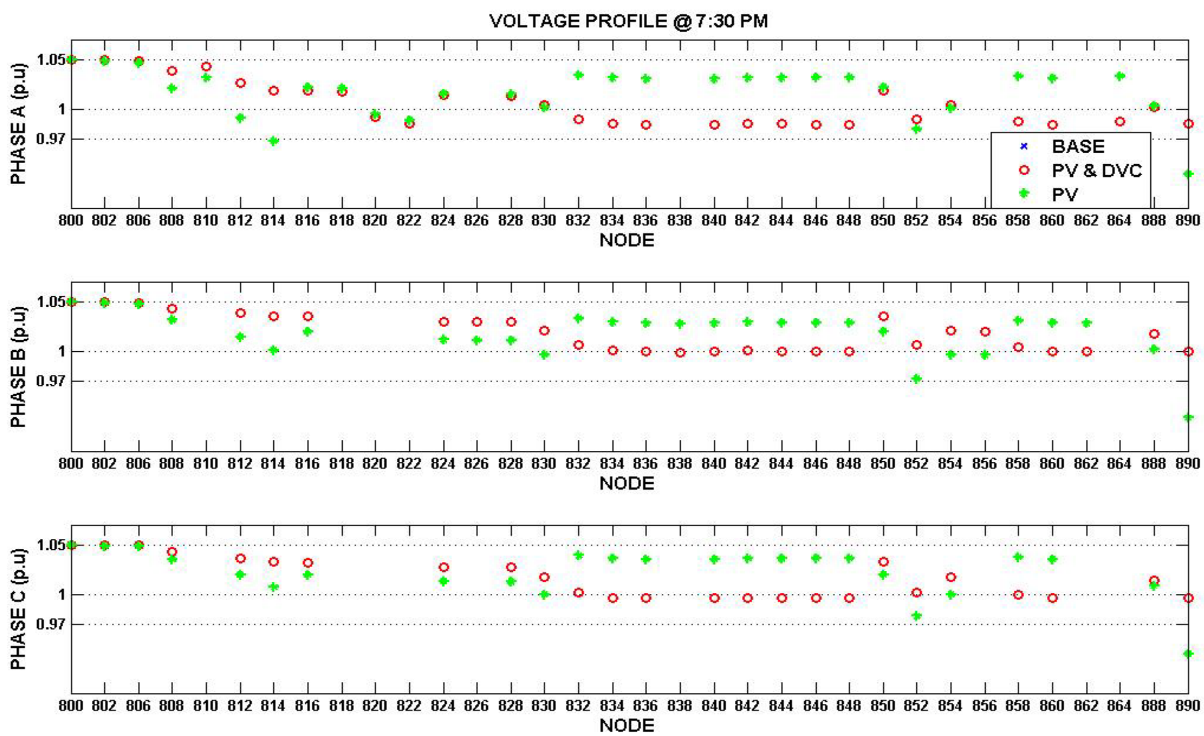


Figure 4.39 Voltage Profile at 7:30 PM (Peak Load)

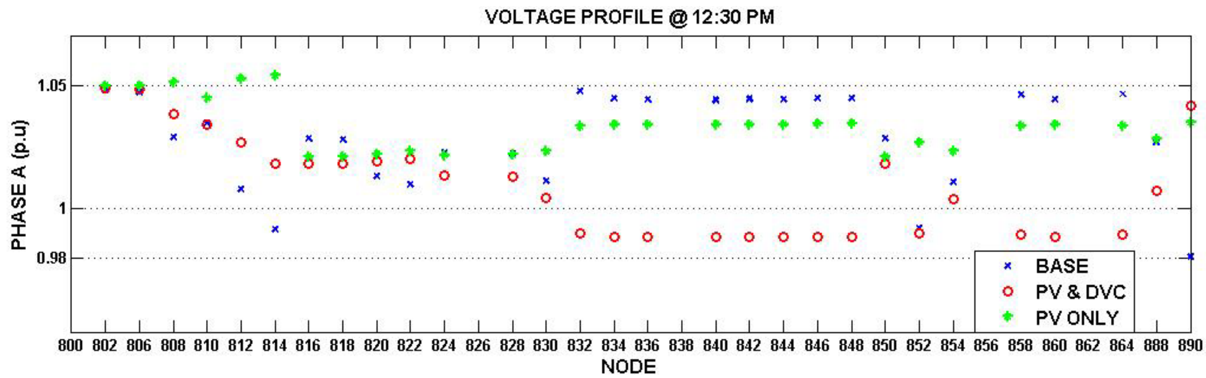


Figure 4.40 Phase A Voltage Profile at 12:30 PM (Peak PV)

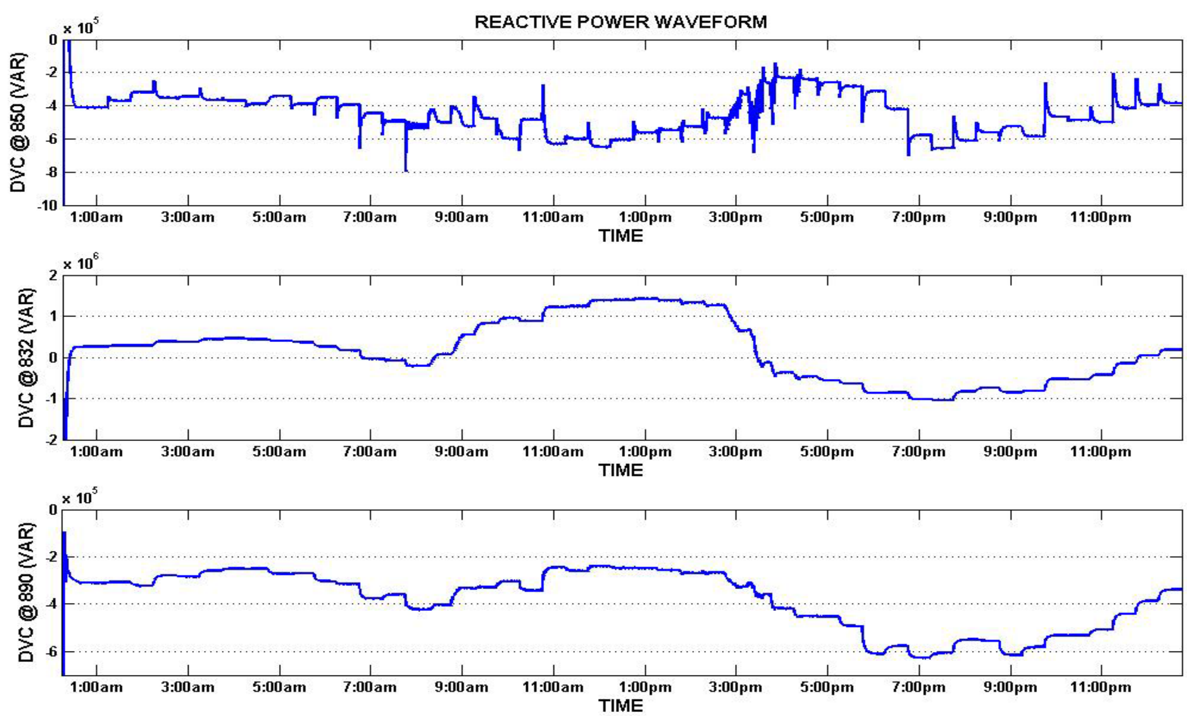


Figure 4.41 Reactive Power Waveform of 3 DVCs

Figure 4.41 shows the reactive power of the three DVCs. The DVC at node 850 generates about 0.65 MVAR. The DVC at node 832 absorb around 1.5 MVAR at noon and generates about 1 MVAR at night. The DVC at node 890 generates about 0.61 MVAR at night. Figure 4.42shows the power loss system waveform.

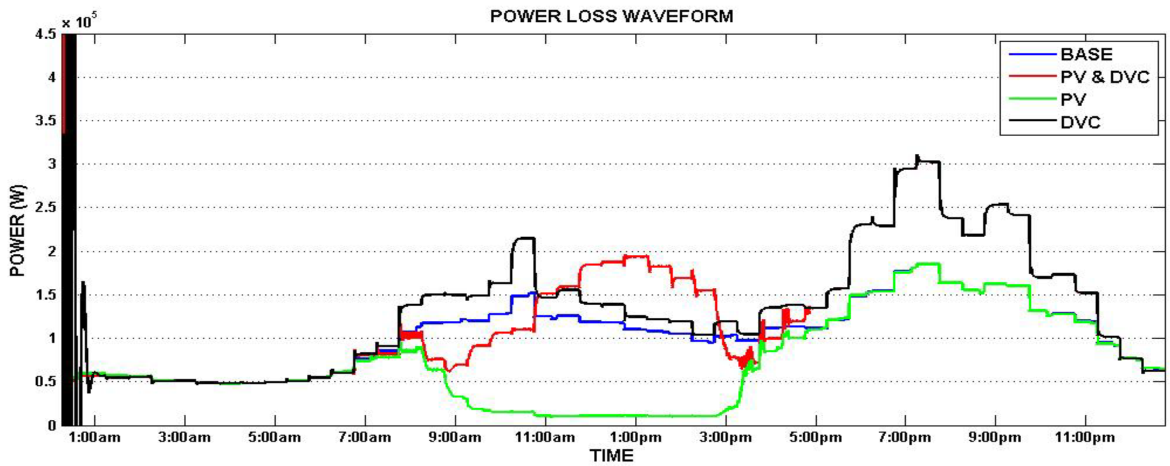


Figure 4.42 Power Loss System Waveform

4.2.4 Case 4: Two DVCs and PV under Cloud with static load

In this case, the goal is to investigate the performance of DVCs under cloudy conditions and to compare it with the performance of conventional devices. We integrate two DVCs into the system. They are used to replace traditional VRs. The cloud transient is simulated as in Chapter 3. PVs also have the same output power as in the base case.

Figure 4.43 shows the voltage profile. After clouds cover all of the PVs at noon, only node 890 has voltage violation. All of the other voltages are within acceptable limits. Compared to base case, there is no serious voltage problem in the system when DVC is used instead of VRs.

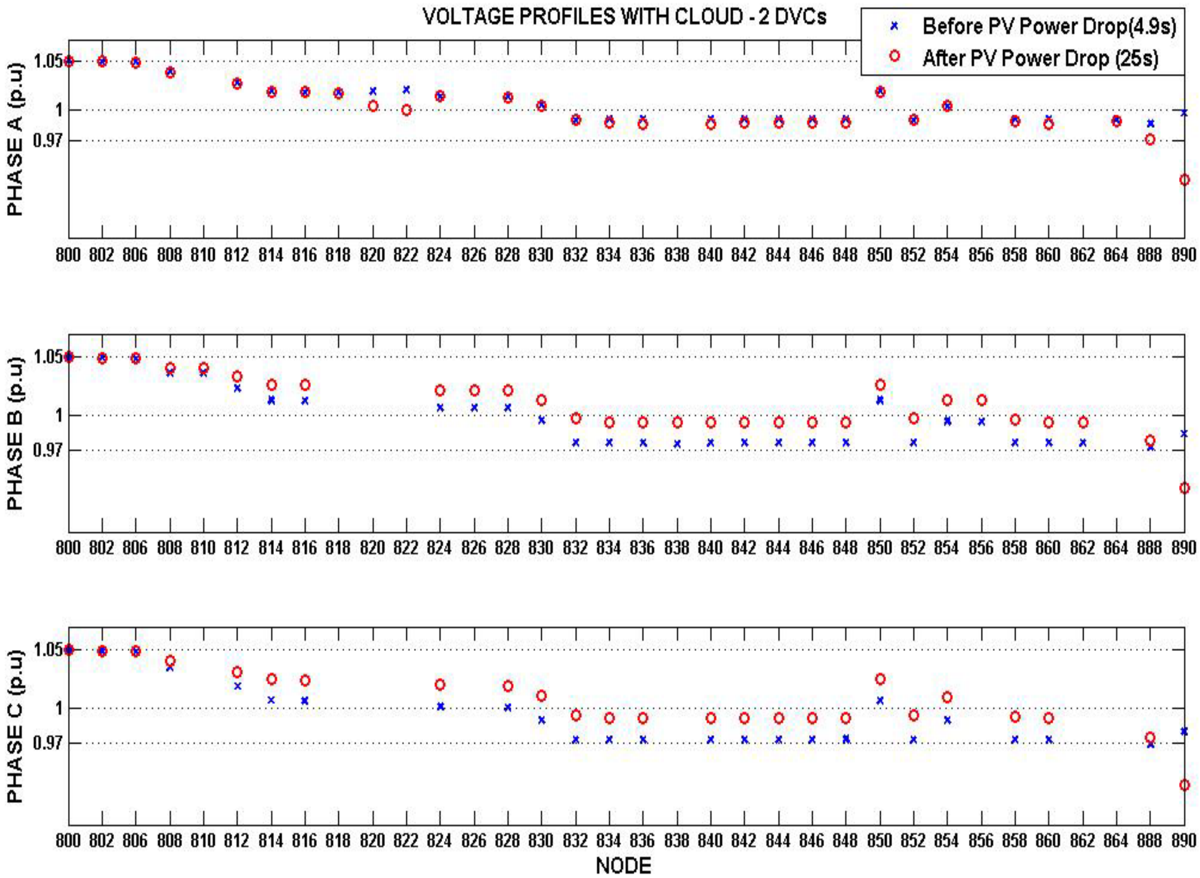


Figure 4.43 Voltage Profiles with cloud

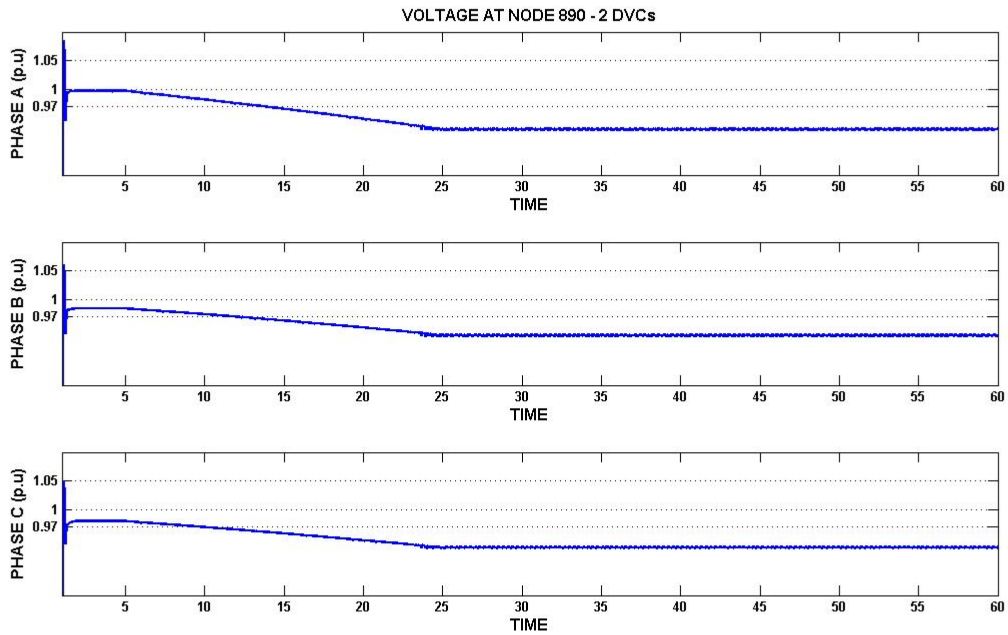


Figure 4.44 Voltage Waveform at node 890

Figure 4.44 shows the voltage waveform at node 890 which has low voltage violation. When clouds begin passing over the PVs, the voltage at node 890 drops, and when all the PVs are covered by the cloud, the voltage is about 0.96 pu.

Figure 4.45 shows the voltage waveform at node 840 which is the last node on the main feeder. As we can see, the voltages are almost kept the same for the entire 60s. There is no apparent voltage drop, though PV output drops significantly.

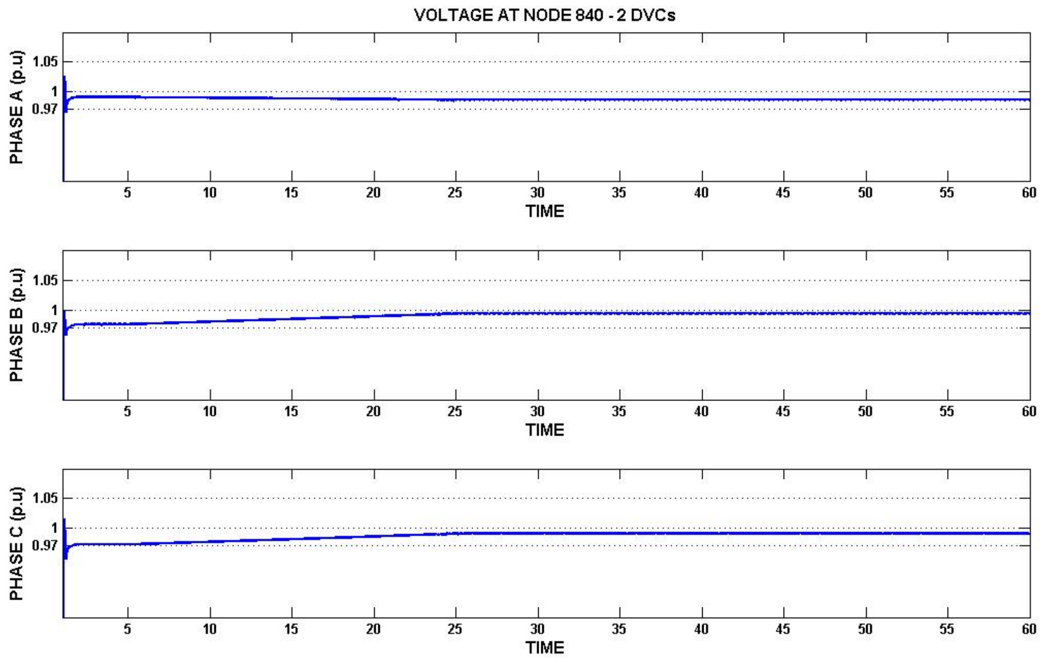


Figure 4.45 Voltage Waveform at node 840

4.2.5 Case 5: One DVC and PV under Cloud with static load

In this case, only one DVC is integrated in the system at node 890. It used to fix the voltage problem and eliminate capacitors.

Figure 4.46 shows the voltage profile. After cloud covers all the PV, the voltages drop except at node 890. The DVC at node 890 keeps the voltage exactly equal to 1.0pu. Compared with Figure 3.13, voltages rise slightly, but the system still has low voltage violation.

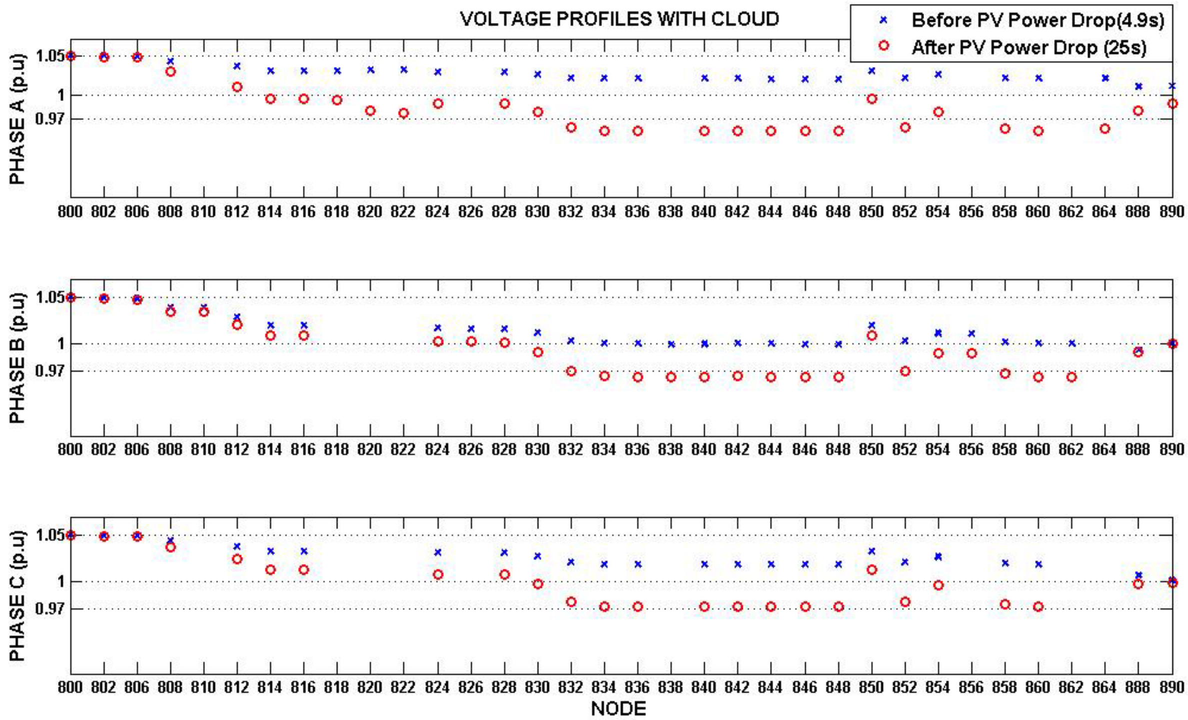


Figure 4.46 Voltage Profile with Cloud

Figure 4.47 shows the voltage waveform at node 890 where the DVC located and Figure 4.48 shows the voltage waveform at node 840 which is the last node in main feeder. Voltages at node 890 stays at 1 pu for the 60 seconds durations. It is not affected by PV output changes. However, voltages at node 840 drops along with the PV output and stays at this low value for about 20 seconds before coming back within the voltage limits.

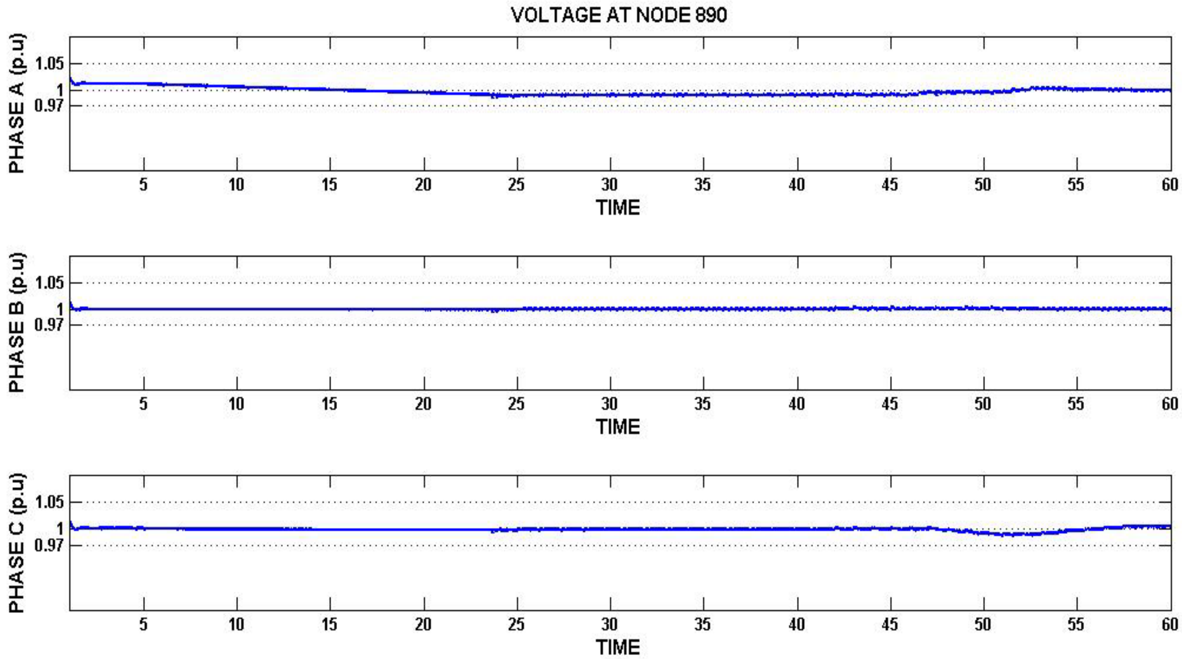


Figure 4.47 Voltage Waveform at node 890

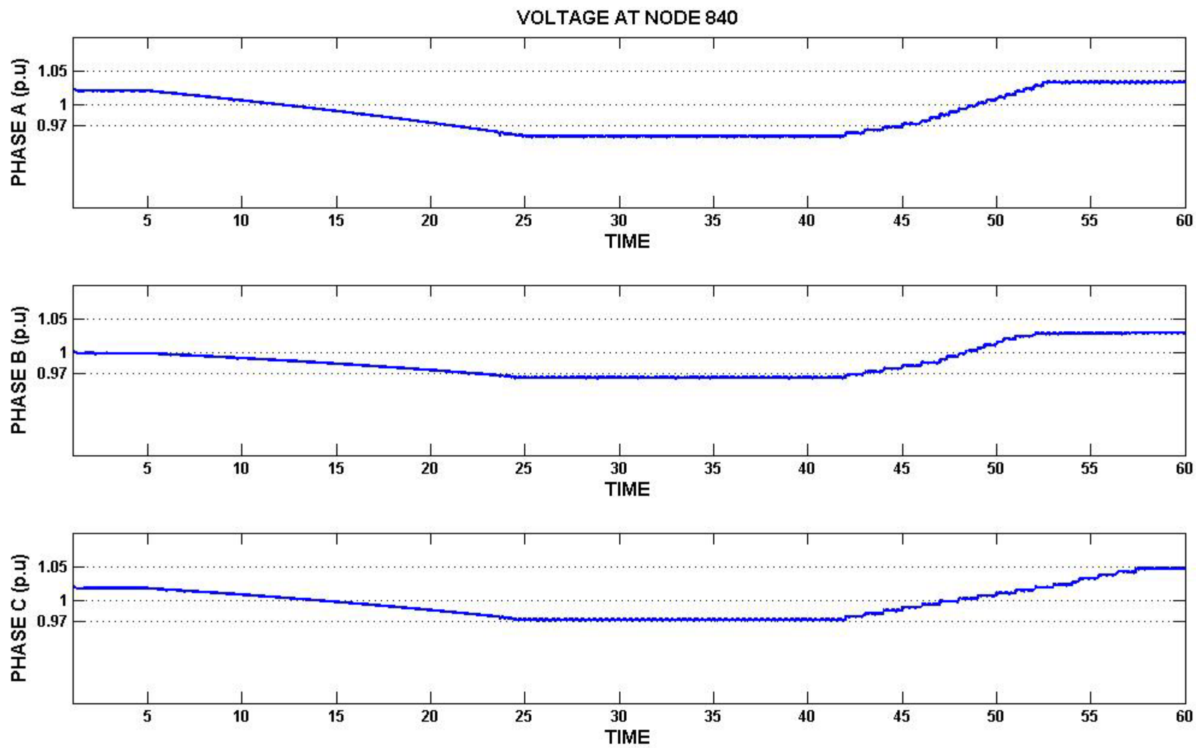


Figure 4.48 Voltage Waveform at node 840

4.2.6 Case 6: 3 DVCs and PV under Cloud with static load

In this case, we integrate three DVCs into the system. Two of them are used to replace VRs and the third is used to fix the voltage problem at node 890 and eliminate capacitors. In this case, the cloud transient is also simulated by decreasing solar irradiation from 1000 to 70 W/m2 over a 20s period of time from 80 to 100s as shown in Figure 3.10. PVs also have the same output power as the cloud study in Chapter 3.

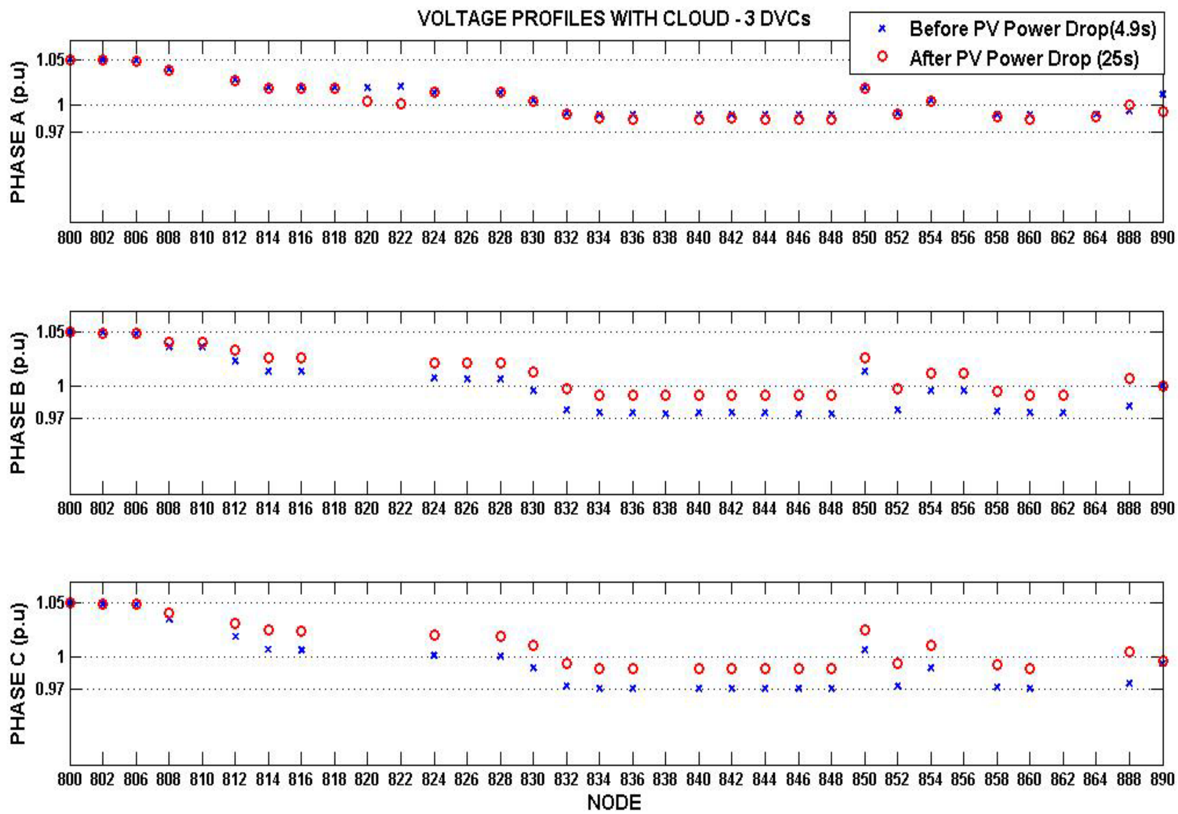


Figure 4.49 Voltage Profiles with DVC

Figure 4.49 shows voltage profile comparison. As we can see, voltages at phase A did not change much. That means clouds did not affect the system. Although the PV output decreases the isolation, the DVC generates more reactive power into the system or absorbs less reactive power from the system which helps the voltages stay in the acceptable limits. Figure 4.50 shows the reactive power waveform of three DVCs.

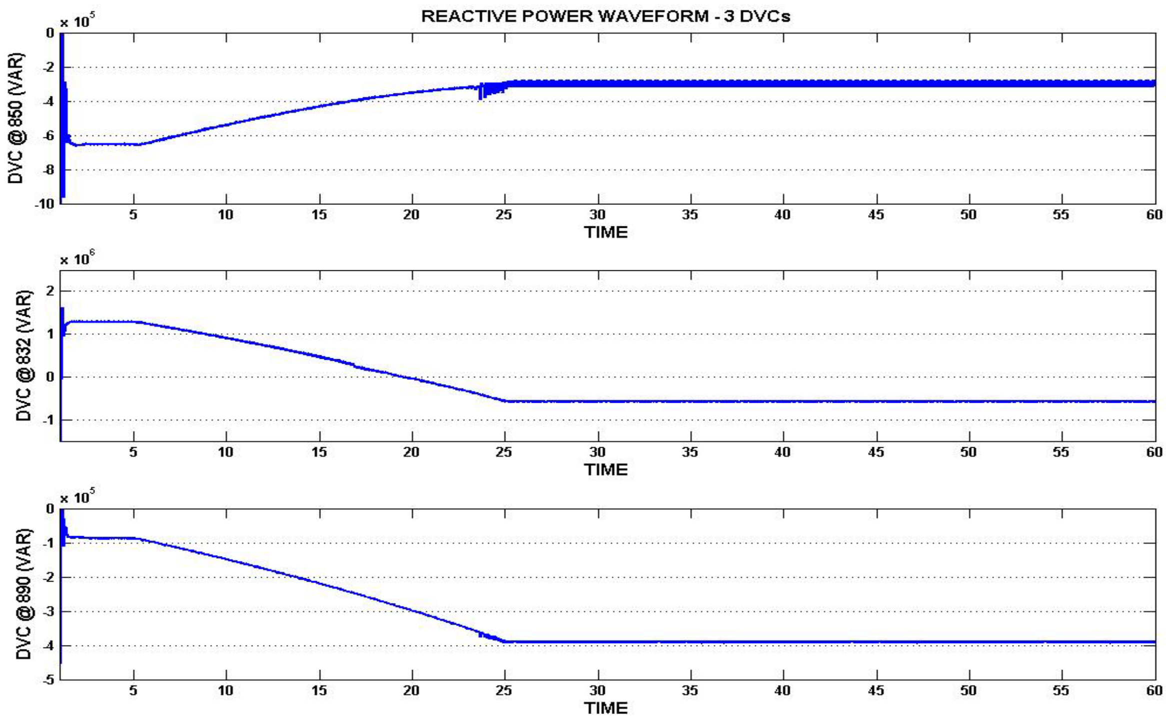


Figure 4.50 Reactive Power Waveform

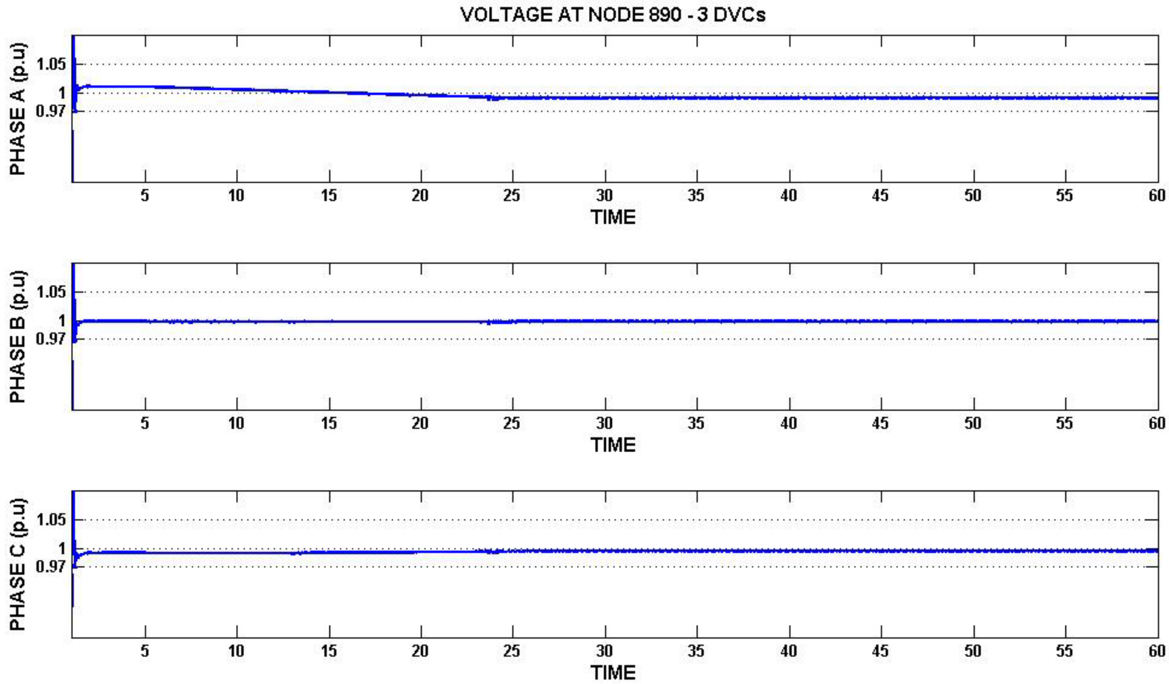


Figure 4.51 Voltage Waveform at node 890

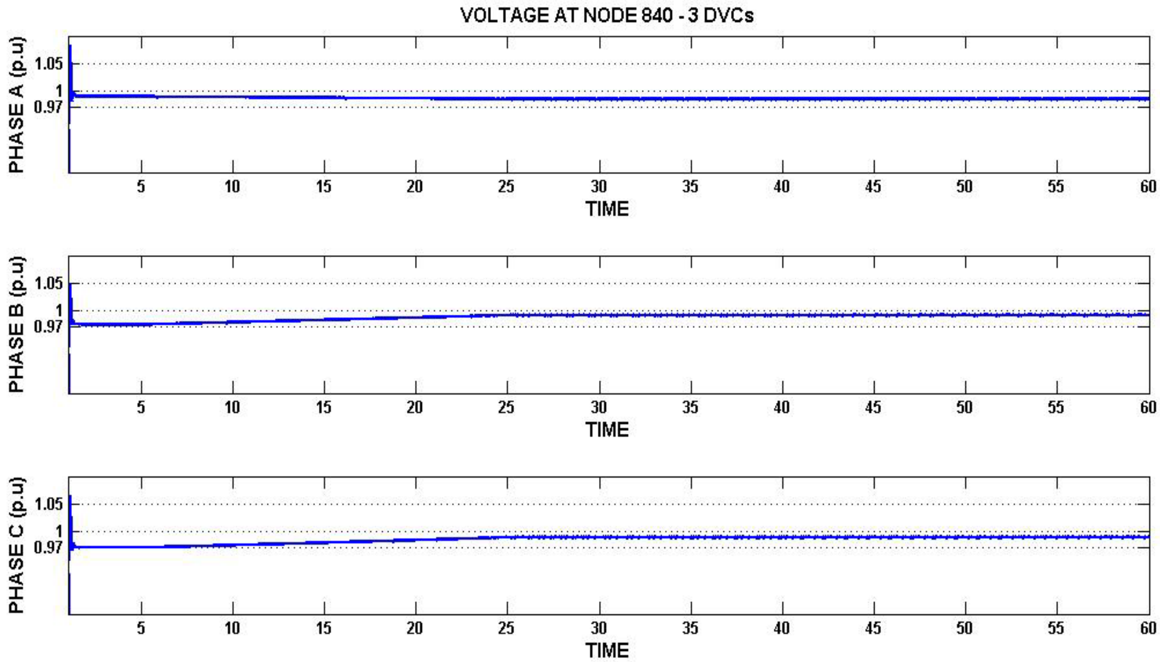


Figure 4.52 Voltage Waveform at node 840

Figure 4.51 shows the voltage waveform at node 890. Figure 4.52 shows the voltage waveform at node 840. As we can see, neither voltage varies with as PV output decreases. So using DVC instead of VR in systems with high penetration of PV could help solve the voltage problem caused by clouds.

4.2.7 Case 7: three DVCs and PV under Cloud with dynamic load

In the previous chapter, the cloud affected the system with dynamic load and caused the motors to stall. So in this case, we will attempt to use DVC to fix this problem. There are three DVCs in the system and they are located at node 832, node 850 and node 890. The clouds are simulated as in Figure 4.53.

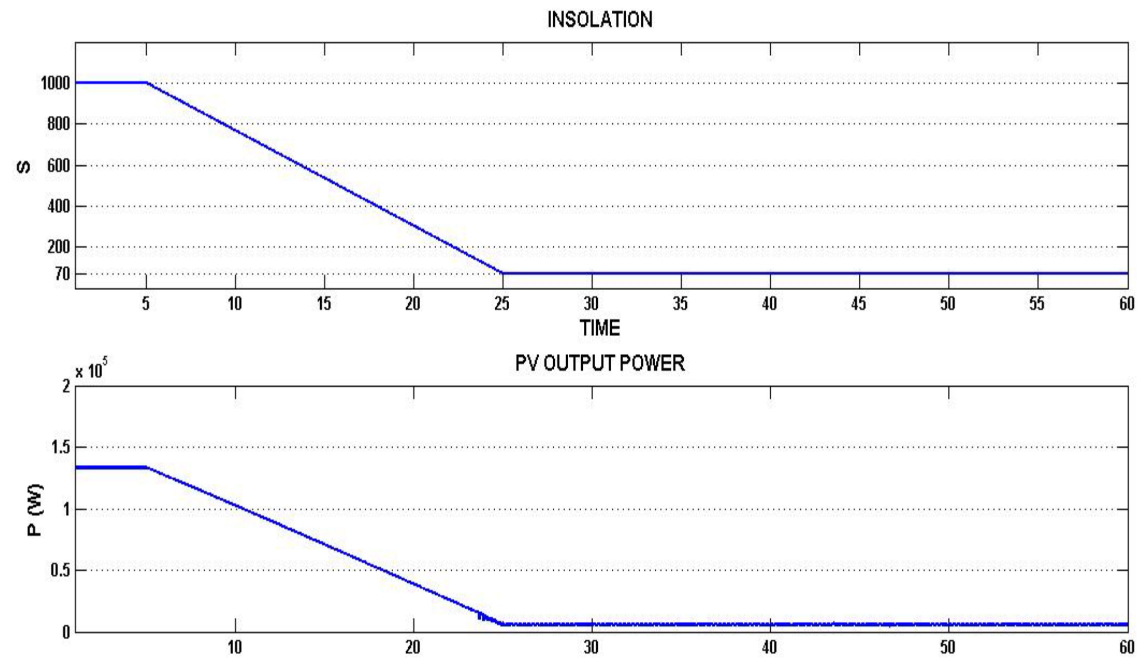


Figure 4.53 PV power changes with sun irradiation

Compared to the large voltage drop from the PV panels after cloud cover in the system without DVC (Figure 3.16, Figure 3.18), voltages in this case with the DVCs doesn't change much. The result is that the motors all work well and do not stall.

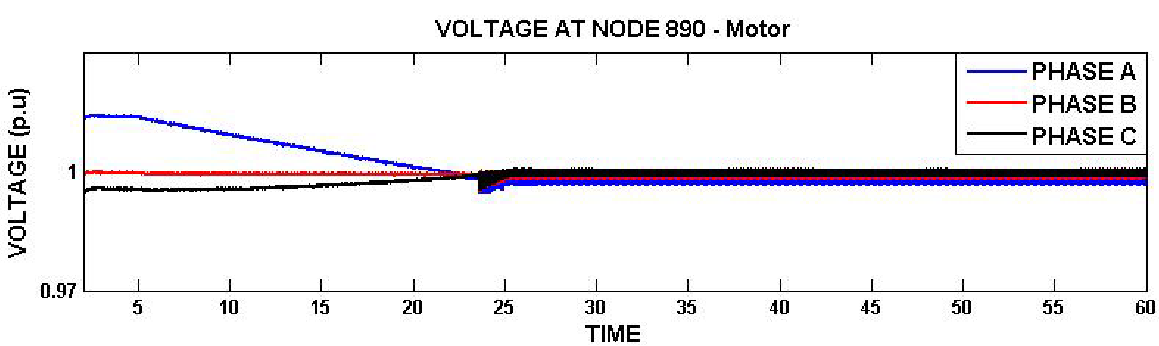


Figure 4.54Voltage Waveform at node 890 with DVC

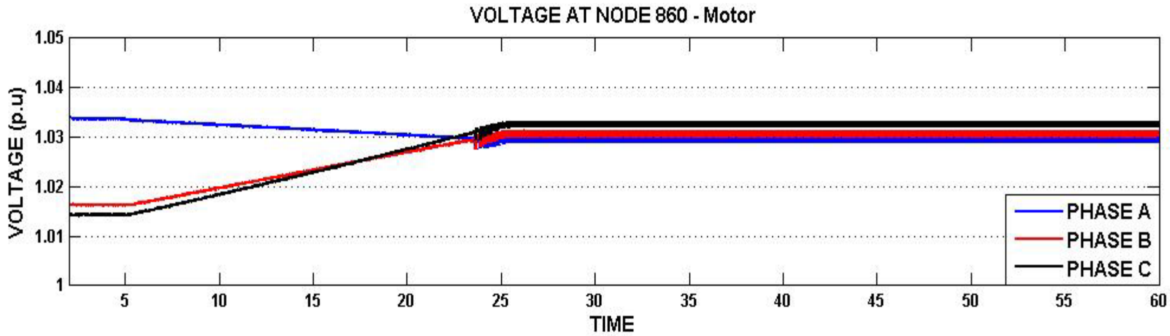


Figure 4.55 Voltage Waveform at node 860 with DVC

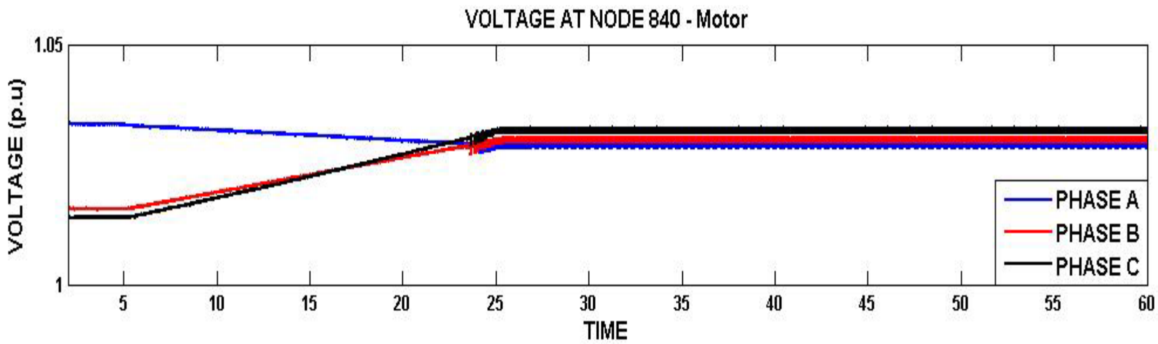


Figure 4.56 Voltage Waveform at node 840 with DVC

Figure 4.54 - Figure 4.56 show the voltage waveform at 3 nodes. Although the PV output also drops in the system, the voltages were not affected much. So the motor will not be affected by clouds. Figure 4.57– Figure 4.58 show the detailed behavior of the motors in this system.

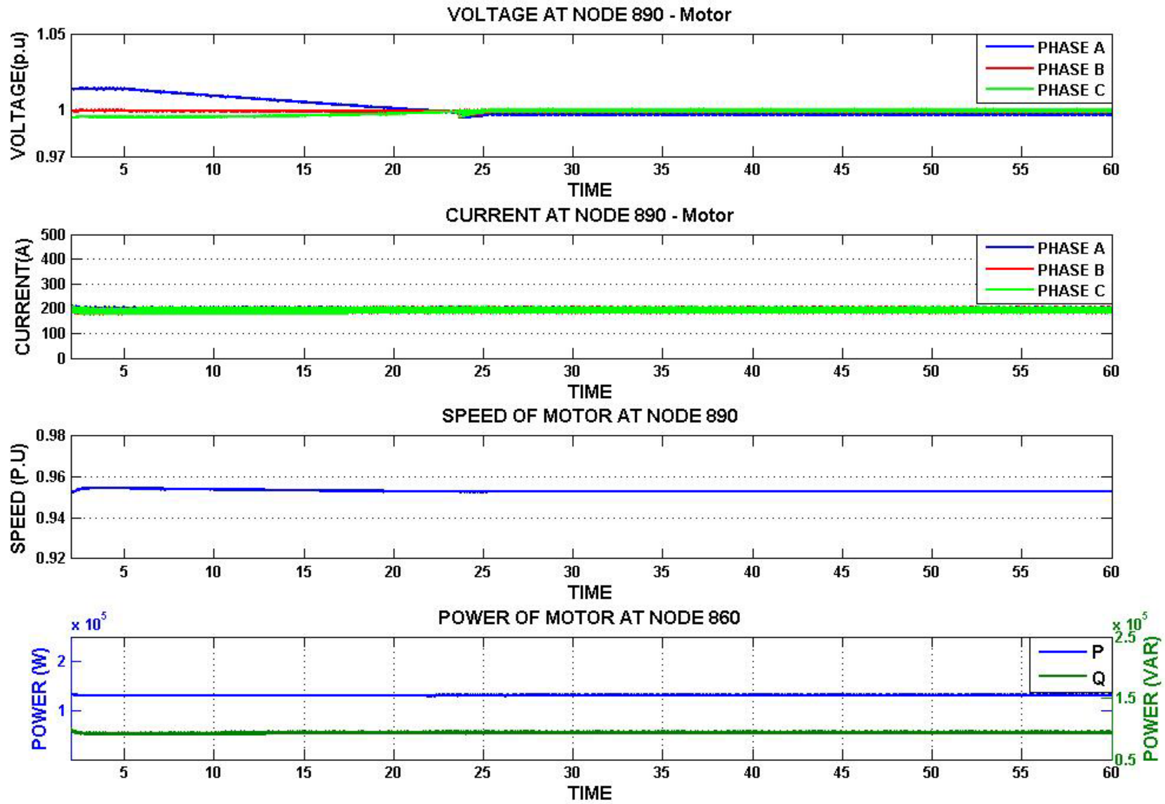


Figure 4.57 Motor Behavior at node 890

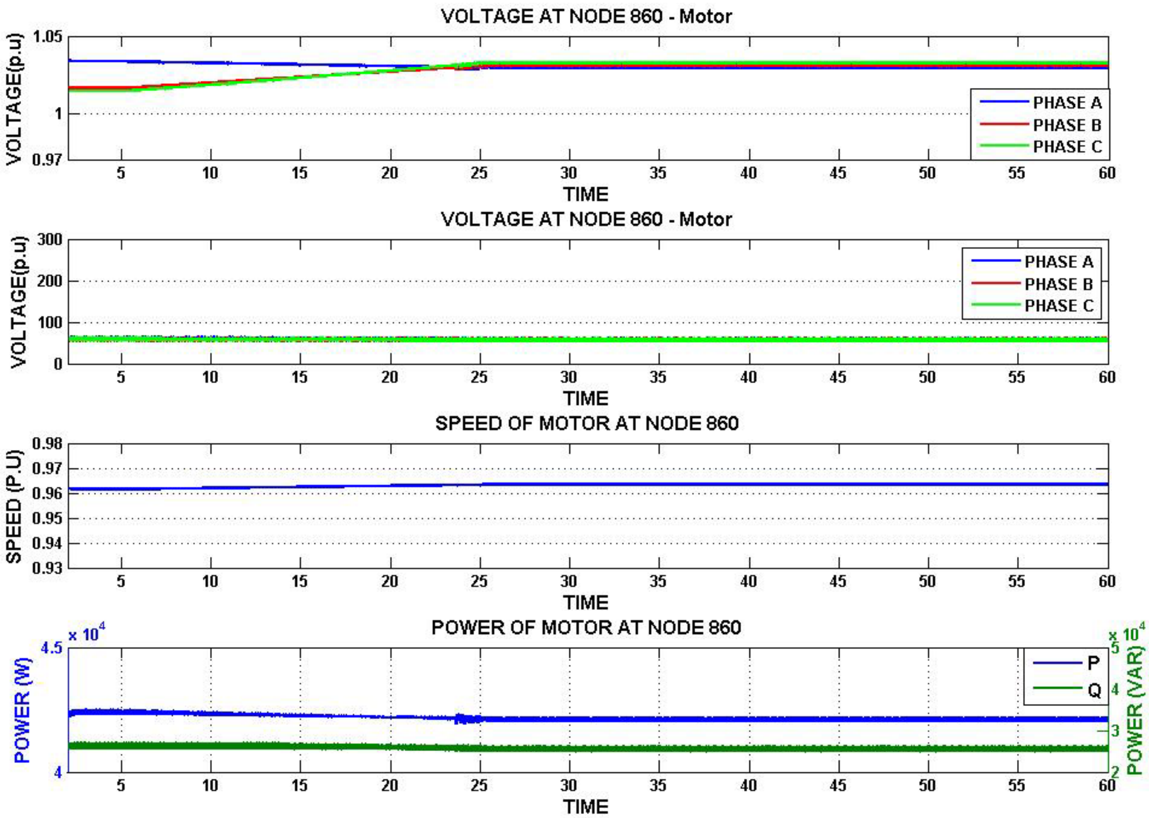


Figure 4.58 Motor Behavior at node 860

4.3 Flat Voltage

Conservation Voltage Reduction (CVR) has been used by utilities to save energy by reducing voltage since the 1950s [16]. CVR aims to maintain the voltage as low as possible within acceptable limits (ANSI range A). Typically, the voltages are kept in the lower half of the ANSI range, from 114V to 120 V without causing harm to consumers' appliances [16]. Many test cases are employed to investigate percentage changes in energy consumption when voltage was reduced. In Northeast utilities system, a significant energy savings could be achieved if the voltage limits were reduced from +5% and -3% to +3% and -5% [18]. Reducing an average 1.6 volt could lead to approximate 1% energy savings at Commonwealth Edison [17]. With an average voltage reduction of 2.1% system of

Snohomish PUD, the customer could save 281 kWh / yr with a net bill reduction of $6.28 / yr[18]. So Implementing CVR can be a good way for utilities to save energy.

If the system has a heavy load feeder or a long feeder, which means the voltage at the end of the feeder are only slightly higher than the lower limits, then the utilities cannot reduce substation voltage. Thus a relatively flat voltage profile is required for implementing CVR. In the conventional system, VR with line-drop compensation and capacitors are often used to keep voltage flat along the feeder [17][19]. In our study, we will use DVC to get a flat voltage profile and a future study could be done to implement CRV to save energy.

The objective of this study is to make the voltage profile flat. Five DVCs were installed in the system to realize this goal. The source voltage is set to 1.0pu. From the previous study, we found that the lowest voltage among three phases is phase A, so in this study phase A is regulated. Another reason to regulator phase A is that there is a lateral in phase A (Node 816, 818, 820, 822) which has a large load connected to it. If we regulate other phases, like phase B, node 822 will have voltage violation.

There are two algorithms to determine optimal placement of VRs in distribution system. The first algorithm uses candidate buses where the VRs are located. After adding VRs at these buses, it is needed to reduce the number of VRs based on economic aspects and objective of placing VR. The second algorithm first finds violation buses and computes the distance from these buses to the substation. It places a VR at the nearest bus. New violation buses are found, and processes is repeated until no violation bus existed, [20][21].

In our system, DVC is used to regulate voltage where it is located just like VR in the conventional system and we do not have candidate buses to place the additional DVCs. So we use the second algorithm to determine the placement of additional DVCs in the system to achieve a completely flat voltage assignment. The voltage limits should not be the regular 0.97 pu – 1.05 pu. Instead, we assume the violated buses have voltage lower than 0.996 pu. We first run the system with three DVCs under peak load condition to find voltage violation buses. Table 4.6 shows the voltages in the system with three DVCs under peak load condition.

Table 4.6 Voltage with three DVCs under peak load condition

NODE	PHASE A	PHASE B	PHASE C		NODE	PHASE A	PHASE B	PHASE C
800	1	1	1		836	0.9922	1.00648	1.00439
802	0.99947	0.99969	0.99965		838	0	1.00601	0
806	0.99913	0.99949	0.99944		840	0.99217	1.00643	1.00436
808	0.99474	0.99996	0.99907		842	0.99295	1.00729	1.00499
810	0	0.99966	0		844	0.99248	1.00669	1.00451
812	0.99528	1.00689	1.00443		846	0.99234	1.0061	1.00427
814	0.99996	1.01633	1.01327		848	0.99232	1.00605	1.00426
816	0.99978	1.01626	1.0132		850	0.99996	1.01633	1.01327
818	0.99887	0	0		852	0.99996	1.01508	1.01187
820	0.97328	0	0		854	0.99606	1.01164	1.00903
822	0.96744	0	0		856	0	1.01134	0
824	0.99801	1.01349	1.01135		858	0.99676	1.01156	1.00875
826	0	1.0131	0		860	0.99249	1.00692	1.0046
828	0.99789	1.01337	1.01121		862	0	1.00646	0
830	0.99605	1.01165	1.00904		864	0.99675	0	0
832	0.99996	1.01508	1.01188		888	1.00929	1.02384	1.02112
834	0.99305	1.00741	1.00509		890	0.98664	0.99981	0.99812

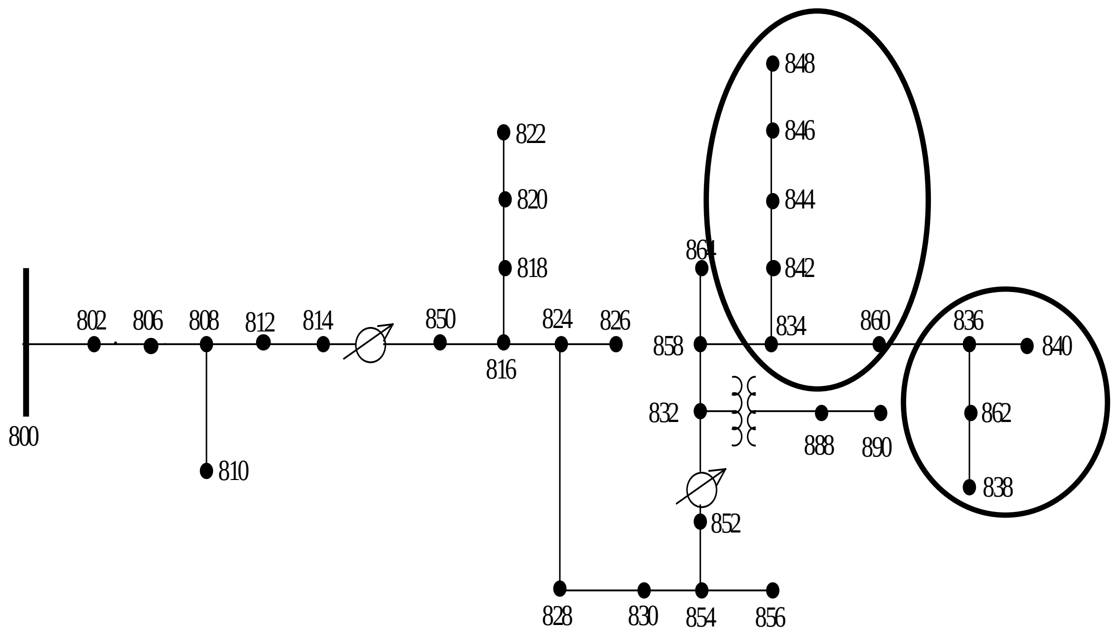
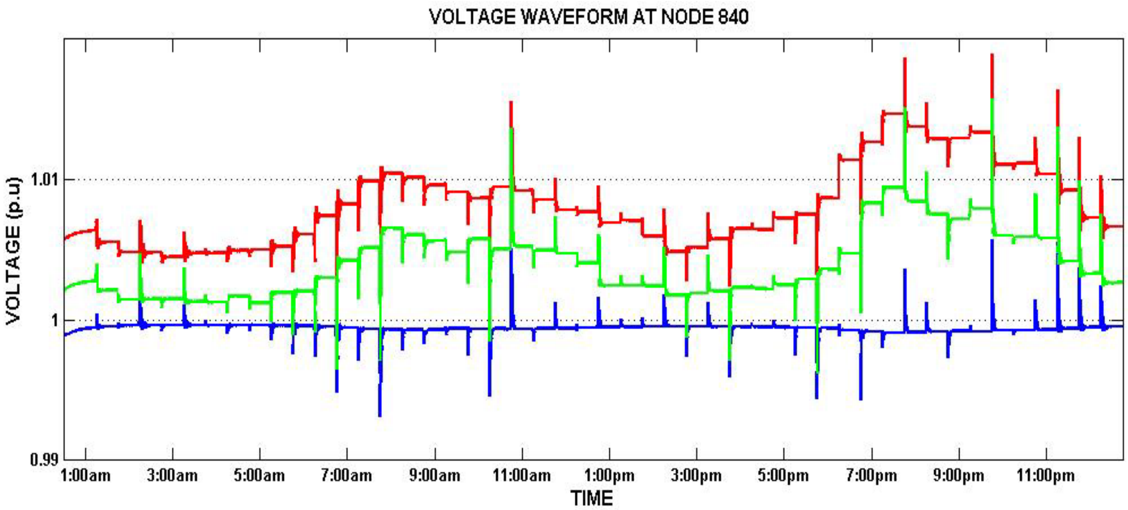
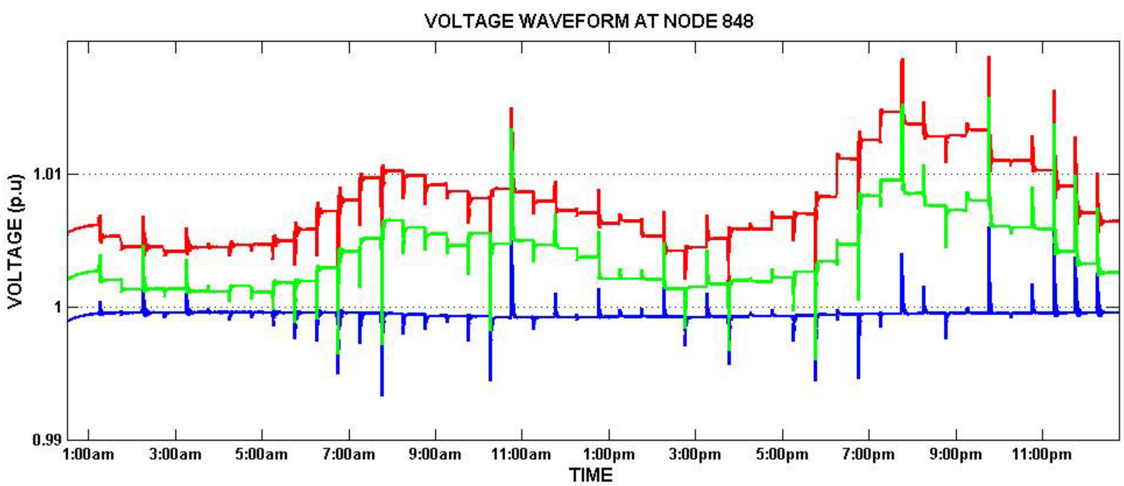


Figure 4.59 Prototype Feeder

Table 4.6, the nodes in the circles have low voltage and the lowest voltage is 0.992 pu. The nearest node in this case is node 834, so we add another DVC at node 834 to improve the voltage profile. Figure 4.60 - Figure 4.61 show the voltage waveforms at node 840 which is at the end of the main feeder and node 850 which has a DVC connected. From the figures, we see that voltages at phase A are kept at 1 pu which indicates that using DVCs could perfectly achieve the goal of keeping the voltages equal to 1 pu.



(a)



(b)

Figure 4.60 (a)-(b) Voltage Waveform at node 840 and node 848

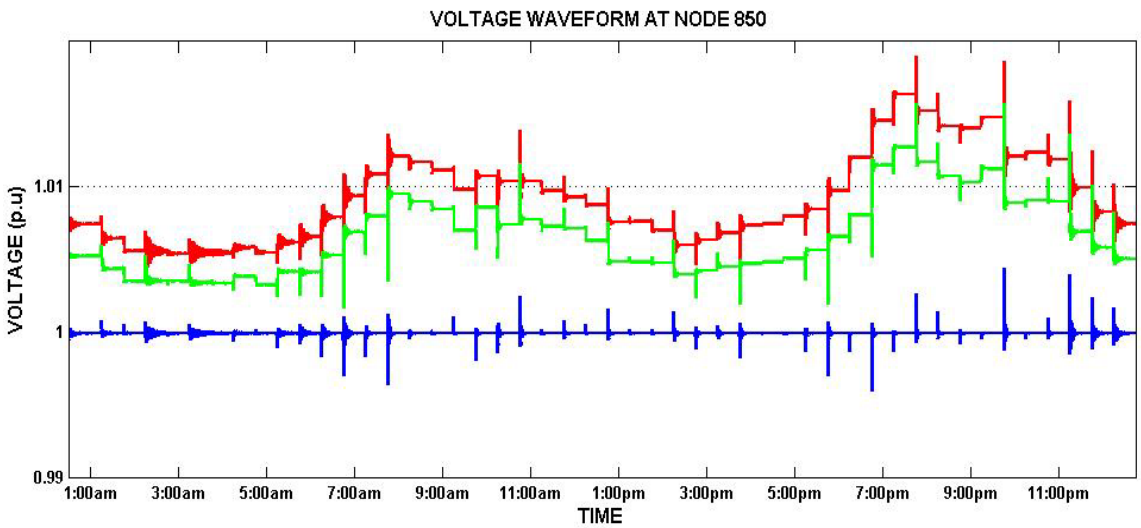


Figure 4.61 Voltage Waveform at node 850

Figure 4.62 - Figure 4.64 shows the voltage profile with four DVCs at 10:30 am (high load), 3:00 pm (light load) and 7:30 pm (peak load). With four DVCs integrated in the system, the voltage profiles are significantly improved. The voltage drop ($V_{max} - V_{min}$) at phase A in the system at peak load is 0.046 pu. In future work, this system could allow for a large voltage reduction when we apply CVR to achieve the goal of saving energy.

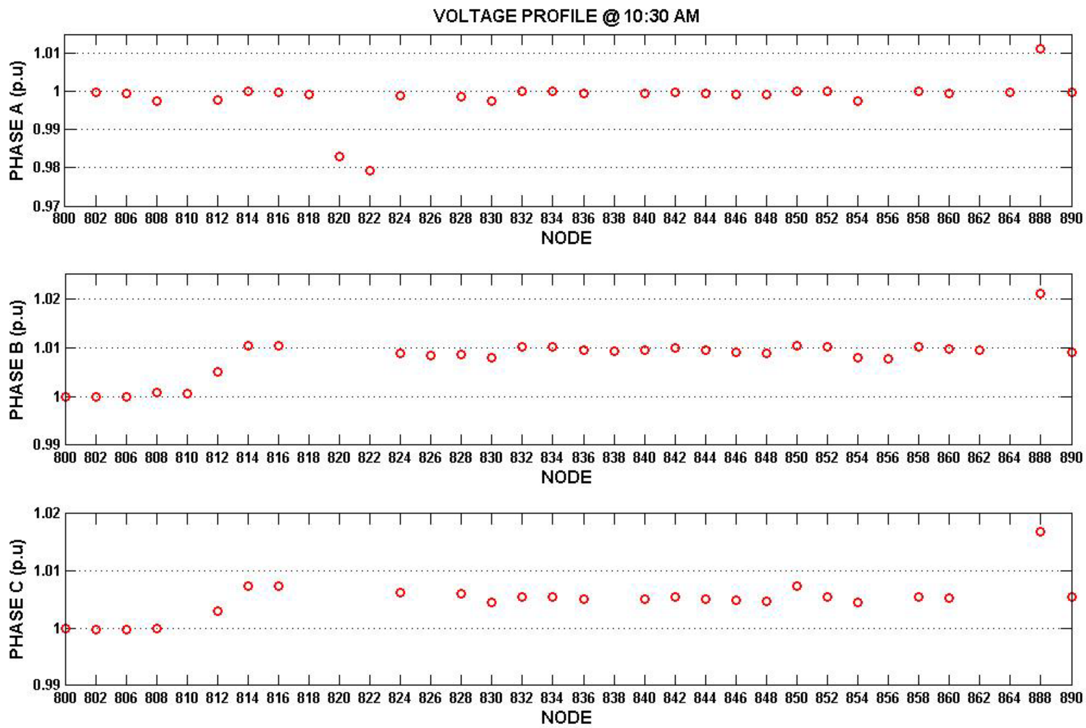


Figure 4.62 Voltage Profile at 10:30 AM (High Load)

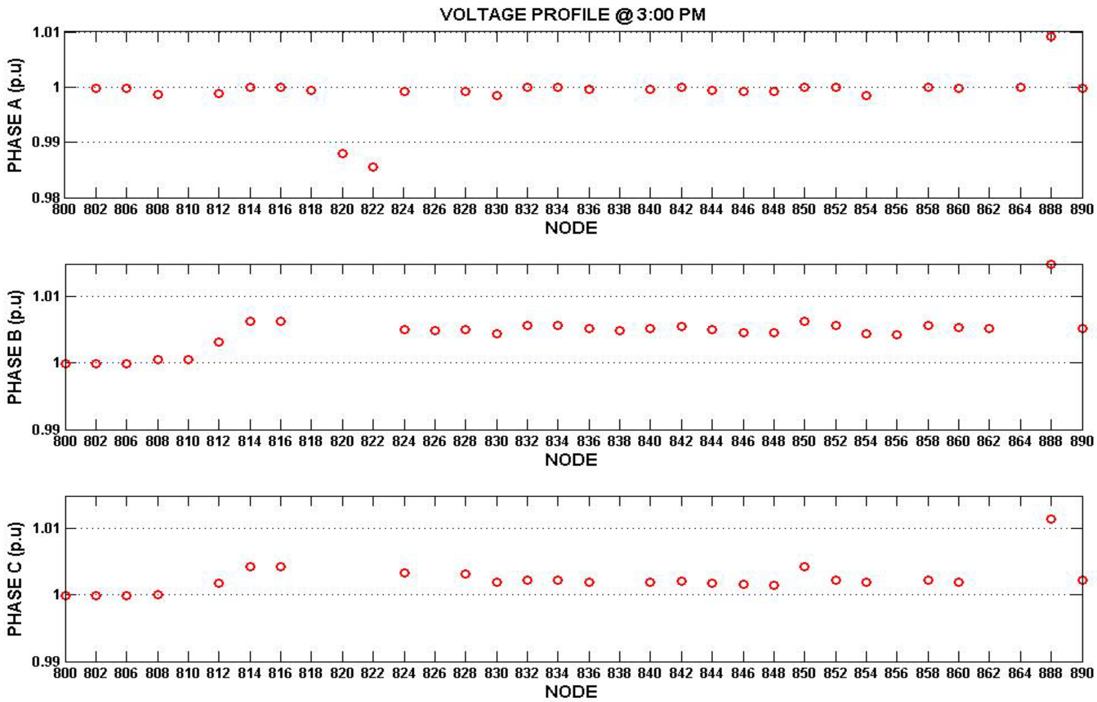


Figure 4.63 Voltage Profile at 3:00 PM (Light Load)

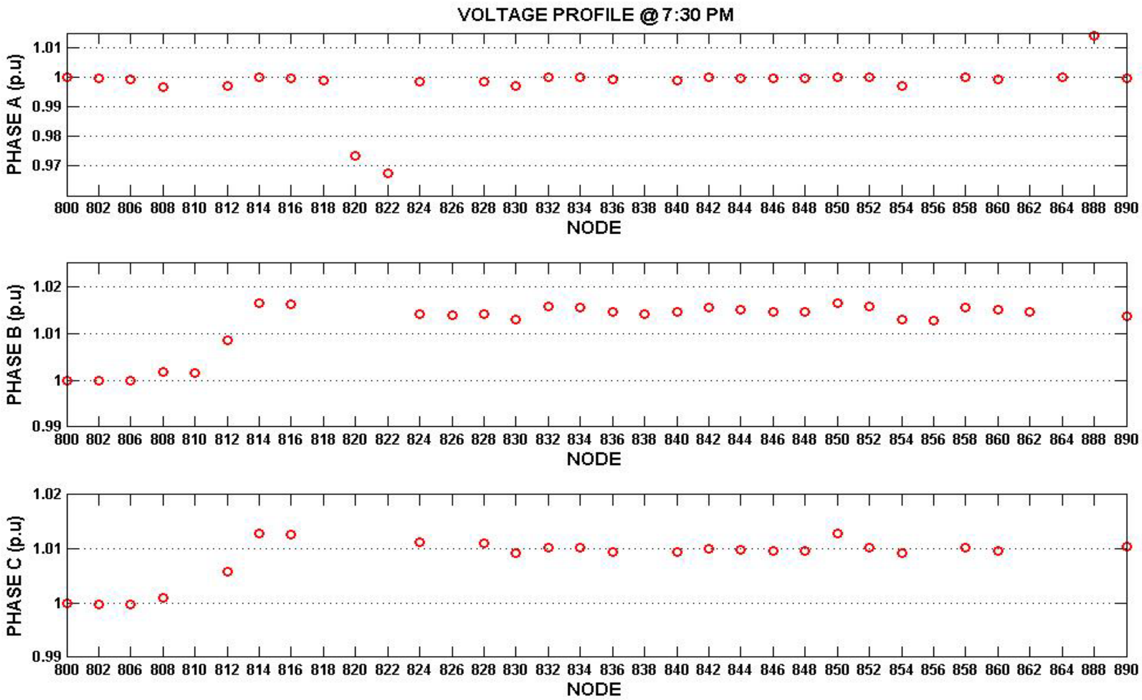


Figure 4.64 Voltage Profile at 7:30 PM (Peak Load)

As Figure 4.64 shows, the voltages at node 820 and node 822 have very low voltages compare to other nodes. There is a heavy load connected at node 822.However, because we do not have single phase DVC, we assume that this is a three phase line and install a DVC at node 822. The results are shown in Figure 4.65 - Figure 4.67.The voltage drop is 0.0176 pu (previous drop was 0.046 pu). The fifth DVC further improves the system performance and results in a flatter voltage profile. This provides a larger margin to design a CVR strategy.

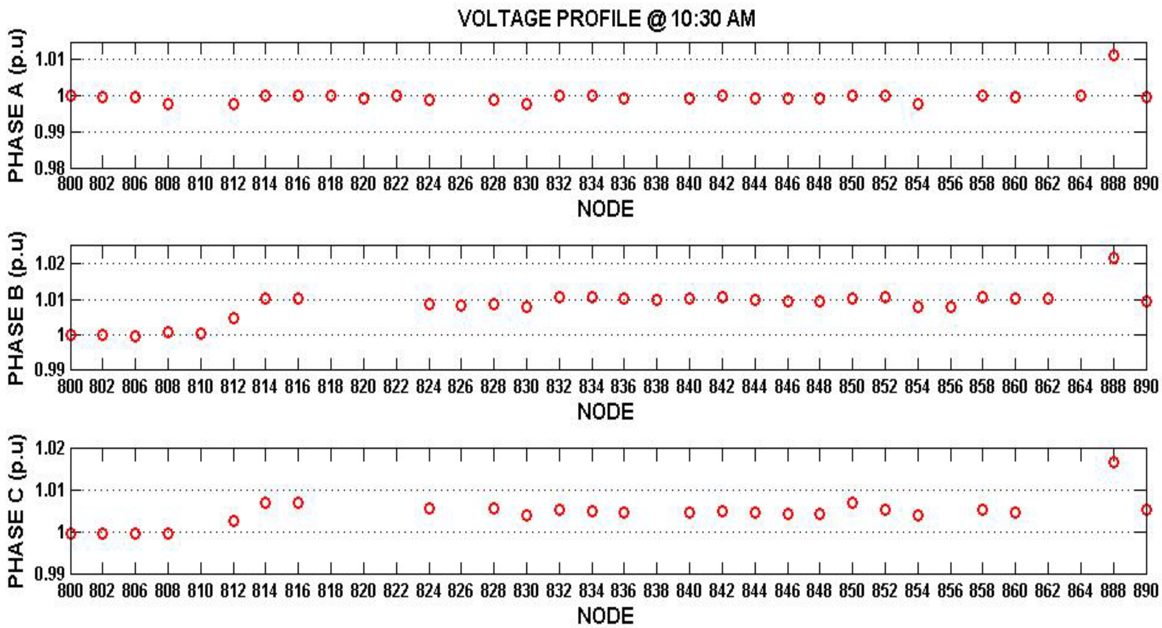


Figure 4.65 Voltage Profile at 10:30 AM (High Load)

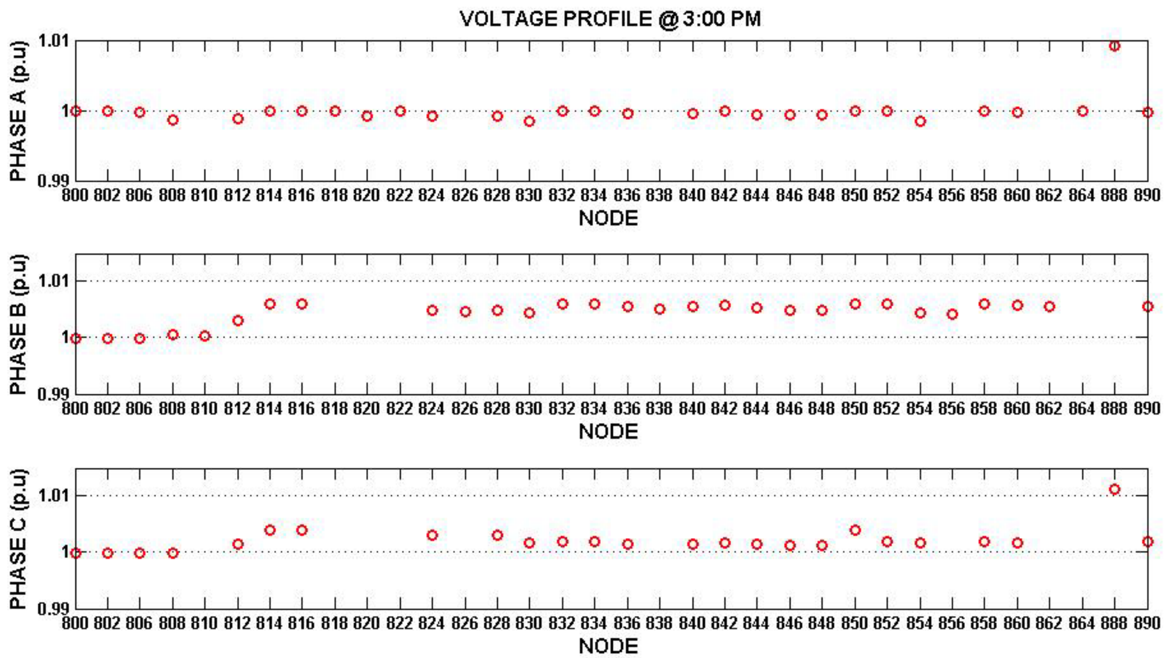


Figure 4.66 Voltage Profile at 3:00 PM (Light Load)

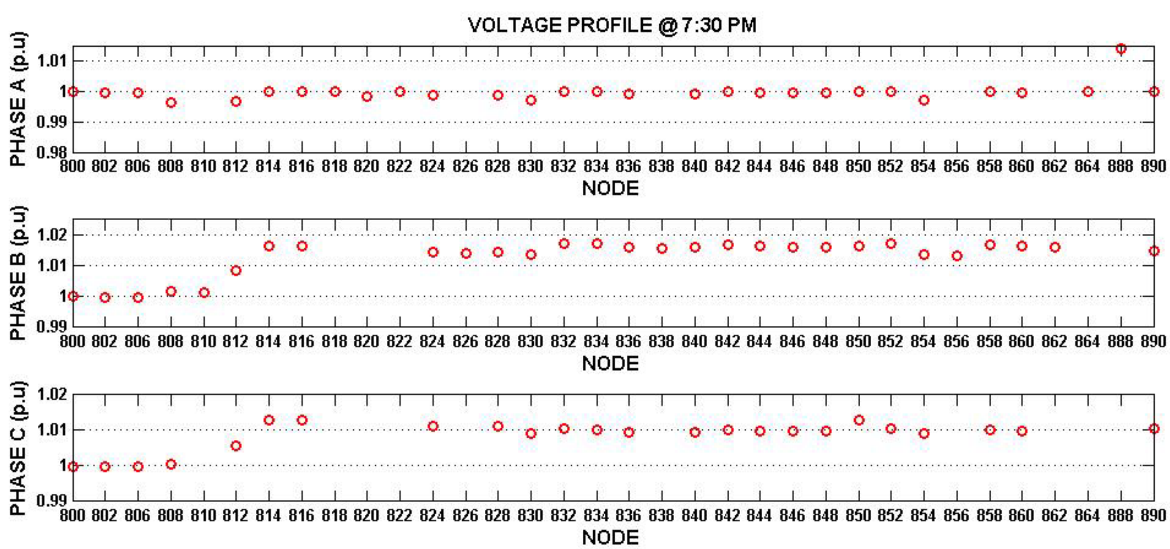


Figure 4.67 Voltage Profile at 7:30 PM (Peak Load)

CHAPTER 5
SUMMARY AND FUTURE WORK

5.1 Summary

High penetration of PV leads to high voltage violation and reverse power flow. It also causes increased operations and abnormal operation of conventional VRs. Although small and medium penetration level of PV could help reduce power losses in the system, high penetration level of PV may increase the power losses in the system. Under cloudy conditions, VRs cannot response to the fast voltage drop which may result in an unstable situation. If there are dynamic loads like motors in the system, low voltage may cause the device stopping working, which may lead to customer' complaints.

Facing these problems, we proposed to use DVC to replace conventional volt-VAR control devices. Based on the results from the case studies, DVC could completely realize the functionality of VRs and capacitors in a distribution system. Furthermore, DVC has better performance on the following aspects:

- When DVC is used to replace capacitors as in 4.1.2 case 2, it can help reduce the number of operations of VRs, which could help reduce the maintenance fee and increase the life time of these devices.
- As in 4.1.1 case 1 illustrates, DVC can provide a flatter voltage profile than conventional volt-VAR control devices. In 4.3, using more DVCs could maintain all the voltage within range 0.99pu to 0.01pu which could not achieve by conventional devices.

DVC also performs well while addressing the problems caused by high PV penetration.

- In 4.2.1case 1 shows that DVC can help prevent high voltage violation caused by PV.

- As in 4.2.2 case 2 illustrates, DVC can solve the frequent operations of VR problem by maintaining the voltage at all times regardless of PV output..
- In both 4.2.4 and 4.2.5, DVC provides a fast response to voltage change which ensures voltage within acceptable limit under all conditions.

5.2 Future Work

In my study, DVC is used to replace VRs and fix voltage problems. DVC is designed as closed loop control, using grid voltage as the reference and providing as much Iq as it can to minimize the reference mismatch. But in the simulation, there is no limitation on the size of the DVC (Q_{max}) or ampere rating. In the future, after adding these constrains, DVC may not regulate the voltage at exactly the desired value limited by Q_{max}. As a result, a centralized intelligent control system is needed. An attempt could be made to recreate similar algorithms for optimal placement of DVCs in the distribution system.

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- How to Make Motors reach stable state before the insolation decreases.

As the VRs have 30s and 40s time delay, we choose 80s as start-up time. Node 890 has a very low voltage and motor at this node is hard to reach stable with low PV penetration, so we need capacitors as auxiliary (Figure A.1). And we also increase the torque of the motor gradually to ensure it doesn’t cause a huge voltage drop (Figure A.2).

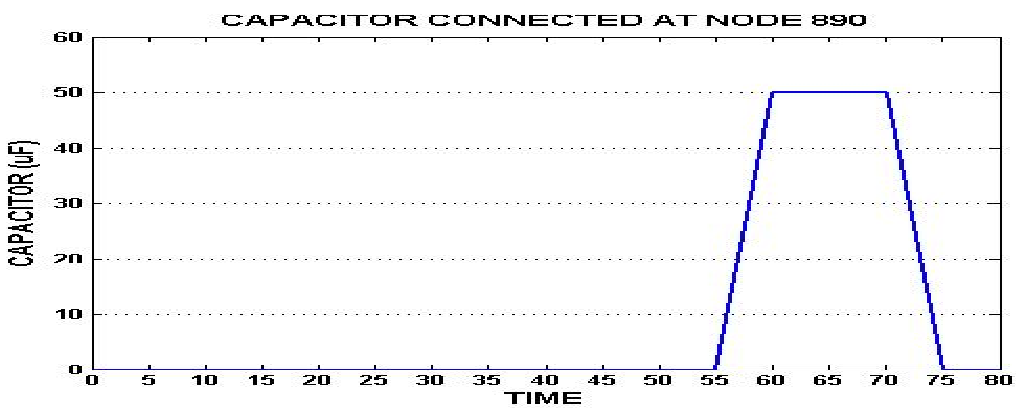

Figure A.1Capacitor connected to Phase A of node 890

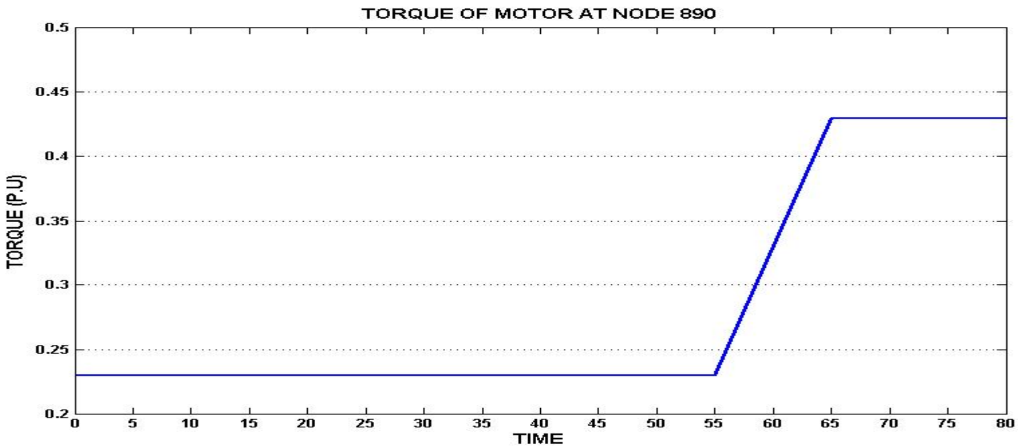

Figure A.2 Torque of Motor at node 890